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HANDBOOK ON ESTIMATING DISSOLVED OXYGEN DEPLETION IN POLLUTED RIVERS

by

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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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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.

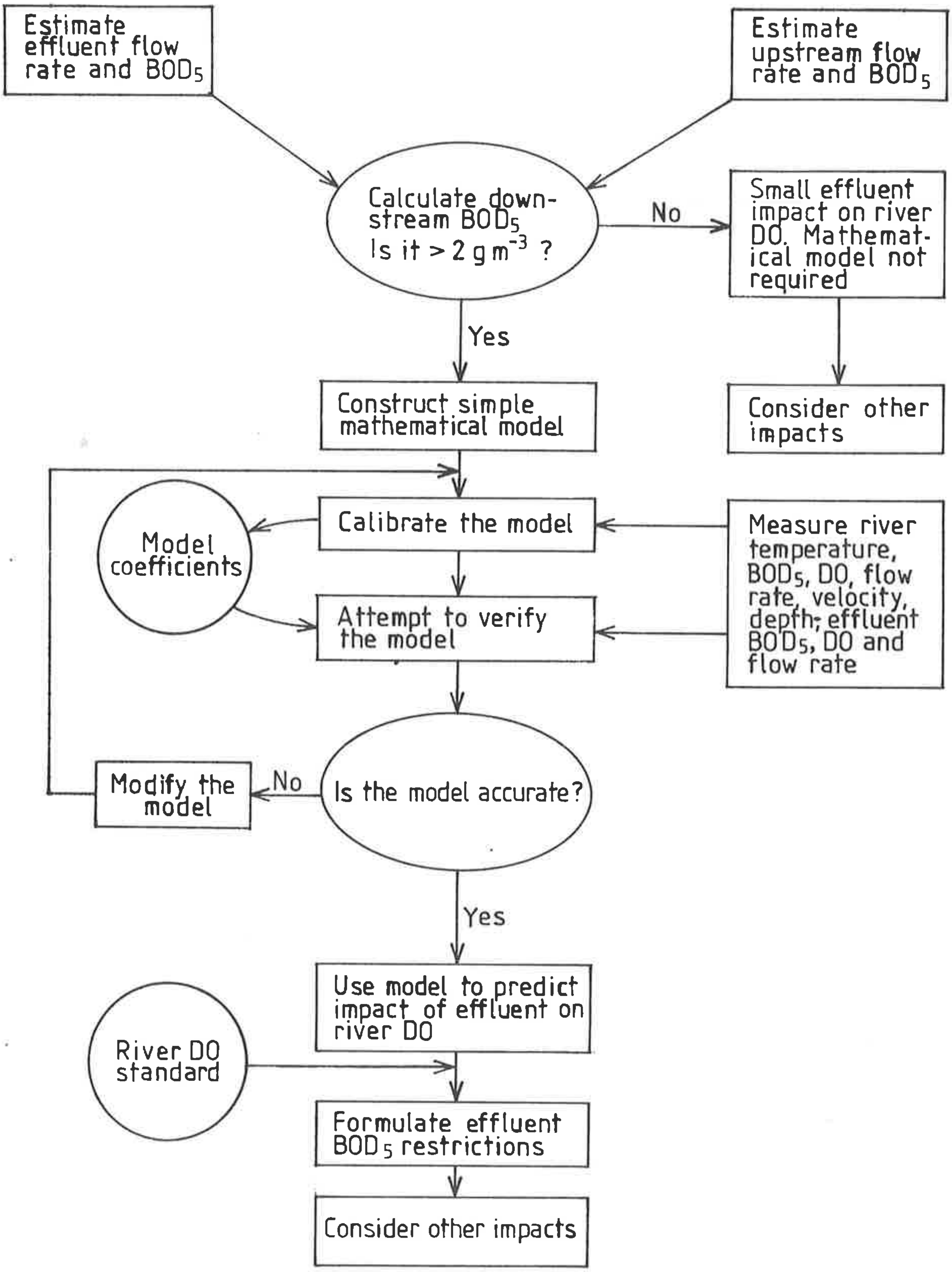


FIG. 1.1 Steps and information required to assess the impact of an effluent on river dissolved oxygen.

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

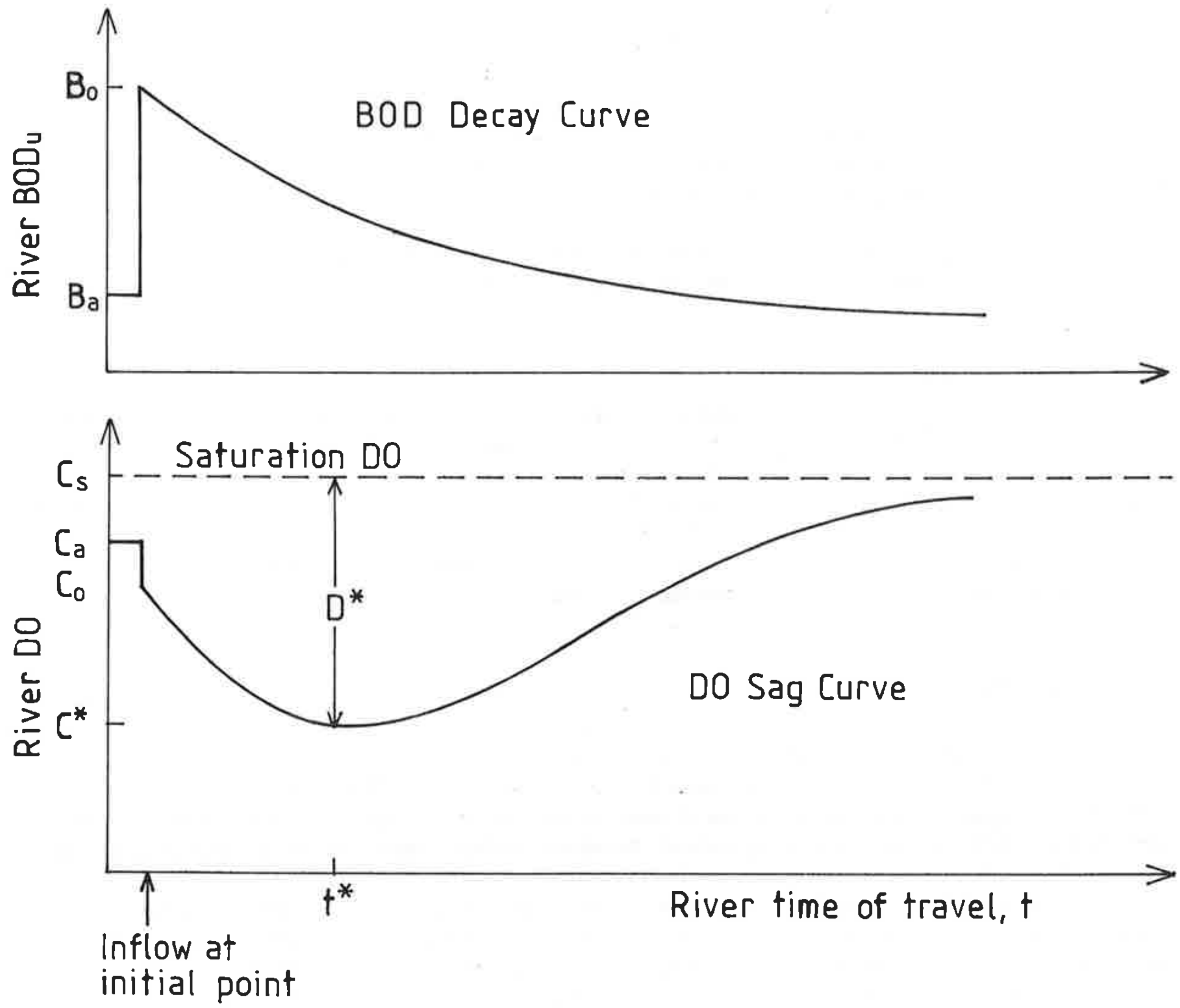
Predictions are made using a verified model, usually for the "worst case" of low river flow and maximum river temperature and waste discharge since DO depletion for such conditions is maximal. There are two modes of prediction: prediction of the DO sag curve resulting from known discharges; or prediction 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.

†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

$$Q_o = Q_a + Q_i \tag{2.1}$$

$$B_o = \frac{Q_a B_a + Q_i B_i}{Q_o} \tag{2.2}$$

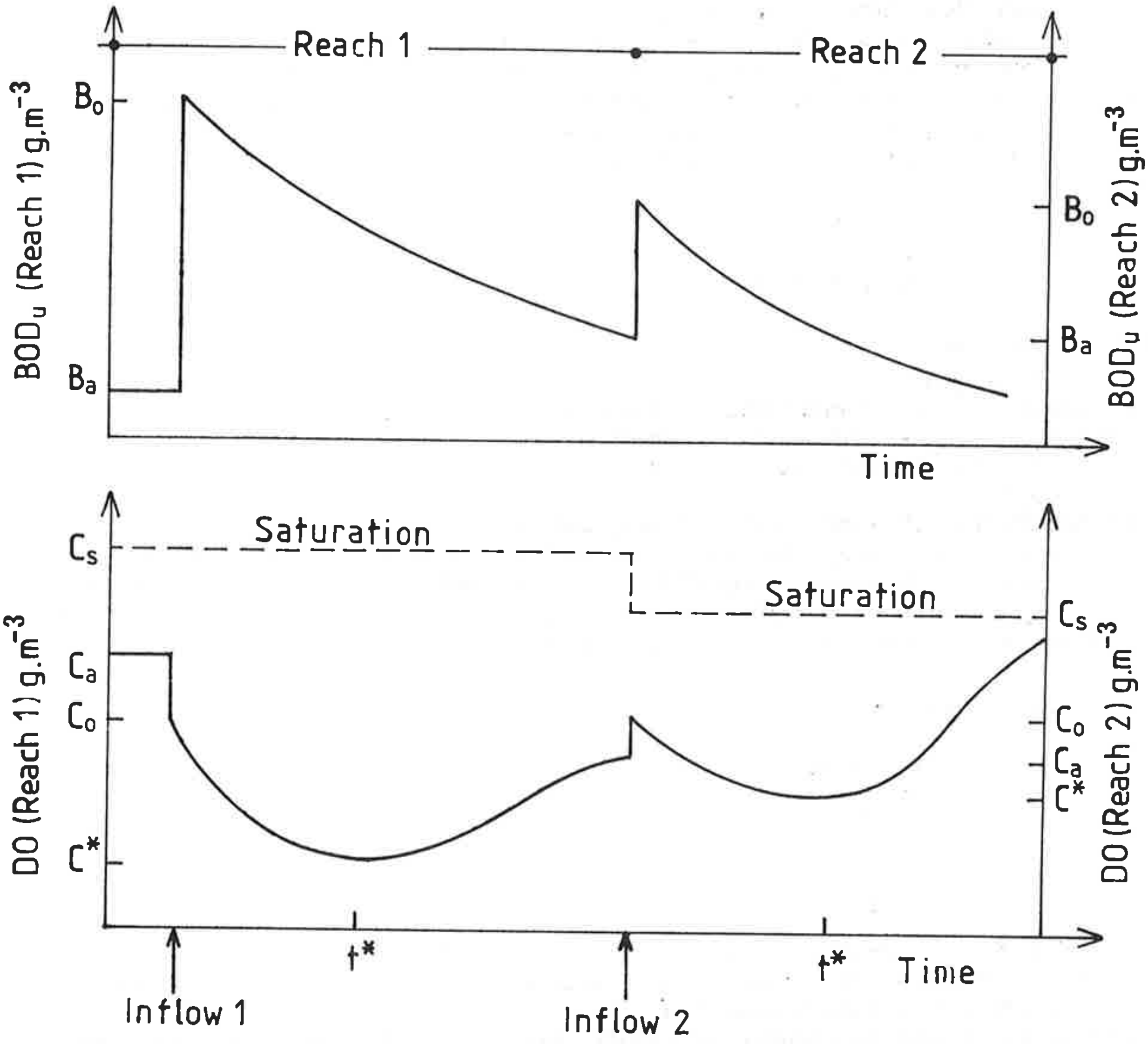
$$C_o = \frac{Q_a C_a + Q_i C_i}{Q_o} \tag{2.3}$$

(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.



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.

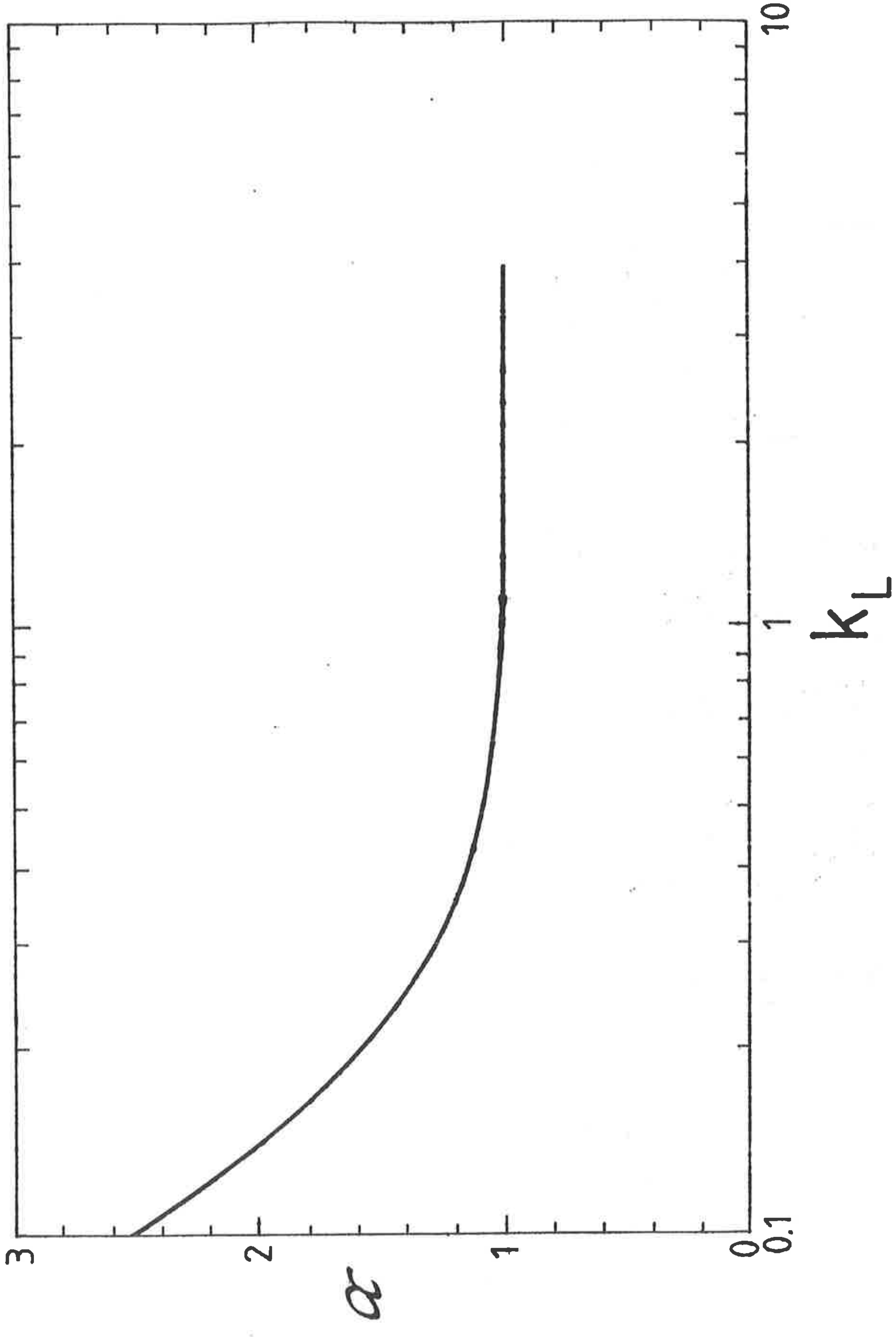


FIG. 2.3 Graph of BOD_u:BOD_5 (α) versus k_L (from McBride 1982b and reproduced by permission of the Journal, Water Pollution Control Federation).

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

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

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.