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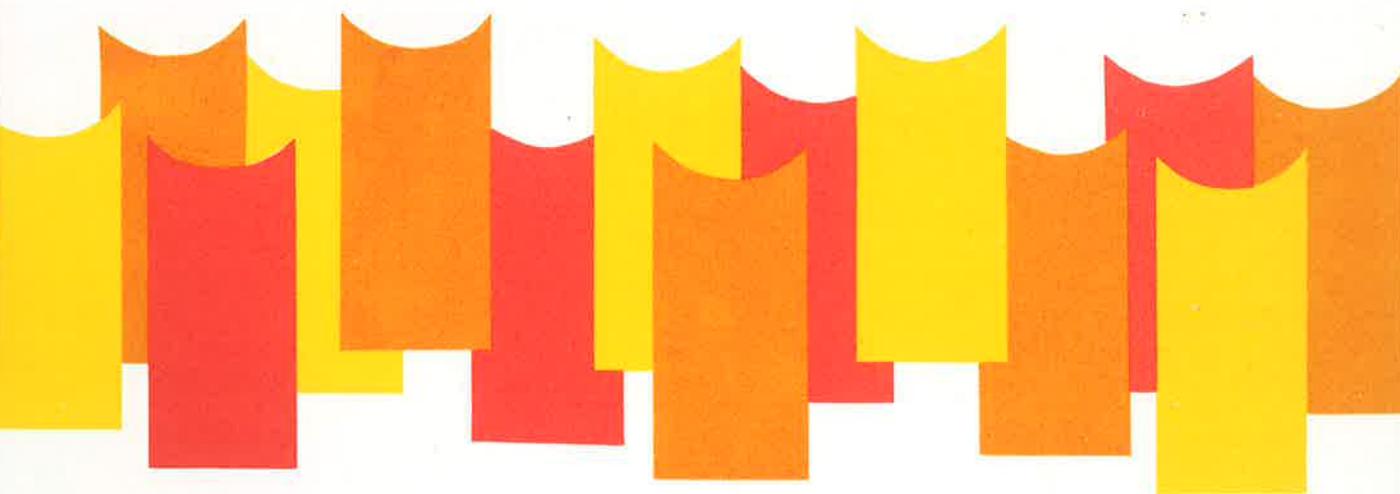
No. 51

Handbook on Estimating Dissolved Oxygen Depletion in Polluted Rivers

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HANDBOOK ON ESTIMATING DISSOLVED OXYGEN DEPLETION IN POLLUTED RIVERS

by

G. B. McBride and J. C. Rutherford

Water Quality Centre,
Ministry of Works and Development,
Hamilton, New Zealand

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ABSTRACT

This handbook briefly describes the mechanisms causing oxygen depletion in polluted rivers. A description is given of a simple model (Streeter-Phelps) that can be used to make preliminary estimates of either river dissolved oxygen concentrations or the assimilative capacity of a river. Extensions of this simple model to allow for benthic oxygen demand, and aquatic plant photosynthesis and respiration are given. Procedures and data requirements for calibrating and verifying the models are described. The model equations can be solved using either the nomographs or the calculator and mini-computer programs supplied. Worked examples demonstrate their use.

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CONTENTS

TABLES

FIGURES

1 INTRODUCTION

1.1 Scope of this Handbook

Problems of excessive depletion of river dissolved oxygen (DO) can often be traced to the discharge of waste organic matter. Depletion may also occur because of the activity of aquatic plants. Although a full description of the processes determining river dissolved oxygen concentration is a formidable task, relatively simple methods can sometimes be used to provide a useful estimate of the extent of oxygen depletion. These methods make use of simple mathematical models. This Handbook documents several such methods and indicates, by worked examples, how they may be applied. Indications of the amount and type of field work required are also given.

Simple mathematical models are useful for making preliminary estimates of the potential impact of an effluent on the DO of a river. Such estimates may indicate that an effluent will not have an adverse effect on river water quality. In this case the discharge may be permitted provided it will not have an adverse impact on other river water quality standards (e.g., appearance, bacterial concentration, temperature). On the other hand the estimate may indicate that further investigation, involving field work and more sophisticated modelling, is justified.

This Handbook considers only simple models that may be solved with nomographs, programmable calculators or small mini-computers. Such models are considered adequate for making preliminary estimates of potential dissolved oxygen depletion. Full details of more sophisticated models which include the effects of unsteady discharge and dispersion are not given here. These latter models are not necessary for making preliminary estimates; it is anticipated that they will be described more fully in a future revision of this Handbook.

1.2 Constructing a Model

In considering the impact of effluent discharge one needs some means of transforming known information on the river and effluent into an estimate of downstream DO. This can best be achieved by using a mathematical model that is based on mathematical descriptions of the important physical and biochemical processes. (Experience has shown that empirical models are of only limited use and that physical models are not feasible for most problems of DO depletion in rivers). Sometimes a combination of several different mathematical models is used on the one problem; a very simple model being used initially, with greater sophistication being introduced if required. Figure 1.1 gives the sequence of events which is used to determine the impact of an effluent on river DO. Note that the decision on whether a mathematical model is required is made on the basis of the empirical "model" that if the river five day biochemical oxygen demand (BOD_5) concentrations are below say 2 g.m.$^{-3}$ then serious DO depletion is unlikely.

In this Handbook it is recommended that investigations of effluent impact commence with a simple model, the basic Streeter-Phelps model which is described in Chapter 2. Some management problems can be solved satisfactorily with this model, and useful insights into many other problems can be gained by first attempting to fit this model. However, if the basic Streeter-Phelps model cannot be verified, or if the effects of aquatic plants are to be included, some modification to the model must be used as is discussed in Chapter 3. Additional field, laboratory and modelling work will then be required.
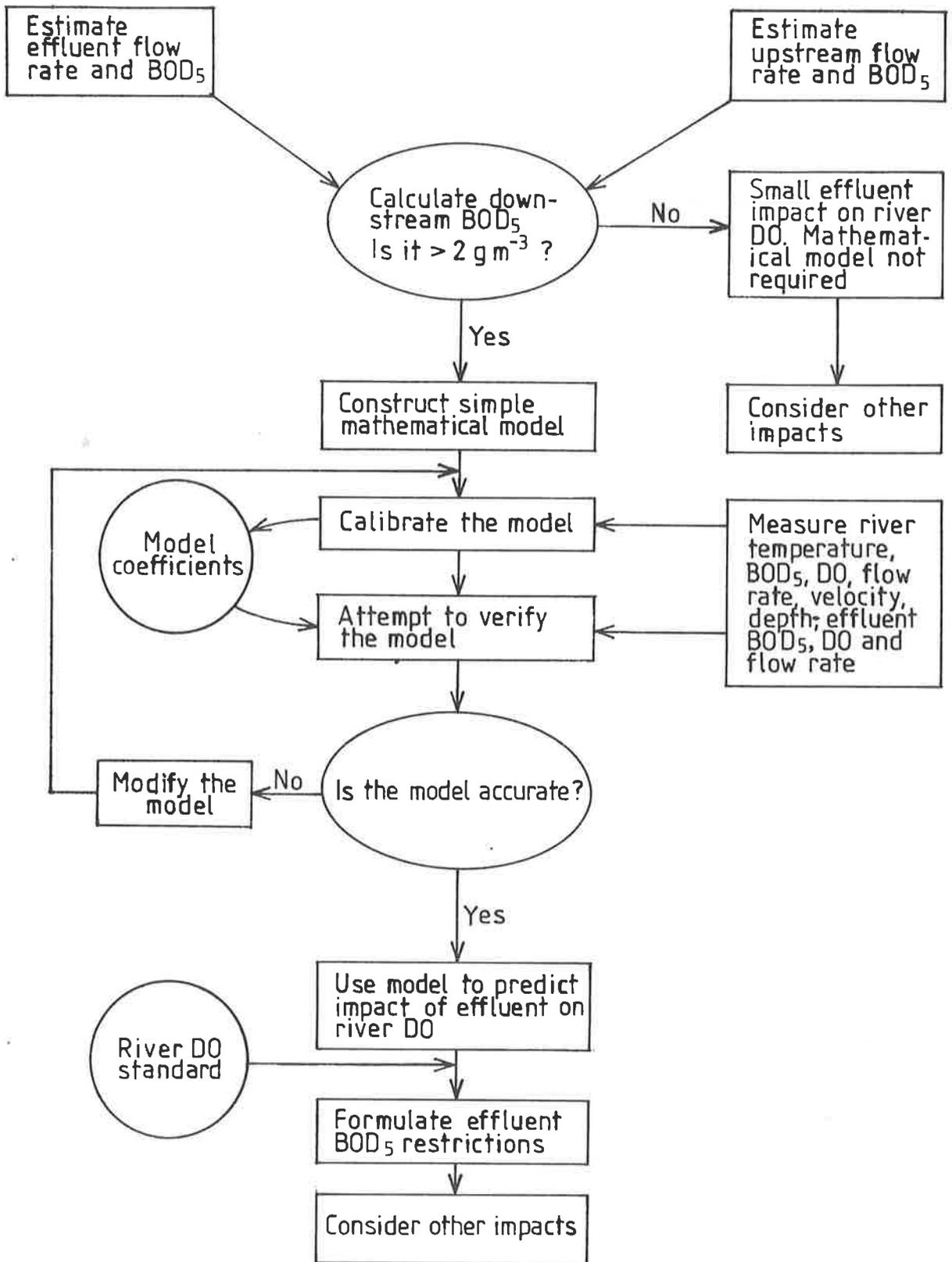
FIG. 1.1 Steps and information required to assess the impact of an effluent on river dissolved oxygen.

1.3 Processes Operating

It is necessary that a mathematical model should take account of the important oxygen transfer processes occurring. Among the many processes in a river carrying waste organic matter, local and overseas experience has identified those of major importance as listed in Table. 1.1

Table 1.1 Important oxygen transfer processes

(1) Always important	(2) Sometimes important	(3) Rarely important or importance unknown in New Zealand
Advection	Benthic BOD exertion	Benthic BOD supply from resuspension of mud
Inflows	Aquatic plant metabolism	Nitrogenous BOD exertion
Reaeration		Dispersion
Aquatic BOD exertion		

Advection is defined as the downstream transport of river water at the mean cross-section velocity. Tributary inflows of unpolluted water may provide significant DO and also dilute the BOD of polluted river water. Polluted tributaries and waste inflows increase river BOD and/or decrease river DO. Reaeration is a physical process that occurs whenever river water is depleted in oxygen; oxygen is transferred, by diffusion, from the atmosphere into the river water. Aquatic BOD exertion refers to the oxygen consumed by planktonic organisms engaged in breaking down complex organic material to simple compounds. Oxygen consumption arises principally from the exertion of "carbonaceous" BOD in which organic carbon material is broken down, ultimately to carbon dioxide. In some situations a further "nitrogenous" oxygen demand is exerted by nitrogen compounds such as ammonia when they are oxidised to nitrate. Although known to be important in UK and USA rivers, nitrogenous BOD exertion has not been quantified in New Zealand.

Benthic BOD exertion refers to the action of organisms resident on the river bed and banks. Aquatic plants consume oxygen continuously in respiration but in the presence of sunlight also produce oxygen by photosynthesis. The result is a net production of oxygen during daylight, but a consumption at night; consequently in some rivers DO levels vary throughout the day being highest in late afternoon and lowest in early morning.

Benthic BOD supply from mud resuspension is probably important in slow-flowing regions of some New Zealand rivers (e.g., in the Hauraki Plains), but has yet to be investigated in any detail. Dispersion is only important when inflows vary rapidly with time, for example, during a slug discharge of BOD.

The basic Streeter-Phelps model described in Chapter 2 includes only the items in column (1) of Table 1.1. The modified Streeter-Phelps model described in Chapter 3 also includes the effects of items in column (2).

1.4 Preliminary Modelling

In the authors' experience it is desirable when tackling a river DO problem to begin by making a preliminary examination using the simplest possible model together with approximate model coefficients derived from the literature and any suitable data that are already available (full data requirements are described in Section 2.2). Such a "desk study" is often valuable in deciding how important the problem is, what processes are likely to be operating, and what field data need to be gathered in order to develop an accurate model. With reference to Fig. 1.1, for preliminary modelling few (if any) field surveys are conducted and model coefficients (e.g., deoxygenation and reaeration coefficients) are estimated from past experience. It is often appropriate to choose "worst case" conditions of low river flow,

maximum river temperature and maximum waste discharge when making preliminary predictions in order to assess whether further investigation is justified. Since model coefficients may not be known accurately, it is desirable to make predictions using a range of different values.

1.5 Model Calibration

Once a preliminary "desk study" has been conducted and a decision made that further investigation is justified, then it is necessary to calibrate the model properly.

Calibration is the process whereby values of the model coefficients are estimated. There are few hard and fast rules about how to estimate the values of model coefficients. Some coefficients can be measured directly while others which cannot easily be measured must be adjusted until a good match is obtained between observations and model predictions.

It is common practice to test the sensitivity of the model to changes in coefficient values. This identifies the "critical" coefficients so that laboratory and field surveys can concentrate on refining the estimates of these coefficients while paying less attention to other model coefficients, and helps to quantify the uncertainty in model predictions.

1.6 Model Verification

Verification follows calibration and is designed to check the validity of the model for prediction. In verification, the calibrated coefficient values are "frozen" and used together with a set of river data *different from that used in calibration* to see how well the observations and predictions match. If good agreement is obtained the model is verified. It must be stressed that river data used for verification must be a different set from that used in calibration. Also the model is strictly only verified for environmental conditions similar to those pertaining to the calibration/verification data.

1.7 Prediction

Predictions are made using a verified model, usually for the "worst case" of low river flow and maximum river temperature and waste discharge since DO depletion for such conditions is maximal. There are two modes of prediction: prediction of the DO sag curve resulting from known discharges; or prediction of the maximum allowable discharges that will not cause the downstream DO to breach a specified standard (often referred to as calculation of assimilative capacity). In the first case the known discharges are specified and the model is used directly to predict the sag curve. In the second case an indirect trial and error process is usually necessary; a first estimate of allowable discharges is made, the model is used to obtain the sag curve, and then the estimates are refined. This process is continued until a satisfactory solution is obtained. In some simple cases the assimilative capacity can be calculated directly, as shown in Section 2.11.

It should be noted that even a carefully constructed and verified model may not make accurate predictions for environmental conditions significantly different from those under which it was developed. It is, therefore, desirable to have carried out the calibration and verification field work for environmental conditions similar to those requiring study.

2 BASIC STREETER-PHELPS MODEL

2.1 Introduction

This model was first developed by Streeter and Phelps (1925) following work carried out on the Ohio River, U.S.A., and has been used many times since. In its simplest form the model predicts a "BOD decay curve" and a "DO sag curve" downstream from an initial point.
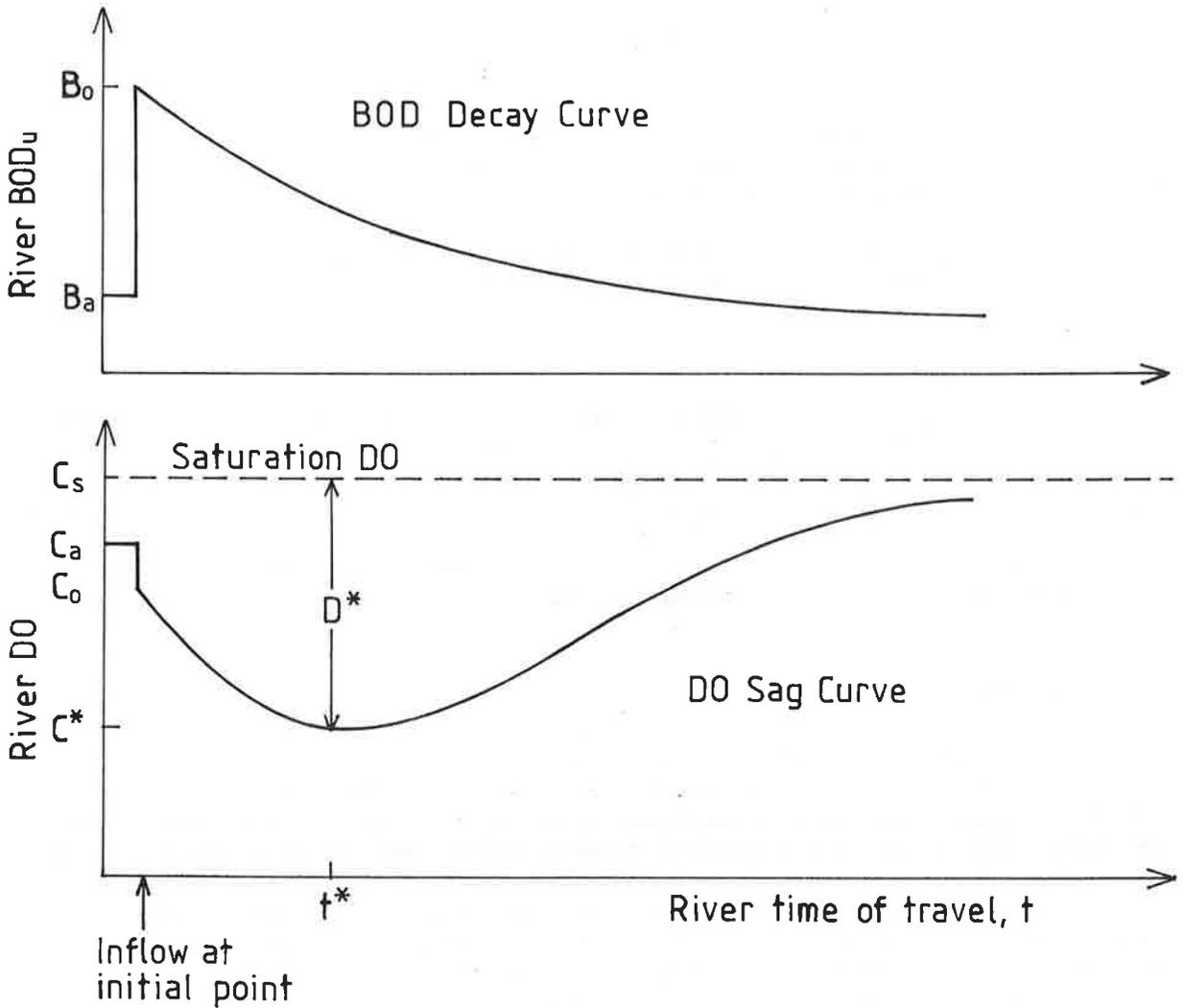
B_a, C_a = river BOD_u and DO just above the inflow
B_o, C_o = initial river BOD_u and DO just downstream from the inflow
C_s = saturation DO
C^*, D^* = critical DO sag and DOD

FIG. 2.1 Typical Streeter-Phelps model solutions: single inflow

These curves are typified on Fig. 2.1 which shows that the river BOD continually decreases downstream from the initial point (where $t = 0$) and the river DO sag reaches its maximum at time-of-travel t^*—the so-called "critical point"—where the river DO is at a minimum. The extent of the sag at the critical point is usually of most concern since that is where environmental stress is greatest.

The basic Streeter-Phelps model assumes that the oxygen balance of any segment of water moving down a river channel is the result of two major competing processes: removal of DO by exertion of BOD, and addition of DO by reaeration. The rate of exertion of BOD and the consequent decrease of DO is assumed to be proportional to the BOD concentration, the constant of proportionality being the deoxygenation coefficient, k_1. It is important to note that the rate of removal of DO is equal to the rate of exertion of the ultimate BOD, BOD_u,

and it is necessary to estimate BOD_u from say BOD_5 measurements using a conversion factor (as discussed in Section 2.4). The rate of reaeration is assumed to be proportional to the DO deficit (DOD)†, the constant of proportionality being the reaeration coefficient, k_2. Thus the basic Streeter-Phelps model has two important coefficients, k_1, and k_2. An increase in the value of k_1 corresponds to a decrease in the critical DO (C* on Fig. 2.1) and also a decrease in the time-of-travel to the critical point (t* on Fig. 2.1). An increase in the value of k_2 corresponds to an increase in the critical DO and also a decrease in the time-of-travel to the critical point.

The initial BOD_u and DO, B_o and C_o in Fig. 2.1 are calculated assuming that the inflow mixes immediately with the river flow. This is a reasonable approximation because the maximum effect of a waste discharge on river DO appears a considerable distance downstream from the inflow.

The model can also be used for rivers with multiple inflows. All inflows are assumed to be constant (inflow rate and massflow do not vary with time). Even when this is not the case the model may still be useful provided time averages of inflow and river data are used.

Various modifications have been made to the basic Streeter-Phelps model and one which is particularly useful is the inclusion of the effects of benthic oxygen demand. This is discussed in detail in Section 3.2. Inclusion of the effects of benthic oxygen demand introduces an additional coefficient, D_B. The basic Streeter-Phelps model is then a special case of the modified Streeter-Phelps model in which $D_B = 0$. In the interests of conciseness, calculator and mini-computer programs are given in the appendices only for the modified Streeter-Phelps model. The user may specify $D_B = 0$ in order to retain the basic Streeter-Phelps model.

The model equations and their solutions are given in Appendix A. River DO studies almost invariably call for repeated use of a model to assess the effects of alternative coefficient values or alternative loadings. It is, therefore, highly desirable to be able to solve model equations quickly and easily. To facilitate this, example programs for solving the Streeter-Phelps model using HP 41CV and TI 59 calculators are given in Appendix B. A mini-computer program written in BASIC is given in Appendix C.

In some cases simple nomographs for calculating the main features of the basic Streeter-Phelps model solutions may be very helpful. This is particularly so in the case of emergency discharges of waste for which answers are required rapidly. Such nomographs are described in Sections 2.10 and 2.11.

2.2 Data Requirements

The Streeter-Phelps model requires the following 12 items to be specified by the user of the model. The first 9 are "environmental inputs" that may be directly measured from field surveys and laboratory work. The last 3 are the model coefficients, for which estimation procedures are given in later sections. The last of these coefficients is only required for the modified model discussed in Chapter 3.

2.2.1 *Environmental inputs*

(a) **River Temperature,** T (in °C).
(b) **Saturation DO,** C_s (in $g.m^{-3}$). This may be obtained from Table 2.1 for a given river temperature, assuming zero salinity and standard atmospheric pressure.
(c) **Upstream river rate of flow,** Q_a (in $m^3.s^{-1}$). This is the river rate of flow just upstream from the initial point.
(d) **Upstream river BOD_5,** L_a (in $g.m^{-3}$). This is the river BOD_5 just upstream from the initial point.
(e) **Upstream river DO,** C_a (in $g.m^{-3}$). This is the river DO just upstream from the initial point.
(f) **Rate of flow, BOD_5 and DO for each inflow:** denoted by Q_i (in $m^3.s^{-1}$), L_i (in $g.m^{-3}$) and C_i (in $g.m^{-3}$) respectively.

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†Dissolved oxygen deficit concentration (DOD) equals saturation concentration minus DO concentration, i.e., $D = C_s - C$ (refer to Fig. 2.1).

(g) **Laboratory BOD decay coefficient,** k_L (in day^{-1}, base e). This is the standard first order coefficient for BOD exertion in the BOD test. It describes the rate at which BOD is exerted in the test bottle and used to convert BOD_5 to BOD_u for inflow and river samples. Use and estimation of k_L is described in Section 2.4.

(h) **River velocity,** U (in $m.s^{-1}$). This is the mean velocity, assumed constant.

(i) **River mean depth,** H (in m), assumed constant.

Table 2.1 Saturation DO versus temperature (from Wilcock 1982a)

Temperature, T (°C)	Saturation DO, C_s ($g.m^{-3}$)
10	11.29
11	11.02
12	10.77
13	10.54
14	10.30
15	10.09
16	9.86
17	9.66
18	9.46
19	9.27
20	9.09
21	8.91
22	8.73
23	8.58
24	8.41
25	8.26
26	8.10
27	7.95
28	7.81
29	7.68
30	7.55

2.2.2 Model coefficients

(j) **River deoxygenation coefficient,** k_1 (in day^{-1}, base e). This describes the rate at which BOD is exerted in the river. An estimation procedure is given in Section 2.5.

(k) **River reaeration coefficient,** k_2 (in day^{-1}, base e). This describes the rate at which reaeration of the river occurs. An estimation procedure is given in Section 2.6.

(l) **Benthic oxygen demand rate,** D_B (in $g.m^{-3}.day^{-1}$). This describes the rate of uptake of oxygen by benthic organisms. Estimation of D_B is discussed in Chapter 3.

Three points of caution must be made about the model coefficients k_1 and k_2.

First, in the literature the coefficients may be quoted to base e or to base 10. It is imperative that the correct base is identified, otherwise gross errors will ensue. For example, if k_2 is the reaeration coefficient to base e and K_2 is the coefficient to base 10, then $k_2 \approx 2.3 K_2$. The same holds true for k_L and k_1. There is some considerable confusion in the literature on the base of coefficients (made worse by the lack of a uniform notation). Note that Eckenfelder (1970, p. 37) quotes three formulae for k_2; if one checks the original papers cited it is clear that the first formula is the base e, whilst the second and last are to base 10. Also, Fair et al. (1968, p. 33–21) use a value of k_2 that may be shown to be to base 10 in a model that requires the coefficient to base e. *This Handbook deals exclusively with coefficients to the base e.*

Second, the k_L and k_1 coefficients should never be confused. As noted above, the first describes BOD exertion *in the BOD test bottle,* while the second describes BOD exertion *in the river.* Early literature on DO modelling (e.g., Phelps 1944) has tended to use k_L as the river deoxygenation coefficient with some success, but this can be explained by the fact that early work was done on large rivers, such as the Ohio, for which one might expect k_1 and k_L to be similar. For smaller rivers k_1 normally exceeds k_L since organisms on the bed and banks of the river have a greater opportunity for "contact" with the organic matter in the river water.

Third, Fair (1939) coined the use of the term river "self-purification constant", defined by $f = k_2/k_1$, and gave a table of f values for sluggish rivers up to rapids and waterfalls. This table has been taken up in subsequent texts, e.g., Fair *et al.* (1968). In the authors' opinion this table is *entirely inappropriate for New Zealand conditions* and will give misleading results, especially when applied to small rivers. This is because the values of k_1 and k_2 used to devise the table are not appropriate for New Zealand rivers.

2.3 Calculation of DO Sag Curve

Procedures given in this section refer to the programmable calculator and mini-computer programs given in Appendices B and C.

2.3.1 Single inflow

The procedure is:
(a) Specify the river temperature, T, in the reach being modelled.
(b) Calculate the saturation DO, C_s, from Table 2.1.
(c) Specify the upstream river rate of flow, BOD_5, and DO;
    Q_a, L_a, C_a.
(d) Specify the inflow rate of flow, BOD_5, and DO; Q_i, L_i, C_i.
(e) Specify the laboratory BOD decay coefficient, k_L, and so convert the upstream river BOD_5, L_a, to upstream river BOD_u, B_a, and the inflow BOD_5, L_i, to inflow BOD_u, B_i, using the method given in Section 2.4.
(f) Calculate the initial river rate of flow, BOD_u and DO (Q_o, B_o and C_o) using

$$(2.1)$$

$$(2.2)$$

$$(2.3)$$

(g) Estimate the river deoxygenation coefficient, k_1 (see Section 2.5).
(h) Specify the river velocity and depth, U and H, and so estimate the river reaeration coefficient, k_2 (see Section 2.6).
(i) Use the program to calculate river BOD_u, BOD_5 and DO at any point downstream from the initial point.

A worked example using this procedure is given in Section 2.7.1.

2.3.2 Multiple inflows

As described above the model predicts BOD_u, BOD_5 and DO curves downstream from a single inflow. However, the model can be extended without undue difficulty to the situation of multiple inflows. To do this the river is subdivided into several reaches, the boundaries being located at each inflow and/or where a change in a model coefficient occurs. The model is then applied to each reach in turn starting at the most upstream point. This situation is depicted in Fig. 2.2. A worked example is given in Section 2.7.2.

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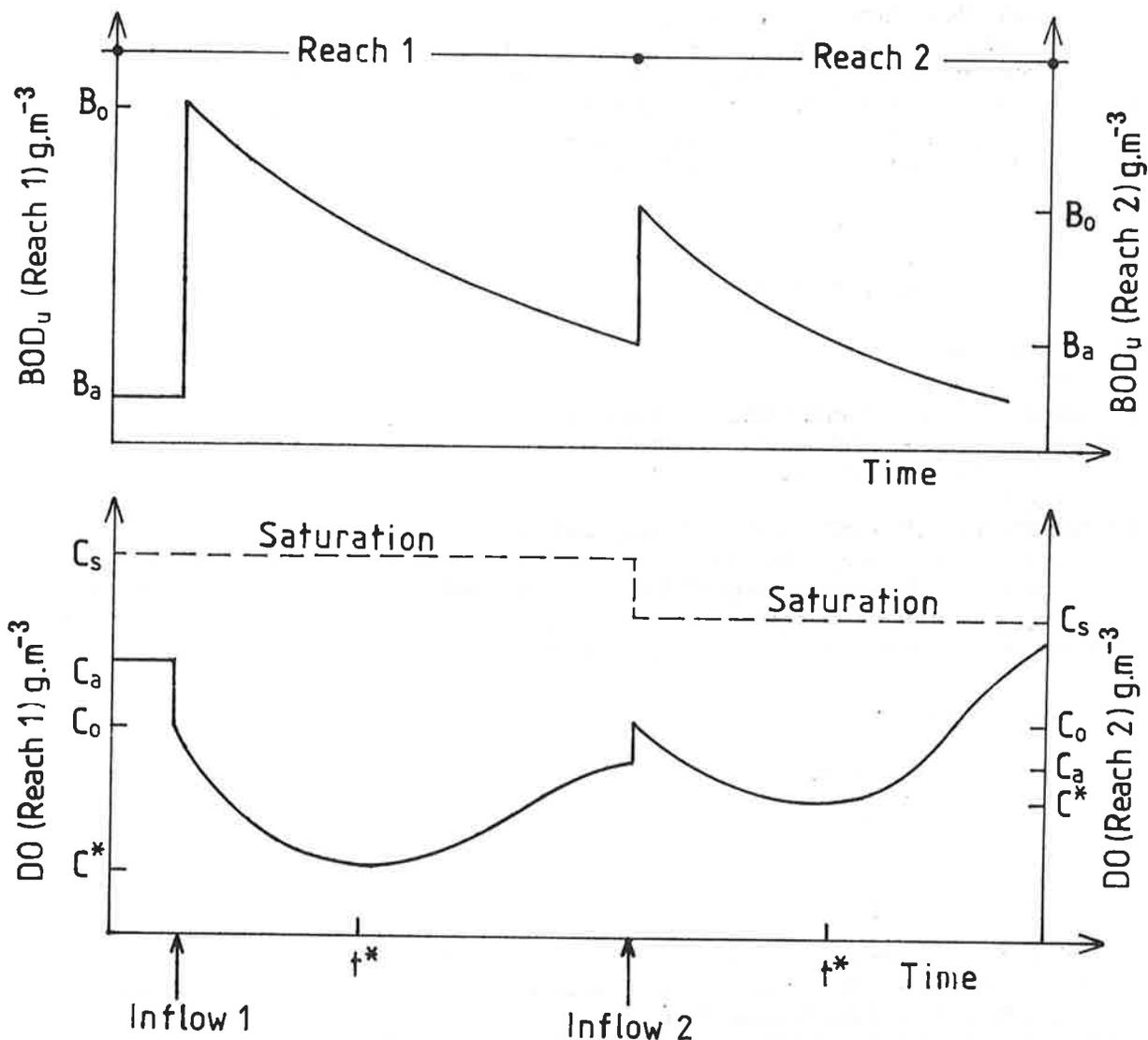
B_a, C_a = river BOD_u and DO just the inflow
B_o, C_o = initial river BOD_u and DO just downstream from the inflow
C_s = saturation DP
C^*, D^* = critical DO sag and DOD

FIG. 2.2 Typical Streeter-Phelps model solutions: multiple inflows

Legend: refer Fig. 2.1.
Note: (a) Model is first applied to Reach 1 and then to Reach 2.
(b) For Reach 2, B_a and C_a are given by model results at the downstream end of Reach 1.
(c) For Reach 2, any model coefficient and/or environmental factor (e.g., temperature, saturation DO, velocity etc.) may change from that applicable in Reach 1.

2.4 Conversion of BOD_5 to BOD_u

For a given k_L the ratio of BOD_u to BOD_5, α, required by the Streeter-Phelps model, can be read from Fig. 2.3.

A variety of methods for estimation of k_L have been developed and these are described in various texts (Phelps 1944; Fair et al. 1968; Velz 1970; Eckenfelder 1970; Nemerow 1974). These methods all employ a series of tests requiring the BOD of similar samples over different time intervals. It will not generally be necessary to carry out laboratory work to estimate k_L; this has already been done for river waters and a number of wastes in New Zealand, and these results are reasonably transferable. A summary of these results for wastes and river waters is given in Table 2.2.
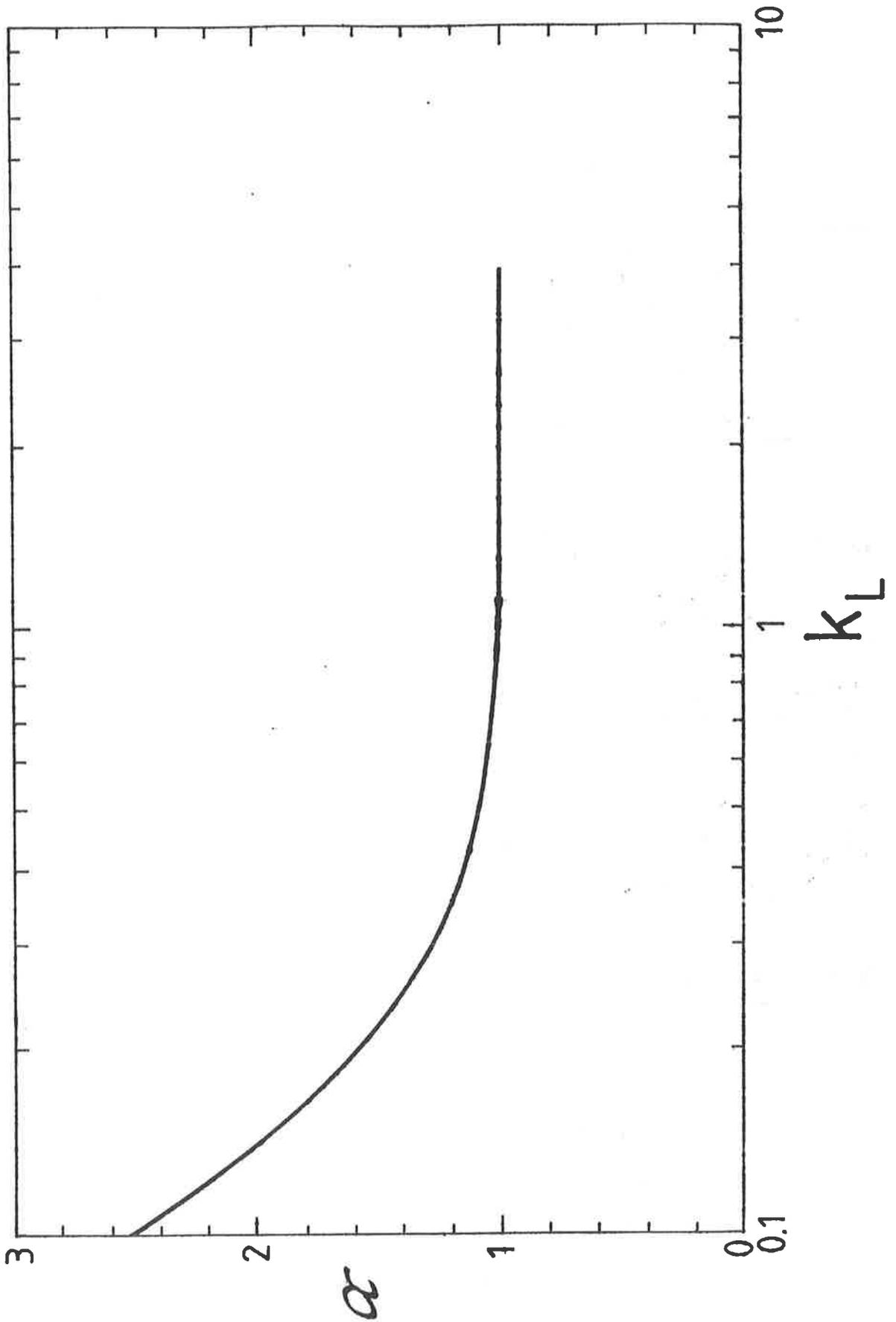
FIG. 2.3 Graph of BOD_u:BOD_5 (α) versus k_L (from McBride 1982b and reproduced by permission of the Journal, Water Pollution Control Federation).

Table 2.2 Laboratory BOD decay coefficient values

Sample	k_L (day^{-1})	Reference
Sewage (primary treatment)	0.23	Cameron (1982)
Dairy factory wastes (raw)	0.44 – 0.62	Barnett *et al.* (1982)
Meatworks wastes (primary treatment)	0.45 – 0.60	Heddle (1982)
Pulp and paper mill wastes (primary treatment)	0.35	M. Piper (Tasman Pulp & Paper Co. *pers. comm.*)
Pulp and paper mill wastes (secondary treatment)	0.25	M. Piper (Tasman Pulp & Paper Co. *pers. comm.*)
Piggery wastes (primary treatment)	0.5 – 0.8	J. Nagels (MWD *pers. comm.*)
Piggery wastes (secondary treatment)	0.37	J. Nagels (MWD *pers. comm.*)
River waters (Waikato and Waipa)	0.4	J. Nagels (MWD *pers. comm.*)

This table shows that k_L can be interpreted as a measure of the stability of these wastes; increasing the degree of treatment leads to a lowering of k_L. The value for New Zealand sewage is consistent with overseas data for sewage; it corresponds to that given by Velz (1970) as the "normal" value of this coefficient. The value for river waters is higher than expected by reference to the literature; explanation of this difference must await the results of studies currently under way.

Table 2.2 and Fig. 2.3 are used to determine a value of α. The conversion of BOD_5 to BOD_u is then achieved by

$$B = \alpha L \qquad (2.4)$$

where B is BOD_u and L is BOD_5.

The procedure is thus:
(a) select k_L from Table 2.2;
(b) determine α from Fig. 2.3;
(c) calculate BOD_u from Eq. 2.4.

2.5 River Deoxygenation Coefficient, k_1

For a preliminary "desk study" this coefficient can be estimated from the range of values observed in other New Zealand rivers (see Table 2.3).

Table 2.3 Values of deoxygenation coefficients in several New Zealand rivers

River	Typical low flow (m^3.s^{-1})	k_1 (day^{-1})	Reference
Tarawera	25	5.2†	Piper (1982), McBride (1982a)
Manawatu	20	0.7 – 12*	Currie and Rutherford (1982)
Mataura	14	2†	McKenzie and McBride (1982)
Waipa	20	0.7†	McBride and Rutherford (1982)
Waikato	180	1.2 – 1.8†	Rutherford (1982)
Waikato	180	0.6 – 0.8†	Rutherford (1982)

†Estimated by model calibration and verification using river DO and BOD_5.
*Using river BOD_5 only. There is evidence that BOD_5 was stored but not exerted and hence these may be overestimated.

The high k_1 value for the Tarawera River is attributable to the large population of bacteria resident on the pumice sediments of this shallow river. For the Manawatu River, high k_1 values occur in reaches where large crops of sewage fungus occur. The usual value of k_1 for the Waikato River appears to be 1.2 – 1.8 day^{-1}; the last entry in Table 2.3 refers to a study made on the Waikato River during passage of large quantities of milk dumped into the river in March 1979. It is thought that the coefficient was lower for this study because the river was not sustaining a sufficient population of bacteria to break the milk down.

Some rivers may be modelled using a single value of k_1 over their entire length (e.g., the Waipa River) while others require a different k_1 for separate river reaches (e.g., the Manawatu River). The value of k_1 may also vary substantially with time (e.g., in the Manawatu River k_1 is thought to depend on the amount and activity of sewage fungus, both of which vary with time).

A caveat must be made concerning the k_1 values tabulated above; they are influenced to some extent by the assumptions made in the models used in their estimation (notably the α, k_2 and D_B values used). Consequently the above estimates should be considered only as approximate guidelines.

2.6   River Reaeration Coefficient, k_2

For most studies this coefficient can be estimated satisfactorily using an empirical equation. Such equations have been derived from laboratory and field data and express k_2^{20} (at 20°C) as a function of stream velocity, U ($m.s^{-1}$), and depth, H(m). The equations listed here for k_2 all refer to 20°C, and values at other temperatures in the range 10–30°C may be calculated using

$$k_2 = 1.024^{T-20} k_2^{20} \tag{2.5}$$

Because equations for k_2 are derived empirically, over limited ranges of flow conditions, care should be taken to ensure that the stream conditions match those used to derive the coefficient. The following equations may be used to calculate k_2^{20} (day^{-1}), in conjunction with Table 2.4 (from Wilcock 1982b).

$$k_2^{20} = 3.74 \ \sqrt{U}/H^{1.5} \tag{2.6}$$

$$k_2^{20} = 5.01 \ U^{0.969}/H^{1.673} \tag{2.7}$$

$$k_2^{20} = 4.75 \ U/H^{1.5} \tag{2.8}$$

$$k_2^{20} = 5.13 \ U/H^{1.33} \tag{2.9}$$

Table 2.4 k_2 equation numbers appropriate for different river conditions

River Velocity U ($m.s^{-1}$)	River Depth, H(m)		
	0.2–0.5	0.5–1.0	> 1.0
0.1 – 0.5	(2.6)	(2.6)	(2.6)
0.5 – 2.0	(2.9)	(2.8)	(2.7)

Note that Eqs. 2.6–2.9 are only valid for U in units of metres per second and H in units of metres.

2.7   Worked Examples

In the following worked examples we follow the procedure of Section 2.3. The tables, figures and equations that are used in the procedure have been grouped together in Appendix D, for convenience.

17

2.7.1 Single inflow of dairy factory waste

Take a river with temperature T = 22°C, so that the saturation DO is, from Table 2.1, C_s = 8.73 g.m^{-3}. The upstream river rate of flow, BOD$_5$ and DO are Q_a = 4.9 m^3.s^{-1}, L_a = 1.3 g.m^{-3} and C_a = 8.6 g.m^{-3} respectively. The inflow data are Q_i = 0.1 m^3.s^{-1}, L_i = 210 g.m^{-3} and C_i = 3.6 g.m^{-3}. For the river water k_L = 0.4 day^{-1} from Table 2.2 so that, from Fig. 2.3, α = 1.16 and from Eq. 2.4 the upstream BOD$_u$ is $B_a \simeq$ 1.5 g.m^{-3}. For the waste take k_L = 0.5 day^{-1} from Table 2.2 (the median value for dairy factory waste) so that, from Fig. 2.3, α = 1.09 and, from Eq. 2.4, the inflow BOD$_u$ is B_i = 1.09 × 210 ≃ 230 g.m^{-3}. Eqs. 2.1 − 2.3 then give initial values of Q_o = 5 m^3.s^{-1}, $B_o \simeq$ 6 g.m^{-3}, C_o = 8.5 g.m^{-3}.

Assume that the river deoxygenation coefficient has been calibrated at $k_1 \simeq$ 2 day^{-1}. The river velocity and depth are U = 0.4 m.s^{-1} and H = 1.5 m for which Table 2.4 indicates that Eq. 2.6 should be used to estimate the reaeration coefficient. Therefore k_2 = 1.024^2 × 3.74 × $\sqrt{0.4}$/1.5 $^{1.5}$ ≃ 1.35 day^{-1}.

Using the calculator programs in Appendix B the results summarised in Table 2.5 were obtained.

Table 2.5 Results for example 2.7.1

River Distance (km)	River BOD$_u$, B (g.m^{-3})	River BOD$_5$,L (g.m^{-3})	River DO, C (g.m^{-3})
0	6.00	5.20	8.50
5	4.49	3.87	7.18
10	3.36	2.90	6.43
15	2.52	2.17	6.08
19	2.00	1.72	5.98
20	1.89	1.63	5.97
21	1.78	1.53	5.98
25	1.41	1.22	6.04
30	1.06	0.91	6.19
40	0.59	0.51	6.64
50	0.33	0.29	7.10
60	0.19	0.16	7.51
70	0.10	0.09	7.84

In this example the critical point is located 20 km from the initial station (see also Fig. 2.4).

2.7.2 Multiple inflows

In this example take the same river as in case 2.7.1 but also with
   (i) a meatworks waste inflow at 10 km where
      Q_i = 0.15 m^3.s^{-1}, L_i = 100 g.m^{-3} and C_i = 0 g.m^{-3};
   (ii) a change in river depth from H = 1.5 m to H = 1.8 m, at 25 km;
   (iii) a tributary inflow at 30 km where
      Q_i = 1 m^3.s^{-1}, L_i = 1 g.m^{-3}, C_i = 8.7 g.m^{-3}. The temperature of the tributary water is 22°C.

Before proceeding we must calculate the BOD$_u$ for these new inflows. For the meatworks waste we take a median value of k_L = 0.5 day^{-1} from Table 2.2 and so, from Fig. 2.3, α = 1.09 and, from Eq. 2.4, B_i = 1.09 × 100 = 109 g.m^{-3}. For the tributary we take the same k_L value as for the river (0.4 day^{-1}) and from Fig. 2.3, α = 1.16 and, from Eq. 2.4, $B_i \simeq$ 1.2 g.m^{-3}. We must also compute the change in reaeration coefficient. Table 2.4 still indicates that Eq. 2.6 should be used, so that the reaeration coefficient downstream from 25 km is
   k_2 = 1.024^2 × 3.74 × $\sqrt{0.4}$/1.8$^{1.5}$ ≃ 1.03 day^{-1}

Using the calculator programs in Appendix B the results summarised in Table 2.6 (also graphed on Fig. 2.4) were obtained.

18
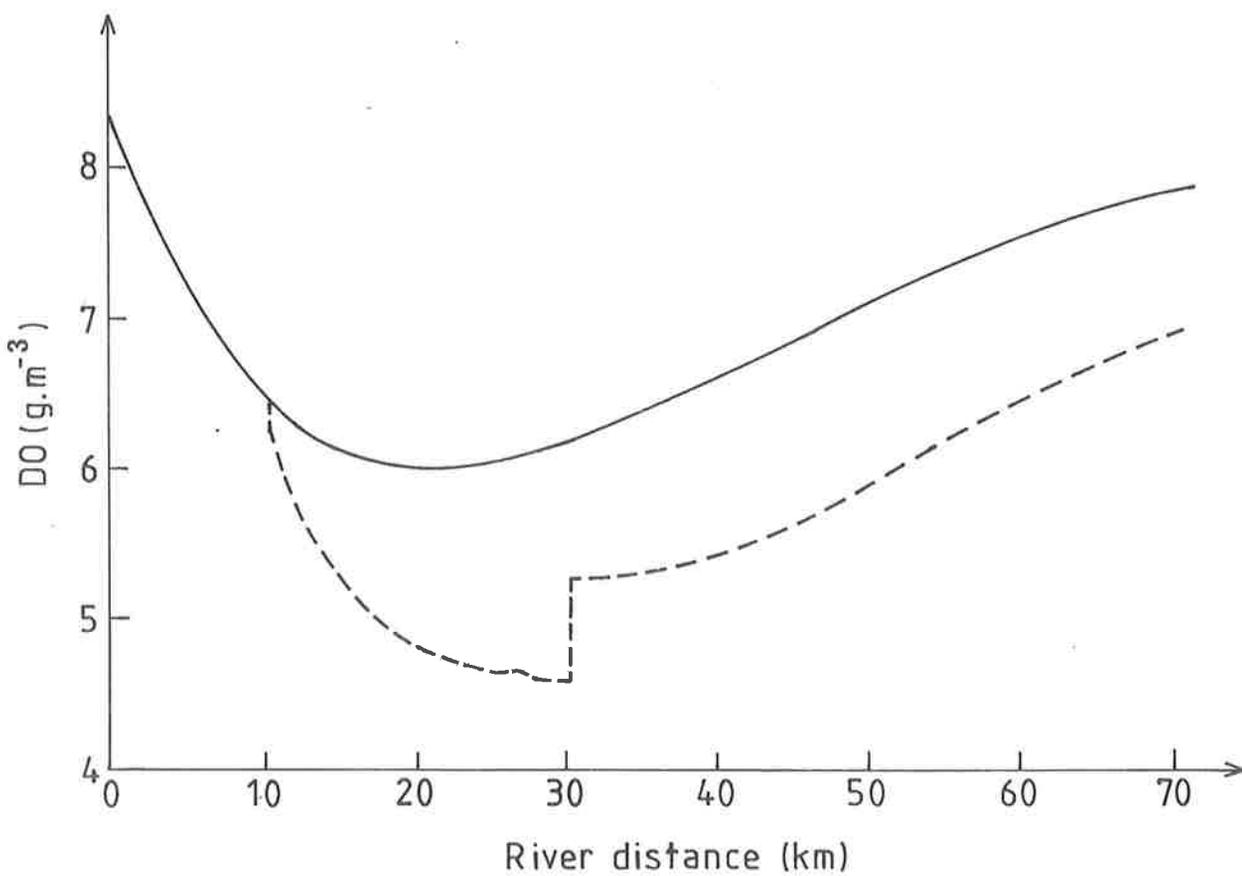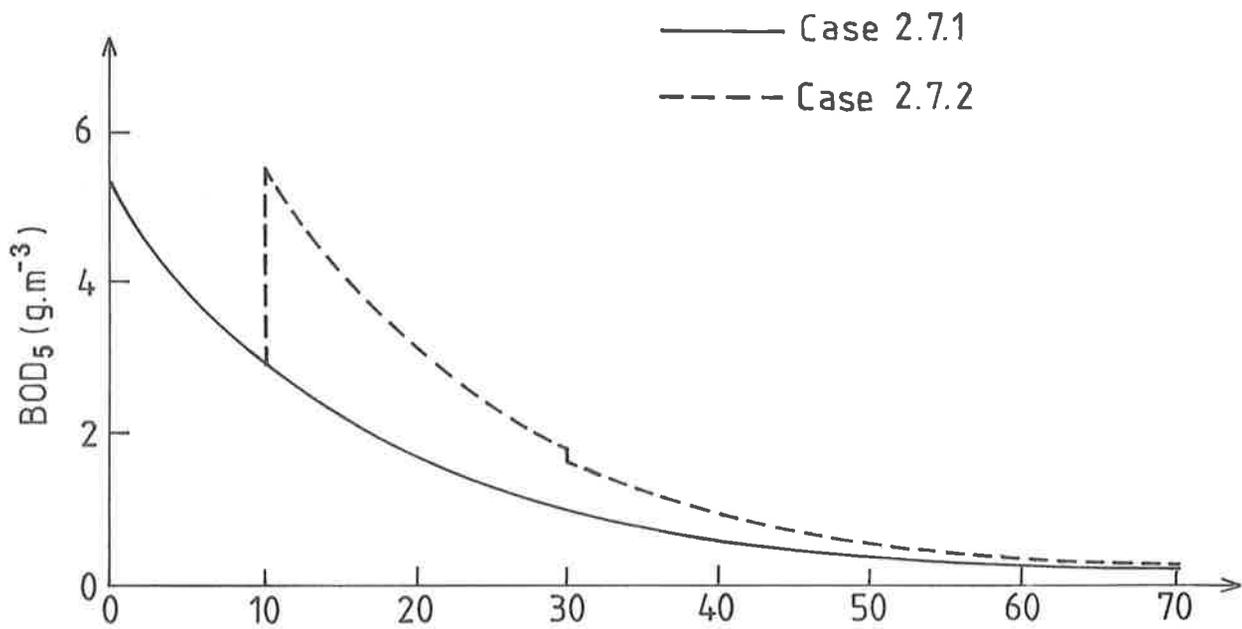
FIG. 2.4 Graph of results for worked examples

Table 2.6 Results for example 2.7.2

River Distance (km)	River BOD_u, B $(g.m^{-3})$	River BOD_5, L $(g.m^{-3})$	River DO, C $(g.m^{-3})$
0	6.00	5.30	8.50
5	4.49	3.87	7.18
10	3.36	2.90	6.43
10†	6.44	5.55	6.25
15	4.82	4.16	5.22
20	3.61	3.11	4.75
24	2.86	2.47	4.64
25*	2.70	2.33	4.64
26	2.55	2.20	4.61
28	2.27	1.96	4.57
29	2.14	1.85	4.57
30	2.02	1.75	4.57
30†	1.89	1.63	5.24
35	1.42	1.22	5.29
40	1.06	0.91	5.43
50	0.59	0.51	5.89
60	0.33	0.29	6.40
70	0.19	0.16	6.87

† Refers to values calculated for full mixing of the inflow with the river water.
* Reaeration coefficient changed at 25 km to 1.03 day^{-1}.

Comparison of the results in Tables 2.5 and 2.6 (as shown on Fig. 2.4) shows that the effect of the meatworks inflow at 10 km is to about double the river BOD_5 and slightly reduce the river DO at the point of inflow. Also the critical point is now located 25 km from the initial station and the DO has been reduced by about 1.3 g.m^{-3}. This critical point occurs just upstream of the point where the river depth increases to 1.8 m. The effect of this depth change is to create another critical point 5 km downstream. At the tributary inflow a substantial addition of DO is obtained by mixing and DO recovery is apparent.

2.8 Preliminary Modelling

As discussed in Section 1.4 it is highly desirable when tackling a new river DO problem to begin by making a preliminary examination or "desk study". The basic Streeter-Phelps model is an ideal tool for doing this. For such a "desk study" it is usually sufficient to use whatever data are already available to estimate the environmental inputs to the model (listed in Section 2.2) and to use literature values for the model coefficients k_1 and k_2 (see Sections 2.5 and 2.6).

There may be a large uncertainty associated with some of the inputs and/or coefficients. It is desirable to select upper and lower bounds for each, make a number of predictions, and hence estimate likely upper and lower bounds for river BOD and DO concentrations. Often "worst case" conditions (i.e., low river flow, maximum river temperature, and maximum waste discharge) will be examined to decide whether a DO problem is likely to occur.

Once a preliminary "desk study" has been undertaken, the results should be examined carefully in the light of management objectives. It may be found that management decisions can be made on the basis of the desk study. In some cases, however, it may be deemed necessary to refine the predictions.

2.9 Model Calibration and Verification

Once a preliminary analysis of the DO problem has been undertaken and a decision has been made that further refinement is justified, then the next step is to undertake a careful calibration of the model (see Fig. 1.1). Note that at this stage modification of the model is probably not justified.

2.9.1 Field work

For calibration it is necessary to undertake the following field work.
(a) Select a period of steady river flow, usually a low flow when DO depletion is most noticeable.

(b) Where possible, select a period when inflows are steady in flow and composition. If this is not feasible (for example, because the inflow shows a marked diurnal variation) then it is necessary to make measurements at regular intervals over a long period (for diurnally varying inflows over at least 24 hours) and average the results obtained.

(c) Measure river temperature over the reach being modelled. It is desirable to make measurements at several locations and times and to average the results.

(d) Measure the average DO and BOD_5 at the upstream end of the reach.

(e) Measure the average flow, DO and BOD_5 of the inflows.

(f) Measure the average river flow, mean depth and mean velocity.

(g) Measure the average DO and BOD_5 concentrations at a number of sites, at least four, downstream from the major inflows. These sites should be selected on the basis of preliminary model calculations so as to describe the DO sag and recovery as completely as practicable. Surface samples should be taken from as close to the thalweg as possible, using bridges, boats or even wading (on small rivers). Do not sample within 20 × river width of a major inflow.

2.9.2 *Model calibration*

Model calibration now involves deriving the combination of coefficients (k_1 and k_2 for the basic Streeter-Phelps model) which gives the best fit between observed and predicted BOD and DO. There are no hard and fast rules about model calibration but the authors have found that the following procedure works fairly well.

(a) Using measured values of U and H, estimate the reaeration coefficient, k_2, from Table 2.4 as described in Section 2.6.

(b) Predict river DO concentrations using a range of k_1 values together with the k_2 value estimated in step (a). Select the value of k_1 which gives the best overall fit between observed and predicted DO concentrations. Goodness of fit can usually be gauged adequately by inspection of a graph of observed and predicted DO.

(c) Predict river BOD_5 concentrations using the k_1 value estimated in step (b), and compare these with observed river BOD_5 concentrations. If the observed and predicted BOD_5 concentrations match fairly closely then calibration has been achieved.

It should be noted that a failure to succeed in step (c) may be because river BOD_5 concentrations do not always accurately reflect concentrations of oxidisable organic matter, especially where waste concentrations are low and large algal populations exist (say, greater than 10^4 cells.cm^{-3}). Consequently it may not always be possible to achieve a good fit between observed and predicted river BOD_5 concentrations. The user must exercise his judgment in attempting to match observed and predicted BOD. River BOD_5 concentrations can normally be measured most accurately where concentrations are high (i.e., close to the outfall) but very close to an inflow (say, less than 20 × river width) mixing may be incomplete and a single sample may give a poor estimate of average concentrations.

2.9.3 *Sensitivity analysis*

Having undertaken calibration as described above it is informative to make predictions of BOD and DO for a range of values of k_1 and k_2. In this manner it is possible to gauge the sensitivity of predictions to uncertainties in the values of these model coefficients so that their likely range of values can be assessed.

2.9.4 *Model verification*

In order to test whether or not the calibrated model can adequately predict DO depletion, the model must be verified. This necessitates conducting the same field work as for calibration (see Section 2.9.1) under a different set of river flow and/or inflow conditions. Model coefficients are then "frozen" at their calibrated values and predictions made of river BOD and DO. These are then compared with observed river BOD and DO concentrations and if the fit is considered acceptable the model is said to be verified. If the fit is unacceptable then it is advantageous to undertake a sensitivity analysis (as described in Section 2.9.3) which may indicate that a satisfactory match can be obtained using model coefficients somewhere within their likely range derived during calibration.

Failing this it may be necessary to take account of other factors influencing river DO as described in Chapter 3.

2.10 Nomographs for Calculation of Location and Magnitude of Critical Oxygen Sag

In some cases it may be sufficient to calculate the location and magnitude of the critical DO sag caused by a particular waste inflow located at the initial point. This may be particularly so when an emergency waste discharge occurs or is contemplated. Simple nomographs may be used to perform these calculations (McBride 1982b), so long as two criteria are met:
- data required by the model (e.g., velocity, temperature, etc.) are constant;
- inflows downstream from the initial point can be neglected.

2.10.1 Procedure

The following procedure is used.
(a) Specify the river temperature, T.
(b) Calculate the saturation dissolved oxygen, C_s, from Table 2.1.
(c) Specify the upstream river rate of flow, BOD_5 and DO; Q_a, L_a, C_a.
(d) Specify the inflow rate of flow, BOD_5 and DO; Q_i, L_i, C_i.
(e) Specify the laboratory BOD decay coefficient, k_L, and so convert the upstream river BOD_5, L_a, to upstream river BOD_u, B_a, and the inflow BOD_5, L_i, to inflow BOD_u, B_i, using the method in Section 2.4.
(f) Calculate the initial river BOD_u and DO using

$$B_o = \frac{Q_a B_a + Q_i B_i}{Q_a + Q_i} \qquad (2.10)$$

$$C_o = \frac{Q_a C_a + Q_i C_i}{Q_a + Q_i} \qquad (2.11)$$

(g) Estimate the river deoxygenation coefficient, k_1 (see Section 2.5).
(h) Specify the river velocity and depth, U and H, and so estimate the river reaeration coefficient, k_2 (see Section 2.6).
(i) Calculate the dimensionless "self-purification constant", f, from
$$f = k_2/k_1 \qquad (2.12)$$
(j) Calculate the initial "deficit-load ratio", R_o, from

$$R_o = \frac{C_s - C_o}{B_o} \qquad (2.13)$$

(k) Using f and R_o read the nomographs on Figs. 2.5 and 2.6 to obtain values of R^* and τ^*.
(l) Calculate the critical DO from
$$C^* = C_s - R^* B_o \qquad (2.14)$$
(m) Calculate the location of the critical point from
$$x^* = 86.4 \frac{U\tau^*}{k_1} \qquad (2.15)$$
where U is m.s^{-1} and k_1 is in day^{-1}.

2.10.2 Worked example

Consider the single inflow case studied in Section 2.7.1, so that
$C_s = 8.73°C$, $B_o = 6$ g.m^{-3}, $C_o = 8.5$ g.m^{-3}, $k_1 = 2$ day^{-1}, U = 0.4 m.s^{-1} and $k_2 = 1.35$ day^{-1}.
From the above procedure, f = 1.35/2 = 0.675 and $R_o = \dfrac{8.73 - 8.5}{6}$
$\simeq 0.04$. From Figs. 2.5 and 2.6, $R^* \simeq 0.46$ and $\tau^* = 1.20$. Using Eqs. 2.14 and 2.15
$C^* = 8.73 - 0.46 \times 6 \simeq 5.97$ g.m^{-3}
$x^* = 86.4 \times 0.4 \times 1.20/2 \simeq 20.7$ km

These answers agree with the calculations made in Table 2.5.

2.11 Nomographs for Calculation of Assimilative Capacity

The Streeter-Phelps river DO model may be used to calculate the maximum allowable waste discharge in order to keep the downstream DO above a specified minimum level. For rivers with multiple waste inflows these maximum allowable discharges may be found by

running the model with numbers of combinations of waste loads from each inflow. For a river with a single waste inflow, located at the initial point, a simple nomograph approach is available (McBride 1982b), so long as two criteria are met:
- data required by the model (e.g., velocity, temperature, etc.) are constant;
- inflows downstream from the initial point can be neglected.

2.11.1 Procedure

The following procedure is used.
(a) Specify the river temperature, T.
(b) Calculate the saturated dissolved oxygen, C_s, from Table 2.1.
(c) Specify the minimum allowable river DO, C^*.
(d) Specify the upstream river DO, C_a.
(e) Set the initial river DO to the upstream river DO*, i.e.,
   $C_o = C_a$.
(f) Specify the laboratory BOD decay coefficient, k_L, and so calculate the BOD_u: BOD_5 ratio, α, for river water (see Section 2.4).
(g) Estimate the river deoxygenation coefficient, k_1 (see Section 2.5).
(h) Specify river velocity and depth, U and H, and so estimate the river reaeration coefficient, k_2 (see Section 2.6).
(i) Calculate the dimensionless "self-purification constant", f, from

$$f = k_2/k_1 \tag{2.16}$$

(j) Calculate the dimensionless initial DO deficit, d_o, from

$$d_o = \frac{C_s - C_o}{C_s - C^*} \tag{2.17}$$

(k) Using f and d_o read the value of b_o from Fig. 2.7.
(l) Calculate the allowable initial river BOD_u from

$$B_o = b_o(C_s - C^*) \tag{2.18}$$

(m) Calculate the allowable initial river BOD_5 from

$$L_o = B_o/\alpha \tag{2.19}$$

2.11.2 Worked example

Consider again the single inflow case studied in Section 2.7.1. Since T = 22°C, Table 2.1 gives C_s = 8.73 g.m^{-3}. The minimum allowable river DO is specified as 6 g.m^{-3}. The given data are C_a = 8.6 g.m^{-3}, α = 1.16, k_1 = 2 day^{-1} and k_2 = 1.35 day^{-1}. From step (e) we take C_o = 8.6 g.m^{-3}.

From the above procedure, then f = 0.675 and $d_o = \dfrac{8.73 - 8.6}{8.73 - 6} \simeq 0.05$

From Fig. 2.7, $b_o \simeq 2.2$. Using Eqs. 2.18 and 2.19, B_o = 2.2 × (8.73 – 6) ≈6.0 g.m^{-3} and L_o = 6.0/1.16 ≃ 5.2 g.m^{-3}.

Note that the predicted initial B_o coincides with that specified for the case in Section 2.7.1. This is as expected since the minimum DO calculated for that case (5.97 g.m^{-3} at 20 km) is very close to the specified minimum for this example (C^* = 6 g.m^{-3}). It should also be noted that this procedure, in step (e), assumes that C_o = C_a. This assumption is necessary because C_o cannot be specified in advance. However, for all but very large anoxic discharges (e.g., Tasman's pulp and paper mill waste to the Tarawera River) this is a reasonable assumption.

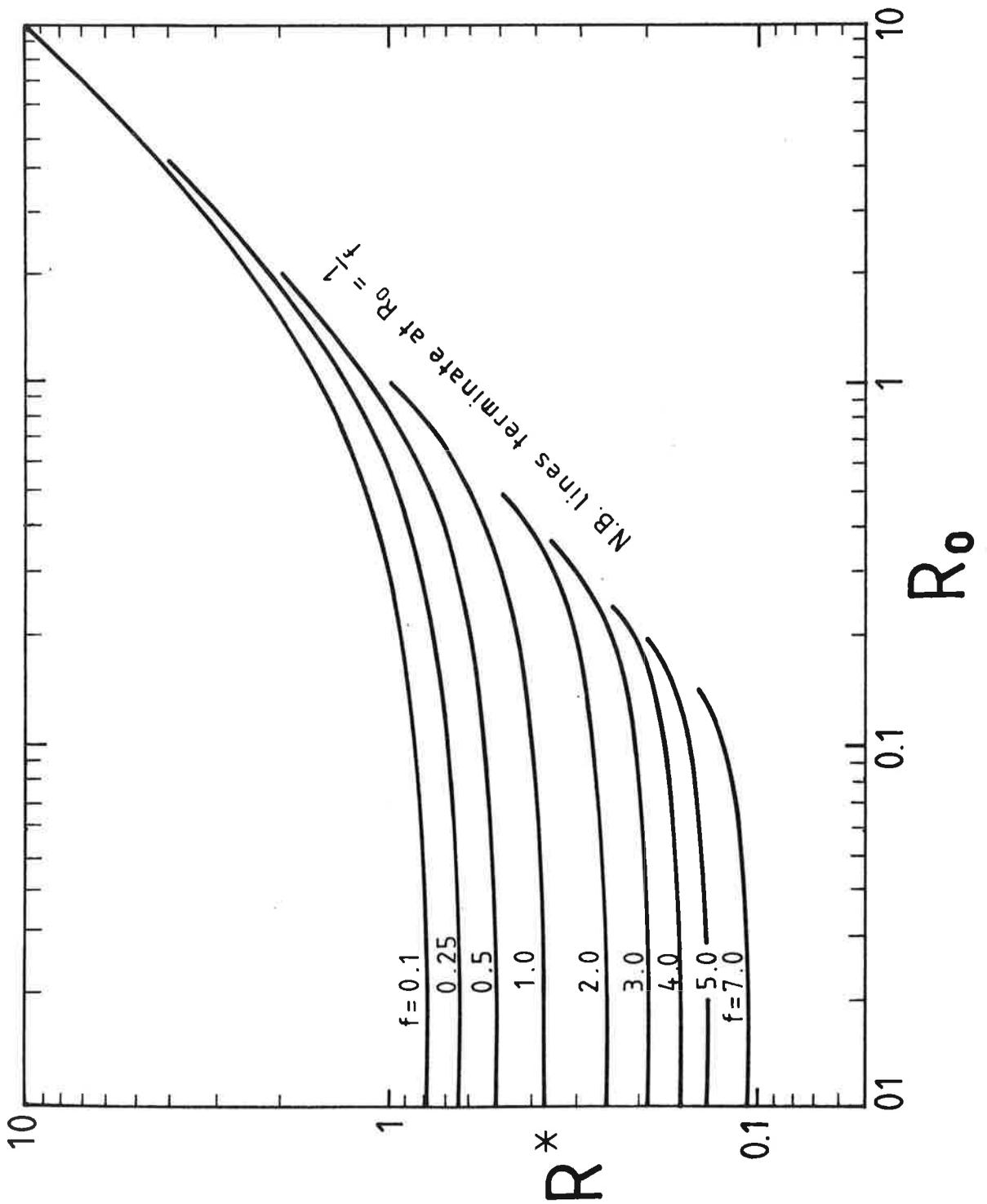**FIG. 2.5** Deficit nomograph (from McBride 1982b and reproduced by permission of the Journal, Water Pollution Control Federation)
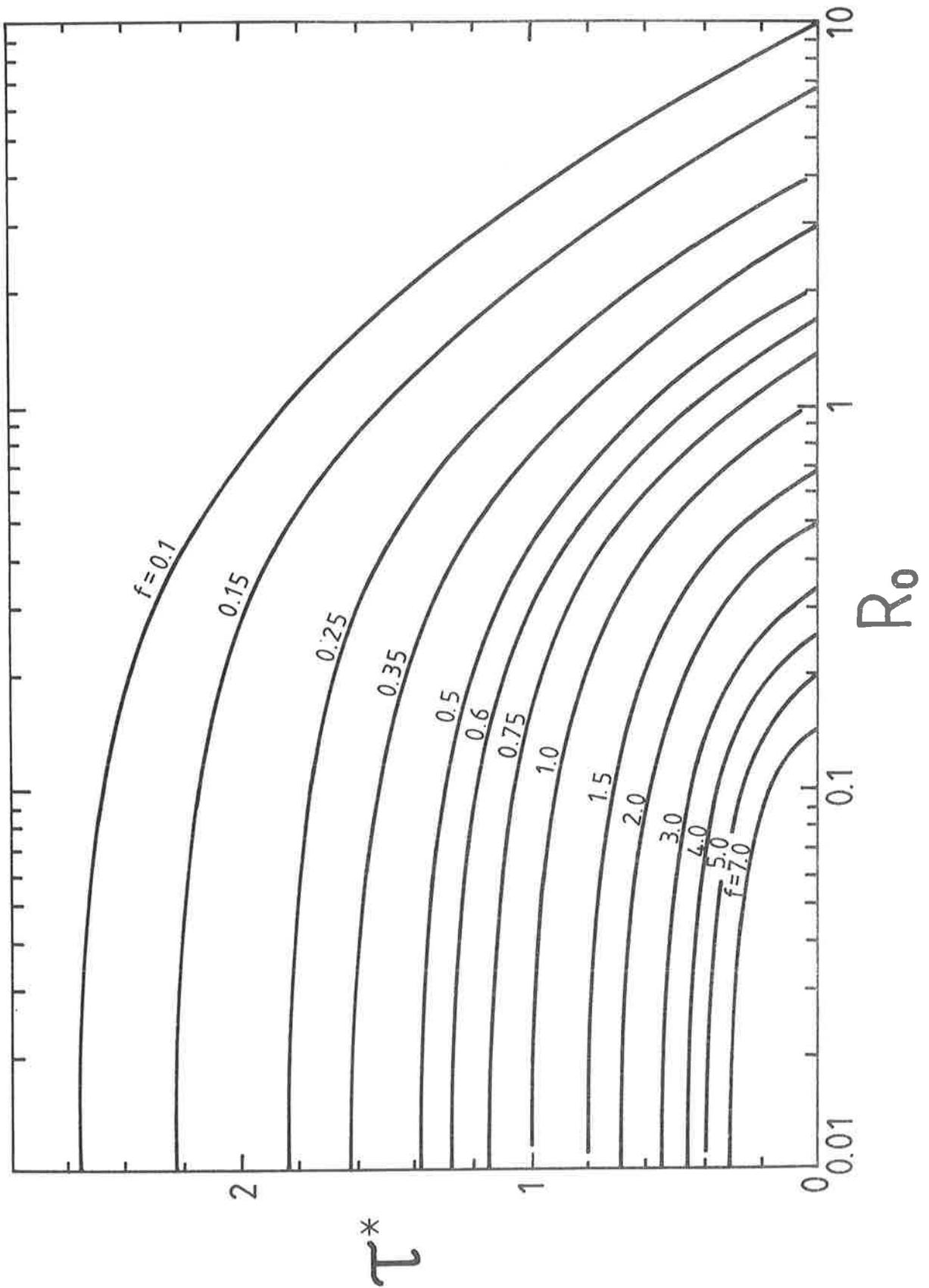
FIG. 2.6 Location nomograph (from McBride 1982b and reproduced by permission of the Journal, Water Pollution Control Federation)
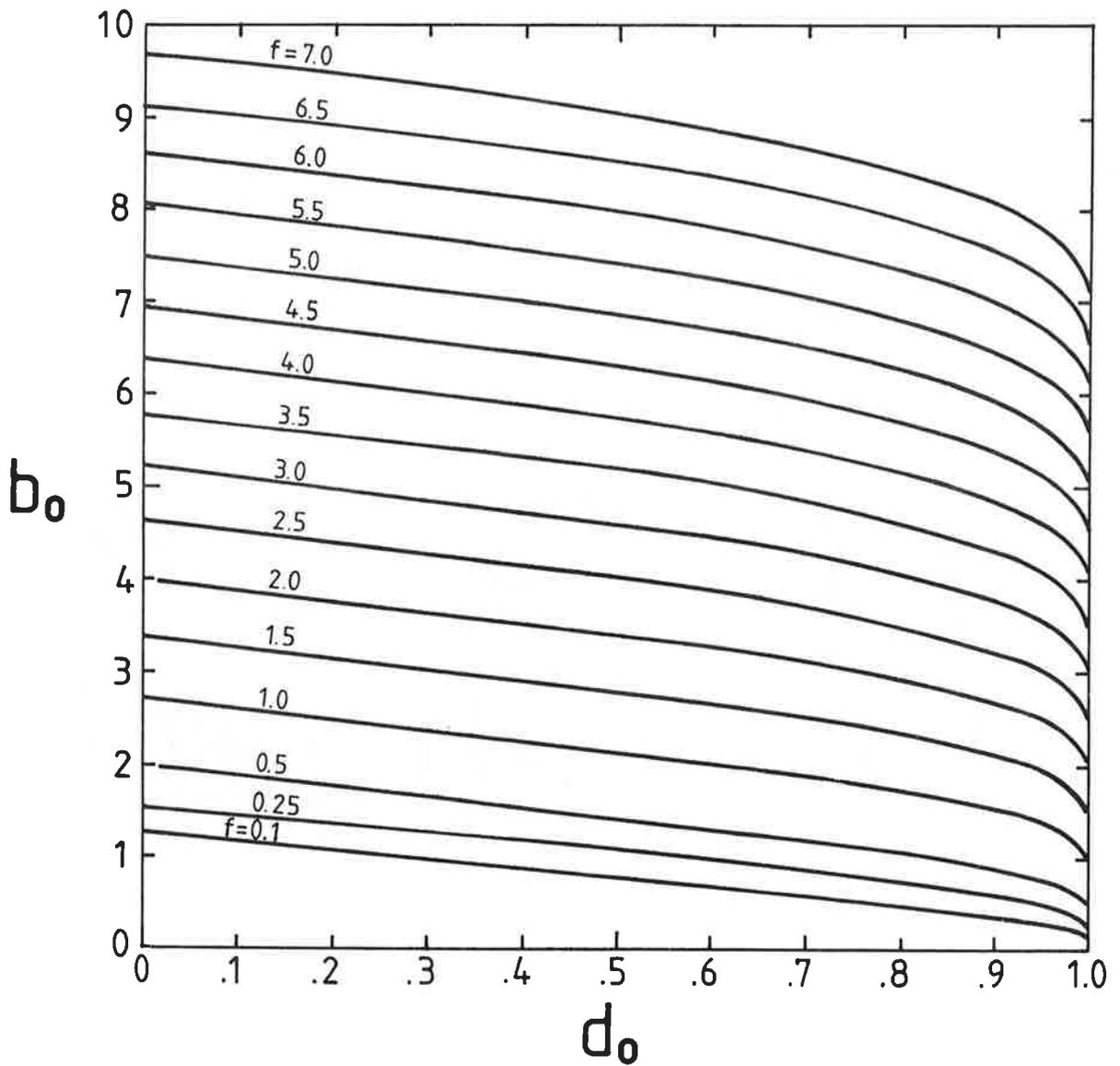
FIG. 2.7 Assimilative capacity nomograph (from McBride 1982b and reproduced by permission of the Journal, Water Pollution Control Federation)

3 REFINEMENTS TO THE STREETER-PHELPS MODEL

3.1 Introduction

In some circumstances DO dynamics in a river cannot adequately be simulated using the basic Streeter-Phelps model described in Chapter 2. This will normally become apparent at the stage of calibrating the model. If it is not found possible to calibrate the model, careful consideration should be given to whether by making certain simplifications, sufficiently good calibration could be achieved to meet management objectives. For example, if a diurnal variation in river DO occurs as a result of aquatic plant metabolism, it may be sufficient to average river DO measurements over 24 hours and hence calibrate the model so that it predicts mean daily DO concentrations. If, after careful consideration, it is decided that such simplifications will not allow management objectives to be met, then further refinements to the model are justified. Such refinements make the model equations more complex and additional modelling, field and laboratory work is required.

Two refinements to the Streeter-Phelps model are described here. The first considers the effects of benthic oxygen demand and the second considers the effects of aquatic plants.

3.2 Benthic Oxygen Demand

Below an outfall which discharges waste organic matter into a river it is not uncommon to find muds and/or slime communities which exert an oxygen demand on the overlying water.

Benthic communities remove material from the water, store it, subsequently break it down and exert an oxygen demand. Although the size and activity of the benthic community is related to antecedent waste discharges on time scales of the order of days there may be no relationship between the instantaneous benthic oxygen demand rate and the BOD concentration of the overlying water. Consequently benthic demand often cannot be accounted for by the basic Streeter-Phelps model and the model must be modified. As a first approximation the benthic oxygen demand rate (expressed in $g.m^{-3}.day^{-1}$) may be assumed constant over the length of a river to be modelled.

3 REFINEMENTS TO THE STREETER-PHELPS MODEL

3.1 Introduction

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Benthic communities remove material from the water, store it, subsequently break it down and exert an oxygen demand. Although the size and activity of the benthic community is related to antecedent waste discharges on time scales of the order of days there may be no relationship between the instantaneous benthic oxygen demand rate and the BOD concentration of the overlying water. Consequently benthic demand often cannot be accounted for by the basic Streeter-Phelps model and the model must be modified. As a first approximation the benthic oxygen demand rate (expressed in $g.m^{-3}.day^{-1}$) may be assumed constant over the length of a river to be modelled.

A constant benthic oxygen demand rate may occur in a river reach whose depth, velocity and biological population do not change greatly with distance. The Streeter-Phelps equations, modified by the inclusion of a constant benthic oxygen demand rate, can still be solved analytically (as in Appendix A) and hence are comparatively straightforward to use. Where benthic oxygen demand rate clearly does change with distance, it may still be possible to model the river by dividing it into several segments in each of which benthic oxygen demand rate is constant and then applying the model to each segment in turn starting at the most upstream point (see for example Section 3.4).

Benthic oxygen demand rate is most commonly measured on an areal basis (i.e., $g.m^{-2}.day^{-1}$). For inclusion in the model, however, it is necessary to divide by the mean depth thereby expressing the demand on a volumetric basis (i.e., $g.m^{-3}.day^{-1}$). In the following sections symbol D_B refers to benthic oxygen demand rate expressed as $g.m^{-3}.day^{-1}$.

3.2.1 Prediction with benthic oxygen demand

The procedures outlined in Section 2.3 are followed as for the basic Streeter-Phelps model except that the following step is inserted between steps (f) and (g):

"(f') Specify benthic oxygen demand rate, D_B."

Appendices B and C explain how D_B is entered into the calculator and mini-computer programs.

3.2.2 Model calibration with benthic oxygen demand

One approach commonly used is to estimate the benthic oxygen demand rate, D_B, during model calibration using observed river BOD and DO concentrations. The steps taken are as follows:

(a) Using measured values of U and H, estimate the reaeration coefficient, k_2, from the method given in Section 2.6.
(b) Predict river BOD_5 using a range of values of the river deoxygenation coefficient, k_1, and select the value which gives the best fit between observed and predicted river BOD_5 concentrations. (Note: refer to the caveat in Section 2.9.2 about matching BOD concentrations).

(c) Predict river DO concentrations using a range of D_B values together with the k_1 and k_2 values estimated in (a) and (b) above. Select the D_B value which gives the best fit between observed and predicted river DO concentrations.

(d) It is desirable to undertake a sensitivity analysis as described in Section 2.9.3 to investigate how predictions change with changes in the values of model coefficients.

3.2.3 *Direct measurements of benthic oxygen demand*

Direct assessment of benthic oxygen demand rate can be made in the field, using chambers which isolate a parcel of water above a particular part of the river bed and enable the rate of uptake of oxygen to be observed. Alternatively cores of river sediment can be taken back to the laboratory where the oxygen uptake rate can be measured under controlled conditions of temperature, light and turbulence. Both *in situ* and laboratory studies of benthic oxygen demand require specialist equipment and expertise. Before embarking on such work it is desirable to seek the advice of someone with experience in the techniques, e.g., Water Quality Centre, MWD, Hamilton.

3.3 Aquatic Plant Metabolism

In many rivers a diurnal variation in DO is observed, notably during summer. This variation is attributable to the metabolism of aquatic plants which liberate oxygen during daylight hours as a by-product of photosynthesis and consume oxygen continuously in respiration. The rates of both photosynthesis and respiration per unit plant biomass are strongly dependent on temperature. In addition, the rate of photosynthesis per unit biomass is strongly dependent on light intensity and hence in rivers has a maximum near midday. By comparison respiration varies only slightly with changes in light intensity and can be approximated as constant. Maximum DO concentrations are usually observed in the late afternoon and minimum concentrations in the early morning. During periods of rapid growth plants may liberate more oxygen than they consume when averaged over a 24 hour period and thus they may make a net contribution to the oxygen resources of a river. Conversely, during periods of decline plants may consume more oxygen than they produce and thus cause a net reduction in river DO. Much of the time, however, plants produce and consume roughly the same amount of oxygen over a 24 hour period and hence cause no net change in river DO.

Three plant communities may influence river DO concentrations: phytoplankton (the free floating microscopic plants), macrophytes (the attached water weeds), and periphyton (the slimes and other attached microscopic plants).

As a first approximation the effects of aquatic plants may be incorporated into the basic Streeter-Phelps model by defining three coefficients, in addition to those required for the basic model.

(a) Net respiration rate, R. This is the net rate of consumption of oxygen per unit volume $(g.m^{-3}.day^{-1})$ averaged over 24 hours. (Note: R can be negative if the plants make a net contribution to river oxygen concentration). This term is handled in much the same way as the benthic oxygen demand rate, D_B, discussed in Section 3.2.

(b) Amplitude of diurnal variation, A. This is half the difference between maximum and minimum DO concentration $(g.m^{-3})$ at any particular site in the river. (Note: it is assumed that in any reach A is constant).

(c) Time of the maximum DO, t_p. This is measured in hours.

3.3.1 *Prediction with aquatic plant metabolism*

The procedures outlined in Section 2.3 are followed as for the basic Streeter-Phelps model with two exceptions:

- the following step is inserted between steps (f) and (g):
  "(f') Estimate net respiration rate, R $(g.m^{-3}.day^{-1})$."
- After step (i) there is added another step:
  "(j) Estimate the amplitude of diurnal DO variation, A, and time of peak DO concentration, t_p. Then the river DO at any time is

$$C(x,t) = \overline{C}(x) + A \cos \left[\frac{2\pi(t-t_p)}{24} \right] \qquad (3.1)$$

where $C(x,t)$ = DO concentration at distance x and time t, in hours, $\overline{C}(x)$ = daily mean DO concentration at distance x (calculated at step (i))."

28

3.3.2 *Model Calibration with aquatic plant metabolism*

The steps in calibrating a model which includes the effects of aquatic plant metabolism are as follows.

(a) Using measured values of U and H estimate the reaeration coefficient, k_2, from the method given in Section 2.6.

(b) Predict river BOD_5 using a range of values of the river deoxygenation rate coefficient, k_1, and select the value which gives the best fit between observed and predicted river BOD_5 concentrations (but see caveat in Section 2.9.2).

(c) Determine the daily mean DO concentration profile (the mean sag curve). If data are collected at regular time intervals at each site the daily mean DO can be found by taking the mean of samples. Alternatively, for irregular data, DO concentrations at each site may be plotted against time and the mean value estimated by eye. Plots of DO versus time at each site are also used to estimate the amplitude of diurnal variation and time of peak DO (see step (e) below).

(d) Predict daily mean DO concentration using a range of values of the net respiration rate, R, together with the k_1 and k_2 values selected above. Choose the R value which gives the best fit between observed and predicted DO concentrations.

(e) For each site, plot DO concentration against time. Estimate the amplitude of diurnal variation, A (in $g.m^{-3}$), and the time of the peak DO, t_p (in hours).

(f) It is desirable to undertake a sensitivity analysis to determine the effects of variations of model coefficients, as described in Section 2.9.3.

3.4 Worked example using mini-computer program HAND

3.4.1 *Introduction*

The lower Waikato River (see Fig. 3.1) receives waste inflows from several dairy factories, abattoirs and municipalities and during low summer flows experiences some depletion of dissolved oxygen. A study of water quality in the river was made by MWD between 1973 and 1978 (see for example, Strachan 1979). Included in this study were intensive surveys lasting at least 24 hours during which river and inflow BOD, DO, temperature and flow were measured. These data have been used to calibrate and verify a "research" computer model (Rutherford 1977; Strachan 1979) and are used here to calibrate and verify a modified Streeter-Phelps model. This was done using the mini-computer program described in Appendix C.

3.4.2 *River Survey Results*

Figure 3.2 shows mean, maximum and minimum river DO and BOD_5 measured over a 24-hour period 23–24 January 1974 and Table 3.1 summarises the flow and composition of the major inflows. This shall be called survey #1 and used to calibrate a modified Streeter-Phelps model. One striking feature of the observed concentrations is the large diurnal variation which is taken to be attributable to the large number of phytoplankton present in the lower Waikato River during summer. The mean DO concentrations shown in Fig. 3.2 are the arithmetic average of seven samples at each site.

As discussed above, the aim of model calibration is to fit the observed mean DO sag by judicious selection of: river deoxygenation coefficient, k_1; benthic oxygen demand rate, D_B; and net respiration rate, R. The diurnal variation is fitted by amplitude, A, and time of peak, t_p.

When samples of Waikato River water containing phytoplankton are incubated for five days in the dark during the BOD_5 test, the algae exert an oxygen demand which would not be exerted in the river. Thus the Waikato River BOD_5 concentrations do not accurately reflect the concentration of oxidisable organic waste matter. Phytoplankton concentrations increase along the river as a result of algal growth and tributary inflows. The "corrected" BOD_5 concentrations shown in Fig. 3.2 are the arithmetic average of measured BOD_5 minus the minimum BOD_5 at each site. This correction is made on the basis that effluent discharge to the river is intermittent and the minimum BOD_5 may be taken as an estimate of "false" BOD exerted by algae.

Figure 3.2 also shows maximum, minimum and mid-range river DO and BOD_5 measured over a 24-hour period 16–17 April 1975, and Table 3.1 summarises the flow and composition of the major inflows. This shall be called survey #2 and used to verify the model. Only three samples were taken at each site during this survey: two in the afternoon (near peak DO) and

BRIDGE SITES

1   Tuakau
2   Mercer
3   Rangiriri
4   Huntly
5   Ngaruawahia
6   Horotiu
7   Fairfield
8   Cobham
9   Narrows
10 Fergusson
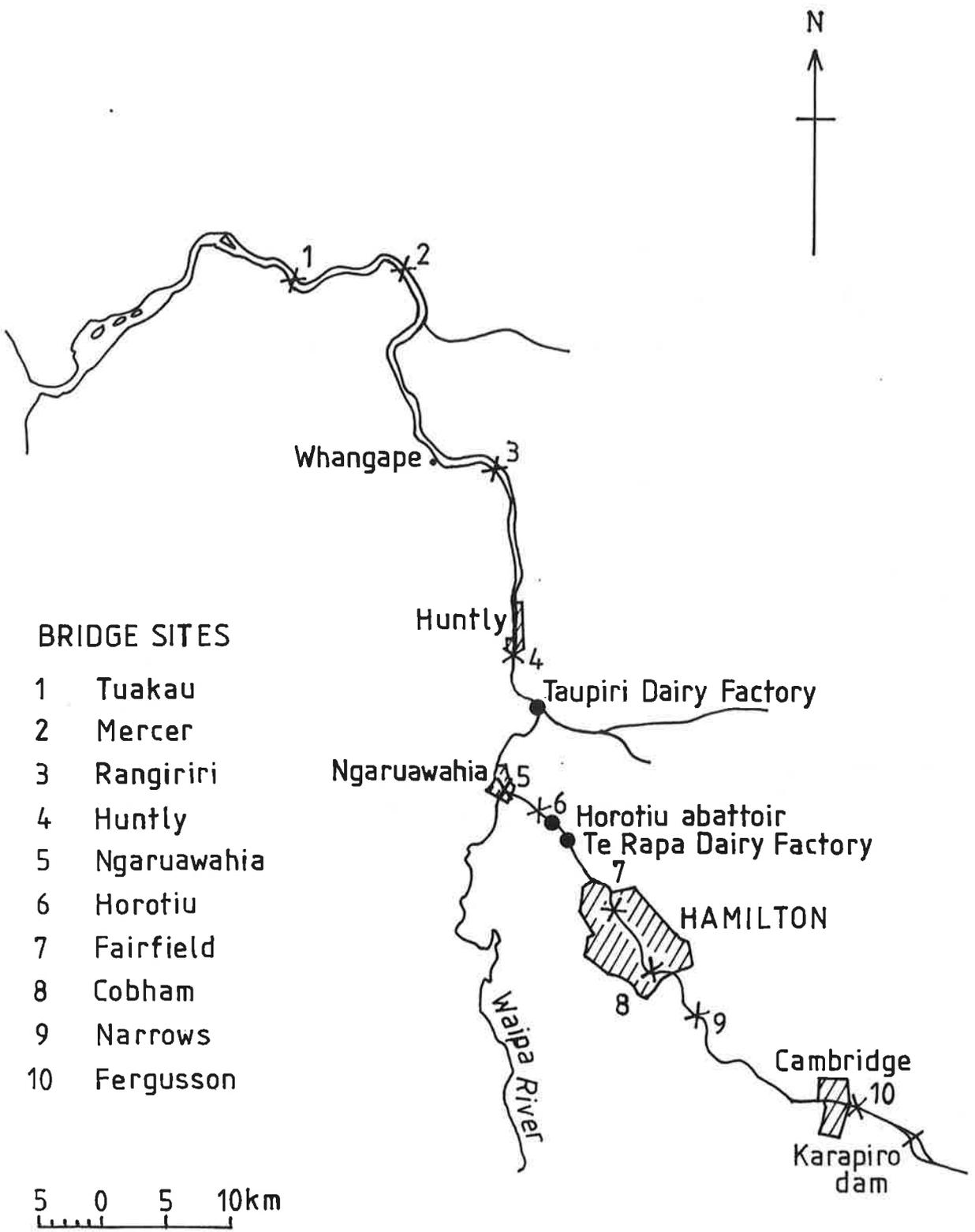
FIG. 3.1   Waikato River bridge sites

WAIKATO INTENSIVE SURVEY #1

CTD BOD5
MIN BOD5
MAX BOD5
MEAN DO
MIN DO
MAX DO

WAIKATO INTENSIVE SURVEY #2

MID DO
MIN DO
MAX DO
CTD BOD5
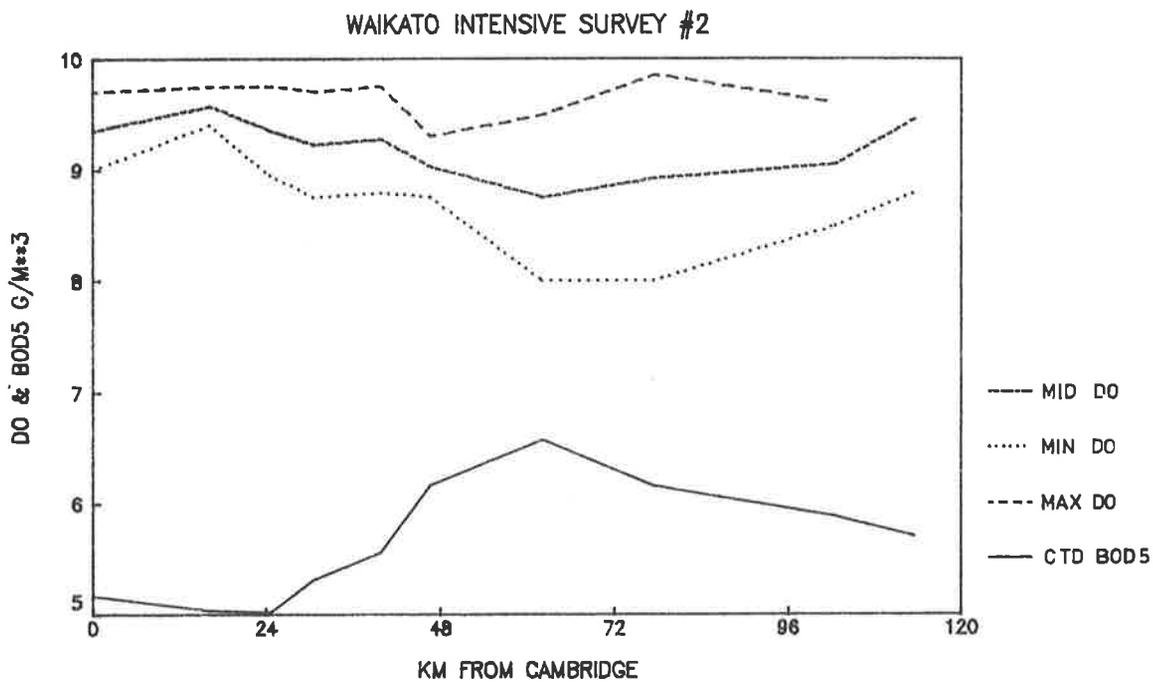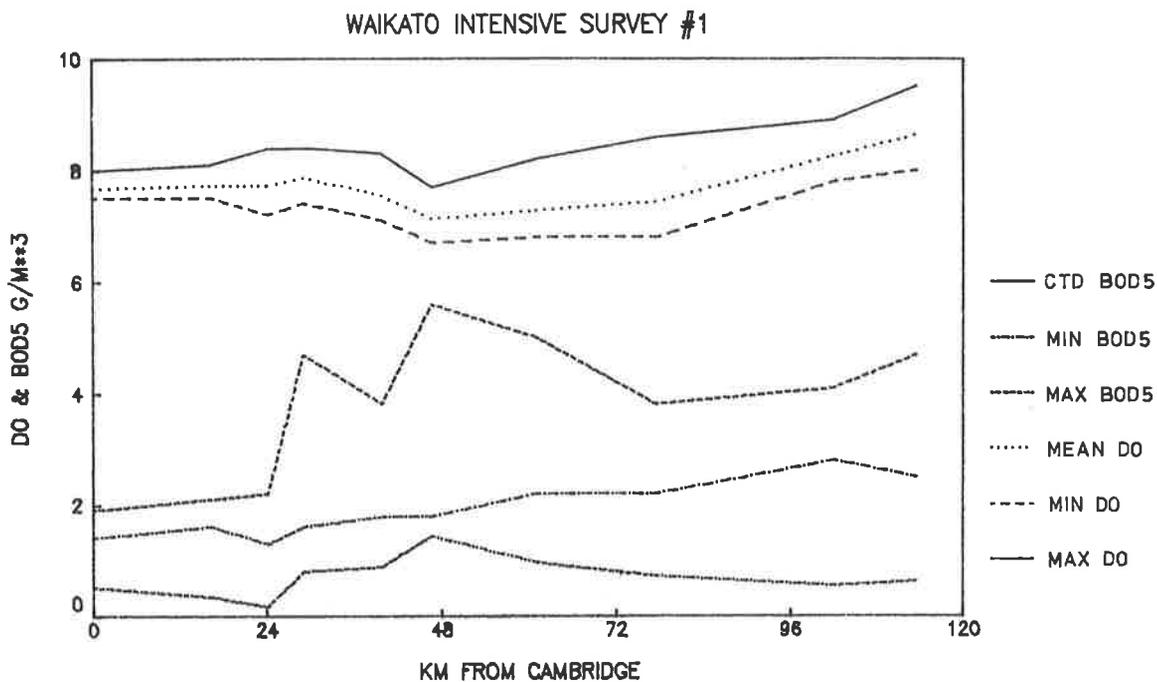
FIG. 3.2 Observed river BOD$_5$ and DO concentrations

NOTES: 1 For intensive survey # 2, BOD$_5$ is plotted after adding 5 g.m^{-3}.
    2 For method of calculating corrected BOD$_5$ (CTD BOD$_5$), see text.
    3 MID denotes mid-range, see text.

Table 3.1 Summary of upstream and inflow data

	km	Intensive Survey # 1				Intensive Survey # 2			
		Q $(m^3.s^{-1})$	L $(g.m^{-3})$	C $(g.m^{-3})$	I^* $(t.day^{-1})$	Q $(m^3.s^{-1})$	L $(g.m^{-3})$	C $(g.m^{-3})$	I^* $(t.day^{-1})$
Waikato at Cambridge	0	150	0.5	7.7	–	190	0.5	9.5	–
Cambridge Sewage	0	–	–	–	0.4	–	–	–	0.4
Tributaries	24	2	3	5	–	5	2	5	–
Hamilton sewage	28	–	–	–	6.5	–	–	–	6.5
Dairy factory	36	–	–	–	1	5	4.5	5	–
Abattoir	40	–	–	–	15	–	–	–	11
Tributary (Waipa)	46	25	1	6.6	–	30	1	8	–
Tributary	54	3	5	5	–	10	4	5	–
Huntly Sewage	62	–	–	–	0.6	–	–	–	0.6
Tributaries	82	3	3	5	–	10	2	5	–
Tributaries	102	5	3	5	–	5	2	5	–

* I = massflow of BOD_5 from inflow, C = DO, L = BOD_5 and Q = flow rate.
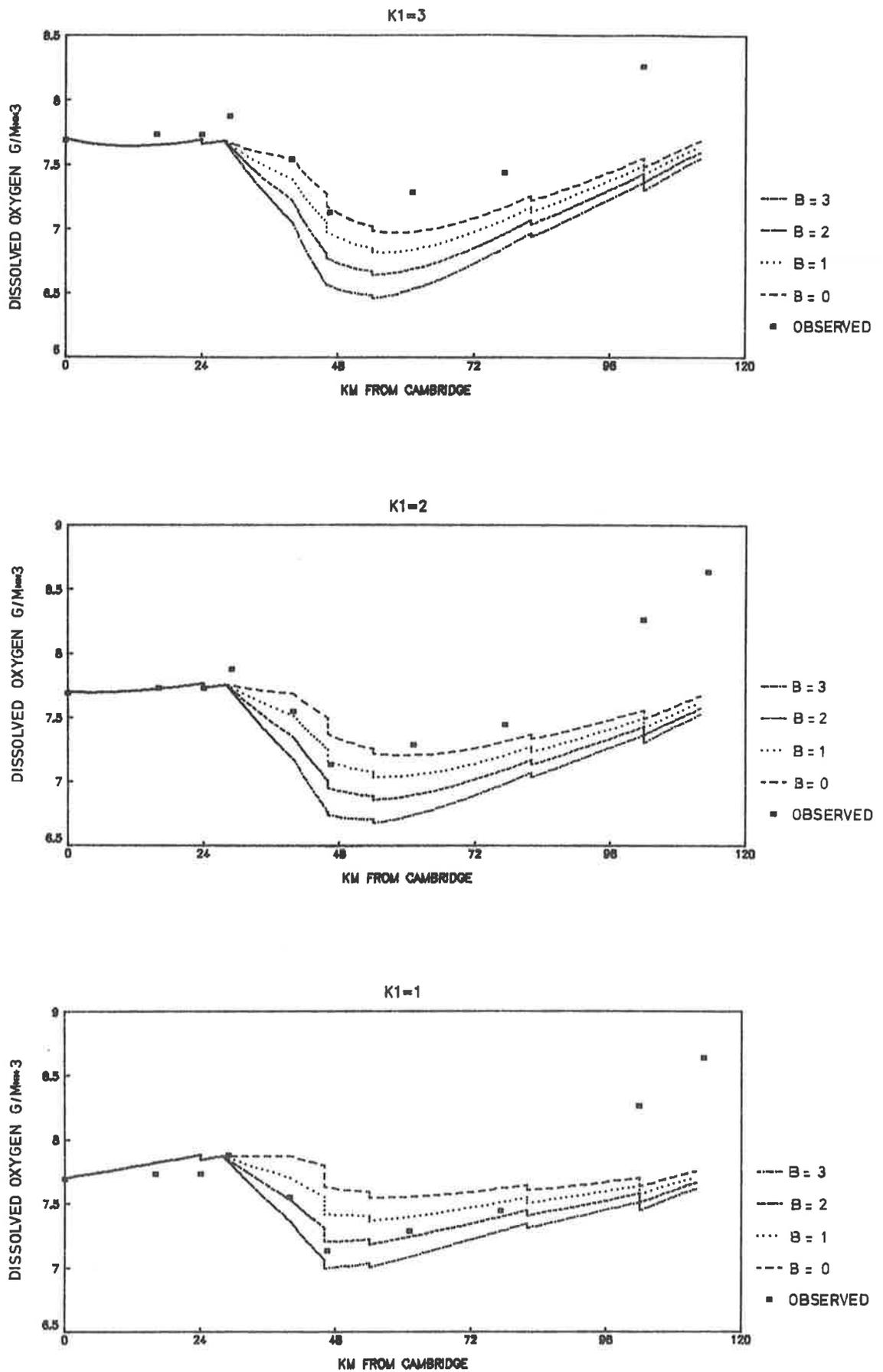
FIG. 3.3 Calibration: DO simulations to select k_1 and D_B values between Hamilton (km 28) and Ngaruawahia (km 46). Note: D_B is denoted B in legends

33

one early in the morning (near minimum DO). Arithmetic averages of DO and BOD_5 samples would be biased estimates of mean values and so mid-range values were used to provide better estimates. Too few data were available to "correct" BOD_5 as had been done for survey #1; instead a constant "false" BOD_5 of 0.75 $g.m^{-3}$ was assumed.

3.4.3 *Model calibration*

Standard values of k_L of 0.40 day^{-1} (river water) and 0.48 day^{-1} (waste inflows) were adopted (see Section 2.4). Values for k_2 were estimated from the empirical formulae as described in Section 2.6. Thus the five model coefficients which remained to be determined during model calibration were: river deoxygenation coefficient, k_1; benthic oxygen demand rate, D_B; net respiration rate, R; amplitude of diurnal DO variation, A; and time of DO maximum, t_p. It was assumed that D_B would be non-zero only in the reach between Hamilton City (km 28) and Ngaruawahia (km 46) where the major waste inflows occur. The numbers of phytoplankton per unit volume were known to increase with distance downstream and consequently it was expected that both R and A would increase with distance downstream.

A three step strategy was adopted for model calibration. Step one was to select values of k_1 and D_B to give a good fit to BOD_5 and DO in the reach Hamilton (km 28) to Ngaruawahia (km 46). Step two was to select R to give a good fit to daily average DO in the reach Ngaruawahia (km 46) to Tuakau (km 110). Step three was to estimate the amplitude of diurnal DO variation and time of maximum DO.

Step One

A series of simulations was made with values of river deoxygenation coefficient $k_1 = 1, 2$ and 3 day^{-1} and benthic oxygen demand rate $D_B = 0, 1, 2$ and 3 $g.m^{-3}.day^{-1}$. Note D_B was assumed non-zero only between Hamilton (km 28) and Ngaruawahia (km 46). Results of these simulations are shown in Fig. 3.3. Note that at km 46 the sampling site lies upstream from the tributary inflow. It can be seen that several combinations of k_1 and D_B gave a reasonable fit between observed and predicted river DO in the reach Hamilton (km 28) to Ngaruawahia (km 46). Figure 3.4 indicates, however, that the best match between observed and predicted river BOD_5 was obtained with k_1 between 1.0 and 2.0 day^{-1}. Thus a reasonable
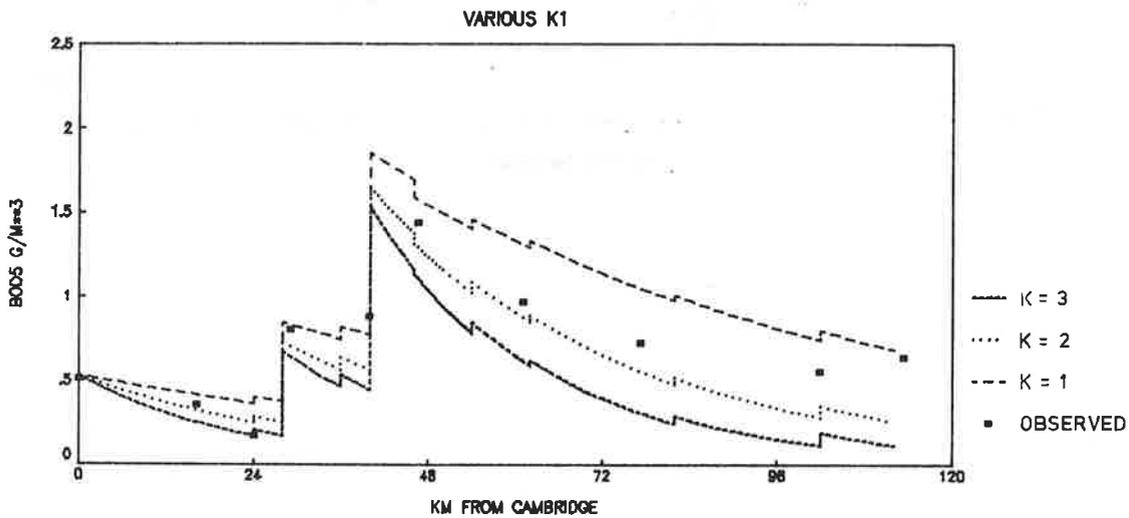
FIG. 3.4 Calibration: BOD_5 simulations to select k_1 values.

fit between both observed and predicted river BOD_5 and DO was obtained with $k_1 = 1.0$ day^{-1}, D_B between 2 and 3 $g.m^{-3}.day^{-1}$ and also with $k_1 = 2.0$ day^{-1}, D_B between 1 and 2 $g.m^{-3}.day^{-1}$. There could be some merit in making D_B higher between km 40–46 than between km 28–40 but this is not done here. Two sets of coefficients were used in subsequent predictions: $k_1 = 1.0$, $D_B = 3.0$; and $k_1 = 2.0$, $D_B = 2.0$.

Step Two

Using $k_1 = 1.0$ and 2.0 day^{-1} throughout the river together with $D_B = 3.0$ and 2.0 $g.m^{-3}.day^{-1}$ respectively in the reach Hamilton (km 28) to Ngaruawahia (km 46), then further simulations were made using net respiration rates $R = -1, -2$ and -3 $g.m^{-3}.day^{-1}$ in the reach Ngaruawahia (km 46) to Tuakau (km 110). Results are shown in Fig. 3.5. Note that negative R implies that photosynthesis exceeds respiration and that aquatic plants make a net

contribution to the oxygen resources of the river. On the basis of the fit between observed and predicted river DO concentrations the following values were selected: $R = -1$ $g.m^{-3}.day^{-1}$ between Ngaruawahia (km 46) and Whangape (km 82) and $R = -2$ $g.m^{-3}.day^{-1}$ between Whangape and Tuakau (km 110).
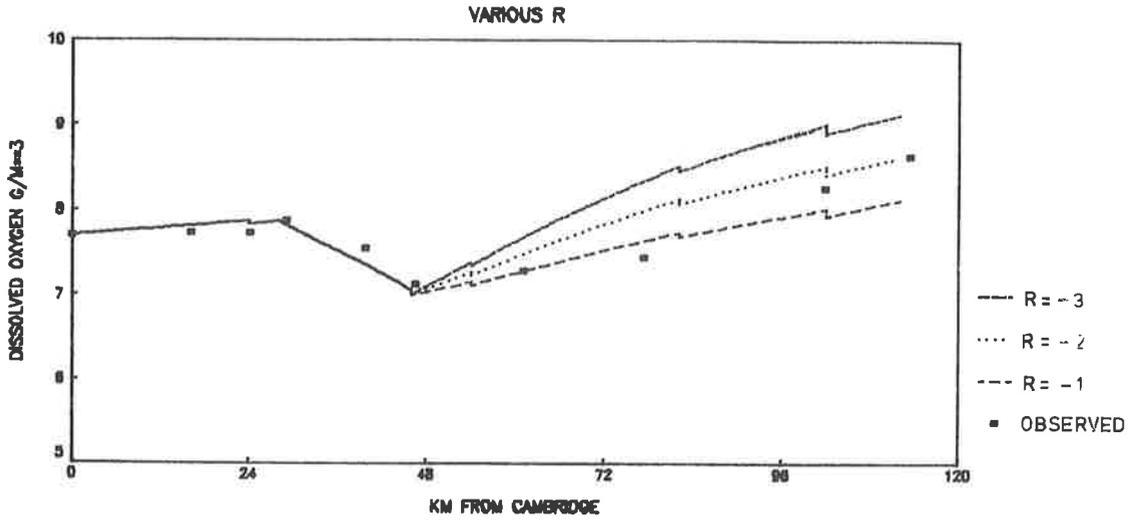
FIG. 3.5 Calibration: DO simulations to select R values between Ngaruawahia (km 46) and Tuakau (km 110)

Step Three

The final stage of calibration was to graph the amplitude of diurnal variation of DO versus distance and to calculate that a simple linear regression line $A = 0.50 + 0.010x$ (where x = km below Cambridge and A = amplitude of diurnal DO variation in $g.m^{-3}$) explained about 65% of the variation (with seven points). Peak DO occurred close to 1700 hours while minimum DO occurred close to 0500 hours at all seven sites. Thus $t_p = 1700$. Table 3.2 summarises the calibrated model coefficients. Figure 3.6 shows observed and predicted DO at the completion of model calibration.
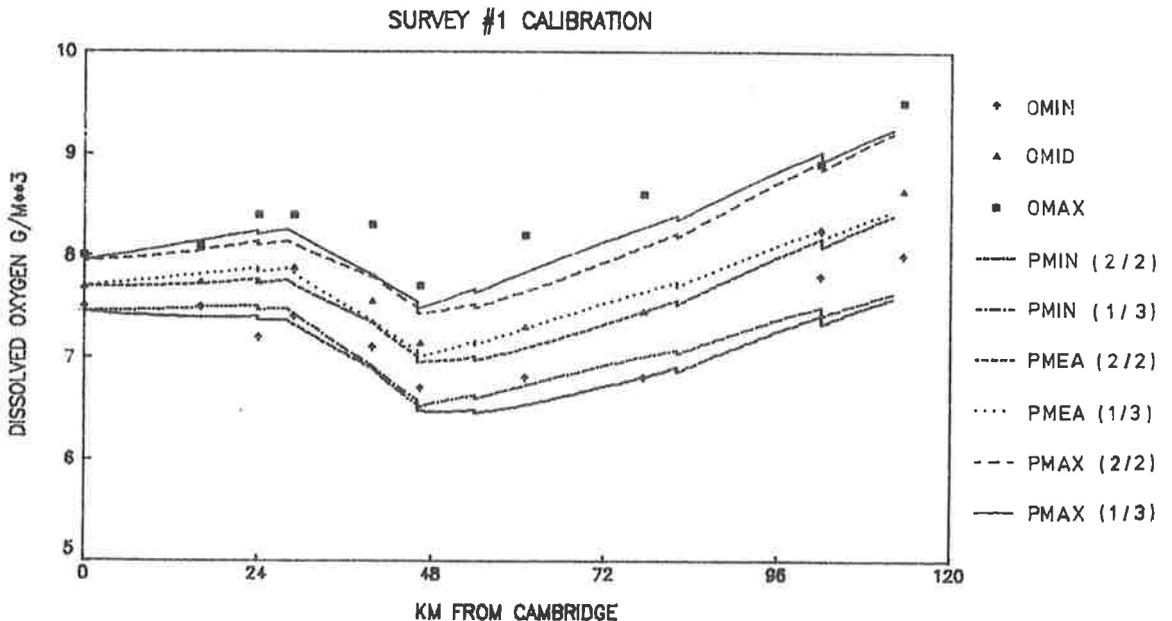
FIG. 3.6 Calibration: observed and predicted DO
Notes (i) OMIN, OMID, OMAX = observed minimum, mid-range and maximum DO.
(ii) PMIN, PMEA, PMAX = predicted minimum, mean and maximum DO.
(iii) (1 / 3) denotes $k_1 = 1$ and $D_B = 3$.

3.4.4 Model Verification

The coefficients derived during model calibration (and summarised in Table 3.2) were then used together with the input data shown in Table 3.1 to simulate river BOD_5 and DO at the time of intensive survey #2.

35

Table 3.2 Summary of model input data coefficients

Reach	Variable		Cambridge-Hamilton 0–28 km	Hamilton-Horotiu 28–40 km	Horotiu-Ngaruawahia 40–46 km	Ngaruawahia-Taupiri 46–54 km	Taupiri-Whangape 54–82 km	Whangape-Mercer 82–102 km	Mercer-Tuakau 102–110 km
Survey #1	U	$m.s^{-1}$	0.75	0.75	0.65	0.65	0.50	0.50	0.40
	H	m	2.5	2.5	2.0	2.0	1.50	1.50	1.25
	T	°C	21	21	21	21	22	22	23
Survey #2	U	$m.s^{-1}$	1.0	1.0	0.70	0.70	0.70	0.50	0.50
	H	m	2.5	2.5	2.25	2.25	2.25	1.75	1.75
	T	°C	18	18	18.1	18.1	18.1	18.2	18.2
Low flow[a]	k_1	day^{-1}	1 or 2	1 or 2	1 or 2	1 or 2	1 or 2	1 or 2	1 or 2
	D_B	$g.m^{-3}.day^{-1}$	0	3 or 2	3 or 2	0	0	0	0
	R	$g.m^{-3}.day^{-1}$	0	0	0	−1	−1	−2	−2
High flow[b]	k_1	day^{-1}	1 or 2	1 or 2	1 or 2	1 or 2	1 or 2	1 or 2	1 or 2
	D_B	$g.m^{-3}.day^{-1}$	0	0	0	0	0	0	0
	R	$g.m^{-3}.day^{-1}$	0	0	0	−1	−1	−2	−2

(a) $Q > 200\ m^3.s^{-1}$ during preceding 14 days
(b) $Q < 200\ m^3.s^{-1}$ during preceding 14 days

Figure 3.7 shows observed and predicted river BOD_5. The observed BOD_5 at Huntly (km 62) is considerably higher than predicted, for reasons unknown. Generally, however, observed and predicted river BOD_5 match reasonably well given the fairly large uncertainty inherent in the former. The value $k_1 = 1$ day^{-1} appears to give a slightly better fit than $k_1 = 2$ day^{-1}.
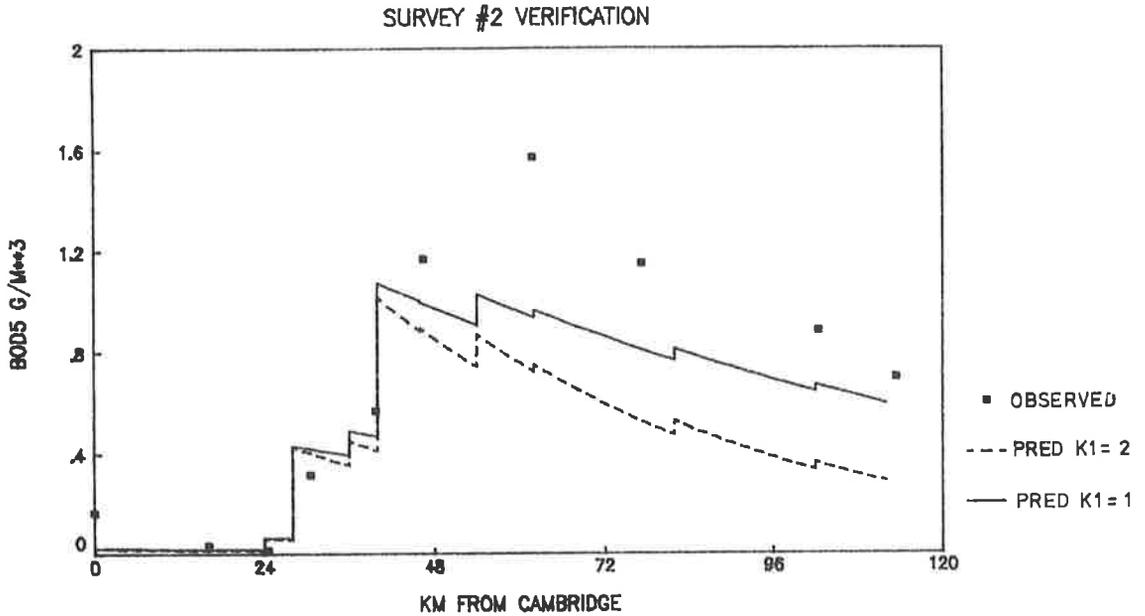
FIG. 3.7 Verification: observed and predicted BOD_5

Figure 3.8 shows observed maximum, mid-range and minimum together with predicted mean DO. It is clear that the predicted mean DO is approximately 0.5 g.m^{-3} lower than the observations below Hamilton (28 km). The main difference between river conditions prevailing during surveys #1 and #2 is flow rate: 150 m^3.s^{-1} and 190 m^3.s^{-1} at Karapiro
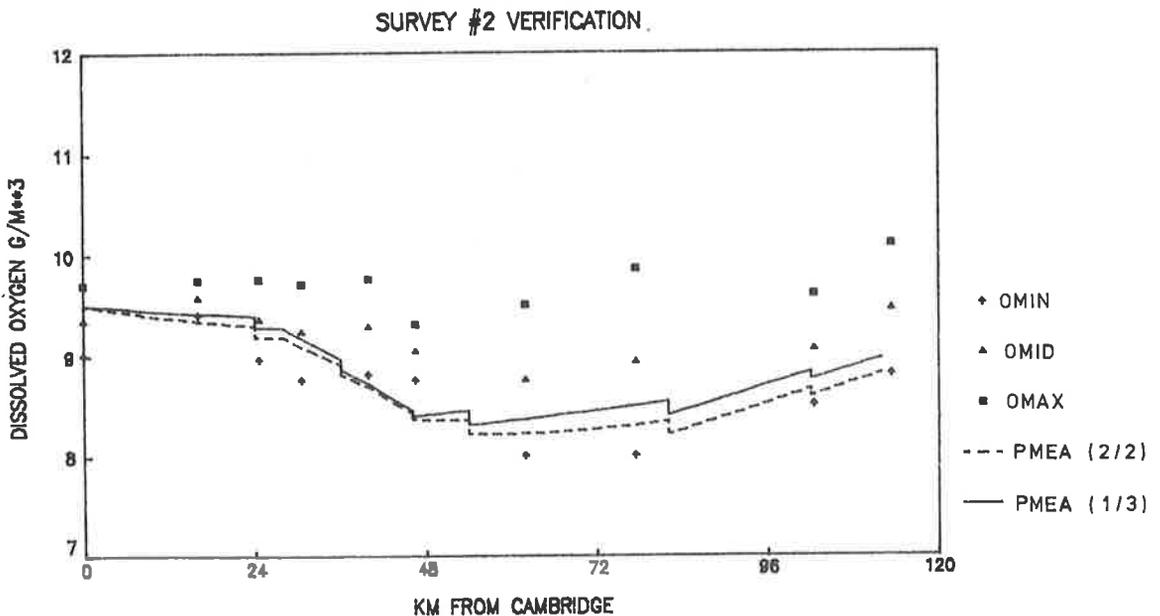
FIG. 3.8 Verification: observed and predicted DO with $D_B = 2$–3 g.m^{-3}.day^{-1} between Hamilton (km 28) and Ngaruawahia (km 46)

respectively. The higher flow during and preceding survey #2 might be expected to have had some influence on benthic oxygen demand. Figure 3.9 shows observed and predicted river DO making the assumption that $D_B = 0$ in the reach Hamilton (km 28) to Ngaruawahia (km 46) rather than the calibration values of 3.0 and 2.0 g.m^{-3}.day^{-1}. The fit between observed

mid-range and predicted mean DO concentrations is improved. Also shown on Fig. 3.9 are the maximum and minimum river DO concentrations predicted from the mean together with the amplitude of diurnal variation estimated earlier as a function of distance. These predictions match observations quite well.

SURVEY #2 VERIFICATION
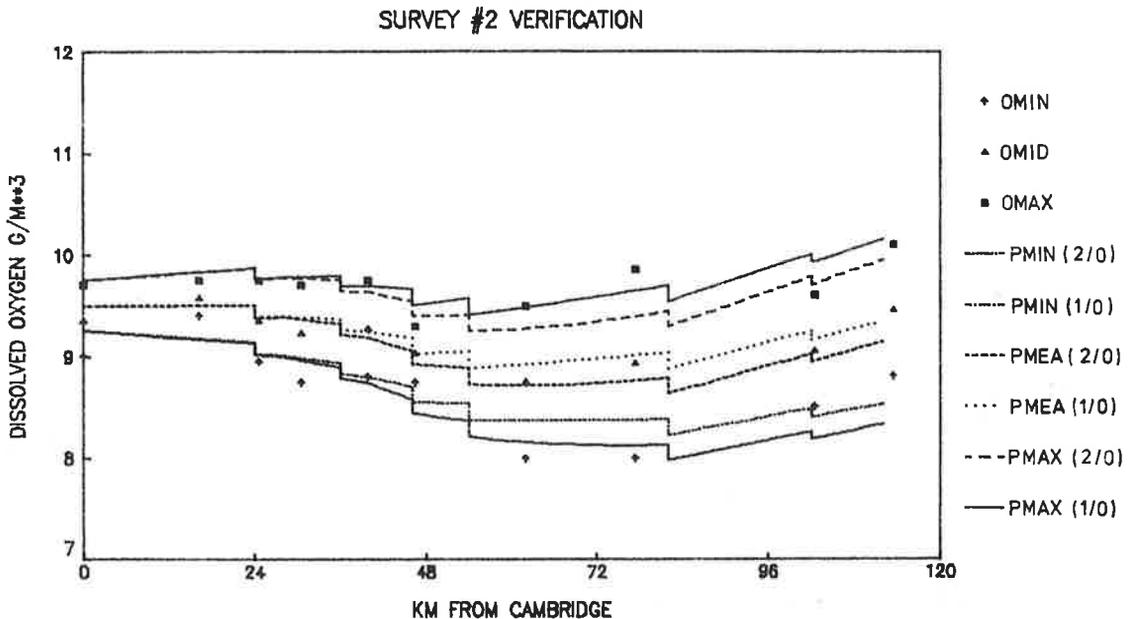
FIG. 3.9 Verification: observed and predicted DO with $D_B = 0$

The conclusions to be reached from these simulations are
(1) k_1 can be taken in the range $1.0 - 2.0$ day^{-1}.
(2) D_B needs to be non-zero only in the reach Hamilton to Ngaruawahia and then only during prolonged periods of low flow. It can be taken to have a value in the range between 1 and 3 $g.m^{-3}.day^{-1}$. After high flows D_B can be taken as zero.
(3) R needs to be negative between Ngaruawahia and Tuakau (implying a net contribution by phytoplankton to river DO) and can be taken to lie in the range -1.0 to -2.0 $g.m^{-3}.day^{-1}$.
(4) A can be taken to increase downstream from about 0.5 $g.m^{-3}$ to 1.5 $g.m^{-3}$; t_p is close to 1700 hours.

These coefficients can be expected to give reasonable predictions of river DO and BOD_5 under low flow conditions similar to those prevailing during these two surveys. One major difficulty when making predictions is to estimate the value of D_B and the best that can be done on the basis of the currently available information is to assume $D_B = 1-3$ $g.m^{-3}.day^{-1}$ when river flow is low and has been low for some time (say two weeks) and to assume $D_B = 0$ when river flow is high (say above 200 $m^3.s^{-1}$) or has been high (say during the preceding two weeks).

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5 ACKNOWLEDGEMENTS

APPENDICES

Appendix A: Modified Streeter-Phelps Model Equations and Solutions

The modified Streeter-Phelps model equations are

$$\frac{dL}{dt} = -k_1 L \tag{A1}$$

$$\frac{dD}{dt} = \alpha k_1 L - k_2 D + D_B \tag{A2}$$

$$B = \alpha L \tag{A3}$$

with initial conditions

$$\left. \begin{array}{l} B = B_o \\ D = D_o \end{array} \right\} \text{ at } t = 0$$

where

t = river time-of-travel from initial point, days
B = river BOD_u, $g.m^{-3}$
L = river BOD_5, $g.m^{-3}$
α = ratio of river BOD_u to BOD_5, dimensionless
D = river DOD, $g.m^{-3}$
k_1 = river deoxygenation coefficient (base e), day^{-1}
k_2 = river reaeration coefficient (base e), day^{-1}
D_B = benthic oxygen demand rate, $g.m^{-3}.day^{-1}$

With $D_B = 0$ the equations describe the basic Streeter-Phelps model.

The analytical solutions to Equations A1–A3 are

$$B = B_o e^{-k_1 t} \tag{A4}$$

$$
D = \begin{cases}
D_o e^{-k_2 t} + \dfrac{k_1 B_o}{k_2 - k_1} [e^{-k_1 t} - e^{-k_2 t}] + \dfrac{D_B}{k_2}[1 - e^{-k_2 t}] & : k_1 \neq k_2 \quad (A5) \\[4mm]
[D_o + k t B_o] e^{-kt} + \dfrac{D_B}{k}[1 - e^{-kt}] & : k_1 = k_2 = k \quad (A6)
\end{cases}
$$

The river DOD is defined by

$$D = C_s - C \tag{A7}$$

where
C = river DO, $g.m^{-3}$
C_s = saturation river DO, $g.m^{-3}$

The river time-of-travel from the initial point can be calculated from given data on river distance (x in km) and on river velocity (U in $m.s^{-1}$) from

$$t = \frac{x}{86.4 U} \tag{A8}$$

Appendix B: Calculator Programs

This appendix gives two programs that both perform the same task: the first is written for an HP 41CV calculator and the second is written for a TI 59 calculator.

Each program makes the same use of registers. The basic Streeter-Phelps model (Chapter 2) may be solved using these programs by storing a zero in register 08. The modified Streeter-Phelps model (Chapter 3) may be solved by entering the benthic oxygen demand rate or net respiration rate in register 08. The registers are

REGISTER											
00	C_s	01	B_o	02	C_o	03		U	04		k_1
05	k_2	06	x_o	07	α	08	D_B or R				

where

C_s = saturation river DO, $g.m^{-3}$
B_o = initial river BOD_u, $g.m^{-3}$
C_o = initial river DO, $g.m^{-3}$
U = river velocity, $m.s^{-1}$
k_1 = river deoxygenation coefficient (base e), day^{-1}
k_2 = river reaeration coefficient (base e), day^{-1}
x_o = initial river distance, km
α = ratio of river $BOD_u : BOD_5$
D_B = river benthic oxygen demand rate, $g.m^{-3}.day^{-1}$
R = net respiration rate, $g.m^{-3}.day^{-1}$

Programs are run by selecting an incremental distance ($\triangle x$) and then calculating B, L and C at that distance downstream (upstream).

B.1 Program for HP 41CV

Step	Key Stroke	Step	Key Stroke	Step	Key Stroke
01	LBL ALPHA DOMODEL ALPHA	28	RCL 04	55	×
02	STO + 06	29	−	56	RCL 00
03	RCL 06	30	÷	57	+
04	XEQ ALPHA PSE ALPHA	31	STO 13	58	LBL 02
05	x ≳ y	32	RCL 02	59	RCL 07
06	RCL 03	33	RCL 00	60	RCL 01
07	÷	34	−	61	RCL 11
08	86.4	35	+	62	×
09	÷	36	×	63	STO 01
10	CHS	37	RCL 13	64	R/S
11	STO 10	38	RCL 11	65	x ≳ y
12	RCL 04	39	×	66	÷
13	×	40	CHS	67	R/S
14	e^x	41	+	68	R ↓
15	STO 11	42	RCL 00	69	RCL 12
16	RCL 05	43	+	70	1
17	RCL 10	44	GTO 02	71	−
18	×	45	LBL 01	72	RCL 08
19	e^x	46	RCL 01	73	RCL 05
20	STO 12	47	RCL 10	74	÷
21	RCL 05	48	×	75	×
22	RCL 04	49	×	76	+
23	x =y?	50	RCL 02	77	STO 02
24	GTO 01	51	+	78	R/S
25	RCL 01	52	RCL 00	79	GTO ALPHA DOMODEL ALPHA
26	×	53	−		
27	x≳ y	54	RCL 11		

Instructions

Step	Action	Input	Keys	Output
1	Key in program	–	–	–
2	Initialise program	–	GTO . 000	–
3	Store data in registers 00–08	$C_s, B_o, C_o, U, k_1, k_2, x_o, \alpha, D_B$	C_s STO 00 etc.	–
4	If any change in U, k_1 or k_2 enter into appropriate register. Select $\triangle x$ and run program to obtain new x and B	$\triangle x$	$\triangle x$ R/S	New x displayed for 1 second; B at new x displayed
5	Run program to obtain new L	–	R/S	L at new x displayed
6	Run program to obtain new C	–	R/S	C at new x displayed
7	If no inflow at new x, go to step 4 or finish	–	–	–
8	If inflow at x calculate new initial B by adding inflow to river flow	B_i, Q_i, Q_a, Q_o	RCL 01 Q_a × Q_i ENTER B_i × + Q_o ÷ STO 01	New initial B
9	Calculate new initial L	–	RCL 07 ÷	New initial L
10	Calculate new C by adding inflow to river flow	C_i, Q_i, Q_a, Q_o	RCL 02 Q_a × Q_i ENTER C_i × + Q_o ÷ STO 02	New initial C
11	Go to step 4	–	–	–

Example use

The following sequence computes the entries for 10 and 25 km on Table 2.6. The program has already been initialised.

Key Strokes	Display	Comment
8.73 STO 00 6 STO 01 8.6 STO 02 0.4 STO 03 2 STO 04 1.35 STO 05 0 STO 06 1.16 STO 07 0 STO 08	–	Registers loaded with model data
10 R/S	10 for 1 sec., then 3.36	B at 10 km before inflow mixing
R/S	2.90	L at 10 km before inflow mixing
R/S	6.43	C at 10 km before inflow mixing
RCL 01 5 × 0.15 ENTER 109 × + 5.15 ÷ STO 01	6.44	B at 10 km after inflow mixing
RCL 07 ÷	5.55	L at 10 km after inflow mixing
RCL 02 5 × 0.15 ENTER 0 × + 5.15 ÷ STO 02	6.25	C at 10 km after inflow mixing
15 R/S	25 for 1 sec. then 2.70	B at 25 km
R/S	2.33	L at 25 km
R/S	4.64	C at 25 km
1.03 STO 05	1.03	Change in k_2 stored in 05 register.

■
■
■

43

Table B.2 Program for TI 59

Step	Key Stroke	Step	Key Stroke	Step	Key Stroke
000	2nd Lbℓ	050	04	100	10
001	A	051	÷	101	×
002	SUM	052	(	102	RCL
003	06	053	RCL	103	01
004	x ≳ t	054	05	104	)
005	RCL	055	−	105	×
006	06	056	RCL	106	RCL
007	2nd Pause	057	04	107	11
008	x ≳ t	058	)	108	=
009	÷	059	×	109	+/−
010	RCL	060	(	110	+
011	03	061	RCL	111	RCL
012	÷	062	11	112	00
013	8	063	−	113	=
014	6	064	RCL	114	x ≳ t
015	.	065	12	115	2nd Lbℓ
016	4	066	)	116	C
017	+/−	067	+	117	RCL
018	=	068	(	118	01
019	STO	069	RCL	119	×
020	10	070	00	120	RCL
021	×	071	−	121	11
022	RCL	072	RCL	122	=
023	04	073	02	123	STO
024	=	074	)	124	01
025	INV	075	×	125	R/S
026	ℓnx	076	RCL	126	÷
027	STO	077	12	127	RCL
028	11	078	=	128	07
029	RCL	079	+/−	129	=
030	05	080	+	130	R/S
031	×	081	RCL	131	x ≳ t
032	RCL	082	00	132	+
033	10	083	=	133	RCL
034	=	084	x ≳ t	134	08
035	INV	085	GTO	135	×
036	ℓnx	086	C	136	(
037	STO	087	2nd Lbℓ	137	RCL
038	12	088	B	138	12
039	RCL	089	(	139	−
040	04	090	RCL	140	1
041	x ≳ t	091	00	141	)
042	RCL	092	−	142	÷
043	05	093	RCL	143	RCL
044	2nd x = t	094	02	144	05
045	B	095	−	145	=
046	RCL	096	RCL	146	STO
047	01	097	04	147	02
048	×	098	×	148	R/S
049	RCL	099	RCL		

Step	Action	Input	Keys	Output
1	Key in program	–	–	–
2	Initialise program	–	GTO 000	–
3	Store data in registers 00–08	C_s, B_o, C_o, U, k_1 k_2, x_o, α, D_B	C_s STO 00 etc.	–
4	If any change in U, k_1 or k_2 enter into appropriate register. Select $\triangle x$ and run program to compute new B	$\triangle x$	$\triangle x$ A	New x displayed for $\frac{1}{2}$ second; B at new x displayed
5	Run program to obtain new L	–	R/S	L at new x displayed
6	Run program to obtain new C	–	R/S	C at new x displayed
7	If no inflow at new x, go to step 4 or finish	–	–	–
8	If inflow at x calculate new initial B by adding inflow to river flow	B_i, Q_i, Q_a, Q_o	(RCL 01 $\times$ Q_a + $Q_i \times B_i$) $\div$ Q_o = STO 01	New initial B
9	Calculate new initial L	–	$\div$ RCL 07 =	New initial L
10	Calculate new C by adding inflow to river flow	C_i, Q_i, Q_a, Q_o	(RCL 02 $\times$ Q_a + $Q_i \times C_i$) $\div$ Q_o = STO 02	New initial C
11	Go to step 4	–	–	–

Example use

The following sequence computes the entries for 10 and 25 km on Table 2.6. The program has already been initialised.

Key Strokes	Display	Comment
8.73 STO 00 6 STO 01 8.5 STO 02 0.4 STO 03 2 STO 04 1.35 STO 05 0 STO 06 1.16 STO 07 0 STO 08	–	Registers loaded with model data
10 A	10 for $\frac{1}{2}$ sec. then 3.36	B at 10 km before inflow mixing
R/S	2.90	L at 10 km before inflow mixing
R/S	6.43	C at 10 km before inflow mixing
(RCL 01 × 5 + 0.15 × 109) ÷ 5.15 = STO 01	6.44	B at 10 km after inflow mixing
÷ RCL 07 =	5.55	L at 10 km after inflow mixing
(RCL 02 × 5 + 0.15 × 0) ÷ 5.15 = STO 02	6.25	C at 10 km after inflow mixing
15 A	25 for $\frac{1}{2}$ sec. then 2.70	B at 25 km
R/S	2.33	L at 25 km
R/S	4.64	C at 25 km
1.03 STO 05	1.03	Change in k_2 stored

■
■
■

Appendix C: Mini-Computer Program

Description, flow chart listing and worked example are given of a mini-computer program that can be used to solve the Streeter-Phelps equations (modified to include a benthic oxygen demand term) in a river which can be approximated as a number of uniform reaches.

Program documentation:

Program name: HAND

Programmer: J. C. Rutherford
Water Quality Centre
Ministry of Works and Development
Private Bag
Hamilton

Date: September 1982

Language: BASIC-11/RT-11 V2

Computer: PDP 11/34
Ministry of Works and Development
Hamilton

Compatible computers: Those running RT-11 or TSX-Plus operating systems.

Format for input data: Either
(i) free format entered interactively, or
(ii) from disc files created separately.

User Notes: (i) The program prints messages on the terminal to tell the operator the sequence of steps required to run the program.

Input/output example: Appended

Program flow chart: Appended

Program listing: Appended

```
                     **********************
                       PROGRAM HAND
                     **********************


     IS THERE OBSERVED DATA FILED FOR COMPARISON <YES>? ─────────── blank means 'YES'

     ENTER FILE NAME FOR FILED DATA <NO FILE> : ? DX1:TRIAL.DAT

     FILE HEADER - 'SOME TRIAL DATA FOR HAND'
     CORRECT FILE <YES>?                                       these data were stored
                                                               previously in file ' DX1: TRIAL. DAT '
     DO YOU WANT AN INPUT DATA LISTING <NO>? YES               (on a diskette)

                                                               line 1 is a header
     LINE         X             BOD5         DO
      1          30            3.5          8                  'SOME TRIAL DATA FOR HAND, X, BOD5, DO '
      2          40            2.5          7.5
      3          60            1.5          5
      4          75            1.5          5
      5          90            1            6



     ENTER U/S BOUNDARY (KM) : ? 0 ───────────────────────── entered by the user


                  **********************
                        SIMULATION 1
                  **********************


                  **********************
                        REACH 1
                  **********************


     ENTER D/S BOUNDARY  (KM) :? 25 ──────────────────────── ditto
     REACH LENGTH  (KM) = 25

     ENTER VELOCITY  (M/S)  :    ? 1  ⎫
     ENTER MEAN DEPTH  (M)  :    ? 2.5 ⎬ ─────────────────── ditto
     ENTER TEMPERATURE (C)  :    ? 15  ⎭
     SATURATION DO  (G/M^3) = 10.1674        NEW VALUE <RETAIN> : ? 10

                                                             calculated from temperature but the
     ENTER U/S FLOW   (M^3/S) :   ? 250 ⎫                    user can overwrite the calculated value
     ENTER U/S BOD5   (G/M^3) :   ? 1   ⎬ ─────────────────
     ENTER U/S DO     (G/M^3) :   ? 10  ⎭                    entered by the user

     INFLOW - ENTER T (TRIB) P (POINT) <NEITHER> : ?

     CONVERT BOD5 TO BODU
     INFLOW KL (/DAY) : .48              NEW VALUE <RETAIN> : ? ⎫
     INCUBATION DAYS : 5                 NEW VALUE <RETAIN> : ? ⎬  the user can enter these values
     RIVER KL (/DAY) : .4                NEW VALUE <RETAIN> : ? ⎬  but here the defaults are used
     INCUBATION DAYS : 5                 NEW VALUE <RETAIN> : ? ⎭
```

48

```
ESTIMATED K2  (/DAY) : .960693          NEW VALUE <RETAIN> : ? .95
ENTER K1  (/DAY) : ? 2
ENTER REF TEMP  (C) <RIVER TEMP> : ?
ENTER DB (G/M^3-DAY) <G/M^2-DAY> : ? 0

*******************************************

    DEOXYGENATION COEFFICIENT  K1 = 2  /DAY
    REAERATION COEFFICIENT     K2 = .95  /DAY
    BENTHIC UPTAKE RATE        DB = 0  G/M^3-DAY

*******************************************

ENTER DISTANCE STEP  (KM) <TIME STEP> : ? 5

DO YOU WANT ANOTHER REACH <YES>?

         **********************
              REACH 2
         **********************


ENTER D/S BOUNDARY  (KM) :? 50
REACH LENGTH  (KM) = 25
U/S VELOCITY   (M/S) : 1                 NEW VALUE <RETAIN> : ?
U/S MEAN DEPTH  (M) : 2.5                NEW VALUE <RETAIN> : ?
U/S TEMPERATURE (C) : 15                 NEW VALUE <RETAIN> : ?
SATURATION DO  (G/M^3) = 10.1674         NEW VALUE <RETAIN> : ? 10


INFLOW - ENTER T (TRIB) P (POINT) <NEITHER> : ? P

ENTER BOD5 MASSFLOW  (KG/DAY) : ? 100000

CONVERT BOD5 TO BODU
INFLOW KL (/DAY) : .48                   NEW VALUE <RETAIN> : ?
INCUBATION DAYS  : 5                     NEW VALUE <RETAIN> : ?
RIVER KL (/DAY)  : .4                    NEW VALUE <RETAIN> : ?
INCUBATION DAYS  : 5                     NEW VALUE <RETAIN> : ?

U/S K2  (/DAY) : .95                     DO YOU WANT NEW ESTIMATE <YES>? NO
U/S K1  (/DAY) : 2                       NEW VALUE <RETAIN> : ?
U/S DB (G/M^3-DAY) : 0                   DO YOU WANT TO CHANGE IT <YES>?
ENTER DB (G/M^3-DAY) <G/M^2-DAY> : ? 2

**********************************************

    DEOXYGENATION COEFFICIENT  K1 = 2  /DAY
    REAERATION COEFFICIENT     K2 = .95  /DAY
    BENTHIC UPTAKE RATE        DB = 2  G/M^3-DAY

**********************************************


CHANGE DISTANCE AND/OR TIME STEP <RETAIN>?

DO YOU WANT ANOTHER REACH <YES>?

         **********************
              REACH 3
         **********************
```

the value 0.960693 was estimated from depth and velocity using an empirical equation but the user can overwrite the estimated value.

the deoxygenation coefficient, k_1, may be known at another temperature (eg from another modelling study in winter) in which case a temperature correction can be made.

note that values from the previous reach are prompted but the user can overwrite with new values.

a point source is located at the upstream end of reach 2 ie at kilometre 25.

again values from the previous reach are prompted. For subsequent simulations, values from previous simulations are prompted.

```
ENTER D/S BOUNDARY  (KM) :? 75
REACH LENGTH  (KM) = 25
U/S VELOCITY  (M/S) : 1              NEW VALUE <RETAIN> : ? .75
U/S MEAN DEPTH  (M) : 2.5            NEW VALUE <RETAIN> : ? 2
U/S TEMPERATURE (C) : 15             NEW VALUE <RETAIN> : ? 17.5
SATURATION DO  (G/M^3) = 9.64965     NEW VALUE <RETAIN> : ? 9.5


INFLOW - ENTER T (TRIB) P (POINT) <NEITHER> : ? T
```
a tributary is located at upstream boundary of reach 3 ie at kilometre 50.
```
ENTER INFLOW FLOW  (M^3/S) :? 50
ENTER INFLOW BOD5  (G/M^3) :? 5
ENTER INFLOW DO    (G/M^3) :? 5

CONVERT BOD5 TO BODU
INFLOW KL (/DAY) : .48              NEW VALUE <RETAIN> : ?
INCUBATION DAYS  : 5               NEW VALUE <RETAIN> : ?
RIVER KL (/DAY)  : .4              NEW VALUE <RETAIN> : ?
INCUBATION DAYS  : 5               NEW VALUE <RETAIN> : ?

U/S K2  (/DAY) : .95               DO YOU WANT NEW ESTIMATE <YES>?
ESTIMATED K2  (/DAY) : 1.12047     NEW VALUE <RETAIN> : ? 1.15
U/S K1  (/DAY) : 2                 NEW VALUE <RETAIN> : ?
U/S DB (G/M^3-DAY) : 2             DO YOU WANT TO CHANGE IT <YES>?
ENTER DB (G/M^3-DAY) <G/M^2-DAY> : ? 1

*********************************************

     DEOXYGENATION COEFFICIENT  K1 = 2  /DAY
     REAERATION COEFFICIENT     K2 = 1.15  /DAY
     BENTHIC UPTAKE RATE        DB = 1  G/M^3-DAY

*********************************************


CHANGE DISTANCE AND/OR TIME STEP <RETAIN>?

DO YOU WANT ANOTHER REACH <YES>?

         **********************
                 REACH 4
         **********************


ENTER D/S BOUNDARY  (KM) :? 100
REACH LENGTH  (KM) = 25
U/S VELOCITY  (M/S) : .75            NEW VALUE <RETAIN> : ? .5
U/S MEAN DEPTH  (M) : 2              NEW VALUE <RETAIN> : ? 1.5
U/S TEMPERATURE (C) : 17.5           NEW VALUE <RETAIN> : ?
SATURATION DO  (G/M^3) = 9.64965     NEW VALUE <RETAIN> : ? 9.5


INFLOW - ENTER T (TRIB) P (POINT) <NEITHER> : ?
```
reach 4 has no inflow but velocity and depth change, as do k_2 and D_B.
```
CONVERT BOD5 TO BODU
INFLOW KL (/DAY) : .48              NEW VALUE <RETAIN> : ?
INCUBATION DAYS  : 5               NEW VALUE <RETAIN> : ?
RIVER KL (/DAY)  : .4              NEW VALUE <RETAIN> : ?
INCUBATION DAYS  : 5               NEW VALUE <RETAIN> : ?

U/S K2  (/DAY) : 1.15              DO YOU WANT NEW ESTIMATE <YES>?
ESTIMATED K2  (/DAY) : 1.22402     NEW VALUE <RETAIN> : ? 1.25
U/S K1  (/DAY) : 2                 NEW VALUE <RETAIN> : ?
U/S DB (G/M^3-DAY) : 1             DO YOU WANT TO CHANGE IT <YES>?
ENTER DB (G/M^3-DAY) <G/M^2-DAY> : ? 0
```

```
********************************************

    DEOXYGENATION COEFFICIENT   K1 = 2    /DAY
    REAERATION COEFFICIENT      K2 = 1.25 /DAY
    BENTHIC UPTAKE RATE         DB = 0  G/M^3-DAY

********************************************


CHANGE DISTANCE AND/OR TIME STEP <RETAIN>?

DO YOU WANT ANOTHER REACH <YES>? NO

DO YOU WANT A LISTING <NO>?

DO YOU WANT TO FILE BOD5 & DO PROFILES <NO>?
DO YOU WANT GRAPHS PLOTTED <YES>?
```

can list and/or file predicted BODs and DO
at a distance step of 5 km (specified above).
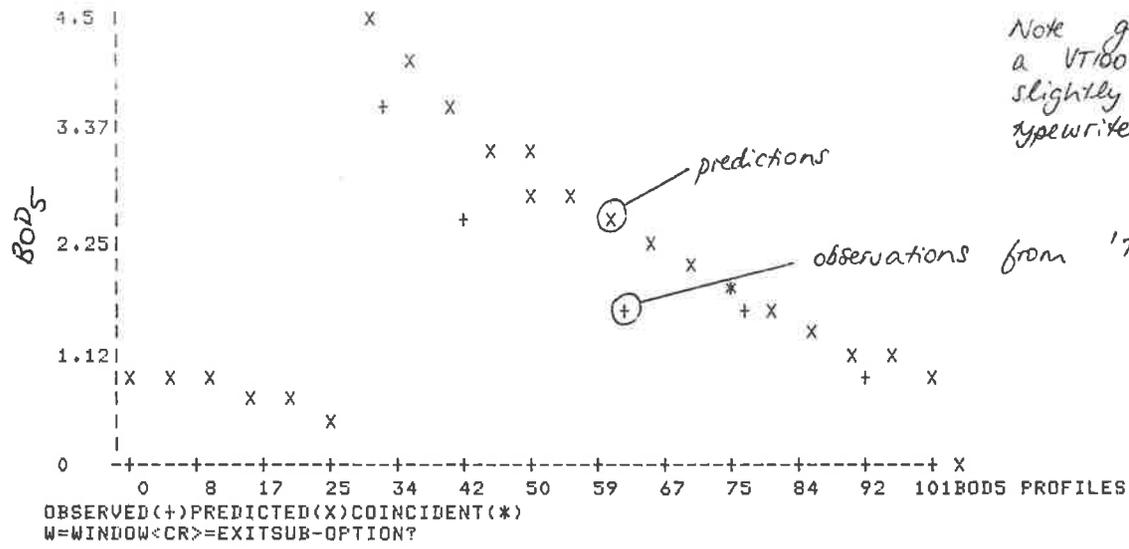
```
4.5 |                    X
     |                   X
     |                  X
3.37 |                 +   X
     |                    X  X
     |                     X  X
2.25 |                +      (X)
     |                      X
     |                    X
     |                  (+)    *
1.12 |                        + X
     |X  X  X              X
     |          X  X          + X
     |             X       X  X
     |                   +     X
  0 --+----+----+----+----+----+----+----+----+----+----+----+---+ X
     0    8   17   25   34   42   50   59   67   75   84   92  101BOD5 PROFILES
OBSERVED(+)PREDICTED(X)COINCIDENT(*)
W=WINDOW<CR>=EXITSUB-OPTION?
```

BOD5

predictions

observations from 'TRIAL.DAT'

```
10 |X  X  X
    |        X  X  *
    |           X
7.5 |          +  X
    |            X
    |          + X
    |            X
    |            X  X
  5 |                 X  X  X  *  X  X  X  *  X
    |                    +        +              X
2.5 |
    |
  0 --+----+----+----+----+----+----+----+----+----+----+----+---+ X
     0    8   17   25   34   42   50   59   67   75   84   92  101DO PROFILES
OBSERVED(+)PREDICTED(X)COINCIDENT(*)
W=WINDOW<CR>=EXITSUB-OPTION? W
```

DO
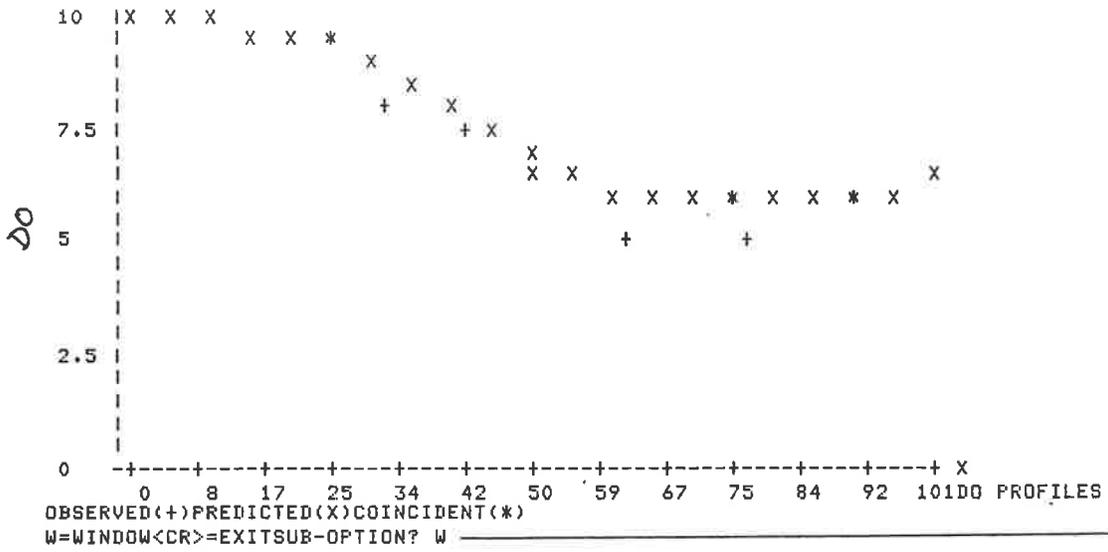
user can window in on a region of special interest and expand the x and/or y scales.
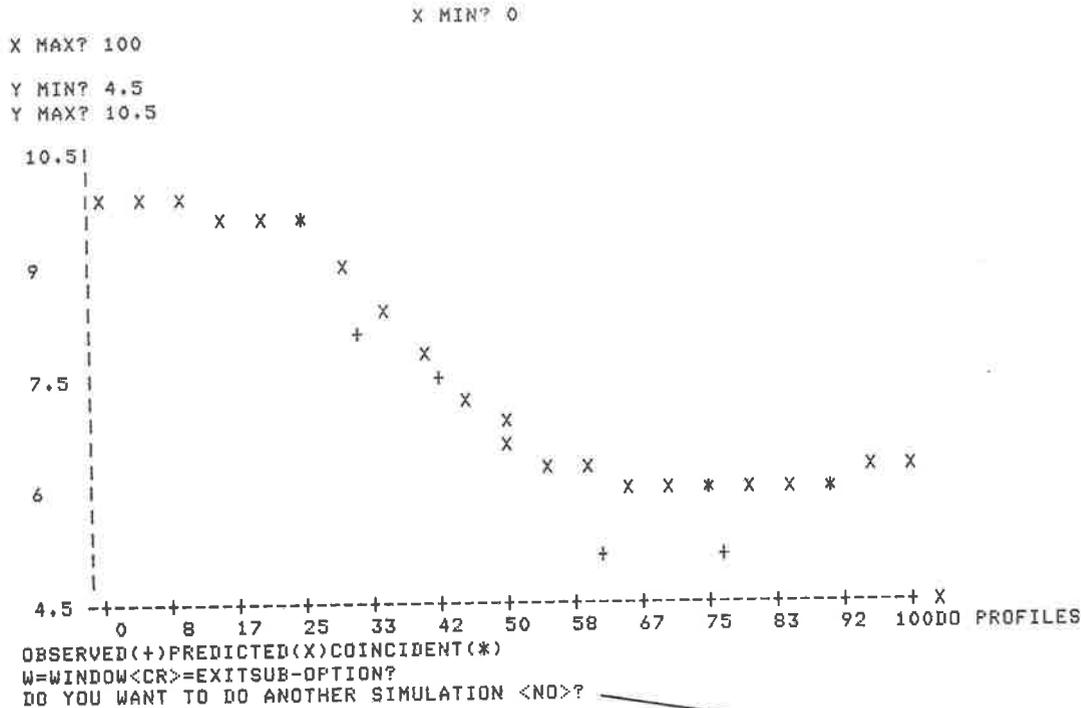
```
                              X MIN? 0
X MAX? 100

Y MIN? 4.5
Y MAX? 10.5

 10.5|
     |
     |X  X  X
     |          X  X  *
     |
  9  |                  X
     |
     |                    X
     |               +
     |                    X
 7.5 |                  +
     |                    X
     |                    X
     |                    X
  6  |                      X  X   X  X  *  X  X  *      X  X
     |
     |
     |               +            +
     |
 4.5 -+----+----+----+----+----+----+----+----+----+----+----+----+ X
      0    8    17   25   33   42   50   58   67   75   83   92  100DO PROFILES
OBSERVED(+)PREDICTED(X)COINCIDENT(*)
W=WINDOW<CR>=EXITSUB-OPTION?
DO YOU WANT TO DO ANOTHER SIMULATION <NO>?

PROGRAM TERMINATING


READY
```

up to 20 simulations can be done with the same set of reach boundaries. model coefficients k_1 k_2 D_B and input data U H T S Q etc are retained and prompted in subsequent simulations thus facilitating rerun of simulations with one or more coefficients the same.

Flow Chart for HAND

```
┌──────────────────────────────────────┐
│ Input observed BOD₅ and DO           │
│ profiles from disc file              │
└──────────────────────────────────────┘
                  │
                  ▼
┌──────────────────────────────────────┐
│ Enter location of upstream boundary  │
└──────────────────────────────────────┘
                  │
                  ▼
┌──────────────────────────────────────┐
│ Enter (or change) upstream discharge,│◄───┐
│ BOD₅ and DO concentration            │    │
└──────────────────────────────────────┘    │
                  │                          │
                  ▼                          │
┌──────────────────────────────────────┐    │
│ Increment reach number               │    │
└──────────────────────────────────────┘    │
                  │                          │
                  ▼                          │
┌──────────────────────────────────────┐    │
│ Enter (or change) location of        │    │
│ downstream boundary of the reach     │    │
└──────────────────────────────────────┘    │
                  │                          │
                  ▼                          │
┌──────────────────────────────────────┐    │
│ Enter (or change) velocity depth,    │    │
│ temperature (assumed constant in     │    │
│ each reach)                          │    │
└──────────────────────────────────────┘    │
                  │                          │
                  ▼                          │
┌──────────────────────────────────────┐    │
│ Enter (and/or change) saturation DO  │    │
└──────────────────────────────────────┘    │
                  │                          │
                  ▼                          │
┌──────────────────────────────────────┐    │
│ Specify (or change) nature of inflow │    │
│ (point source, tributary or neither) │    │
│ at the upstream boundary of the      │    │
│ reach, and either: BOD₅ mass-flow,   │    │
│ or discharge and concentration of    │    │
│ BOD₅ and DO as appropriate           │    │
└──────────────────────────────────────┘    │
                  │                          │
                  ▼                          │
┌──────────────────────────────────────┐    │
│ Convert BOD₅ to BODᵤ                 │    │
└──────────────────────────────────────┘    │
                  │                          │
                  ▼                          │
┌──────────────────────────────────────┐    │
│ Specify (and/or change) deoxygenation│    │
│ coefficient, reaeration coefficient  │    │
│ and benthic oxygen demand rate       │    │
│ (assumed constant in each reach)     │    │
└──────────────────────────────────────┘    │
                  │                          │
         Yes      ▼                          │
     ◄──────◇ Another reach? ◇               │
                  │ No                       │
                  ▼                          │
┌──────────────────────────────────────┐    │
│ Specify (or change) distance interval│    │
│ at which predictions are to be made  │    │
└──────────────────────────────────────┘    │
                  │                          │
                  ▼                          │
┌──────────────────────────────────────┐    │
│ Calculate BOD₅ and DO profiles       │    │
└──────────────────────────────────────┘    │
                  │                          │
                  ▼                          │
┌──────────────────────────────────────┐    │
│ List file and/or graph profiles if   │    │
│ required                             │    │
└──────────────────────────────────────┘    │
                  │                          │
                  ▼                    Yes   │
     ◄──────◇ Another simulation? ◇─────────┘
                  │
                  ▼
            ┌──────────┐
            │ Stop     │
            └──────────┘
```
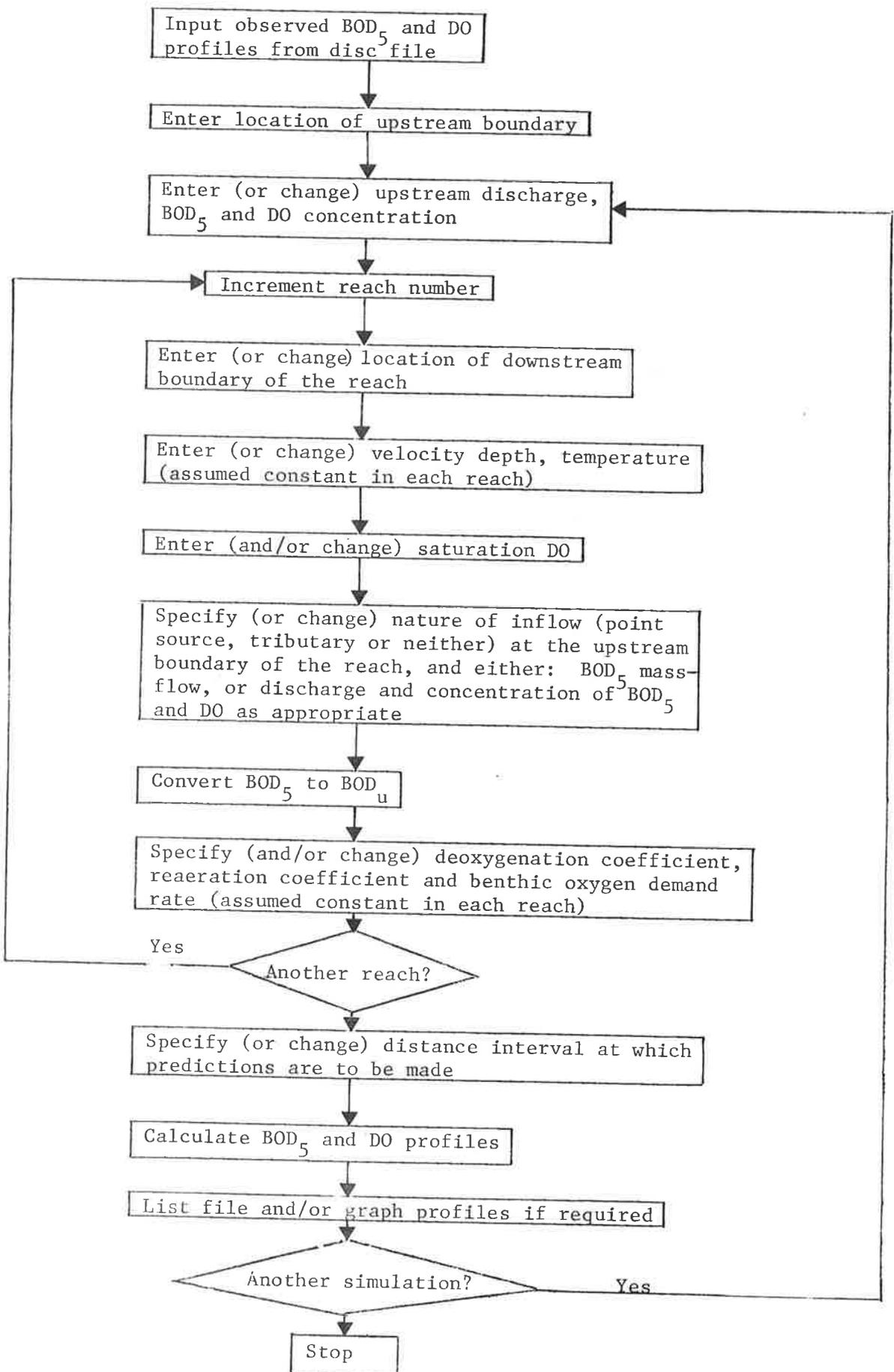
54

```
LIST


HAND2      18-MAY-83   14:00:36

3 R9$=CHR$(13)
5 P9$=CHR$(32)
10 DIM X2(50%)
20 DIM B2(50%)
30 DIM D2(50%)
40 DIM L(20%)
50 DIM U(20%)
60 DIM H(20%)
70 DIM T(20%)
80 DIM S(20%)
90 DIM Q0(20%)
100 DIM B0(20%)
110 DIM D0(20%)
120 DIM K1(20%)
130 DIM K2(20%)
140 DIM K3(20%)
150 DIM Q1(20%)
160 DIM B1(20%)
170 DIM D1(20%)
180 DIM F(20%)
190 DIM I$(20%)
200 DIM S$(60%)
210 DIM S8$(60%)
220 DIM S9$(60%)
230 DIM X9%(50%)
240 DIM B9%(50%)
250 DIM D9%(50%)
260 DIM A%(200%)
270 DIM X(200%)
280 DIM B(200%)
290 DIM D(200%)
300 DIM X8%(200%)
310 DIM B8%(200%)
320 DIM D8%(200%)
340 Z1=1.14339
350 Z2=-9.07877E-03
360 Z3=0
370 Z4=0
380 O%=0%
390 S%=0%
400 K8=.48
410 K9=.4
420 I=5
430 F1%=60%
440 F2%=20%
450 S1$='
460 S2$='
470 L$='********************'
475 E$=CHR$(27)
480 C$=E$+"[2J"+E$+"[H"
490 PRINT E$+"<"
500 P1$=E$+"[4;67H"
510 P2$=E$+"[5;67H"
520 P3$=E$+"[6;67H"
530 P4$=E$+"[8;67H"
540 P5$=E$+"[9;67H"
550 P6$=E$+"[11;67H"
555 P7$=E$+"[2;67H"
560 GO TO 750
570 Z%=.5+(X1-X0)*F1%/X8
580 IF Z%<0% THEN Z%=-1% \ GO TO 590
581 IF Z%>F1% THEN Z%=-1%
590 RETURN
620 Z%=.5+(Y1-Y0)*F2%/Y8
630 IF Z%<0% THEN Z%=-1% \ GO TO 650
631 IF Z%>F2% THEN Z%=-1%
650 RETURN
670 IF INT(Z+.5)<>INT(Z) THEN Z=INT(Z+.5) \ GO TO 680
671 Z=INT(Z)+.5
680 RETURN
710 A1$=SEG$(A1$,I%,I%)
720 IF A1$>="a" THEN A1$=CHR$(ASC(A1$)-32)
730 RETURN
750 REM ******************************************************************
770 PRINT
780 PRINT C$;S1$;L$
790 PRINT S2$;'PROGRAM HAND'
800 PRINT S1$;L$
810 PRINT
820 PRINT
```

```
830 PRINT 'IS THERE OBSERVED DATA FILED FOR COMPARISON <YES>';
831 INPUT A1$
841 GOSUB 710
842 A$=A1$
843 IF A$='N' THEN 1160
850 D4= 1.00000E|10
860 D4=-1.00000E+10
870 PRINT
880 PRINT 'ENTER FILE NAME FOR FILED DATA <NO FILE> : ';
881 INPUT F9$
890 IF F9$='' THEN 820
900 OPEN F9$ FOR INPUT AS FILE 4%
910 LINPUT #4%,B$
920 B1%=POS(B$,',',1%)
930 IF B1%<>0% THEN B$=SEG$(B$,1%,B1%-1%)
940 I%=0%
950 PRINT
960 PRINT 'FILE HEADER - "';B$;'"'
970 PRINT 'CORRECT FILE <YES>';
971 INPUT A1$
980 GOSUB 710
981 A$=A1$
982 IF A$='N' THEN 820
990 IF END #4 GO TO 1080
1000 LINPUT #4%,B$
1010 I%=I%+1%
1015 IF END #4 GO TO 1080
1020 INPUT #4%,X2(I%),B2(I%),D2(I%)
1030 IF B2(I%)>B4 THEN B4=B2(I%)
1040 IF D2(I%)>D4 THEN D4=D2(I%)
1050 GO TO 1010
1080 K2%=I%-1%
1090 CLOSE #4%
1100 IF X2(1%)>X2(K2%) THEN S%=1%
1110 PRINT
1120 PRINT 'DO YOU WANT AN INPUT DATA LISTING <NO>';
1121 INPUT A1$
1130 GOSUB 710
1131 A$=A1$
1132 IF A$<>'Y' THEN 1160
1133 PRINT \ PRINT
1140 PRINT 'LINE','X','BOD5','DO'
1150 FOR J%=1% TO K2%
1151 PRINT J%,X2(J%),B2(J%),D2(J%)
1152 NEXT J%
1160 PRINT \ PRINT \ PRINT \ PRINT
1180 PRINT 'ENTER U/S BOUNDARY (KM) : ';
1181 INPUT L1
1190 X(0%)=L1
1200 0%=0%+1%
1210 PRINT \ PRINT \ PRINT C$;S1$;L$
1220 PRINT S2$;' SIMULATION';0%
1230 PRINT S1$;L$
1240 PRINT
1250 N%=0%
1260 K%=0%
1270 L3=L1
1280 K1(0%)=1.00000E+10
1290 K3(0%)=1.00000E+10
1300 B3=-1.00000E+10
1310 D3=-1.00000E+10
1320 FOR I%=1% TO 60%
1330 S8$(I%)=' '
1340 S9$(I%)=' '
1350 NEXT I%
1360 N%=N%+1%
1370 PRINT
1380 PRINT S1$;L$
1390 PRINT S2$;'    REACH';N%
1400 PRINT S1$;L$
1410 PRINT
1420 IF 0%=1% THEN 1780
1430 L=L(N%)
1440 PRINT 'PREVIOUS D/S BOUNDARY  (KM) :';
1450 PRINT L;
1460 PRINT TAB(40);
1470 PRINT 'NEW VALUE <RETAIN> : ';
1480 INPUT A$
1490 IF A$<>'' THEN L=VAL(A$)
1500 L2=ABS(L3-L)
1510 PRINT 'REACH LENGTH  (KM) =';L2
1520 L3=L
1540 U=U(N%)
1550 PRINT 'PREVIOUS VELOCITY  (M/S) :';
```

```
1560 PRINT U;
1570 PRINT TAB(40);
1580 PRINT 'NEW VALUE <RETAIN> : ';
1590 INPUT A$
1600 IF A$<>'' THEN U=VAL(A$)
1610 H=H(N%)
1630 PRINT 'PREVIOUS MEAN DEPTH   (M) :';
1640 PRINT H;
1650 PRINT TAB(40);
1660 PRINT 'NEW VALUE <RETAIN> : ';
1670 INPUT A$
1680 IF A$<>'' THEN H=VAL(A$)
1690 T=T(N%)
1710 PRINT 'PREVIOUS TEMPERATURE (C) :';
1720 PRINT T;
1730 PRINT TAB(40);
1740 PRINT 'NEW VALUE <RETAIN> : ';
1750 INPUT A$
1760 IF A$<>'' THEN T=VAL(A$)
1770 GO TO 2140
1780 PRINT
1790 PRINT 'ENTER D/S BOUNDARY   (KM) :';
1791 INPUT L
1800 IF F9$<>'' GO TO 1810
1801 IF L1>L THEN S%=1%
1810 IF L<L1 GO TO 1814
1811 IF L=L1 THEN 1820
1812 IF S%=1% GO TO 1816
1813 GO TO 1820
1814 IF S%=0% GO TO 1816
1815 GO TO 1820
1816 PRINT '?BOUNDARY DATA DOES NOT MATCH OBSERVED DATA'
1817 GO TO 8040
1820 L2=ABS(L3-L)
1830 PRINT 'REACH LENGTH   (KM) =';L2
1840 L3=L
1860 IF N%=1% THEN 2090
1870 PRINT 'U/S VELOCITY   (M/S) :';
1880 PRINT U;
1890 PRINT TAB(40);
1900 PRINT 'NEW VALUE <RETAIN> : ';
1910 INPUT A$
1920 IF A$<>'' THEN U=VAL(A$)
1940 PRINT 'U/S MEAN DEPTH   (M) :';
1950 PRINT H;
1960 PRINT TAB(40);
1970 PRINT 'NEW VALUE <RETAIN> : ';
1980 INPUT A$
1990 IF A$<>'' THEN H=VAL(A$)
2010 PRINT 'U/S TEMPERATURE (C) :';
2020 PRINT T;
2030 PRINT TAB(40);
2040 PRINT 'NEW VALUE <RETAIN> : ';
2050 INPUT A$
2060 IF A$<>'' THEN T=VAL(A$)
2080 GO TO 2140
2090 PRINT
2100 PRINT 'ENTER VELOCITY   (M/S)  :',
2101 INPUT U
2110 PRINT 'ENTER MEAN DEPTH   (M)  :',
2111 INPUT H
2120 PRINT 'ENTER TEMPERATURE (C)   :',
2121 INPUT T
2140 L(N%)=L
2150 U(N%)=U
2160 H(N%)=H
2170 T(N%)=T
2180 S=10^(Z1+Z2*T+Z3*T^2+Z4*T^3)
2190 PRINT 'SATURATION DO   (G/M^3) =';
2200 PRINT S;
2210 PRINT TAB(40);
2220 PRINT 'NEW VALUE <RETAIN> : ';
2230 INPUT A$
2240 IF A$='' GO TO 2260
2241 S=VAL(A$)
2242 S(N%)=S
2260 REM -- Inflow
2280 PRINT C$
2290 IF N%>1% THEN 2600
2300 IF O%=1% THEN 2560
2310 Q0=Q0(N%)
2330 PRINT 'PREVIOUS U/S FLOW :';
2340 PRINT Q0;
2350 PRINT TAB(40);
```

```
2360 PRINT 'NEW VALUE <RETAIN> : ';
2370 INPUT A$
2380 IF A$<>'' THEN Q0=VAL(A$)
2390 B0=B0(N%)
2410 PRINT 'PREVIOUS U/S BOD5 :';
2420 PRINT B0;
2430 PRINT TAB(40);
2440 PRINT 'NEW VALUE <RETAIN> : ';
2450 INPUT A$
2460 IF A$<>'' THEN B0=VAL(A$)
2470 D0=D0(N%)
2490 PRINT 'PREVIOUS U/S DO   :';
2500 PRINT D0;
2510 PRINT TAB(40);
2520 PRINT 'NEW VALUE <RETAIN> : ';
2530 INPUT A$
2540 IF A$<>'' THEN D0=VAL(A$)
2550 GO TO 2600
2560 PRINT
2570 PRINT 'ENTER U/S FLOW   (M^3/S) :',
2571 INPUT Q0
2580 PRINT 'ENTER U/S BOD5   (G/M^3) :',
2581 INPUT B0
2590 PRINT 'ENTER U/S DO     (G/M^3) :',
2591 INPUT D0
2600 Q0(N%)=Q0
2610 B0(N%)=B0
2620 D0(N%)=D0
2640 IF O%=1% THEN 3150
2650 I$=I$(N%)
2660 IF I$='P' THEN 2710
2670 IF I$='' THEN 2740
2690 PRINT 'PREVIOUS INFLOW A TRIB - ENTER P (POINT)  N (NONE)  <RETAIN> : ';
2691 INPUT A$
2700 GO TO 2760
2720 PRINT 'PREVIOUS INFLOW A POINT - ENTER T (TRIB)  N (NONE)  <RETAIN> : ';
2721 INPUT A$
2730 GO TO 2760
2750 PRINT 'NO PREVIOUS INFLOW - ENTER T (TRIB)  P (POINT)  <RETAIN> : ';
2751 INPUT A$
2760 IF A$<>'' THEN I$=A$
2770 IF I$='P' THEN 3050
2780 IF I$<>'' GO TO 2790
2781 F=0
2782 GO TO 2580
2790 Q1=Q1(N%)
2810 PRINT 'PREVIOUS INFLOW FLOW :';
2820 PRINT Q1;
2830 PRINT TAB(40);
2840 PRINT 'NEW VALUE <RETAIN> : ';
2850 INPUT A$
2860 IF A$<>'' THEN Q1=VAL(A$)
2870 B1=B1(N%)
2890 PRINT 'PREVIOUS INFLOW BOD5 :';
2900 PRINT B1;
2910 PRINT TAB(40);
2920 PRINT 'NEW VALUE <RETAIN> : ';
2930 INPUT A$
2940 IF A$<>'' THEN B1=VAL(A$)
2950 D1=D1(N%)
2970 PRINT 'PREVIOUS INFLOW DO   :';
2980 PRINT D1;
2990 PRINT TAB(40);
3000 PRINT 'NEW VALUE <RETAIN> : ';
3010 INPUT A$
3020 IF A$<>'' THEN D1=VAL(A$)
3030 F=0
3040 GO TO 3320
3050 F=F(N%)
3070 PRINT 'PREVIOUS MASSFLOW (KG/DAY) :';
3080 PRINT F;
3090 PRINT TAB(40);
3100 PRINT 'NEW VALUE <RETAIN> : ';
3110 INPUT A$
3120 IF A$='' THEN 3660
3130 F=VAL(A$)
3140 GO TO 3290
3150 PRINT
3160 PRINT 'INFLOW - ENTER T (TRIB) P (POINT) <NEITHER> : ';
3161 INPUT I$
3170 IF I$='T' THEN 3210
3180 IF I$='P' THEN 3270
3190 F=0
3200 GO TO 3290
```

```
3210 PRINT
3220 PRINT 'ENTER INFLOW FLOW   (M^3/S) :',
3221 INPUT Q1
3230 PRINT 'ENTER INFLOW BOD5   (G/M^3) :',
3231 INPUT B1
3240 PRINT 'ENTER INFLOW DO     (G/M^3) :',
3241 INPUT D1
3250 F=0
3260 GO TO 3320
3270 PRINT
3280 PRINT 'ENTER BOD5 MASSFLOW  (KG/DAY) : ';
3281 INPUT F
3290 Q1=0
3300 B1=0
3310 D1=S
3320 Q1(N%)=Q1
3330 D1(N%)=D1
3340 B1(N%)=B1
3350 F(N%)=F
3360 I$(N%)=I$
3380 REM -- Convert BOD5 to BODU
3400 PRINT
3410 PRINT 'CONVERT BOD5 TO BODU'
3430 PRINT 'INFLOW KL (/DAY) :';
3440 PRINT K8;
3450 PRINT TAB(40);
3460 PRINT 'NEW VALUE <RETAIN> : ';
3470 INPUT A$
3480 IF A$<>'' THEN K8=VAL(A$)
3500 PRINT 'INCUBATION DAYS  :';
3510 PRINT I;'  ';P9$;
3520 PRINT TAB(40);
3530 PRINT 'NEW VALUE <RETAIN> : ';
3540 INPUT A$
3550 IF A$<>'' THEN I=VAL(A$)
3560 B1=B1/(1-EXP(-I*K8))
3570 F=F/(1-EXP(-I*K8))
3590 PRINT 'RIVER KL (/DAY)  :';
3600 PRINT K9;'  ';P9$;
3610 PRINT TAB(40);
3620 PRINT 'NEW VALUE <RETAIN> : ';
3630 INPUT A$
3640 IF A$<>'' THEN K9=VAL(A$)
3660 PRINT 'INCUBATION DAYS  :';
3670 PRINT I;'  ';P9$;
3680 PRINT TAB(40);
3690 PRINT 'NEW VALUE <RETAIN> : ';
3700 INPUT A$
3710 IF A$<>'' THEN I=VAL(A$)
3720 F1=(1-EXP(-I*K9))
3730 B0=B0/F1 \ REM Factor F1 retained for later use
3740 Q2=Q0+Q1
3750 B2=(Q1*B1+Q0*B0+F/86.4)/Q2
3760 D2=(Q1*D1+Q0*D0)/Q2 \ REM Add Inflow
3780 REM --   Reaeration rate
3800 PRINT
3820 IF O%=1% THEN 3910
3830 K2=K2(N%)
3840 PRINT 'PREVIOUS K2   (/DAY) :';
3850 PRINT K2;
3860 PRINT TAB(40);
3870 PRINT 'DO YOU WANT IT CHANGED <YES>';
3880 INPUT A1$
3890 GOSUB 710
3891 A$=A1$
3892 IF A$='N' THEN 4100
3900 GO TO 3990
3910 IF N%=1% THEN 3990
3930 PRINT 'U/S K2  (/DAY) :';
3940 PRINT K2;
3950 PRINT TAB(40);
3960 PRINT 'DO YOU WANT NEW ESTIMATE <YES>';
3970 INPUT A1$
3980 GOSUB 710
3981 A$=A1$
3982 IF A$='N' THEN 4100
3990 IF U<.5 THEN K2=3.74*U^.5*H^-1.5
3991 IF U<.5 GO TO 4000
3992 IF U=.5 THEN 3997
3993 IF H<.5 THEN K2=5.13*U*H^-1.333
3994 IF H<.5 GO TO 4000
3995 IF H<1 THEN K2=4.75*U*H^-1.5
3996 IF H<1 GO TO 4000
3997 K2=5.01*U^.969*H^-1.673
```

```
4000 K2=K2*1.024^(T-20) \ REM Correct for temperature
4020 PRINT 'ESTIMATED K2   (/DAY) :';
4030 PRINT K2;
4040 PRINT TAB(40);
4050 PRINT 'NEW VALUE <RETAIN> : ';
4060 INPUT A$
4080 IF A$<>'' THEN K2=VAL(A$)
4100 REM -- Deoxygenation rate
4120 IF O%=1% THEN 4210
4130 K1=K1(N%)
4150 PRINT 'PREVIOUS K1   (/DAY) :';
4160 PRINT K1;
4170 PRINT TAB(40);
4180 PRINT 'NEW VALUE <RETAIN> : ';
4190 INPUT A$
4200 GO TO 4310
4210 IF N%=1% THEN 4290
4230 PRINT 'U/S K1   (/DAY) :';
4240 PRINT K1;
4250 PRINT TAB(40);
4260 PRINT 'NEW VALUE <RETAIN> : ';
4270 INPUT A$
4280 GO TO 4310
4290 PRINT 'ENTER K1   (/DAY) : ';
4291 INPUT A$
4300 IF A$='' THEN K1=.25
4310 IF A$='' THEN 4370
4320 K1=VAL(A$)
4340 PRINT 'ENTER REF TEMP  (C) <RIVER TEMP> : ';
4341 INPUT A$
4350 IF A$<>'' THEN K1=K1*1.047^(VAL(A$)-T)
4370 REM -- Benthic uptake rate
4390 IF O%=1% THEN 4460
4400 K3=K3(N%)
4420 PRINT 'PREVIOUS DB (G/M^3-DAY) :';K3;P9$;
4430 PRINT TAB(40);
4440 PRINT 'DO YOU WANT TO CHANGE IT <YES>';
4441 INPUT A1$
4450 GO TO 4520
4460 IF N%=1% THEN 4540
4490 PRINT 'U/S DB (G/M^3-DAY) :';K3;P9$;
4500 PRINT TAB(40);
4510 PRINT 'DO YOU WANT TO CHANGE IT <YES>';
4511 INPUT A1$
4520 GOSUB 710
4521 A$=A1$
4522 IF A$='N' THEN 4600
4540 PRINT 'ENTER DB (G/M^3-DAY) <G/M^2-DAY> : ';
4541 INPUT A$
4550 IF A$<>'' THEN K3=VAL(A$)
4560 GO TO 4600
4580 PRINT 'ENTER DB (G/M^2-DAY) <ZERO> : ';
4581 INPUT A$
4590 IF A$='' THEN K3=0
4591 IF A$<>'' THEN K3=VAL(A$)/H
4600 PRINT
4610 PRINT C$;L$;L$
4620 PRINT
4630 PRINT '     DEOXYGENATION COEFFICIENT  K1 =';K1;' /DAY'
4640 PRINT '     REAERATION COEFFICIENT     K2 =';K2;' /DAY'
4650 PRINT '     BENTHIC UPTAKE RATE        DB =';K3;' G/M^3-DAY'
4660 PRINT
4670 PRINT L$;L$
4680 PRINT
4690 PRINT
4700 K1(N%)=K1
4710 K2(N%)=K2
4720 K3(N%)=K3
4730 K1=K1/24
4740 K2=K2/24
4750 K3=K3/24 \ REM Convert to /hour
4770 REM -- Select computation steps
4790 IF O%=1% GO TO 4792
4791 GO TO 4800
4792 IF N%=1% THEN 4860
4800 PRINT
4810 PRINT 'CHANGE DISTANCE AND/OR TIME STEP <RETAIN>';
4811 INPUT A1$
4820 GOSUB 710
4821 A$=A1$
4822 IF A$='' THEN 4910
4840 REM -- A1 = Distance step    A2 = Time step
4860 PRINT 'ENTER DISTANCE STEP  (KM) <TIME STEP> : ';
4861 INPUT A$
```

```
4870 IF A$='' GO TO 4880
4871 A1=VAL(A$)
4872 A2=A1/U/3.6
4873 GO TO 4910
4880 PRINT 'ENTER TIME STEP  (HOUR) : ';
4881 INPUT A$
4890 IF A$='' GO TO 4910
4891 A2=VAL(A$)
4892 A1=A2*U*3.6
4910 REM   ****************************************************************
4930 M%=INT(L2/A1)
4940 IF S%=1% THEN A1=-A1 \ REM  Number of steps in the reach
4950 K%=K%+1%
4960 X(K%)=X(K%-1)
4970 B(K%)=B2*F1
4980 D(K%)=D2 \ REM  Store mixed values
5000 REM -- Calculate sag in the reach
5020 FOR J%=1% TO M%
5030 K%=K%+1%
5040 T1=A2*J% \ REM  Travel time along this reach only
5050 X(K%)=X(K%-1)+A1 \ REM  Increment total distance
5070 REM -- BOD5 & DO
5090 B(K%)=B2*EXP(-K1*T1)*F1
5100 IF K1=K2 THEN D(K%)=S-K3/K2-EXP(-K2*T1)*(S-D2-K3/K2)-EXP(-K1*T1)*T1*K1*B2
5101 IF K1=K2 GO TO 5110
5102 P1=S-K3/K2-EXP(-K2*T1)*(S-D2-K3/K2-K1*B2/(K2-K1))
5108 P2=EXP(-K1*T1)*K1*B2/(K2-K1)
5109 D(K%)=P1-P2
5110 IF B(K%)>B3 THEN B3=B(K%)
5120 IF D(K%)>D3 THEN D3=D(K%)
5130 NEXT J%
5150 REM -- Reinitialise
5170 D0=D(K%)
5180 B0=B(K%)
5190 Q0=Q2
5200 IF S%=1% THEN A1=A1*-1
5210 K1=K1*24
5220 K2=K2*24
5230 K3=K3*24 \ REM  Convert back to /day
5240 PRINT
5250 PRINT 'DO YOU WANT ANOTHER REACH <YES>';
5251 INPUT A1$
5260 GOSUB 710
5261 A$=A1$
5262 IF A$='N' THEN 5280
5270 IF N%=20% THEN PRINT 'SORRY, YOU CAN ONLY HAVE 20 REACHES'
5271 IF N%=20% GO TO 5280
5272 PRINT C$;
5273 GO TO 1360
5280 PRINT
5290 PRINT 'DO YOU WANT A LISTING <NO>';
5291 INPUT A1$
5300 GOSUB 710
5301 A$=A1$
5302 IF A$<>'Y' THEN 5350
5310 PRINT C$
5320 PRINT P9$,'X','BOD5','DO'
5330 PRINT
5340 FOR J%=1% TO K%
5341 PRINT J%,X(J%),B(J%),D(J%)
5342 NEXT J%
5350 PRINT
5360 PRINT 'DO YOU WANT TO FILE BOD5 & DO PROFILES <NO>';
5361 INPUT A1$
5370 GOSUB 710
5371 A$=A1$
5372 IF A$<>'Y' THEN 5570
5380 PRINT
5390 PRINT 'ENTER OUTPUT FILE NAME (5 CHAR, NO EXTENT) : ';
5391 INPUT F$
5400 F1$=F$+'B.SDT'
5410 F2$=F$+'D.SDT'
5420 PRINT
5430 PRINT 'ENTER OUTPUT FILE HEADER  : ';
5431 INPUT H$
5440 OPEN F1$ FOR OUTPUT AS FILE 8%
5450 PRINT #8%,H$,'X,BOD5'
5460 FOR J%=1% TO K%
5470 PRINT #8%,X(J%),',',B(J%)
5480 NEXT J%
5490 CLOSE 8%
5500 OPEN F2$ FOR OUTPUT AS FILE 9%
5510 PRINT #9%,H$,'X,DO'
5520 FOR J%=1% TO K%
```

61

```
5530 PRINT #9%,X(J%),',',D(J%)
5540 NEXT J%
5550 CLOSE 9%
5570 REM   ***********************************************************
5590 PRINT C$;'DO YOU WANT GRAPHS PLOTTED <YES>';
5600 INPUT A1$
5610 GOSUB 710
5611 A$=A1$
5612 IF A$='N' THEN 7900
5620 IF S%=0% THEN 5710
5630 Z9=X(1%)
5640 IF F9$='' GO TO 5650
5642 IF X2(1%)>Z9 THEN Z9=X2(1%)
5650 FOR I%=1% TO K%
5660 X(I%)=Z9-X(I%)
5670 NEXT I%
5680 FOR J%=1% TO K2%
5690 X2(J%)=Z9-X2(J%)
5700 NEXT J%
5710 X5=X(1%)
5720 IF F9$='' GO TO 5730
5722 IF X2(1%)<X5 THEN X5=X2(1%)
5730 IF INT(X5+.5)<>INT(X5) THEN X5=INT(X5)+.5 \ GO TO 5740
5731 X5=INT(X5)
5740 X6=X(K%)
5750 IF F9$='' GO TO 5760
5752 IF X2(K2%)>X6 THEN X6=X2(K2%)
5760 B5=0
5770 B6=B3
5780 IF F9$='' GO TO 5790
5782 IF B4>B6 THEN B6=B4
5790 D5=0
5800 D6=D3
5810 IF F9$='' GO TO 5820
5812 IF D4>D6 THEN D6=D4
5820 Z=X6
5821 GOSUB 670
5822 X6=Z
5830 Z=B6
5831 GOSUB 670
5832 B6=Z
5840 Z=D6
5841 GOSUB 670
5842 D6=Z
5850 T9=X6-X5
5860 U9=X6
5870 V9=X5
5880 G%=0%
5890 FOR I%=1% TO N%
5900 IF K1(I%)=K1(I%-1%) THEN 5910
5901 X1=X(I%)
5902 X0=X5
5903 X8=T9
5904 GOSUB 570
5905 S8$(Z%)='I'
5910 IF K3(I%)=K3(I%-1%) THEN 5920
5911 X1=X(I%)
5912 X0=X5
5913 X8=T9
5914 GOSUB 570
5915 S9$(Z%)='I'
5920 NEXT I%
5930 X7=X6-X5
5940 B7=B6-B5
5960 REM -- Form print positions
5980 FOR I%=1% TO K%
5981 X1=X(I%)
5982 X0=X5
5983 X8=X7
5984 GOSUB 570
5990 X8%(I%)=Z%
5991 Y1=B(I%)
5992 Y0=B5
5993 Y8=B7
5994 GOSUB 620
6000 B8%(I%)=Z%
6010 NEXT I%
6020 FOR I%=1% TO K2%
6021 X1=X2(I%)
6022 X0=X5
6023 X8=X7
6024 GOSUB 570
6030 X9%(I%)=Z%
6031 Y1=B2(I%)
```

```
6032 YO=B5
6033 Y8=B7
6034 GOSUB 620
6040 B9%(I%)=Z%
6050 NEXT I%
6070 REM -- Sort
6090 FOR I%=1% TO K%
6091 A%(I%)=X8%(I%)+200%*B8%(I%)
6092 NEXT I%
6100 FOR I%=1% TO K%-1%
6110 A9%=0%
6120 FOR J%=I% TO 1% STEP -1%
6130 IF A9%<>0% THEN 6170
6140 A9%=-1%
6150 IF A%(J%)>=A%(J%+1%) GO TO 6160
6151 P%=A%(J%)
6152 A%(J%)=A%(J%+1%)
6153 A%(J%+1%)=P%
6154 A9%=0%
6160 NEXT J%
6170 NEXT I%
6180 FOR I%=1% TO K%
6190 B8%(I%)=A%(I%)/200%
6200 X8%(I%)=A%(I%)-B8%(I%)*200%
6210 NEXT I%
6220 FOR I%=1% TO K2%
6221 A%(I%)=X9%(I%)+200%*B9%(I%)
6222 NEXT I%
6230 FOR I%=1% TO K2%-1%
6240 A9%=0%
6250 FOR J%=I% TO 1% STEP -1%
6260 IF A9%<>0% THEN 6300
6270 A9%=1%
6280 IF A%(J%)>=A%(J%+1%) GO TO 6290
6281 P%=A%(J%)
6282 A%(J%)=A%(J%+1%)
6283 A%(J%+1%)=P%
6284 A9%=0%
6290 NEXT J%
6300 NEXT I%
6310 FOR I%=1% TO K2%
6320 B9%(I%)=A%(I%)/200%
6330 X9%(I%)=A%(I%)-B9%(I%)*200%
6340 NEXT I%
6360 REM -- Plot points
6380 GOSUB 7240
6385 P8$='BOD5 PROFILES'
6390 FOR I%=F2% TO 0% STEP -1%
6400 FOR G1%=0% TO F1%
6401 S$(G1%)=' '
6402 NEXT G1%
6410 FOR I1%=J% TO 200%
6420 IF B8%(I1%)<>I% THEN 6460
6430 IF X8%(I1%)<0% THEN 6450
6431 IF X8%(I1%)>100% THEN 6450
6440 IF S$(X8%(I1%))=' ' THEN S$(X8%(I1%))='X' \ GO TO 6450
6441 S$(X8%(I1%))='*'
6450 NEXT I1%
6460 J%=I1%
6470 FOR I1%=K1% TO 50%
6480 IF B9%(I1%)<>I% THEN 6520
6490 IF X9%(I1%)<0% THEN 6510
6491 IF X9%(I1%)>100% THEN 6510
6500 IF S$(X9%(I1%))=' ' THEN S$(X9%(I1%))=' + ' \ GO TO 6510
6501 S$(X9%(I1%))='*'
6510 NEXT I1%
6520 PRINT
6530 GOSUB 7420
6540 NEXT I%
6550 GOSUB 7530
6560 IF M9%<>0% GO TO 6580
6561 PRINT P6$;
6562 GO TO 5930
6580 REM -- Repeat for DO graph
6600 X7=T9
6610 X6=U9
6620 X5=V9
6630 D7=D6-D5
6640 G%=1%
6650 GO TO 6680
6660 X7=X6-X5
6670 D7=D6-D5
6680 FOR I%=1% TO K%
6681 X1=X(I%)
```

63

```
6682 XO=X5
6683 X8=X7
6684 GOSUB 570
6690 X8%(I%)=Z%
6691 Y1=D(I%)
6692 YO=D5
6693 Y8=D7
6694 GOSUB 620
6700 D8%(I%)=Z%
6710 NEXT I%
6720 FOR I%=1% TO K2%
6721 X1=X2(I%)
6722 XO=X5
6723 X8=X7
6724 GOSUB 570
6730 X9%(I%)=Z%
6731 Y1=D2(I%)
6732 YO=D5
6733 Y8=D7
6734 GOSUB 620
6740 D9%(I%)=Z%
6750 NEXT I%
6760 FOR I%=1% TO K%
6761 A%(I%)=X8%(I%)+200%*D8%(I%)
6762 NEXT I%
6770 FOR I%=1% TO K%-1%
6780 A9%=0%
6790 FOR J%=I% TO 1% STEP -1%
6800 IF A9%<>0% THEN 6840
6810 A9%=-1%
6820 IF A%(J%)>=A%(J%+1%) GO TO 6830
6821 P%=A%(J%)
6822 A%(J%)=A%(J%+1%)
6823 A%(J%+1%)=P%
6824 A9%=0%
6830 NEXT J%
6840 NEXT I%
6850 FOR I%=1% TO K%
6860 D8%(I%)=A%(I%)/200%
6870 X8%(I%)=A%(I%)-D8%(I%)*200%
6880 NEXT I%
6890 FOR I%=1% TO K2%
6891 A%(I%)=X9%(I%)+200%*D9%(I%)
6892 NEXT I%
6900 FOR I%=1% TO K2%-1%
6910 A9%=0%
6920 FOR J%=I% TO 1% STEP -1%
6930 IF A9%<>0% THEN 6970
6940 A9%=-1%
6950 IF A%(J%)>=A%(J%+1%) GO TO 6960
6951 P%=A%(J%)
6952 A%(J%)=A%(J%+1%)
6953 A%(J%+1%)=P%
6954 A9%=0%
6960 NEXT J%
6970 NEXT I%
6980 FOR I%=1% TO K2%
6990 D9%(I%)=A%(I%)/200%
7000 X9%(I%)=A%(I%)-D9%(I%)*200%
7010 NEXT I%
7020 GOSUB 7240
7025 P8$='DO PROFILES'
7030 FOR I%=F2% TO 0% STEP -1%
7040 FOR G1%=0% TO F1%
7041 S$(G1%)=' '
7042 NEXT G1%
7050 FOR I1%=J% TO 200%
7060 IF D8%(I1%)<>I% THEN 7100
7070 IF X8%(I1%)<0% GO TO 7090
7071 IF X8%(I1%)>100% THEN 7090
7080 IF S$(X8%(I1%))=' ' THEN S$(X8%(I1%))='X' \ GO TO 7090
7081 S$(X8%(I1%))='*'
7090 NEXT I1%
7100 J%=I1%
7110 FOR I1%=K1% TO 50%
7120 IF D9%(I1%)<>I% THEN 7160
7130 IF X9%(I1%)<0% THEN 7150
7131 IF X9%(I%)>100% THEN 7150
7140 IF S$(X9%(I1%))=' ' THEN S$(X9%(I1%))=' + ' \ GO TO 7150
7141 S$(X9%(I1%))='*'
7150 NEXT I1%
7160 PRINT
7170 GOSUB 7420
7180 NEXT I%
```

```
7190 GOSUB 7530
7200 IF M9%=1% THEN 7900
7210 PRINT P6$;
7220 GO TO 6660
7240 REM     ***************************************************************
7260 REM -- Printing Subroutines
7280 J%=1%
7290 K1%=1%
7300 Q%=Q%+1%
7310 PRINT C$;R9$;
7410 RETURN
7420 K1%=I1%
7430 IF 1*I%/5>I%/5% THEN 7480
7440 IF G%<>0% GO TO 7450
7441 G9=B5+I%*B7/F2%
7442 IF ABS(G9)<ABS(B7)/10000 THEN G9=0
7450 IF G%<>1% GO TO 7460
7451 G9=D5+I%*D7/F2%
7452 IF ABS(G9)<ABS(D7)/10000 THEN G9=0
7460 PRINT P9$;SEG$(STR$(G9),1%,4%);
7470 IF I%=0% THEN RETURN
7480 PRINT TAB(5%);'I';
7490 FOR L%=0% TO F1%
7500 IF S$(L%)<>' ' THEN PRINT TAB(L%+5%+1%);S$(L%);
7510 NEXT L%
7520 RETURN
7530 PRINT TAB(5%);'-+';
7540 FOR J%=1% TO F1% STEP 5%
7550 PRINT '----+';
7560 NEXT J%
7570 M9%=0%
7580 IF S%<>1% GO TO 7590
7581 X6=Z9-X5
7582 X5=Z9-X5
7583 X7=-X7
7590 PRINT ' X        '
7600 IF X6<10 THEN U1$='#.##'
7601 IF X6<10 GO TO 7610
7602 IF X6<100 THEN U1$='##.#'
7603 IF X6<100 GO TO 7610
7604 U1$='####'
7610 FOR J%=0% TO F1% STEP 5%
7620 X=X5+J%*X7/F1%
7630 IF ABS(X)<ABS(X7)/10000 THEN X=0
7640 PRINT TAB(5%+J%-1%);
7650 PRINT USING U1$,X;
7660 NEXT J%
7665 PRINT P7$;P8$
7670 PRINT P1$;'OBSERVED(+)';P2$;'PREDICTED(X)';P3$;'COINCIDENT(*)'
7680 PRINT P4$;'W=WINDOW';P5$;'<CR>=EXIT';P6$;'SUB-OPTION';
7700 INPUT A1$
7710 GOSUB 710
7711 A$=A1$
7712 IF A$='W' GO TO 7720
7713 M9%=1%
7714 RETURN
7720 PRINT P6$;S1$;P5$;S1$;P4$;S1$;
7730 PRINT P4$;'X MIN';
7740 INPUT X5
7750 PRINT P5$;'X MAX';
7760 INPUT X6
7770 PRINT P5$;S1$;P4$;S1$
7780 PRINT P4$;'Y MIN';
7790 INPUT Y2
7800 PRINT P5$;'Y MAX';
7810 INPUT Y3
7820 IF G%<>0% GO TO 7830
7821 B5=Y2
7822 B6=Y3
7830 IF G%<>1% GO TO 7840
7831 D5=Y2
7832 D6=Y3
7840 IF S%=0% THEN 7880
7850 IF X5<=X6 GO TO 7860
7851 T=X6
7852 X6=X5
7853 X5=T
7860 X6=Z9-X6
7870 X5=Z9-X5
7880 RETURN
7900 REM     ***************************************************************
7920 IF S%=0% THEN 7990
7930 FOR I%=1% TO K%
```

```
7940 X(I%)=Z9-X(I%)
7950 NEXT I%
7960 FOR I%=1% TO K2%
7970 X2(I%)=Z9-X2(I%)
7980 NEXT I%
7990 PRINT C$;'DO YOU WANT TO DO ANOTHER SIMULATION <NO>';
8000 INPUT A1$
8010 GOSUB 710
8011 A$=A1$
8012 IF A$<>'Y' THEN 8040
8020 IF O%<20% THEN 1200
8030 PRINT 'SORRY, YOU CAN ONLY DO 20 SIMULATIONS'
8040 PRINT
8050 PRINT 'PROGRAM TERMINATING'
8060 PRINT
8070 END

READY
```

Appendix D: Compendium of Equations, Tables and Figures for Procedure of Section 2.3

Equations

For conversion of $BOD_5(L)$ to BOD_u, (B), use Eq. 2.4

$$B = \alpha L \tag{2.4}$$

where α is obtained from Fig. 2.3.

For calculation of the reaeration coefficient k_2 at 20° use one of Eqs. 2.6–2.9, selected using Table 2.4, and correct to river temperature using Eq. 2.5.

$$k_2 = 1.024^{T-20} k_2{}^{20} \tag{2.5}$$

$$k_2{}^{20} = 3.74 \sqrt{U}/H^{1.5} \tag{2.6}$$

$$k_2{}^{20} = 5.01 \, U^{0.969}/H^{1.673} \tag{2.7}$$

$$k_2{}^{20} = 4.75 \, U/H^{1.5} \tag{2.8}$$

$$k_2{}^{20} = 5.13 \, U/H^{1.33} \tag{2.9}$$

where U = mean river velocity $(m.s^{-1})$;
　　　　 H = river depth (m)

Tables and Figures

Copies of Tables 2.1–2.4 and Fig. 2.3 follow.

Table 2.1 Saturation DO versus temperature (from Wilcock 1982a)

Temperature, T (°C)	Saturation DO, C_s $(g.m^{-3})$
10	11.29
11	11.02
12	10.77
13	10.54
14	10.30
15	10.09
16	9.86
17	9.66
18	9.46
19	9.27
20	9.09
21	8.91
22	8.73
23	8.58
24	8.41
25	8.26
26	8.10
27	7.95
28	7.81
29	7.68
30	7.55

Table 2.2 Laboratory BOD decay coefficient values

Sample	k_L (day^{-1})	reference
Sewage (primary treatment)	0.23	Cameron (1982)
Dairy factory wastes (raw)	0.44–0.62	Barnett *et al.* (1982)
Meatworks wastes (primary treatment)	0.45–0.60	Heddle (1982)
Pulp and paper mill wastes (primary treatment)	0.35	M. Piper (Tasman Pulp & Paper Co., *pers. comm.*)
Pulp and paper mill wastes (secondary treatment)	0.25	M. Piper (Tasman Pulp & Paper Co., *pers. comm.*)
Piggery wastes (primary treatment)	0.5–0.8	J. Nagels (MWD, *pers. comm.*)
Piggery wastes (secondary treatment)	0.37	J. Nagels (MWD, *pers. comm.*)
River waters (Waikato and Waipa)	0.4	J. Nagels (MWD, *pers. comm.*)

Table 2.3 Values of deoxygenation coefficients in several New Zealand rivers

River	Typical low flow ($m^3.s^{-1}$)	k_1 (day^{-1})	Reference
Tarawera	25	5.2[+]	Piper (1982), McBride (1982a)
Manawatu	20	0.7–12[*]	Currie and Rutherford (1982)
Mataura	14	2[+]	McKenzie and McBride (1982)
Waipa	20	0.7[+]	McBride and Rutherford (1982)
Waikato	180	1.2–1.8[+]	Rutherford (1982)
Waikato	180	0.6–0.8[+]	Rutherford (1982)

[+]Estimated by model calibration and verification using river DO and BOD$_5$.
[*]Using river BOD$_5$ only. There is evidence that BOD$_5$ was stored but not exerted and hence these may be over-estimated.

Table 2.4 k_2 equation numbers appropriate for different river conditions

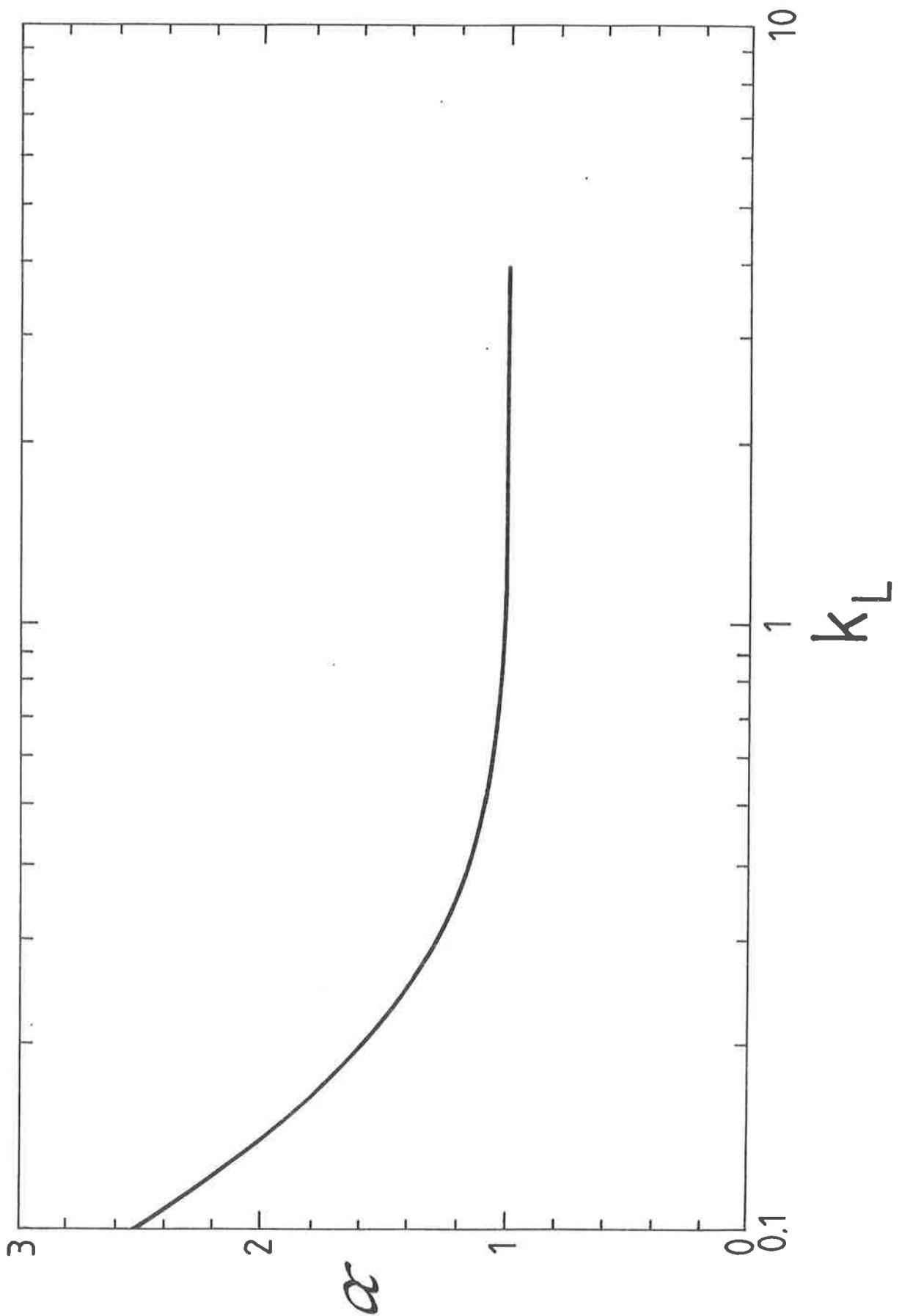| River Velocity U ($m.s^{-1}$)	River Depth, H(m)		
	0.2–0.5	0.5–1.0	>1.0
0.1–0.5	(2.6)	(2.6)	(2.6)
0.5–2.0	(2.9)	(2.8)	(2.7)

FIG. 2.3 Graph of BOD_u:BOD_5 (α) versus k_L (from McBride 1982b and reproduced by permission of the Journal, Water Pollution Control Federation).

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12. A review of the habitat requirements of fish in New Zealand rivers. Compiled by D. F. Church, S. F. Davis, and M. E. U. Taylor ($3)   1979
13. The Ruahine Range: A situation review and proposals for integrated management of the Ruahine Range and the rivers affected by it. A. Cunningham and P. W. Stribling ($5)   1978
14. A Survey of New Zealand peat resources. A. Davoren ($10)   1978
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22. A review of some biological methods for the assessment of water quality with special reference to New Zealand. Part 2. ($4)   1981
23. Hydrology of the catchments draining to the Pauatahanui Inlet. R. J. Curry ($3)   1981
24. Potential for contamination of the Heretaunga Plains aquifers ($10)   1982

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2. Wetlands. ($1)   1975
5. Forest operations guideline. ($2)   1978
6. A guideline for the construction of access tracks and firebreaks. ($2)   1980
7. A guideline to skifield development. ($2)   1980
8. A wetlands guideline. ($5)   1982