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FLOW AND WATER QUALITY MODELLING ON THE MIDDLE THAMES

Report for National Power Plc

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WATER QUALITY MODELLING on the MIDDLE THAMES

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WATER QUALITY MODELLING on the MIDDLE THAMES

1 EXECUTIVE SUMMARY

This modelling study was undertaken by the Institute of Hydrology on behalf of National Power Plc. The purpose of the study was to assess the impact of increased abstractions from the Thames at Sutton Courtenay on water flow and quality regimes further downstream. The additional abstraction will be required for the proposed Didcot 'B' power station.

The IH **QUASAR** river flow and water quality model was set up and calibrated for the Thames from Eynsham (just upstream of Oxford) down to Cookham (just upstream of Maidenhead). **QUASAR** has previously been used for studies of several UK rivers including the Thames.

The extent to which abstractions for the proposed power station might affect the river depends on the level of abstractions and the prevailing conditions in the river. The effect is likely to be most pronounced during periods of low flow, when the availability of river water is limited and when dilution of effluent from sewage treatment works is low.

QUASAR was calibrated using data for 1974, an 'average' year; the calibrated parameter values were then validated using data for 1975, a 'dry' year. Two additional 'dry' years, 1976 and 1989, were also used for model simulations.

At present the level of gross and net abstractions are controlled by a licence, which defines three tiers of permitted abstractions as a function of flow in the river. Three main cases were considered;

1 - abstractions controlled by existing licence.
2 - increased abstractions within each tier of the existing licence.
3 - existing licence with an extra tier for the increased abstractions.

Given the existing water supply abstractions and sewage treatment works discharges, the model simulations indicate that the additional effect on downstream flow and quality regimes of increased abstractions for Didcot Power Station will be small.

One reason for the small overall effect is that a proportion of the abstraction is returned to the river with a dissolved oxygen concentration higher than in the main river water, as the cooling water becomes thoroughly aerated. The general effect is therefore to improve river quality on many days in each year.

2 INTRODUCTION and OBJECTIVES

Water is abstracted from the Thames at Sutton Courtenay to provide cooling water for the National Power coal-fired power station at Didcot (the 'A' station). There are proposals for the construction of a new gas-fired power station at Didcot (the 'B' station) for which additional cooling water will be required.

The present abstractions are governed by a licence granted in 1968, with variations in 1983 and 1989. The licence limits both the gross and the net abstraction from the river. In brief, the maximum annual gross abstraction is 1.64 m^3 s^{-1} (11.4 thousand million gallons per year), with a maximum hourly limit of 2.36 m^3 s^{-1} (1.871 million gallons per hour). Additional constraints are imposed when the naturalised flow at Days Weir falls below given thresholds (Table 2.1). At Days Weir the naturalised flow is defined as the flow measured at the weir plus the net abstraction for Didcot power station just upstream.

For the new 'B' station it is proposed that the gross abstraction will remain the same; however the maximum net abstraction will be increased by 0.36 m^3 s^{-1}. The target net abstractions over the range of threshold flows at Days Weir are given in Table 2.2. For flows of less than 2.10 m^3 s^{-1}, the net abstraction of 0.36 m^3 s^{-1} would provide sufficient water for the 'B' station, but would not supply any water for the 'A' station.

The objective of this water quality modelling study is to investigate how the increased abstractions would affect flows and water quality downstream. The effects of abstractions from the river will be most pronounced in dry years. One average year, 1974, and three dry years - 1975, 1976, and 1989 - were used in the modelling study. These years have adequate flow and quality data not only for the river, but also for the main abstractions and the discharges from sewage treatment works.

The model was calibrated on the data for 1974; the derived model parameters were then validated using data for 1975. Data for all four years were then used to assess the relative effects of different abstraction regimes.

The results of the model runs were presented in a draft report to National Power Plc, and then discussed with the NRA. As a result of those discussions, some additional work was carried out; temperature was included as an additional variable to be modelled, and an extra scenario was specified. There was also considerable discussion on what constituted a 'worst case' scenario, and the way in which the quality of the power station return water should be calculated.

This revised report takes account of the comments raised by the NRA. In particular, an additional case has been introduced; this is based on the premise that the power station does not exist so that there are no abstractions at Didcot. The results of the simulations presented here are based on the conservative assumption that evaporation is the only process that effects the cooling water in its passage through the power station. This means that the chemical and biological load of the return water remains the same as the load of the input water, but because of the loss of water through evaporation, the concentrations are higher. It was also agreed that in the context of this modelling study, the years 1976 and 1989 could be considered as 'worst case' scenarios.

The main text of the report presents the results of the simulations carried out using the IH water quality model **QUASAR** (**QUA**lity **S**imulation **A**long **R**ivers). A more detailed description of the structure of **QUASAR**, and the calibration and validation runs are included as Appendices.

Table 2.1 Constraints on Hourly Abstractions - Existing Licence

Flow at Days Weir (Q_{Days})	Maximum Gross Abs. ($m^3\ s^{-1}$)	Maximum Net Abs. ($m^3\ s^{-1}$)	Return ($m^3\ s^{-1}$)
$3.16 < Q_{Days}$	2.37	0.79	1.58
$2.10 < Q_{Days} < 3.16$	1.58	0.53	1.05
$Q_{Days} < 2.10$	0.53	0.26	0.27

Table 2.2 Target Hourly Abstractions for Didcot 'A' and 'B' Stations

Flow at Days Weir (Q_{Days})	Maximum Gross Abs. ($m^3\ s^{-1}$)	Maximum Net Abs. ($m^3\ s^{-1}$)	Return ($m^3\ s^{-1}$)
$3.16 < Q_{Days}$	2.37	1.15	1.22
$2.10 < Q_{Days} < 3.16$	1.58	0.76	0.82
$Q_{Days} < 2.10$	0.53	0.36	0.17

3 MODELLING STUDY

3.1 Structure of the model

QUASAR was set up for the river Thames from Eynsham down to Cookham, a distance of over 100 km. The river is represented in the model by 14 reaches (Figure 3.1); the characteristics of each reach are given in Table 3.1. The reach boundaries are determined by points in the river where there is a change in the water quality or flow due to the confluence with a tributary, the location of an effluent from a sewage treatment works (STW), a major abstraction, or a weir.

The locations of the major tributaries, and the main discharges and abstractions are also shown in Figure 3.1.

3.2 Data

3.2.1 Flow data

The daily flow data used in the model were retrieved from the National Surface Water Archive (SWA) held at IH. The archive holds data for gauging stations on the main Thames, and for the most important tributaries; the flow data are supplied to the SWA by Thames NRA. Inflows at the top end of the model were derived from the daily flow record at Eynsham; the naturalised flow at Days weir (the bottom of reach 6) determines the rate at which water may be abstracted for the power station.

The SWA gauging station summary sheet for Days weir is reproduced as Table 3.2. The summary shows that up to 1973 the daily naturalised flows are equivalent to the gauged flows; after 1973 naturalisation procedure for the gauged flows takes account of the net abstractions at Didcot power station only. The majority of the abstraction from the Thames for Farmoor reservoir, which is located just upstream of Eynsham and the top reach of the model, is returned to the Thames via STW effluents above Days Weir. For this reason further adjustment of the flow records at Days Weir is not considered necessary nor practical.

All the main tributaries are gauged; however in some cases the gauging stations are located some way upstream of the confluence with the Thames. In these cases an adjustment factor based on catchment area, was used to estimate the contribution of the total inflow from the ungauged area. These factors were provided by Thames NRA.

Details of the major abstractions and discharges available from the Public Register were provided by Thames NRA; a summary of these data is given in Table 3.3.

3.2.2 Water quality data

Water samples at a large number of sites on the Thames have been taken on a regular basis since 1974. Sample frequency varies from weekly to monthly, with samples being taken on average once a fortnight; relatively few algae data are available. The river water quality data used for this study were provided by Thames NRA from the data archive.

Thames NRA also hold water quality data for all the major effluent discharges. The water quality data that are in the public domain were provided for the purposes of this study by the NRA. A summary of the data for the main discharges is given in Tables 3.4 to 3.7.

3.2.3 Purge water quality

For the purpose of comparing the relative effects of different abstraction scenarios on downstream water quality, it was necessary to make certain assumptions about the quality of the water that is returned to the river after its passage through the power station cooling water system.

At one extreme, it might be assumed that the return water has the same quality as the abstracted river water. This would be equivalent to a consumptive use of water together with its chemical and biological constituents within the plant. Concentrations in the return water would therefore be the same as the concentrations in the abstracted river water.

At the other extreme, it might be assumed that the only process that occurs within the plant is the evaporation of pure water. This would leave the mass of the chemical and biological constituents in the remaining water unchanged, but the concentrations would be higher.

The reality is somewhere between these two assumptions. The cooling water system provides high temperatures and aeration, which helps to promote biological activity and the consequent oxidisation of organic material in the water. It was not possible to model the processes in the power station and thus calculate what the quality of the return water would be. For the simulation runs it was decided to assume a full concentration factor, based on the ratio of the volume of the abstracted to the volume of the return water. This ratio was then used to calculate the quality of the return water directly from the quality of the abstracted water.

This assumption of full concentration is considered to be conservative, as comparison of observed records of abstracted and return water quality shows that the concentrations of BOD and ammonia fall as a result of the passage through a power station re-circulating system.

water that is abstracted. During its circulation through the power station, the water falls through air for a considerable distance, and is well aerated. Observations show that concentrations are at between 105 and 110% saturation. These values have been assumed for the DO concentrations of the return water.

Another effect arises from the fact that the temperature of the water returned to the river may be higher than the river temperature. The licence prohibits the discharge of water back into the river at a temperature higher than 27 ^{o}C, so the return water is cooled if necessary. For the purposes of the model simulations, it was assumed that the temperature of the return water was always 3 ^{o}C above the temperature of the abstracted river water.

Location map and reach structure

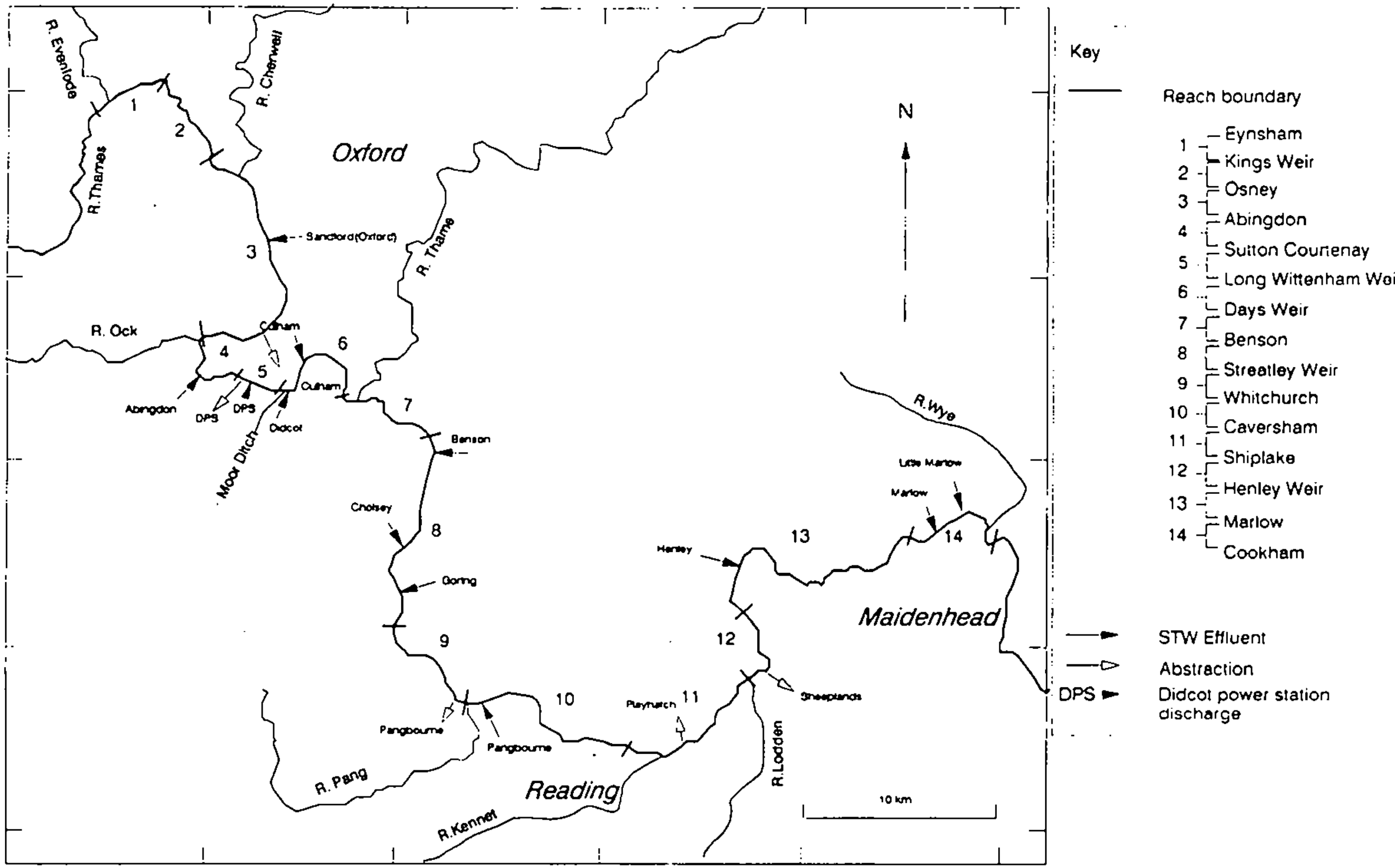


Figure 3.1

Table 3.1 Reach Characteristics

REACH NUMBER	LOCATION	TRIBUTARIES	DISCHARGES	ABSTRACTIONS	LENGTH (km)	NO. OF CELLS
	Eynsham					
1		Evenlode			4.5	1
	Kings Weir					
2		Ock			5.7	1
	Osney					
3		Cherwell	Oxford (Sandford)	Culham	14.8	3
	Abingdon					
4			Abingdon		4.5	1
	Sutton Courtney					
5			Didcot Power Station	Didcot Power Station	3.0	1
	Long Wittenham Weir					
6		Moor Ditch	Didcot, Culham		6.3	1
	Days Weir					
7		Thame			6.4	1
	Benson					
8			Benson, Cholsey, Goring		11.6	2
	Streatley Weir					
9				Pangbourne	6.4	1
	Whitchurch					
10		Pang	Pangbourne		10.8	2
	Caversham					
11		Kennet		Playhatch, Sheeplands	8.9	1
	Shiplake					
12		Loddon			4.5	1
	Henley Weir					
13			Henley		14.5	3
	Marlow					
14		Wye	Marlow, Little Marlow		6.0	1
	Cookham					

Gauging Station Summary

Table 3.2

THAMES AT DAYS WEIR

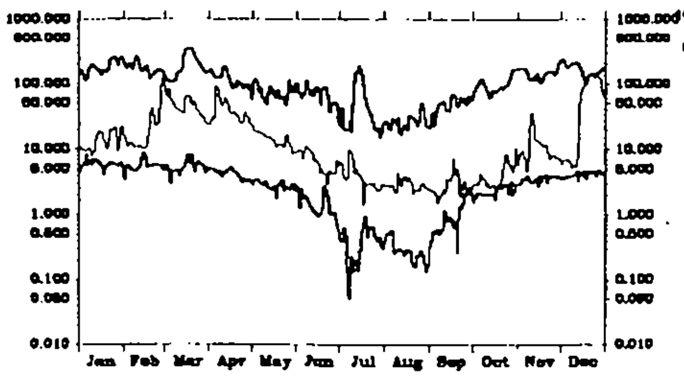
Station Number
039002

Gauged Flows
1938-1990

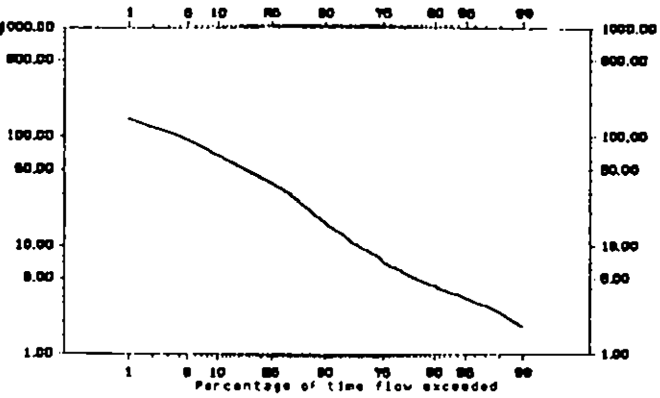
Measuring Authority: NRA - Thames

Grid Reference: 41 (SU) 568 935

Daily Flow Hydrograph (m^3s^{-1})
Max. and min. daily mean flows from 1938 to 1990 excluding those for the featured year (1989)



Flow Duration Curve (m^3s^{-1})



Flow Statistics

Units: m^3s^{-1} unless otherwise stated

Mean flow	28.15	
Mean flow (ls^{-1}/km^2)	8.17	
Mean flow ($10^6m^3/yr$)	888.3	
Peak flow & date		
Highest daily mean & date	349.0	19 Mar 1947
Lowest daily mean & date	0.050	7 Jul 1976
10 day minimum & end date	0.163	15 Jul 1976
60 day minimum & end date	0.338	2 Sep 1976
10% exceedance	67.510	
50% exceedance	16.240	
95% exceedance	3.269	
Mean annual flood	147.9	
Bankfull flow		

Catchment Characteristics

Catchment area (km^2)	3445.0
Level stn. (mOD)	46.00
Max alt. (mOD)	330
IH Baseflow index	0.65
FSR slope (m/km)	0.37
1941-70 rainfall (mm)	716
FSR stream freq. (junctions/km^2)	
FSR percentage urban	

Factors Affecting Flow Regime

- Abstraction for public water supply.
- Flow reduced by industrial and/or agricultural abstraction.
- Augmentation from effluent returns.

Rainfall and Runoff

	Rainfall (mm) (1939-1989)					Runoff (mm) (1938-1990)				
	Mean	Max/Yr		Min/Yr		Mean	Max/Yr		Min/Yr	
Jan	66	132	1948	13	1987	43	104	1939	5	1976
Feb	47	135	1950	3	1959	41	85	1977	4	1976
Mar	54	152	1947	5	1961	36	127	1947	4	1976
Apr	47	99	1961	4	1984	23	64	1951	3	1976
May	59	131	1979	15	1956	16	48	1983	2	1976
Jun	55	124	1985	5	1942	11	31	1955	1	1976
Jul	54	117	1950	5	1955	7	38	1968	0	1976
Aug	67	149	1977	3	1940	6	15	1977	0	1976
Sep	60	129	1974	5	1959	6	29	1946	1	1959
Oct	65	163	1949	6	1978	11	58	1960	2	1959
Nov	70	176	1940	8	1945	24	96	1960	3	1978
Dec	73	316	1965	18	1988	35	108	1968	4	1975
Annual	717	975	1960	492	1964	257	478	1960	92	1973

Station and Catchment Description

Adjustable thin-plate weir (5.48m) plus 15 radial gates replaced, in 1969, a barrage of radial and buck gates. Rating formulae based upon gaugings - tailwater calibration applies for flows > 70 cumecs; above 100 cumecs overspill occurs. Daily naturalised flows available for POR (equal to gauged flows up to 1973) - allow for Didcot P S losses only.

Mixed geology (Oolitic Limestone headwaters, Oxford Clay below). Predominately rural with development concentrated along the valley.

Summary of Archived Data

Gauged Flows and Rainfall

Key:	All rain-fall	Some or no rain-fall
All daily, all peaks	A	a
All daily, some peaks	B	b
All daily, no peaks	C	c
Some daily, all peaks	D	d
Some daily, some peaks	E	e
Some daily, no peaks	F	f
No gauged flow data	*	.

	01234	56789
1930s	-----	---fC
1940s	CCCCC	CCCCC
1950s	CCCCC	CCCCC
1960s	CCCCC	CCCCC
1970s	CCCCC	CCCCC
1980s	CCCCC	CCCCC
1990s	f	

Naturalised Flows

Key:	
All daily, all monthly	A
Some daily, all monthly	B
Some daily, some monthly	C
Some daily, no monthly	D
No daily, all monthly	E
No daily, some monthly	F
No naturalised flow data	-

	01234	56789
1930s	-----	---CA
1940s	AAAAA	AAAAA
1950s	AAAAA	AAAAA
1960s	AAAAA	AAAAA
1970s	AAAAA	AAAAA
1980s	AAAAA	AAAAA
1990s	D	

Table 3.3 Major Abstractions and Discharges ($m^3 s^{-1}$)

ABSTRACTIONS

Culham	0.04
Didcot Power Station	2.37*
Pangbourne	0.05
Playhatch	0.08
Sheeplands	0.18

* note : the net abstraction at Didcot is at present 0.79 $m^3 s^{-1}$

DISCHARGES (data for 1989)

	Flow (m^3 s^{-1})	Consent conditions (95 percentile) BOD (ATU) (mg l^{-1})	Amm. N (mg l^{-1})
Oxford (Sandford) STW	0.47	75	20
Abingdon STW	0.11	20	20
Didcot Power station	variable but <1.58		
Didcot STW	0.06	90	35
Culham STW	0.01	20	-
Benson STW	0.02	35	5
Cholsey STW	0.04	75	20
Goring STW	0.01	30	15
Pangbourne STW	0.03	30	20
Henley STW	0.03	17	15
Little Marlow STW	0.40	20	5

Source of data : Licenced and consented quantities

Table 3.4 Data for Major Discharges, 1974

LOCATION	FLOW	NITRATE			DO			BOD			AMMONIA			TEMPERATURE			ORTHO-P		
	mean ($m^3 s^{-1}$)	mean	min	max	mean	min	max	mean	min	max	mean	min	max	mean	min	max	mean	min	max
		($mg\ l^{-1}$)			($mg\ l^{-1}$)			($mg\ l^{-1}$)			($mg\ l^{-1}$)			(°C)			($mg\ l^{-1}$)		
Oxford STW (Sandford)	0.37	15.9	10.4	23.0	7.3	7.3	7.3	4.7	1.8	10.7	5.8	0.8	11.3	14.6	10.0	20.5	4.3	6.8	8.5
Abingdon STW	0.10	12.7	12.7	12.7	5.0	5.0	5.0	15.4	15.4	15.4	25.2	25.2	25.2	16.0	16.0	16.0	7.2	7.2	7.2
Didcot STW	0.05	6.9	0.1	22.5	5.0	5.0	5.0	29.3	3.2	160.0	2.8	0.2	7.5	13.3	8.5	19.0	7.9	7.9	7.9
Culham STW	0.01	26.0	19.3	33.0	5.0	5.0	5.0	7.4	4.6	10.0	1.6	0.4	2.8	10.8	6.0	18.0	2.0	2.0	2.0
Benson STW	0.02	20.1	13.7	27.8	5.0	5.0	5.0	9.1	2.8	30.0	0.8	0.1	4.4	12.8	9.0	18.5	2.0	2.0	2.0
Cholsey STW	0.03	6.6	2.5	15.2	5.0	5.0	5.0	9.4	2.3	36.5	5.3	2.6	9.1	13.8	9.5	19.0	13.2	6.1	17.8
Goring STW	0.01	38.0	34.0	42.4	5.0	5.0	5.0	16.5	7.5	35.8	2.9	0.8	7.5	13.4	9.5	20.0	2.0	2.0	2.0
Pangbourne STW	0.03	27.7	17.2	35.2	5.0	5.0	5.0	18.2	8.1	32.2	4.0	1.0	9.2	13.2	8.0	20.5	8.4	8.4	8.4
Henley STW	0.03	19.9	14.9	30.8	5.0	5.0	5.0	16.6	8.2	30.1	4.5	0.7	13.8	13.6	10.0	19.0	10.3	10.3	10.3
Marlow STW	0.01	24.1	18.1	33.5	5.0	5.0	5.0	6.4	2.6	11.2	0.4	0.1	2.6	12.8	10.0	17.0	7.5	7.5	7.5
Little Marlow STW	0.32	17.4	12.6	25.3	7.3	7.3	7.3	11.4	4.9	19.1	2.3	0.9	4.7	13.3	10.0	18.0	4.0	3.2	7.6

Table 3.5 Data for Major Discharges, 1975

LOCATION	FLOW	NITRATE			DO			BOD			AMMONIA			TEMPERATURE			ORTHO-P		
	mean ($m^3 s^{-1}$)	mean	min	max	mean	min	max	mean	min	max	mean	min	max	mean	min	max	mean	min	max
		($mg\ l^{-1}$)			($mg\ l^{-1}$)			($mg\ l^{-1}$)			($mg\ l^{-1}$)			(°C)			($mg\ l^{-1}$)		
Oxford STW (Sandford)	0.37	13.6	4.5	27.5	7.6	4.8	9.5	11.5	1.3	140.0	8.0	0.2	23.6	15.2	9.0	23.5	7.3	4.2	10.5
Abingdon STW	0.10	16.4	12.7	37.0	5.0	5.0	5.0	15.4	15.4	15.4	25.2	25.2	25.2	16.0	16.0	16.0	7.2	7.2	7.2
Didcot STW	0.05	3.4	0.1	11.8	5.0	5.0	5.0	30.8	2.7	164.0	6.5	0.5	34.5	14.5	10.0	23.0	7.9	7.9	7.9
Culham STW	0.01	23.3	18.0	30.8	5.0	5.0	5.0	13.2	6.2	21.9	4.1	0.4	8.8	10.7	7.0	13.5	2.0	2.0	2.0
Benson STW	0.02	17.8	14.4	22.5	5.0	5.0	5.0	14.2	3.7	39.2	1.6	0.1	4.9	13.3	9.0	21.5	2.0	2.0	2.0
Cholsey STW	0.03	5.4	3.5	8.9	5.0	5.0	5.0	12.7	6.1	29.1	7.1	2.3	12.5	13.7	9.0	20.0	10.1	5.6	11.5
Goring STW	0.01	37.6	32.6	44.2	5.0	5.0	5.0	16.1	8.4	32.6	4.1	1.4	10.6	13.2	9.3	20.5	2.0	2.0	2.0
Pangbourne STW	0.03	25.3	11.8	35.6	5.0	5.0	5.0	13.6	10.0	23.9	3.8	1.2	7.9	12.8	7.0	22.0	8.4	8.4	8.4
Henley STW	0.03	15.6	9.0	23.9	5.0	5.0	5.0	16.8	6.7	31.5	6.4	2.1	13.2	13.6	7.0	20.0	10.3	10.3	10.3
Marlow STW	0.01	18.0	12.5	25.6	5.0	5.0	5.0	4.3	0.9	0.9	0.2	0.1	0.7	12.6	6.0	19.0	7.5	7.5	7.5
Little Marlow STW	0.32	16.2	10.4	26.0	7.3	7.3	7.3	9.6	0.5	19.8	1.8	0.1	6.5	13.9	8.0	20.0	3.8	0.1	7.7

Table 3.6 Data for Major Discharges, 1976

LOCATION	FLOW	NITRATE			DO			BOD			AMMONIA			TEMPERATURE			ORTHO-P		
	mean (m^3 s^{-1})	mean	min	max	mean	min	max	mean	min	max	mean	min	max	mean	min	max	mean	min	max
		(mg l^{-1})			(mg l^{-1})			(mg l^{-1})			(mg l^{-1})			(°C)			(mg l^{-1})		
Oxford STW (Sandford)	0.33	22.4	12.0	42.0	8.5	6.6	10.7	6.2	1.0	25.0	4.9	0.3	11.1	15.7	8.5	26.0	8.7	6.1	10.5
Abingdon STW	0.10	29.6	20.3	39.7	5.0	5.0	5.0	7.1	4.2	14.1	6.8	0.8	15.6	13.7	7.0	22.0	7.2	7.2	7.2
Didcot STW	0.07	1.7	0.1	4.9	5.0	5.0	5.0	12.2	4.3	25.1	7.3	0.8	27.0	14.5	9.0	25.0	7.9	7.9	7.9
Culham STW	0.01	29.3	25.1	31.9	5.0	5.0	5.0	6.3	2.5	13.5	1.7	1.0	3.8	13.4	6.0	17.0	2.0	2.0	2.0
Benson STW	0.03	27.3	20.3	38.4	5.0	5.0	5.0	7.4	3.3	19.5	1.7	0.2	4.4	12.1	7.0	22.0	2.0	2.0	2.0
Cholsey STW	0.03	3.5	0.1	6.9	5.0	5.0	5.0	27.4	3.7	71.4	9.6	2.7	16.6	13.0	6.0	21.0	14.7	10.7	18.3
Goring STW	0.01	39.6	37.2	45.0	5.0	5.0	5.0	12.4	7.8	22.5	2.7	1.1	4.4	10.9	6.0	18.0	2.0	2.0	2.0
Pangbourne STW	0.00	35.1	24.0	40.0	5.0	5.0	5.0	8.9	3.9	23.4	2.8	0.9	8.2	13.1	7.0	22.0	11.7	11.7	11.7
Henley STW	0.03	17.7	11.6	23.6	5.0	5.0	5.0	15.7	8.1	26.5	4.8	0.5	9.7	12.4	7.0	21.0	12.6	11.0	13.8
Marlow STW	0.02	20.1	8.6	29.1	5.0	5.0	5.0	6.1	3.4	21.8	0.6	0.0	3.9	12.9	7.0	20.0	6.2	4.6	8.6
Little Marlow STW	0.31	18.9	10.8	35.0	6.8	6.8	6.8	9.5	3.2	19.3	2.3	0.1	7.0	13.5	8.0	22.5	4.5	3.1	8.1

Table 3.7 Data for Major Discharges, 1989

LOCATION	FLOW	NITRATE			DO			BOD			AMMONIA			TEMPERATURE			ORTHO-P		
	mean ($m^3 s^{-1}$)	mean ($mg\ l^{-1}$)	min	max	mean ($mg\ l^{-1}$)	min	max	mean ($mg\ l^{-1}$)	min	max	mean ($mg\ l^{-1}$)	min	max	mean (°C)	min	max	mean ($mg\ l^{-1}$)	min	max
Oxford STW (Sandford)	0.47	9.9	2.4	119.0	5.0	5.0	5.0	21.4	1.9	72.0	9.0	0.7	20.5	16.1	8.0	25.3	7.6	4.0	11.4
Abingdon STW	0.11	10.0	4.1	14.4	5.0	5.0	5.0	10.7	4.9	18.9	7.5	5.1	13.6	14.8	8.0	22.0	10.1	7.4	11.3
Didcot STW	0.06	3.2	0.5	20.5	5.0	5.0	5.0	11.5	1.5	32.5	12.1	0.5	28.0	16.4	11.5	22.0	5.2	0.5	10.6
Culham STW	0.01	24.6	13.1	36.8	5.0	5.0	5.0	6.8	2.7	15.1	2.5	0.4	15.2	12.0	0.9	18.5	7.5	4.4	8.8
Benson STW	0.02	27.6	15.2	39.4	5.0	5.0	5.0	8.7	3.0	40.5	1.4	0.0	10.7	8.4	6.6	10.2	14.5	9.1	20.5
Cholsey STW	0.04	14.7	0.5	33.0	0.7	0.6	0.9	26.4	6.1	173.2	7.7	2.7	18.7	15.2	6.5	21.0	12.1	5.9	16.2
Goring STW	0.01	29.6	25.0	32.3	5.0	5.0	5.0	3.9	1.4	10.2	0.7	0.3	1.5	16.2	10.0	19.0	9.6	8.2	11.7
Pangbourne STW	0.03	7.9	3.6	12.4	5.0	5.0	5.0	9.8	3.3	23.1	6.5	1.1	15.6	15.9	10.0	22.0	12.8	10.3	14.5
Henley STW	0.03	8.6	4.1	15.3	5.0	5.0	5.0	21.8	8.8	33.9	13.5	4.4	23.0	15.7	11.0	19.0	11.1	5.2	13.3
Marlow STW	NO LONGER IN OPERATION																		
Little Marlow STW	0.40	13.7	7.7	18.8	5.0	5.0	5.0	9.5	4.2	24.7	3.5	0.4	15.6	16.3	11.0	20.0	7.5	4.7	9.8

4 ABSTRACTION SCENARIOS

The model was used to simulate flow and water quality in the river under various abstraction scenarios. Case 0 is an additional case and assumes no abstractions at Didcot. Case 1 is a baseline case and represents existing conditions. Cases 2 and 3 assume increased abstractions for the new power station that follow the constraints on gross and net abstractions summarised in Table 4.1. The model predictions for cases 2 and 3 should be compared with the 'baseline' case 1 to assess the effect of different levels of abstraction for Didcot.

Case 0 : Existing conditions, no power station

This case was set up to determine what the water quality of the river would have been, if the power station had not been in operation.

Case 1 : Existing conditions

The level of abstraction is controlled by the existing licence.

Case 2 : Future conditions (standard)

This case assumes higher net abstraction rates at all 3 levels. The 'A' station requires a minimum of 0.79 $m^3 s^{-1}$ to run at full capacity, and 0.40 $m^3 s^{-1}$ to run just two of the four units); the expected requirement for the 'B' station is 0.36 $m^3 s^{-1}$. In this case the net abstractions were chosen so that the 'B' station can run at all times, and that the 'A' station can run at full capacity (tier 1), half capacity (tier 2) and not at all (tier 3).

Case 3 : Future conditions (4 $m^3 s^{-1}$)

This case is the same as **Case 1**, except that the maximum net abstraction of 1.15 $m^3 s^{-1}$ is only allowed when the flow at Days Weir is greater than 4 $m^3 s^{-1}$.

Table 4.1 Abstraction rates for different cases

Case 1

Flow at Days Weir (Q_{Days})	Maximum Gross Abs. ($m^3\ s^{-1}$)	Maximum Net Abs. ($m^3\ s^{-1}$)	Return ($m^3\ s^{-1}$)
$3.16 < Q_{Days}$	2.37	0.79	1.58
$2.10 < Q_{Days} < 3.16$	1.58	0.53	1.05
$Q_{Days} < 2.10$	0.53	0.26	0.27

Case 2

Flow at Days Weir (Q_{Days})	Maximum Gross Abs. ($m^3\ s^{-1}$)	Maximum Net Abs. ($m^3\ s^{-1}$)	Return ($m^3\ s^{-1}$)
$3.16 < Q_{Days}$	2.37	1.15	1.22
$2.10 < Q_{Days} < 3.16$	1.58	0.76	0.82
$Q_{Days} < 2.10$	0.53	0.36	0.17

Case 3

Flow at Days Weir (Q_{Days})	Maximum Gross Abs. ($m^3\ s^{-1}$)	Maximum Net Abs. ($m^3\ s^{-1}$)	Return ($m^3\ s^{-1}$)
$4.00 < Q_{Days}$	2.37	1.15	1.22
$3.16 < Q_{Days} < 4.00$	2.37	0.79	1.58
$2.10 < Q_{Days} < 3.16$	1.58	0.53	1.05
$Q_{Days} < 2.10$	0.53	0.26	0.27

5 Implications for Water Quality

5.1 Flow

The years 1975, 1976, and 1989 were drier than average and therefore represent periods when abstractions from the river would be expected to have the most impact on downstream quality and flow regimes. The following comments relate to the flow at Days Weir.

1974 was characterised by a steady recession, with occasional events of short-duration, from February to August. There was a general increase in flow from September until the end of the year. The pattern of the recession in the early part of 1975 was similar to 1974, but the flows in this period were higher. From July onwards, however, flows were below the 1974 levels. There was no autumn recovery, and by the end of December flows had reached the long-term minimum.

From the start of 1976, flows remained below the long-term minimum until September; by the end of December, flows approached the long-term maximum.

1989 followed the usual pattern of recession from February onwards; flows approached the long-term minimum in October before a very rapid rise to maximum levels in December. 1990 has also been a dry year characterised by a sustained period of low-flows; the flows did not fall to the historic minimum levels of 1976.

For the period before 1973 when the 'A' station at Didcot was commissioned, the naturalised flows at Days Weir are the gauged flows; since then the naturalised flows are the flows that would have been measured had the power station not been operating.

A convenient way of assessing the flow regime, and what changes would be caused by abstractions is the flow duration curve. The first column of Table 5.1 gives the percentiles of the flow duration curve for 'natural' flows at Days Weir for the period 1939 to 1989. The remaining columns show the same percentiles of the flow duration curve under different abstraction criteria. In each case the net abstraction has been subtracted from the daily flows of the naturalised flow sequence. For the purposes of this analysis it has been assumed that the net abstractions are made at the rates shown in Tables 2.1 and 2.2; in practice the actual day to day requirements for water at Didcot might be lower.

Tables 5.2 and 5.3 summarise selected flow measures for each of the four years used in the modelling study, for each of the four cases. Graphs of the distribution of flows at Days in 1976 for cases 1 and 2, and cases 1 and 3 are shown in Figures 5.1 and 5.2 respectively. Note that in each figure the distribution plot for present conditions (case 1) is shown by a dashed line; the predicted distribution (case 2 or case 3) is shown by a full line.

5.2 Water Quality

The following section discusses the water quality implications of the model runs. There can be considerable variation in the values of the water quality determinants from day to day. A convenient way of expressing the results, also used by the NRA in their classification of freshwater river quality standards, is to describe the distribution of values in terms of percentiles of the distribution. Thus the 5 % is the value that would not be exceeded on average more than 5 percent of the time. Where relevant, a note of the values used in the NRA classification of river quality standards is given at the foot of the appropriate Table. The results of the simulations are also expressed in terms of the number of days in a year when a given concentration is exceeded. For BOD, DO and ammonia an exceedance is counted when the concentration is worse than the class 1b standard; for nitrate and ortho-phosphate the EC guideline was used.

5.2.1 Nitrate (as N)

Nitrate concentrations in the Thames vary considerably, but follow a regular pattern with generally low values in mid-summer and high values in winter or during periods of high flows. In general the nitrate levels are always well above the limiting concentrations for algal growth.

Comparison of the statistics of case 0 with cases 1 to 3 in Table 5.4 suggest that there is a very small improvement in river water quality in 1974 and 1975. In the drier years of 1976 and 1989, Table 5.5 suggests an improvement in river water quality under cases 1 to 3 when compared with case 0. This is probably a result of increased activity in the river during periods of low flow, caused by the higher temperature of the return flow. The number of exceedances are shown in Table 5.6.

5.2.2 Dissolved oxygen, DO

Mean dissolved oxygen levels in the river are generally high and close to saturation. However the occurrence of algal blooms and the associated rise in BOD when the algae die mean that DO concentrations can fall very rapidly. These situations are most common during periods of low-flows and when solar radiation is high.

In addition algae generally generate oxygen by photosynthesis during the day, and remove oxygen at night by respiration. These diel variations have not been modelled in the present study.

Tables 5.7 and 5.8 show very small differences between case 1 and cases 2 and 3. The proposed extra abstraction would appear to have little additional effect on dissolved concentrations. This occurs because the return flow from the power station is well aerated, and has a higher DO than the river water from which the abstraction was made. However in 1976, when there were sustained periods of low flow and elevated algae levels in the downstream reaches, the model simulates low DO concentrations. A summary of the exceedances is given in Table 5.9.

5.2.3 Biochemical oxygen demand BOD, (ATU)

Tables 5.10 and 5.11 summarise the effects of different abstractions on BOD. Again comparison of case 1 with cases 2 and 3 indicates that the effects of the proposed increased abstractions are small and generally less than 0.1 mg l^{-1}. This is supported by the table of exceedances (Table 5.12).

5.2.4 Ammonia

Tables 5.13 and 5.14 summarise the results for ammonia; for cases 2 and 3 the results indicate insignificant increases in ammonia concentrations over case 1. The exceedances are shown in Table 5.15.

5.2.5 Ortho-phosphate

The ortho-phosphate results are summarised in Table 5.16 and 5.17. Levels in the river are generally high, and are not limiting for algae. Comparison of cases 2 and 3 with case 1 indicates that the abstractions at Didcot have insignificant effects on downstream concentrations.

5.2.6 Temperature

Tables 5.19 and 5.20 show that the effects of the different abstraction scenarios on river water temperature are small. As to be expected there is an overall increase in river temperature due to the operation of the power station.

5.3 Conclusions

Comparison of the model predictions for case 1 (existing conditions) and cases 2 and 3 indicate that the effects of increased abstractions on downstream flow and water quality regimes will be small, and are generally within the measurement or prediction errors. This applies both in terms of concentrations and in terms of the number of exceedances even under the 'worst case' scenarios of 1976 and 1989.

The model runs were carried out to allow the relative effects of different abstraction scenarios to be assessed. The results are based on the full concentration assumption for the return water.

Figure 5.1

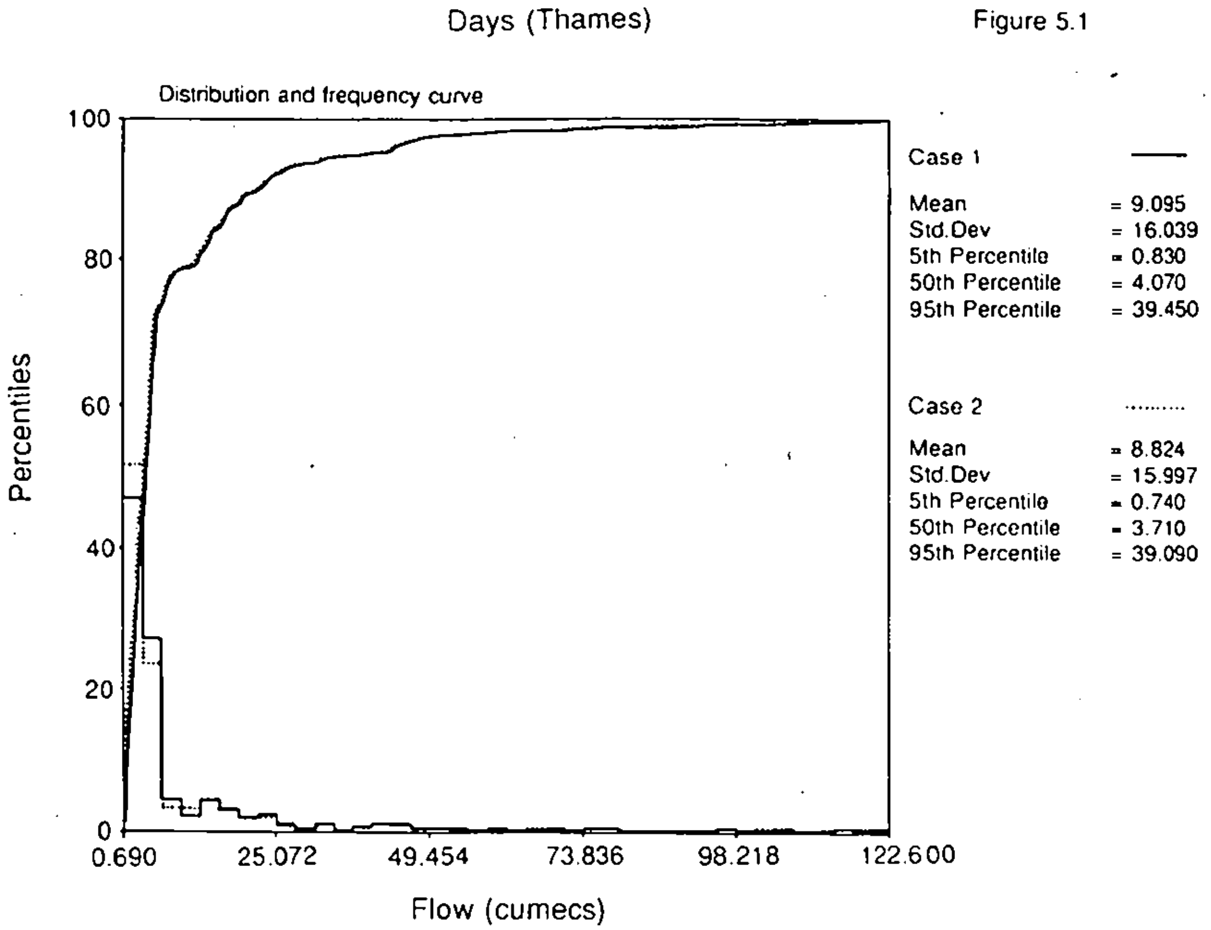


Figure 5.2

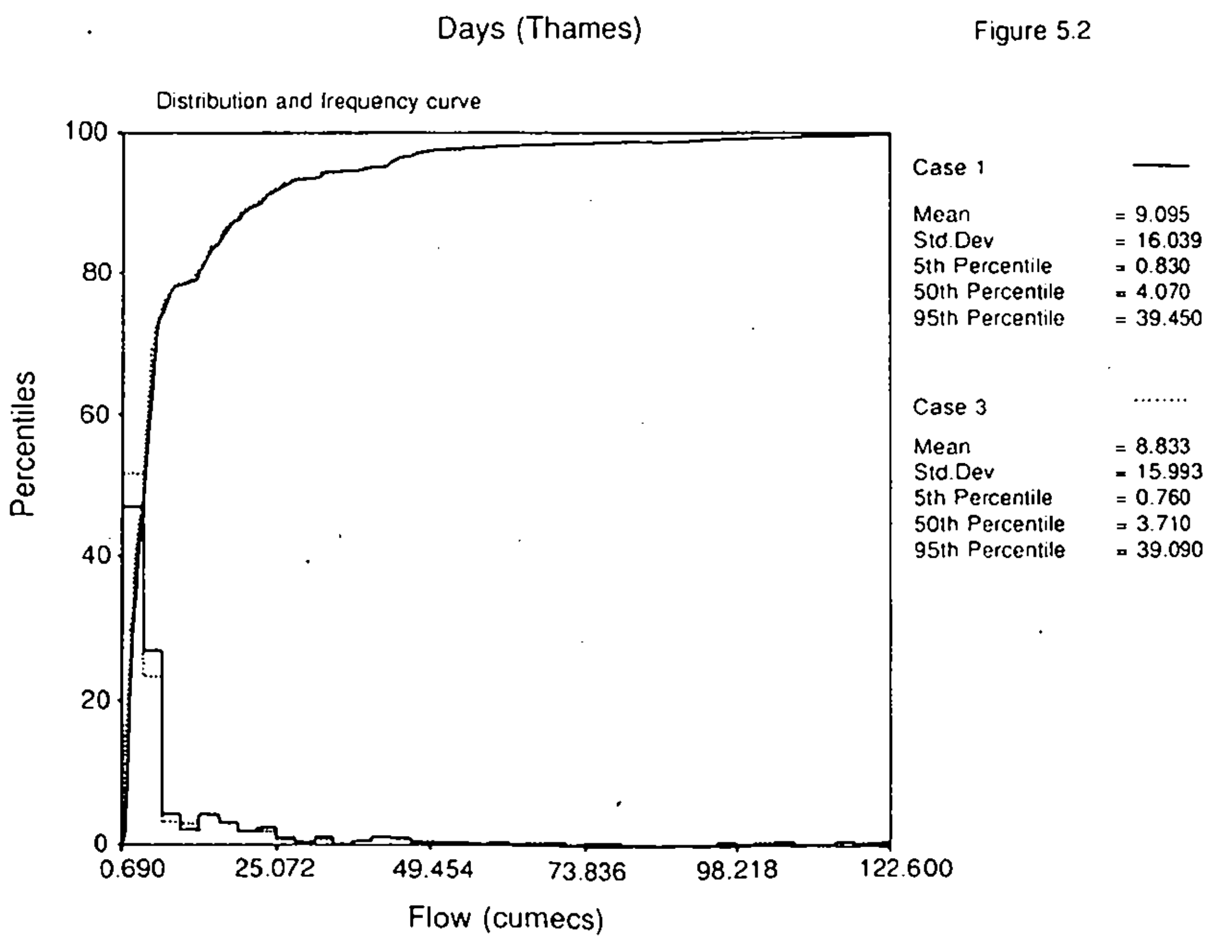


Table 5.1 Thames at Days Weir: Flow duration table under different abstraction scenarios ($m^3 s^{-1}$)

	NATURALISED	EXISTING LICENCES	INCREASED NET ABS.	INCREASED NET ABS. existing licence applies when flow < $4 m^3 s^{-1}$
Case:	0	1	2	3
5%	94.0	93.3	93.0	92.9
10%	67.7	66.9	66.5	66.6
20%	44.7	43.9	43.5	43.5
30%	32.5	31.7	31.3	31.4
40%	22.9	22.1	21.7	21.7
50%	16.5	15.7	15.4	15.4
60%	12.1	11.4	11.0	11.0
70%	8.9	8,1	7.7	7.7
80%	6.2	5.4	5.0	5.0
90%	4.3	3.5	3.2	3.2
95%	3.3	2.6	2.3	2.6
99%	1.8	1.5	1.4	1.5
MEAN	28.3	27.5	27.2	27.2

Table 5.2 Flow (m^3s^{-1}) 1974 and 1975:

1974	CASE	0	1	2	3
DAYS WEIR:					
MEAN:		26.3	25.5	25.2	25.2
STANDARD DEVIATION:		24.8	24.8	24.8	24.8
5%		4.5	3.7	3.3	3.4
95%		78.1	77.3	77.0	77.0
STREATLEY WEIR:					
MEAN:		31.0	30.2	29.9	29.9
STANDARD DEVIATION:		29.6	29.6	29.6	29.6
5%		5.4	4.6	4.3	4.3
95%		98.9	98.1	97.7	97.7
COOKHAM:					
MEAN:		47.1	46.3	45.9	45.9
STANDARD DEVIATION:		39.1	39.1	39.1	39.1
5%		12.3	11.5	11.1	11.1
95%		136.7	135.9	135.6	135.6

1975	CASE	0	1	2	3
DAYS WEIR:					
MEAN:		22.3	21.5	21.1	21.2
STANDARD DEVIATION:		27.0	27.0	27.0	28.0
5%		3.8	3.0	2.6	3.0
95%		84.7	83.9	83.6	83.6
STREATLEY WEIR:					
MEAN:		26.2	25.4	25.0	25.1
STANDARD DEVIATION:		31.3	31.3	31.3	31.3
5%		4.5	3.8	3.4	3.8
95%		98.6	97.8	97.4	97.4
COOKHAM:					
MEAN:		41.7	40.9	40.5	40.6
STANDARD DEVIATION:		40.1	40.1	40.1	40.0
5%		11.6	10.9	10.6	10.9
95%		137.3	136.6	136.2	136.2

Table 5.3 Flow (m^3s^{-1}) 1976 and 1989:

1976 CASE	0	1	2	3
DAYS WEIR:				
MEAN:	9.7	9.1	8.8	8.9
STANDARD DEVIATION:	16.1	16.0	16.0	16.0
5%	1.1	0.8	0.7	0.8
95%	40.2	39.5	39.1	39.1
STREATLEY WEIR:				
MEAN:	11.3	10.7	10.4	10.5
STANDARD DEVIATION:	18.8	18.8	18.7	18.7
5%	1.4	1.1	1.0	1.1
95%	49.1	48.3	47.9	47.9
COOKHAM:				
MEAN:	21.0	20.3	20.1	20.2
STANDARD DEVIATION:	25.2	25.1	25.0	25.0
5%	5.0	4.7	4.6	4.7
95%	68.7	67.9	67.6	67.6

1989 CASE	0	1	2	3
DAYS WEIR:				
MEAN:	18.5	17.8	17.4	17.5
STANDARD DEVIATION:	22.5	22.4	22.4	22.4
5%	3.2	2.6	2.3	2.6
95%	67.5	66.7	66.3	66.3
STREATLEY WEIR:				
MEAN:	22.0	21.2	20.9	20.9
STANDARD DEVIATION:	27.3	27.2	27.2	27.2
5%	4.1	3.5	3.2	3.2
95%	84.3	83.5	83.1	83.1
COOKHAM:				
MEAN:	38.6	35.8	35.4	35.5
STANDARD DEVIATION:	25.6	35.5	35.5	35.5
5%	11.4	10.8	10.5	10.8
95%	115.4	114.6	114.3	114.3

Table 5.4 Nitrate (mgl^{-1} as N) 1974 and 1975:

1974	CASE	0	1	2	3
DAYS WEIR:					
MEAN:		6.84	6.83	6.84	6.84
STANDARD DEVIATION:		2.30	2.31	2.30	2.30
5%		4.00	3.99	4.02	4.01
95%		12.66	12.66	12.65	12.65
STREATLEY WEIR:					
MEAN:		6.96	6.95	6.96	6.96
STANDARD DEVIATION:		2.54	2.55	2.55	2.55
5%		4.12	4.15	4.18	4.16
95%		13.38	13.40	13.40	13.40
COOKHAM:					
MEAN:		6.54	6.53	6.54	6.54
STANDARD DEVIATION:		2.04	2.04	2.03	2.03
5%		4.25	4.24	4.27	4.24
95%		12.20	12.15	12.14	12.14

1975	CASE	0	1	2	3
DAYS WEIR:					
MEAN:		6.10	6.00	5.97	5.98
STANDARD DEVIATION:		1.36	1.38	1.40	1.38
5%		3.72	3.59	3.53	3.56
95%		8.35	8.29	8.28	8.28
STREATLEY WEIR:					
MEAN:		6.28	6.23	6.24	6.24
STANDARD DEVIATION:		1.38	1.38	1.39	1.38
5%		3.81	3.75	3.75	3.73
95%		8.46	8.46	8.46	8.46
COOKHAM:					
MEAN:		6.08	6.07	6.08	6.07
STANDARD DEVIATION:		0.91	0.89	0.88	0.89
5%		4.71	4.76	4.77	4.76
95%		7.65	7.59	7.58	7.58

EC drinking water limit is 11.29 mg l^{-1} as N

Table 5.5 Nitrate (mgl^{-1} as N) 1976 and 1989:

1976	CASE 0	1	2	3
DAYS WEIR:				
MEAN:	8.21	7.50	7.47	7.49
STANDARD DEVIATION:	2.16	2.48	2.50	2.49
5%	5.90	5.15	5.10	5.15
95%	13.01	12.92	12.93	12.92
STREATLEY WEIR:				
MEAN:	8.17	7.64	7.64	7.64
STANDARD DEVIATION:	2.30	2.62	2.64	2.62
5%	5.90	4.81	4.80	4.81
95%	13.00	12.94	12.95	12.94
COOKHAM:				
MEAN:	8.63	8.55	8.58	8.55
STANDARD DEVIATION:	1.29	1.30	1.29	1.30
5%	7.40	7.35	7.41	7.38
95%	11.25	11.14	11.12	11.14

1989	CASE 0	1	2	3
DAYS WEIR:				
MEAN:	13.32	11.01	11.25	11.12
STANDARD DEVIATION:	2.70	1.66	1.62	1.70
5%	9.90	8.31	8.94	8.29
95%	18.63	13.48	13.67	13.67
STREATLEY WEIR:				
MEAN:	12.24	10.34	10.49	10.42
STANDARD DEVIATION:	2.03	1.56	1.50	1.56
5%	9.73	7.42	7.77	7.42
95%	16.23	12.94	13.07	13.13
COOKHAM:				
MEAN:	8.63	7.86	7.87	7.87
STANDARD DEVIATION:	0.90	1.15	1.13	1.15
5%	7.40	5.84	5.89	5.85
95%	10.42	9.65	9.68	9.68

EC drinking water limit is 11.29 mg l^{-1} as N

Table 5.6 Nitrate Exceedances (all years):

CASE	0	1	2	3
DAYS WEIR:				
1974	27	27	27	27
1975	0	0	0	0
1976	47	45	45	45
1989	256	131	150	143
STREATLEY WEIR:				
1974	30	30	30	30
1975	0	0	0	0
1976	49	47	47	47
1989	212	79	85	84
COOKHAM:				
1974	25	25	25	25
1975	0	0	0	0
1976	17	17	17	17
1989	0	0	0	0

Table 5.7 Dissolved Oxygen (mgl^{-1}) 1974 and 1975:

1974 CASE	0	1	2	3
DAYS WEIR:				
MEAN:	10.71	10.11	10.27	10.27
STANDARD DEVIATION:	1.87	2.25	2.13	2.15
5%	7.35	5.87	6.46	6.46
95%	14.42	13.53	13.77	13.77
STREATLEY WEIR:				
MEAN:	10.28	9.47	9.66	9.65
STANDARD DEVIATION:	1.86	2.57	2.43	2.45
5%	6.35	4.01	4.82	4.73
95%	12.94	12.41	12.46	12.46
COOKHAM:				
MEAN:	10.09	9.73	9.82	9.81
STANDARD DEVIATION:	1.15	1.45	1.37	1.39
5%	7.80	6.79	7.01	6.97
95%	11.76	11.70	11.73	11.73

1975 CASE	0	1	2	3
DAYS WEIR:				
MEAN:	8.54	8.10	8.12	8.11
STANDARD DEVIATION:	3.24	3.18	3.26	3.24
5%	3.04	1.73	2.18	1.73
95%	12.85	11.55	11.61	11.55
STREATLEY WEIR:				
MEAN:	8.80	8.41	8.52	8.47
STANDARD DEVIATION:	2.74	3.28	3.23	3.26
5%	2.56	0.82	0.97	0.97
95%	11.51	11.41	11.49	11.48
COOKHAM:				
MEAN:	9.98	9.83	9.90	9.87
STANDARD DEVIATION:	2.75	3.11	3.09	3.10
5%	2.86	2.32	2.40	2.32
95%	14.25	15.22	15.27	15.23

NRA river quality standards (50%ile): Class 1a: 9mg l^{-1} (95%ile): Class 1a: 80% sat
Class 1b: 9mg l^{-1} Class 1b: 60% sat
Class 2a: 7mg l^{-1} Class 2 : 40% sat

Table 5.8 Dissolved Oxygen (mgl^{-1}) 1976 and 1989:

1976	CASE 0	1	2	3
DAYS WEIR:				
MEAN:	10.50	9.12	9.50	9.17
STANDARD DEVIATION:	3.33	3.49	3.41	3.49
5%	3.89	1.78	2.41	1.78
95%	14.95	14.09	14.31	14.25
STREATLEY WEIR:				
MEAN:	9.51	8.43	8.72	8.46
STANDARD DEVIATION:	3.19	3.87	3.70	3.85
5%	2.80	1.07	1.71	1.18
95%	14.66	14.49	14.56	14.49
COOKHAM:				
MEAN:	8.49	8.32	8.36	8.33
STANDARD DEVIATION:	4.26	4.28	4.30	4.29
5%	0.04	0.00	0.00	0.00
95%	11.85	12.05	12.10	12.07

1989	CASE 0	1	2	3
DAYS WEIR:				
MEAN:	9.62	8.72	8.89	8.78
STANDARD DEVIATION:	3.29	3.83	3.73	3.84
5%	2.45	0.70	0.82	0.70
95%	12.84	12.63	12.69	12.69
STREATLEY WEIR:				
MEAN:	9.38	8.45	8.68	8.53
STANDARD DEVIATION:	3.20	3.63	3.54	3.62
5%	2.29	0.67	0.85	0.67
95%	12.45	12.18	12.22	12.18
COOKHAM:				
MEAN:	9.28	8.99	9.06	9.02
STANDARD DEVIATION:	2.90	3.10	3.08	3.10
5%	2.70	2.17	2.27	2.19
95%	11.92	11.88	11.89	11.89

NRA river quality standards (50%ile): Class 1a: 9mg l^{-1} (95%ile): Class 1a: 80% sat
Class 1b: 9mg l^{-1} Class 1b: 60% sat
Class 2a: 7mg l^{-1} Class 2 : 40% sat

Table 5.9 Dissolved Oxygen Exceedances (all years):

CASE	0	1	2	3
DAYS WEIR:				
1974	0	15	12	12
1975	109	124	123	124
1976	43	66	52	64
1989	57	86	75	84
STREATLEY WEIR:				
1974	5	37	31	32
1975	57	89	88	89
1976	28	91	79	90
1989	59	85	77	85
COOKHAM:				
1974	0	0	0	0
1975	27	32	31	31
1976	84	85	85	85
1989	60	67	67	67

Table 5.10 Biochemical Oxygen Demand (mgl^{-1}) 1974 and 1975:

1974	CASE	0	1	2	3
DAYS WEIR:					
MEAN:		4.72	4.83	4.87	4.86
STANDARD DEVIATION:		2.36	2.48	2.50	2.49
5%		2.43	2.44	2.45	2.45
95%		10.09	10.38	10.40	10.40
STREATLEY WEIR:					
MEAN:		3.97	3.94	3.93	3.93
STANDARD DEVIATION:		1.84	1.84	1.84	1.84
5%		2.12	2.11	2.11	2.11
95%		8.60	8.62	8.61	8.61
COOKHAM:					
MEAN:		3.45	3.42	3.42	3.42
STANDARD DEVIATION:		1.68	1.69	1.69	1.69
5%		1.99	1.98	1.99	1.99
95%		7.72	7.78	7.81	7.81

1975	CASE	0	1	2	3
DAYS WEIR:					
MEAN:		8.07	8.11	8.14	8.13
STANDARD DEVIATION:		3.26	3.07	3.14	3.10
5%		3.73	3.74	3.75	3.75
95%		15.14	13.50	13.92	13.63
STREATLEY WEIR:					
MEAN:		5.43	5.17	5.11	5.14
STANDARD DEVIATION:		1.70	1.49	1.50	1.49
5%		3.27	3.26	3.20	3.24
95%		9.25	8.00	8.01	8.10
COOKHAM:					
MEAN:		4.27	4.19	4.20	4.19
STANDARD DEVIATION:		1.83	1.80	1.81	1.81
5%		2.04	1.93	1.92	1.92
95%		8.82	8.66	8.72	8.66

NRA river quality standards (95%ile): Class 1a: 3mg l^{-1}
Class 1b: 5mg l^{-1}
Class 2a: 9mg l^{-1}

Table 5.11 Biochemical Oxygen Demand (mgl^{-1}) 1976 and 1989:

1976	CASE 0	1	2	3
DAYS WEIR:				
MEAN:	6.67	6.63	6.68	6.64
STANDARD DEVIATION:	5.12	4.76	4.86	4.79
5%	1.68	1.66	1.67	1.66
95%	20.31	18.00	18.61	18.08
STREATLEY WEIR:				
MEAN:	4.97	4.73	4.73	4.72
STANDARD DEVIATION:	3.19	2.82	2.82	2.82
5%	1.62	1.48	1.50	1.48
95%	12.57	10.69	10.73	10.68
COOKHAM:				
MEAN:	5.59	5.72	5.76	5.72
STANDARD DEVIATION:	3.86	4.28	4.34	4.28
5%	1.73	1.71	1.72	1.71
95%	14.55	17.73	17.78	17.73

1989	CASE 0	1	2	3
DAYS WEIR:				
MEAN:	6.07	5.84	5.86	5.86
STANDARD DEVIATION:	2.75	2.80	2.79	2.80
5%	2.41	2.40	2.41	2.41
95%	10.49	10.41	10.47	10.47
STREATLEY WEIR:				
MEAN:	5.14	4.90	4.91	4.91
STANDARD DEVIATION:	2.24	2.22	2.22	2.22
5%	2.24	2.20	2.20	2.20
95%	9.89	9.77	9.81	9.81
COOKHAM:				
MEAN:	4.59	4.53	4.55	4.54
STANDARD DEVIATION:	2.15	2.18	2.19	2.18
5%	1.95	1.90	1.90	1.90
95%	8.77	8.79	8.83	8.79

NRA river quality standards (95%ile): Class 1a: 3mg l^{-1}
Class 1b: 5mg l^{-1}
Class 2a: 9mg l^{-1}

Table 5.12 B.O.D. Exceedances (all years):

CASE	0	1	2	3
DAYS WEIR:				
1974	116	118	120	119
1975	271	272	272	272
1976	214	214	214	214
1989	182	166	166	166
STREATLEY WEIR:				
1974	83	83	83	83
1975	185	167	166	166
1976	196	180	179	180
1989	165	164	164	164
COOKHAM:				
1974	61	61	61	61
1975	115	103	102	102
1976	209	205	205	205
1989	136	133	136	136

Table 5.13 Ammonia ($mg l^{-1}$ as N) 1974 and 1975:

1974	CASE	0	1	2	3
DAYS WEIR:					
MEAN:		0.24	0.23	0.23	0.23
STANDARD DEVIATION:		0.04	0.05	0.05	0.05
5%		0.17	0.15	0.15	0.15
95%		0.29	0.28	0.28	0.28
STREATLEY WEIR:					
MEAN:		0.19	0.18	0.18	0.18
STANDARD DEVIATION:		0.05	0.06	0.06	0.06
5%		0.11	0.09	0.09	0.09
95%		0.26	0.26	0.26	0.26
COOKHAM:					
MEAN:		0.19	0.19	0.19	0.19
STANDARD DEVIATION:		0.06	0.06	0.06	0.06
5%		0.13	0.13	0.13	0.13
95%		0.29	0.29	0.29	0.29

1975	CASE	0	1	2	3
DAYS WEIR:		0.40	0.37	0.37	0.37
MEAN:		0.18	0.14	0.15	0.14
STANDARD DEVIATION:		0.23	0.23	0.23	0.23
5%		0.81	0.71	0.72	0.72
95%					
STREATLEY WEIR:					
MEAN:		0.26	0.23	0.22	0.22
STANDARD DEVIATION:		0.10	0.08	0.08	0.08
5%		0.13	0.11	0.11	0.11
95%		0.49	0.37	0.37	0.37
COOKHAM:					
MEAN:		0.21	0.21	0.21	0.21
STANDARD DEVIATION:		0.06	0.05	0.05	0.05
5%		0.14	0.14	0.14	0.14
95%		0.32	0.29	0.30	0.30

NRA river quality standards (95%ile): Class 1a: 0.31mg l^{-1}
Class 1b: 0.7mg l^{-1}
Class 2a: 2.33mg l^{-1}

Table 5.14 Ammonia (mgl^{-1} as N) 1976 and 1989:

1976	CASE 0	1	2	3
DAYS WEIR:				
MEAN:	0.41	0.37	0.38	0.37
STANDARD DEVIATION:	0.14	0.11	0.12	0.11
5%	0.26	0.25	0.26	0.26
95%	0.68	0.61	0.64	0.61
STREATLEY WEIR:				
MEAN:	0.26	0.22	0.23	0.22
STANDARD DEVIATION:	0.13	0.11	0.11	0.11
5%	0.12	0.11	0.11	0.11
95%	0.50	0.41	0.42	0.41
COOKHAM:				
MEAN:	0.29	0.30	0.30	0.30
STANDARD DEVIATION:	0.09	0.11	0.12	0.11
5%	0.20	0.20	0.20	0.20
95%	0.47	0.60	0.62	0.60

1989	CASE 0	1	2	3
DAYS WEIR:				
MEAN:	0.23	0.23	0.23	0.23
STANDARD DEVIATION:	0.08	0.08	0.08	0.09
5%	0.14	0.11	0.11	0.11
95%	0.38	0.39	0.40	0.40
STREATLEY WEIR:				
MEAN:	0.16	0.15	0.15	0.15
STANDARD DEVIATION:	0.07	0.08	0.08	0.08
5%	0.06	0.05	0.05	0.05
95%	0.29	0.29	0.29	0.29
COOKHAM:				
MEAN:	0.17	0.17	0.17	0.17
STANDARD DEVIATION:	0.06	0.06	0.06	0.06
5%	0.07	0.07	0.07	0.07
95%	0.28	0.28	0.28	0.28

NRA river quality standards (95%ile): Class 1a: 0.31mg l^{-1}
Class 1b: 0.7mg l^{-1}
Class 2a: 2.33mg l^{-1}

Table 5.15 Ammonia Exceedances (all years):

CASE	0	1	2	3
DAYS WEIR:				
1974	0	0	0	0
1975	40	20	26	26
1976	16	7	7	7
1989	6	0	2	2
STREATLEY WEIR:				
1974	0	0	0	0
1975	0	0	0	0
1976	1	1	1	1
1989	0	0	0	0
COOKHAM:				
1974	0	0	0	0
1975	0	0	0	0
1976	0	1	1	1
1989	0	0	0	0

Table 5.16 Ortho-phosphate (mgl^{-1} as P) 1974 and 1975:

1974	CASE	0	1	2	3
DAYS WEIR:					
MEAN:		0.54	0.54	0.53	0.53
STANDARD DEVIATION:		0.24	0.23	0.23	0.23
5%		0.23	0.23	0.23	0.23
95%		0.92	0.92	0.92	0.90
STREATLEY WEIR:					
MEAN:		0.61	0.61	0.61	0.61
STANDARD DEVIATION:		0.28	0.28	0.28	0.28
5%		0.26	0.26	0.26	0.26
95%		1.05	1.06	1.06	1.06
COOKHAM:					
MEAN:		0.67	0.67	0.67	0.67
STANDARD DEVIATION:		0.25	0.25	0.25	0.25
5%		0.35	0.35	0.35	0.35
95%		1.08	1.08	1.09	1.09

1975	CASE	0	1	2	3
DAYS WEIR:					
MEAN:		0.70	0.69	0.68	0.69
STANDARD DEVIATION:		0.36	0.34	0.34	0.34
5%		0.20	0.20	0.20	0.20
95%		1.16	1.13	1.11	1.12
STREATLEY WEIR:					
MEAN:		0.75	0.75	0.75	0.75
STANDARD DEVIATION:		0.38	0.38	0.38	0.38
5%		0.22	0.22	0.22	0.22
95%		1.26	1.26	1.26	1.26
COOKHAM:					
MEAN:		0.76	0.76	0.76	0.76
STANDARD DEVIATION:		0.34	0.34	0.34	0.34
5%		0.28	0.28	0.28	0.28
95%		1.19	1.20	1.20	1.20

EC guideline is 0.17 mg l^{-1} as P

Table 5.17 Ortho-phosphate (mgl^{-1} as P) 1976 and 1989:

1976	CASE	0	1	2	3
DAYS WEIR:					
MEAN:		0.95	0.91	0.90	0.91
STANDARD DEVIATION:		0.30	0.28	0.28	0.28
5%		0.29	0.28	0.29	0.28
95%		1.23	1.18	1.16	1.18
STREATLEY WEIR:					
MEAN:		1.12	1.11	1.12	1.11
STANDARD DEVIATION:		0.37	0.37	0.37	0.37
5%		0.31	0.31	0.31	0.31
95%		1.53	1.54	1.54	1.54
COOKHAM:					
MEAN:		1.37	1.38	1.39	1.38
STANDARD DEVIATION:		0.52	0.53	0.54	0.53
5%		0.39	0.39	0.39	0.39
95%		2.07	2.12	2.13	2.12

1989	CASE	0	1	2	3
DAYS WEIR:					
MEAN:		1.24	1.20	1.20	1.20
STANDARD DEVIATION:		0.49	0.46	0.46	0.46
5%		0.45	0.45	0.45	0.45
95%		1.94	1.86	1.85	1.86
STREATLEY WEIR:					
MEAN:		1.44	1.43	1.45	1.44
STANDARD DEVIATION:		0.59	0.59	0.61	0.60
5%		0.53	0.54	0.54	0.54
95%		2.13	2.30	2.34	2.31
COOKHAM:					
MEAN:		1.47	1.47	1.47	1.47
STANDARD DEVIATION:		0.50	0.49	0.50	0.49
5%		0.65	0.65	0.65	0.65
95%		2.17	2.17	2.18	2.17

EC guideline is 0.17 mg l^{-1} as P

Table 5.18 Ortho-phosphate Exceedances (all years):

CASE	0	1	2	3
DAYS WEIR:				
1974	365	365	365	365
1975	361	361	361	361
1976	366	366	366	366
1989	365	365	365	365
STREATLEY WEIR:				
1974	365	365	365	365
1975	365	365	365	365
1976	366	366	366	366
1989	365	365	365	365
COOKHAM:				
1974	365	365	365	365
1975	365	365	365	365
1976	366	366	366	366
1989	365	365	365	365

Table 5.19 Temperature °C 1974 and 1975.

1974 CASE	0	1	2	3
DAYS WEIR:				
MEAN:	11.25	12.40	12.19	12.20
STANDARD DEVIATION:	4.02	4.76	4.64	4.66
5%	6.68	6.95	6.88	6.88
95%	17.55	19.63	19.21	19.21
STREATLEY WEIR:				
MEAN:	11.17	12.14	11.95	11.95
STANDARD DEVIATION:	4.02	4.62	4.51	4.52
5%	6.49	6.95	6.72	6.72
95%	17.50	19.00	18.76	18.82
COOKHAM:				
MEAN:	11.37	11.86	11.75	11.76
STANDARD DEVIATION:	4.05	4.27	4.22	4.23
5%	6.73	6.95	6.92	6.92
95%	17.59	18.13	17.99	18.00

1975 CASE	0	1	2	3
DAYS WEIR:				
MEAN:	11.77	13.58	13.31	13.39
STANDARD DEVIATION:	4.97	5.06	5.02	5.07
5%	5.71	6.45	6.42	6.42
95%	20.08	21.34	21.11	21.33
STREATLEY WEIR:				
MEAN:	11.76	13.21	12.97	13.04
STANDARD DEVIATION:	5.04	5.06	5.03	5.07
5%	5.83	6.36	6.31	6.31
95%	20.12	21.14	20.97	21.06
COOKHAM:				
MEAN:	12.05	12.63	12.52	12.55
STANDARD DEVIATION:	4.97	4.93	4.93	4.94
5%	6.26	6.60	6.57	6.57
95%	20.55	20.80	20.75	20.80

Table 5.20 Temperature °C 1976 and 1989.

1974	CASE 0	1	2	3
DAYS WEIR:				
MEAN:	11.63	13.81	13.42	13.77
STANDARD DEVIATION:	5.62	5.54	5.50	5.51
5%	3.93	4.60	4.45	4.60
95%	20.20	21.34	20.90	21.17
STREATLEY WEIR:				
MEAN:	11.48	13.22	12.87	13.18
STANDARD DEVIATION:	5.53	5.37	5.34	5.34
5%	3.77	4.32	4.20	4.32
95%	19.82	20.61	20.34	20.57
COOKHAM:				
MEAN:	11.89	12.54	12.40	12.52
STANDARD DEVIATION:	5.72	5.59	5.62	5.59
5%	3.87	4.29	4.18	4.29
95%	21.65	21.87	21.86	21.87

1975	CASE 0	1	2	3
DAYS WEIR:				
MEAN:	11.95	13.62	13.36	13.45
STANDARD DEVIATION:	5.32	5.76	5.70	5.80
5%	5.25	5.95	5.89	5.89
95%	20.74	22.30	22.08	22.30
STREATLEY WEIR:				
MEAN:	11.77	13.08	12.83	12.92
STANDARD DEVIATION:	5.16	5.46	5.40	5.50
5%	5.15	5.38	5.35	5.35
95%	20.13	21.18	20.90	21.18
COOKHAM:				
MEAN:	12.23	12.77	12.66	12.70
STANDARD DEVIATION:	4.99	5.01	5.00	5.03
5%	5.66	5.77	5.75	5.75
95%	19.44	19.74	19.70	19.74

Appendix A Surface water flow and quality model - QUASAR

1 INTRODUCTION

1.1 Background

The model QUASAR (Quality Simulation Along Rivers) has been developed at the Institute of Hydrology to assess the environmental impact of pollutants on river water quality. The model has evolved over a number of years during which time there have been many applications to rivers in the UK and overseas. The model was originally developed as part of the Bedford Ouse Study with the primary objective of simulating the dynamic behaviour of flow and water quality along the river system (Whitehead et al, 1979, 1981). Initial applications involved the use of the model within a real time forecasting scheme collating telemetered data and providing forecasts at key abstraction sites along the river (Whitehead, 1984). The model was also used within a stochastic or Monte Carlo framework to provide information on the distribution of water quality within river systems, particularly in rivers subjected to major effluent discharges (Whitehead and Young, 1979). This technique was later adapted by Warn (1982) to assess mass balance problems within river systems. There has also been a range of model applications to other UK rivers such as the River Tawe to assess heavy metal pollution and the River Thames, to assess the movement and distribution of nitrates and algae along this river system (Whitehead and Williams, 1982, Whitehead and Hornberger, 1984).

QUASAR (QUAlity Simulation Along Rivers) is a water quality and flow model. The model has been developed to combine upstream inputs due to accidental, man made and natural inputs. Forecasting and planning information is generated for key locations along the river. The water quality parameters modelled are nitrate, dissolved oxygen (DO), biochemical oxygen demand (BOD), ammonia, ammonium ion, temperature, ortho-phosphate, pH, and a "conservative" water quality parameter. To model these parameters the river is divided up into reaches. The reach boundaries are determined by points in the river where there is a change in the water quality or flow due to the confluence with a tributary, the location of a sewage treatment final effluent discharge, abstraction, or location of weirs. Water quality changes due to biological or chemical reactions are also considered by ensuring appropriate reach lengths.

Two sets of equations have been developed to represent flow and the nine water quality parameters. One set consists of the differential equations relating the rate of change of these parameters with time. These equations are solved by a "differential equation solver" subroutine in the program. The other set consists of "analytical solutions" or the integrated differential equations. These equations are solved at discrete time intervals, specified in the program as the model time step. The first decision to be made in using QUASAR is whether planning or forecasting information is required.

1.2 Planning Mode

In the stochastic or planning mode a cumulative frequency curve and distribution histogram of a water quality parameter are generated by repeatedly running the model using different input data selected according to probability distributions defined for each input variable. Whitehead and

Young (1979) and Warn (1982) have used this technique, known as Monte Carlo simulation, to provide information which aids in long term planning of water quality management. In this mode statistical data of the water quality and flow in the first reach at the top of the river, and in tributaries, STW discharges, and abstractions at key locations along the river are required. These data include, for each variable input to the model, the mean, standard deviation, and shape that the probability curve takes ie. lognormal, rectangular, or gaussian. Random numbers are generated as water quality and flow values are chosen from these characterized distributions. A mass balance is performed at the top of each reach to include tributaries, discharges, abstractions and any other inputs to the river at that point on the river for each run of the model. The values generated by the model equations represent the water quality or flow at the end of the reach. The model equations are run using the random numbers as the input values either until steady state has been reached or for a maximum of 30 time periods. Steady state is said to have been achieved when the results of successive runs differ by less than 1%. Five hundred and twelve, random numbers are generated. The output is stored and used to produce cumulative frequency distributions and distribution histograms.

1.3 Dynamic Mode

In the forecasting or dynamic mode, the water quality and flow are simulated over selected periods. This allows the possible affects of a pollution event on a river to be investigated. In this mode time series data are required for water quality and flow parameters for the first reach of the river and for tributaries, STW discharges and abstractions along the section of the river of interest. The model run time step, ie. the time interval over which the model will dynamically compute river quality and flow, and the run output length, ie. the number of output steps that the model runs for, must also be specified. Once these data have been input the model can be run. A mass balance is performed at the beginning of each reach for inputs such as tributaries entering at that point on the river. The model input then goes to the differential or analytical equations and the output from each reach is stored and used as the input of the next reach. The model is run for 40 time periods before the specified start of the model run using the "default" values to ensure that the system has reached equilibrium. The output values are used in generating profiles of water quality parameters along the river at a given time or in generating time series data at a specified location.

2 Description of the QUASAR Model Equations

Nine water quality parameters and flow are modelled. In the following subsections a summary of the differential equations is given listing the major processes occurring. A detailed explanation of the processes and the assumptions made in the equations is then given. Analytical solutions (ie integrated differential equations) are given in Appendix A.

2.1 Flow

The flow in the river is represented by:

$$\frac{dX_t}{dt} = \frac{U_t - X_t}{[1 - b] \cdot TC}$$

In this differential equation, X_1 refers to the downstream flow (reach output) and U_1 refers to the upstream flow (reach input). TC is the reach residence time, often referred to as travel time, which varies as a function of flow, and b is a constant defined below.

2.1.1 Development of Equation

As mentioned previously, the river has been divided into reaches. The boundaries of these reaches are located at the confluence of tributaries, weirs, effluents, abstractions, or at other locations where changes in the water quality occur. Each reach is further divided into cells. Flow variation in each cell is analogous to the variation in concentration of a conservative pollutant under the assumption of uniform mixing over the cell. The concentration of a conservative pollutant is described by the lumped parameter equations (Whitehead et. al., 1979, 1981, 1984).

We know that, in all cases:

(i) $V = TC \cdot Q$

(ii) $TC = \dfrac{l}{v \cdot N}$ and

(iii) $\dfrac{dV}{dt} = U_1 - X_1$ (mass balance),

where:
V is the volume of the reach,
TC is the time taken for water to travel down the river,
Q is the average flow in the reach,
l is the length of the reach,
v is the average velocity of the water in the reach,
N is the number of lags (divisions within the reach) and
X1 and U1 are as above.

provided that we are dealing with the continuous case (as we shall be doing). Then, if we assume that the reach is a stirred tank system (which this model does assume) we have:

$X_1 = Q$

Also we have the empirical relationship:

$v = a + b \cdot Q^c$

which is obtained from measuring both v and Q; a, b and c are different constants for each reach; a is almost always zero.

So, we may now derive the equation:

$$\frac{dV}{dt} = d\frac{(TC \cdot Q)}{dt} = Q \cdot \frac{dTC}{dt} + TC \cdot \frac{dQ}{dt}$$

by the chain rule

But

$$\frac{dTC}{dt} = d\frac{\left(\frac{l}{v}\right)}{dt} = -\frac{l}{v^2} \cdot \frac{dv}{dt}$$

$$= \frac{-TC}{b \cdot Q^c} \cdot b \cdot \frac{dQ^c}{dt} = \frac{-TC}{Q^c} \cdot \frac{dQ^c}{dQ} \cdot \frac{dQ}{dt} = \frac{-TC}{Q^c} \cdot c \cdot Q^{c-1} \frac{dQ}{dt} = \frac{-TC \cdot c}{Q} \cdot \frac{dQ}{dt}$$

So

$$\frac{dV}{dt} = TC \cdot \frac{dQ}{dt} - c \cdot TC \cdot \frac{dQ}{dt} = [1 - c] \cdot TC \cdot \frac{dQ}{dt} = U_1 - X_1$$

If

$c = 1$

then this reduces to

$U_1 = X_1$

which is the case for regulated rivers where the water level is kept constant.

If

$c \neq 1$

then we have:

$$\frac{dX_1}{dt} = -\frac{U_1 - X_1}{(1 - c) \cdot TC}$$

as

$X_1 = Q$

from the stirred tank assumption.

The values of N affect the relative importance of floodwave advection and dispersion in a reach; values of N, a, b and c can be determined by calibration on an observed record of downstream flow or from tracer experiments (see Whitehead et. al.,1984).

This then is the continuous solution which is solved by a numerical differential equation solver.

2.2 Nitrate

Two processes affect the rate at which the nitrate concentration changes in the water column. These are nitrification and denitrification. The differential equation describing the rate of change of nitrate concentration with time is given below:

If $c \neq 1$

then

$$\frac{d(X_2)}{dt} = \frac{U_2 - X_2}{TC \cdot (1 - c)}$$

$- K_5 . X_2$ denitrification

$+ K_{15} . X_6$ nitrification

where U_2 and X_2 are the input and output nitrate concentrations and K_5 and K_{15} are the rate coefficients associated with the processes indicated. X_6 is the ammonia concentration.

If $c = 1$

then

$$X_2 = U_2 - K_5 \cdot X_2 \cdot TC + K_{15} \cdot X_6 \cdot TC$$

Note that if the Dissolved Oxygen level goes to zero, then the terms involving K_{15} and K_5 are left out.

2.2.1 Nitrification

Nitrification is the process resulting in the conversion of ammonium to nitrite and then to nitrate. The two biochemical reactions are shown below.

$NH_4^+ + 2\ O_2$ ---(nitrosomas bacteria)---> $NO_2^- + 2\ H_2O$
$NO_2^- + 2\ H_2O$ ---(nitrobacter bacteria)--> $NO_3^- + H_2O + 2H^+$

Curtis, Durrant, and Harman (1974) studied nitrification in rivers in the Trent Basin and found growth rates for nitrosomas and nitrobacter were virtually the same. Laboratory work by Alexander (1965) showed nitrobacter was five times as efficient as nitrosomas in transforming nitrite and ammonium respectively. This indicates that the ammonia (ammonium ion) concentration is the rate controlling process. Knowles and Wakeford (1978) modelled the change in nitrate concentration to be dependant on the temperature, ammonia and nitrosomas concentration. In **QUASAR** the rate of change of nitrate concentration is dependant on the concentration of ammonia, the temperature °C, and the ammonia nitrification rate, K_{15}, which is usually in the range of 0.01 to 0.5 $days^{-1}$. The value for the ammonia nitrification rate can be edited by the user. The equation is given below where T is the temperature in Celsius and K_{15} is the nitrification rate in $days^{-1}$.

$$\text{nitrification} = K_{15}\ .\ 10^{(T\ \cdot\ 0.0293)}\quad (days^{-1})$$

2.2.2 Denitrification

In denitrification, nitrate is reduced to nitrogen gas and oxygen by denitrifying bacteria. The simplified reaction is given below:

$2\ NO_3$ ----> $3\ O_2 + N_2\ (g)$

The oxygen produced is consumed by the bacteria as an oxygen source so does not add to the oxygen concentration in the river. Toms et al., (1975) studied the factors affecting the denitrification process. These researchers found that the process is first order and proportional to the nitrate concentration, and required the presence of mud. They also found that for every 10 °C increase in temperature the rate of denitrification increased by a factor of 1.9 which can be described in the equation as $10^{T\ \cdot\ 0.0293}$. The relationship they developed is:

$$\frac{dNO_3}{dt} = -K\ .\ 10^{(0.0293T\ \cdot\ 0.0294)}\ .\ A\ .\ CN$$

where A (m^2) is the surface area of mud in contact with water, CN is the concentration of nitrate in water in mg l^{-1}, T is the temperature in Celsius. K is a value in the range of 0.29 (clean gravel type bed), to 3.0 (soft muddy bed supporting denitrifying bacteria). In **QUASAR** modelling of denitrification is based on this work. The equation is given below:

$$\text{denitrification} = K_5\ .\ 1.0698\ .\ 10^{(T\ \cdot\ 0.0293)}$$

Note that 1.0698 is calculated from $10^{0.0294}$. K_5 is in units of day^{-1} and in the range of 0.0 to 0.5. The value for K_5 can be edited by the user.

2.3 Conservative

A conservative water quality parameter has been included in the model to describe any conservative determinand, for example chloride. This can be used to get a worst case estimate when modelling a variable not included explicitly in **QUASAR**. U3 and X3, the input and output conservative water quality parameter concentrations, are related by the equation:

If $c \neq 1$

then

$$\frac{d(X_3)}{dt} = \frac{U_3 - X_3}{TC \cdot (1-c)}$$

If $c = 1$

then

$$X_3 = U_3$$

2.4 Dissolved Oxygen

The change in dissolved oxygen concentration is modelled as a result of photosynthetic O_2 production, benthic oxygen demand, reaeration (natural or due to the presence of a weir), nitrification, and loss due to BOD. The differential equation is given below:

If $c \neq 1$

then

$\frac{d(X_4)}{dt}$	$= \frac{U_4 - X_4 + WEIR}{TC \cdot (1-c)}$	
	$+K_{11}$	net algae O_2 contribution
	$-K_4 K_6 X_4$	benthic oxygen demand
	$+K_2(CS - X_2)$	reaeration
	$-4.43 . 10^{(T*0.0293)} . K_{15} X_6$	nitrification
	$-K_1 X_5$	loss due to BOD

If $c = 1$

then

$$X_4 = U_4 + WEIR + [K_{11} - K_4 \cdot K_6 \cdot X_4 + K_2(CS - X_4) - 4.43 \cdot K_{15} \cdot X_6 - K_1 \cdot X_5] \cdot TC$$

where U_4 and X_4 are the input and output dissolved oxygen concentrations and Ki are the rate coefficients associated with the processes indicated. X_5 and X_6 are the BOD and ammonia concentrations respectively and WEIR is the contribution or loss of oxygen due to the presence of a weir in the reach.

2.4.1 Reaeration at Weirs

The contribution or loss of dissolved oxygen due to the presence of a weir in a river is described by the equation, (DOE, 1973).

$$X_4 = CS - \frac{(CS - XO_4)}{RT}$$

where CS is the oxygen saturation concentration, XO_4 is the dissolved oxygen above the weir and RT is the deficit ratio. The DO deficit ratio takes into account the type of weir using a factor B, the pollution of the water (percent saturation), A, the height from the top of the weir to the downstream water level (m), H, and the temperature, T (° C) of the water as shown in the equation below.

$$RT = 1 + 0.38ABH(1 - 0.11H)(1 + 0.046T)$$

There are 4 types of weirs; free, slope, step, and cascade. A free weir or normal weir takes a value of unity for B. A step weir has a value of 1.3 for B. A cascade weir consists of a large number of steps with a value for B of 0.4 and a sloping weir has a sloping face down with a value for B of 0.2. The equation is given below,

2.4.2 Algae Contribution to Dissolved Oxygen

Algae, aquatic plants and phytoplankton utilize water, carbon dioxide, and sunlight to photosynthesize simple sugar and oxygen which is released to the water column. Respiration, which depletes the dissolved oxygen store in the water, occurs throughout the day. These two processes result in the highest dissolved oxygen concentration at midafternoon and the lowest concentration during the early hours of the morning. The two processes are described below and related in the differential equation by K_{11}=P-R where P represents photosynthetic oxygen production and R represents respiration.

2.4.2.1 Photosynthetic Oxygen Production

Photosynthetic oxygen production in river systems has been described by Owens et. al., (1969) in which oxygen production is related to the light intensity and plant biomass or algal levels. They found that once there is sufficient plant biomass to provide adequate and uniform cover of the river bed the plant biomass has apparently no affect on the rate of photosynthesis due to self-shading. Whitehead et. al. (1981) used a modified version of the Owens model and estimated the relevant parameters for the Bedford Ouse. A similar approach was adopted for **QUASAR** and the following relationship developed:

Chlorophyll-a concentrations less than 50 mg/l

$$P = K_a \left(1.08^{(T-20)} I^{0.78}\ 0.317\ Cl_a\right) \text{ (mg/l-day)}$$

Chlorophyll-a concentrations greater than 50 mg/l

$$P = 1.08^{(T-20)} I^{0.78} \left(K_a (0.317 \times 50) + K_b\ 0.317\ Cl_a\right) \text{ (mg/l-day)}$$

Here the user specifies the two rates at which photosynthetic oxygen production occurs, one when the chlorophyll-a concentration is greater than 50 mg/l, K_b, and another when the concentration is less than 50 mg/l, K_a. K_a is usually in the range of 0.0 to 0.03 day^{-1}, and K_b is in the range of 0.0 to 0.02 day^{-1}. The two rates are to take account of the self shading effect at high algae concentrations. Cl_a is the chlorophyll-a concentration g/m^3, I is the solar radiation level at the earth's surface in watt hours per m^2 day. I is only input during sunlight hours determined from longitude and latitude data and also from the time of year. This assumes no cloud cover.

2.4.2.2 Respiration

The loss of oxygen due to algae respiration is described by an equation developed from Kowalczewski and Lack (1971) based on observed algae concentration measured as chlorophyll-a and respiration rate for the River Thames. Cl_a is the chlorophyll-a concentration measured as gm^{-3} and T is the temperature in degrees Celsius.

$$R = (0.14 + 0.013\ Cl_a)\ 1.08^{(T-20)} \text{ (mg/l-day)}$$

2.4.3 Benthic Oxygen Demand

Oxygen is also lost by benthic oxygen demand (river bed or mud respiration). There has been considerable research into this process (Edwards and Rolley, 1965) and the following equation has been used, where M is the benthic oxygen demand,

$$M = \frac{K_4 \quad X_4^{0.45} \quad 1.08^{(T-20)}}{d}$$

where X_4 in the equation refers to the DO concentration mg l^{-1}, d is the river depth in metres, K_4 is the rate of oxygen uptake by the sediment and T is the temperature in degrees Celsius. The original work of Edward and Rolley was conducted on the highly polluted muds of the River Ivel and later studies by Rolley and Owens (1967) showed that the parameter K_4 varied considerably from river to river. In the Thames a value for K_4 of 0.15 day^{-1} was found to provide the best fit to the observed DO data. In **QUASAR** the equation representing benthic oxygen demand is given below:

$$M = \frac{K_4 \quad X_4 \quad 1.08^{(T-20)}}{d}$$

K_4 is the oxygen uptake rate by sediment, usually in the range of 0.0 to 0.1 day^{-1}. This value can be edited by the user. d is the river depth in metres and is specified in the spatial data for the reach, T is the temperature in degrees Celsius.

2.4.4 Reaeration

Oxygen is added to the system by the natural reaeration of the river at the surface. Several workers have developed empirically and physically based equations. Edwards and Gibbs (1964) combined previous work of Churchill et al.,(1962), and Gameson et al.,(1955) to derive the equation:

reaeration = K_2*(CS - X_4)

where K_2 is the reaeration constant given by,

$$K_2 = \frac{9.4 \cdot V^{0.67}}{d^{1.85}}$$

(days^{-1})

V is the stream velocity in ft s^{-1} , d is the river depth in ft. This equation is valid within the experimentally observed ranges (velocity 0.1-5.0 ft s^{-1}; depth 0.4-11.0 ft). Elmore and West (1961) determined the temperature coefficient for the reaerration constant, later used by Churchill et al.,(1962) as shown in the equation below. Note that T is the temperature in degrees Celsius.

$$k_{(T \cdot C)} = k_{(20 \cdot C)} \times 1.024^{(T-20)}$$

CS is the saturation concentration for DO defined as:

$CS = 14.652 - 0.41022T + 0.0079910T^2 - 0.000077774T^3$

In **QUASAR** this equation has been used with the temperature correction applied;

$$K_2 = \frac{38.19 \times \quad V^{0.67} \quad \times 1.024^{(T-20)}}{d^{1.85}}$$

As these variables (river velocity, temperature and depth) are all either input at the beginning of the model or generated during the model run the user does not have direct control of the reaeration coefficient and therefore the amount of oxygen added due to natural reaeration.

2.4.5 Nitrification

If there is ammonia in the water column this will be converted to nitrate. During this reaction oxygen is consumed. Thus there is a term for oxygen depletion as a result of nitrification as discussed in 2.2.1

Nitrification $= 4.57 \cdot 10^{(T \cdot 0.0293)} \cdot K_{15} \cdot X_6$

where K_{15} is the ammonia nitrification rate coefficient generally ranging from 0.0 to 0.5 day^{-1}. The value for K_{15} can be edited by the user. T is the temperature in degrees Celsius, and X_6 is the ammonia concentration. The 4.57 term arises from the stoichiometry of the reaction.

2.4.6 BOD

The biochemical oxygen demand is caused by the decay of organic material in the stream. As the material decays it consumes oxygen, a process which is included in the model as:

BOD $= K_1 \cdot X_5$ (mg/l-day)

where K_1 is the rate coefficient for the loss of BOD and X_5 is the concentration of BOD in the stream. The value for K_1 can be edited by the user.

2.5 Biochemical Oxygen Demand

The change in the biochemical oxygen demand is due to decay, sedimentation and addition due to dead algae. The differential equation describing the rate of change of BOD concentration with time is given below:

If $c \neq 1$

then

$$\frac{d(X_5)}{dt} = \frac{U_5 - X_5}{TC\,(1-c)}$$

$- K_1 \cdot X_5$ BOD decay

$- K_{18} \cdot X_5$ sedimentation

$+ K_{10}$ BOD contribution by algae

If $c = 1$

then

$$X_5 = U_5 - \{K_1 \cdot X_5 - K_{10}\} TC$$

where U_5 and X_5 are the input and output BOD concentrations and K_1 and K_{18} are the rate coefficients associated with the processes indicated.

Note that if the Dissolved Oxygen level goes to zero, then the term involving K_1 is left out.

2.5.1 BOD Decay

The biochemical oxygen demand is caused by the decay of organic material in the stream. As the material decays it consumes oxygen. Knowles and Wakeford (1978) found the rate of change due to oxidation to be dependant on the temperature. This process has been modelled in the same manner:

$BOD = 1.047^{(T-20)} \cdot K_1 \cdot X_5$ (mg/l-day)

where T is the temperature in degrees Celsius, K_1 is the rate coefficient for the loss of BOD and is usually in the range of 0.0 to 2.0 day^{-1} and X_5 is the concentration of BOD in the stream in mg/l. The value for K_1 can be edited by the user.

2.5.2 Loss by Sedimentation

Loss of BOD can also occur by sedimentation. This occurs at a rate proportional to the amount of BOD present. The sedimentation rate is currently set at 0.1 day^{-1}.

2.5.3 BOD Contribution by Algae

As algae die they contribute to the BOD. The rate of contribution is proportional to the product of the concentration of algae and the rate of BOD addition by dead algae, usually in the range of 0.0 to 0.1 day^{-1}. This value can be edited by the user.

2.6 Ammonium Ion

The loss of ammonia is due to oxidation. The differential equation describing the rate of change of ammonia concentration is given below:

$$\frac{d(X_6)}{dt} = \frac{U_6 - X_6}{TC \cdot (1-c)}$$

$$- K_{15} \cdot X_6 \quad \text{loss by nitrification}$$

where U_6 and X_6 are the input and output ammonia concentrations and K_{15} is the nitrification rate. A detailed description of this process is given in section 2.2.1. The ammonia nitrification rate is dependant on the temperature and described by the equation:

Ammonia nitrification rate = $K_{15} \cdot 10^{(T \cdot 0.0293)}$

Note that if the Dissolved Oxygen level goes to zero, then the last (K_{15}) term is left out.

2.7 Ammonia

The concentration of ammonia is not actually produced as an output by the model, but it is computed by the plot program from the ammonia concentration, pH and temperature data. This is determined by considering the following equilibrium:

$NH_4^+ = NH_3(aq) + H^+(aq)$

It is assumed that the modelled Ammonia, NH_3, is the total ammonia present, ie.:

$NH_{3(modelled)} = NH_4^+ + NH_3$

The concentration of the ammonia is then given by the equation:

$$NH_3 = \frac{NH_{3(modelled)}}{(1.0 + 10^{pKA - pH})}$$

where pKA is the dissociation constant, KA adjusted for temperature. The value of pKA is assumed to vary inversely with absolute temperature (this assumption being derived from the equation for Gibbs Free Energy): $pKA = \frac{2754.9}{(T + 273.15)}$ where T is the temperature in degrees Celsius.

2.8 Temperature

The differential equation for temperature is given below where U7 and X7 are the input and output temperatures.

If $c \neq 1$

then

$$\frac{d(X_7)}{dt} = \frac{U_7 - X_7}{TC \cdot (1 - c)}$$

If $c = 1$

then

$$X_7 = U_7$$

2.9 Ortho-phosphate

Changes in Ortho-phosphate are due to decay.

If $c \neq 1$

then

$$\frac{d(X_8)}{dt} = \frac{U_8 - X_8}{TC\ (1 - c)}$$

$$- K_{16} \cdot X_8 \qquad \text{Ortho-phosphate decay}$$

If $c = 1$

then

$$X_8 = U_8 - K_{16} \cdot X_8 \cdot TC$$

where U_8 and X_8 are the input and output ortho-phosphate concentrations and K_{16} is the rate of ortho-phosphate decay usually in the range of 0.0 to 2.0 $days^{-1}$.

2.10 pH

The differential equation for pH is given below where U_9 and X_9 are the input and output pH.

$$\frac{d(X_9)}{dt} = \frac{U_9 - X_9}{TC \cdot (1 - c)}$$

3 Data Requirements

Three sets of data are required to operate **QUASAR**; a catchment structure consisting of a river map, boundary conditions which define the water quality and flow of the tributaries and of the water at the top of the river, and reach parameters consisting of data specific to each reach.

3.1 Catchment Structure

The first step in creating a catchment structure is to determine the river network to be modelled. Tributaries entering the river network need to be specified and finally the river must be divided into reaches. Reach boundaries are determined to be points in the river at which there is a change in the water quality due to the confluence of a tributary, the location of a sewage treatment works effluents discharge, abstractions, and locations of weirs. Water quality changes due to biological or physical chemical reactions should also be considered by ensuring the reach length is not too long. Reach boundaries can also be established at points were water quality monitoring stations are located to be used as calibrating points. Below is a summary of the steps required in establishing a catchment structure.

1. Determine the extent of the river to be modelled.
2. Determine if any tributaries enter the river network which are not being modelled.
3. Establish reach boundaries:

- at the location of tributaries, Sewage Treatment Works Effluent Discharges, weirs, abstractions, monitoring stations
- roughly determine distances between reach boundaries
- further divide the river up by using a reach length of no greater than 5 km as a guide

3.2 Boundary Conditions

The boundary conditions consist of the water quality and flow data of the river network at the points modelling begins and for the tributaries that are not modelled at the point where they enter the river network. Time series data are required in the dynamic mode while statistical data are required in the planning mode.

3.2.1 Planning Mode

In the planning mode each water quality and flow parameter requires a probability distribution and its characteristics to be specified. A choice between three probability distributions is presently available; gaussian, lognormal, or rectangular. The mean and standard deviation are required if lognormal or gaussian distributions are chosen, and lower and upper bounds are required if a rectangular distribution is required. The list below is a summary of the required data:

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	Distribution	-normal -lognormal -rectangular
	Characteristics	-mean, standard deviation -or lower/upper bounds

3.2.2 Dynamic Mode

In the dynamic or forecasting mode time series data of the water quality and flow are required as well as the run and output time step, and the run output length. Time series data consist of daily mean flow values and monthly mean water quality values. The run time step allows the user to specify the time period over which the model equations will operate. The output time step defines the time period for which output data are generated. The run output length specifies the number of output steps that the model will generate. The list below is a summary of the required data:

Daily mean flow data
Monthly mean water quality values
Run time step
Output time step
Run output length

3.3 Reach parameters

Reach parameters consist of data specific to each reach such as the rate coefficients, velocity-flow relationships, spatial data, weir specifications and monthly algae data. They must be specified for each reach.

3.3.1 Rate Coefficients

Rate coefficients are required to describe the rate at which the chemical processes are occurring in the reach. The ratewhich have to be specified include:

Denitrification (0.0 - 0.5 day$_{-1}$)
Biochemical Oxygen Demand decay (0.0 - 2.0 day$_{-1}$)
Ammonia nitrification (0.0 - 0.5 day$_{-1}$)
Oxygen uptake by sediment (0.0 - 1.0 day$_{-1}$)
Addition of BOD by dead algae (0.0 - 0.1 day$_{-1}$)
Photosynthetic oxygen production
- chlorophyll - a up to 50 mg/l (0.0 - 0.03 day$_{-1}$)
- chlorophyll - a above 50 mg/l (0.0 - 0.02 day$_{-1}$)
Decay of ortho-phosphate (0.0 - 2.0 day$_{-1}$)
Sedimentation of BOD (0.0 - 2.0 day$_{-1}$)
Algae Respiration (offset) (0.0 - 2.0 day$_{-1}$)
Algae Respiration (offset) (0.0 - 2.0 day$_{-1}$)

3.3.2 Velocity-Flow Relationship

The reach's velocity - flow relationship has three parameters that relate the velocity of water (m/s) in the reach to its flow in cumecs. The equation is of the form:

velocity (m/s) = A + B . Flow^{C}.

The A, B, and C coefficients are entered into **QUASAR**.

3.3.3 Spatial Data

Spatial data for the reach consist of the reach length and depth, the number of lags (or cells) in the reach and the latitude, longitude, and time zone that the reach is in. Below is a list of the required data for each reach.

length (m)
depth (m)
number of lags (cells)
latitude
longitude
time zone

3.3.4 Weir

The presence of a weir in a reach can be specified in the reach parameters. Four types of weirs can be chosen from, these include: free, slope, step, or cascade (or none). The height from the top of the weir to the downstream water level must also be specified. Below is a list of the required data for each reach.

Type of weir (free, slope, step, cascade, none)
Height (m) Distance from the top of the weir to the downstream water level

3.3.5 Algae Data

Monthly algae data specifying chlorophyll-a concentrations are required in the calculation of dissolved oxygen concentrations.

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Appendix B Calibration and validation of QUASAR

Appendix B: List of Tables

Appendix B: List of Figures

Appendix B; Calibration and Validation of QUASAR

QUASAR was set up for the stretch of the Thames shown in Figure B.1. The input data used in the model included all the available flow and water quality data for the main river and the most important tributaries from Eynsham (just downstream of the Farmoor abstraction) down to Cookham (a gauging site). Full sets of flow and quality data were available for the Thames at Days Weir and Cookham Bridge, while flow data only was available at Sutton Courtenay. The other input data were abstraction rates for the major abstractions, and the discharge and associated water quality data for the sewage treatment works.

The water quality variables - nitrate, dissolved oxygen (DO), biochemical oxygen demand (BOD), ammonia, temperature and ortho-phosphate - are sampled and analysed at most only twice a week; hence linear interpolation was used to estimate the daily values of these quality variables.

Another important input to the model is the level of algae, which are usually indicated by chlorophyll-a concentrations, as this has an important effect on DO and BOD concentrations. **QUASAR** requires monthly inputs of algae data. The initial calibration runs were based on the algae data that were available at the start of the study; these data were for algae concentrations at Egham during the years 1974 to 1975, and for Walton in 1989. Later on in the study, algae data for other, more local, sites on the Thames were obtained for the period 1974 to 1976; the model runs whose results are presented in the main report were based on these local values. Local data were not available for 1989; consequently the 1976 values from the local sites were assumed to apply for this year.

For the initial calibration and validation runs it was assumed that there would be no concentration effect caused by the passage of water through the power station system. The return water was assumed to have the same concentration as the abstracted water.

Flow was calibrated first, since it is fundamental to the mass balance for the quality determinants. The least dependent quality variables, ammonia, ortho-phosphate and BOD, were then calibrated. Ammonia is controlled by one parameter (ammonia nitrification); ortho-phosphate is only controlled by a decay coefficient and BOD is controlled by three terms, two subtracting (BOD decay and Sedimentation) and one adding (addition to BOD by dead algae).

Nitrate and DO were the last variables to be fitted; nitrate is controlled by the denitrification rate, the ammonia nitrification rate and the concentration of ammonia while DO is controlled by the concentrations of BOD, nitrate and ammonia as well as by reaeration, weir aeration, algal respiration and photosynthesis.

The model was calibrated using data for 1974; the initial parameter values were adjusted for successive simulations until a satisfactory match was achieved between the the model predictions and the observed values at the two monitoring sites Days Weir and Cookham. During calibration it was found necessary to divide the river into two stretches, Eynsham to Days Weir and Days Weir to Cookham; different parameter values were used for each stretch (Table B.1).

The chosen parameter values were then validated by running the model for 1975 data and then checking the model predictions with the observed values. The following plots show two sets of model predictions. In each case the same parameter values were used, but with different sets of input data. The first set uses the original algae data, and assumes no concentration, whereas the second set uses the local algae data, and assumes full concentration.

Flow: The model uses accurate measurements of velocity-flow relationships, and flow is measured on a daily basis (more frequently than most of the water quality variables). Plots of the flow calibration at Sutton Courtenay, Days and Cookham are shown in Figures B.2 to B.4 respectively, and indicate a very good fit; note that the the dashed line indicates the observed data, and the full line the model prediction. The validation against the 1975 data also produced good fits (Figure B.16).

Temperature: Temperature has no calibration coefficients, but will have a good fit unless the input data are seriously wrong. However, it is necessary to check as all of the rate coefficients for the other determinants depend on temperature. The fit for temperature was good in all years, confirming the quality of the input data (Figures B.5 and B.17).

Nitrate: The fits for nitrate were excellent. (See Figures B.6 & B.7 and B.18 & B.19).

Dissolved Oxygen: Although the initial fits for dissolved oxygen were poor, a satisfactory fit for 1974 was eventually achieved. The final parameter values reproduced the overall change in DO throughout the year although the model predicts some apparently spurious peaks, and misses other peaks altogether. Given the relatively few observed data points, the model fits were considered to be reasonable (See Figures B.8 & B.9). The initial validation plot (Figure B.20) was considered to be acceptable. The sharp drop in DO arises from a combination of the start of a sustained period of low flows, and relatively high monthly algae concentrations. Figure B.21 illustrates the consequences of assuming full concentration in the return water, particularly at times of low flow; the BOD concentration of the return water is high and thus tends to suppress dissolved oxygen. Given the limited availability of algae data, and that the model runs will be used to assess the effect of different abstraction scenarios, the model calibration was accepted.

BOD: The 1974 model fits for BOD were good, particularly when the lack of algae data is taken into account (See Figures B.10 & B.11). The model reproduces the observed variation in BOD throughout the year. At present the model accepts only monthly algae data, which is appropriate for the frequency of the available data. Algae concentrations are particularly important in the simulation of BOD and hence dissolved oxygen. The validation plot (Figure B.22) was considered to be acceptable. However when full concentration is assumed (Figure B.23), the effect of the enhanced BOD concentration in the return water is again demonstrated. This effect becomes particularly important when flows are low, and a high proportion of the flow at Days' weir is made up of return water. In these circumstances there is an artificially high BOD load in the return water, which is reflected in the predicted values of high BOD and hence low DO at Days.

Ammonia: The model fits for ammonia were poor; a large number of alternative parameter values were tried, but it was not possible to reproduce the pattern of peaks in the limited number of observed values. The number of unexplained missed peaks is a probable indication of errors resulting from intermittent measurements followed by interpolation (see Figures B.12 & B.13 and B.24 & B.25). The effect of the concentration assumption is again illustrated by consistently higher predicted values. In reality ammonia will tend to be stripped out during passage through the cooling system. The model fit was considered to be satisfactory for the this study, whose main purpose is to investigate the relative effects of different abstraction scenarios.

Ortho-phosphate: Ortho-phosphate has fairly constant levels, with values of around 1 mg l^{-1} the norm for both the observed and modelled data (See Figures B.14 & B.15 and B.26 & B.27).

Table B.1 Calibrated Parameter Values

	Eynsham - Days	Days - Cookham
Process:		
Denitrification	0.003	0.002
BOD Decay	0.12	0.15
Ammonia Nitrification	0.35	0.10
Sediment O_2 uptake	1.0	1.5
Dead algae BOD contribution	0.035	0.015
Algal photosynthetic O_2 production <50 mg l^{-1}	0.20	0.20
Algal ph. 0_2 prod. >50 mg l^{-1}	0.06	0.06
Orthophosphate decay	0.10	0.02
Sedimentation of BOD	0.10	0.10
Algae respiration offset	0.14	1.2
Slope	0.020	0.060

Location map and reach structure

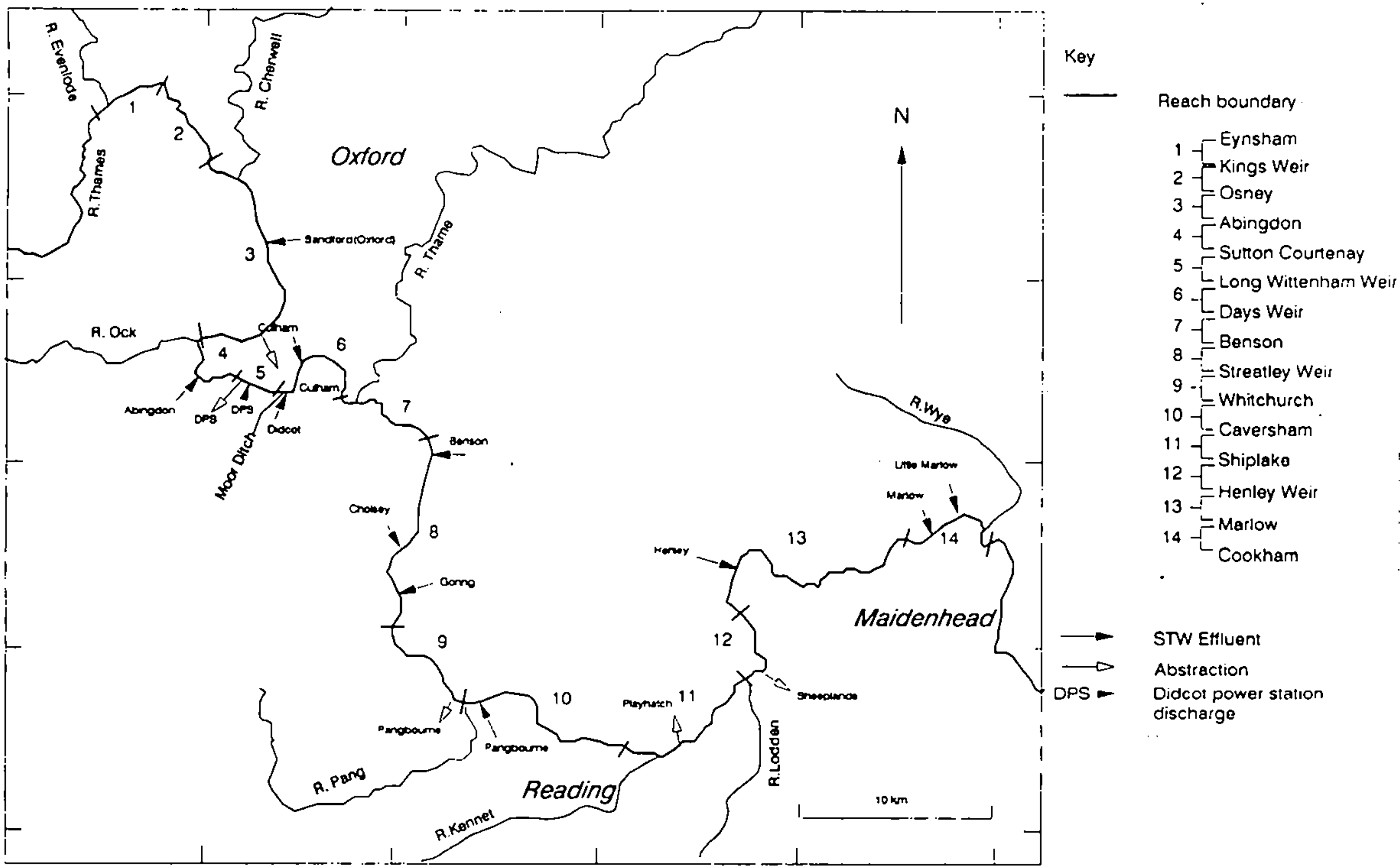
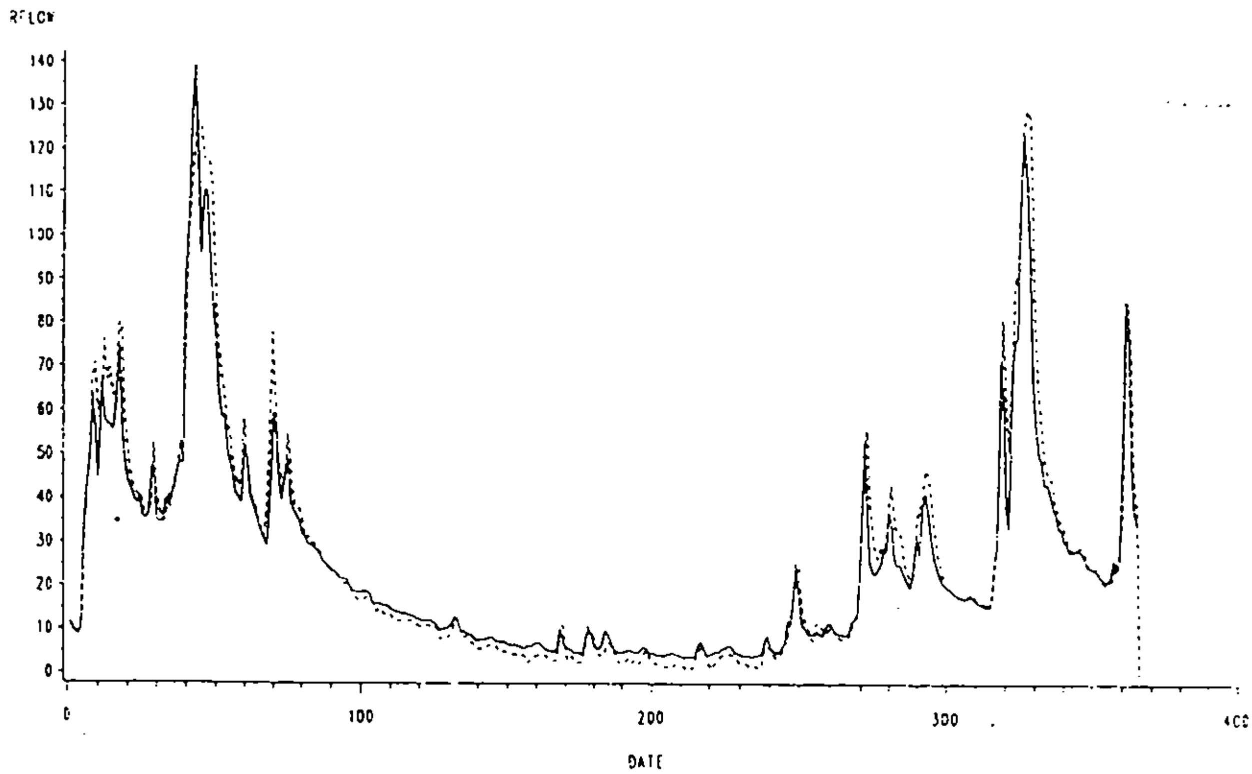


Figure B.1

Sutton Courtenay 1974 Flow

Figure B.2

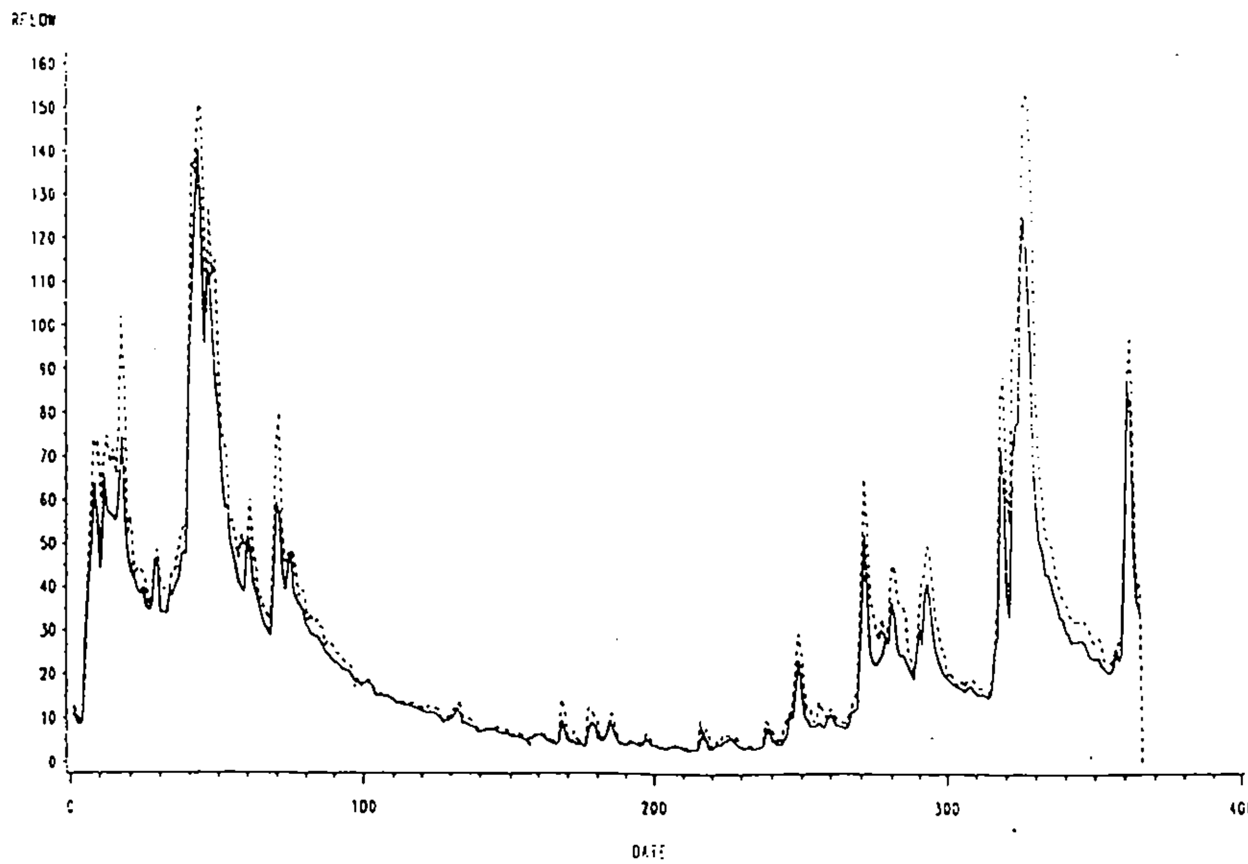
Observed is the dotted line
Modelled is the solid line



Days 1974 Flow

Figure B.3

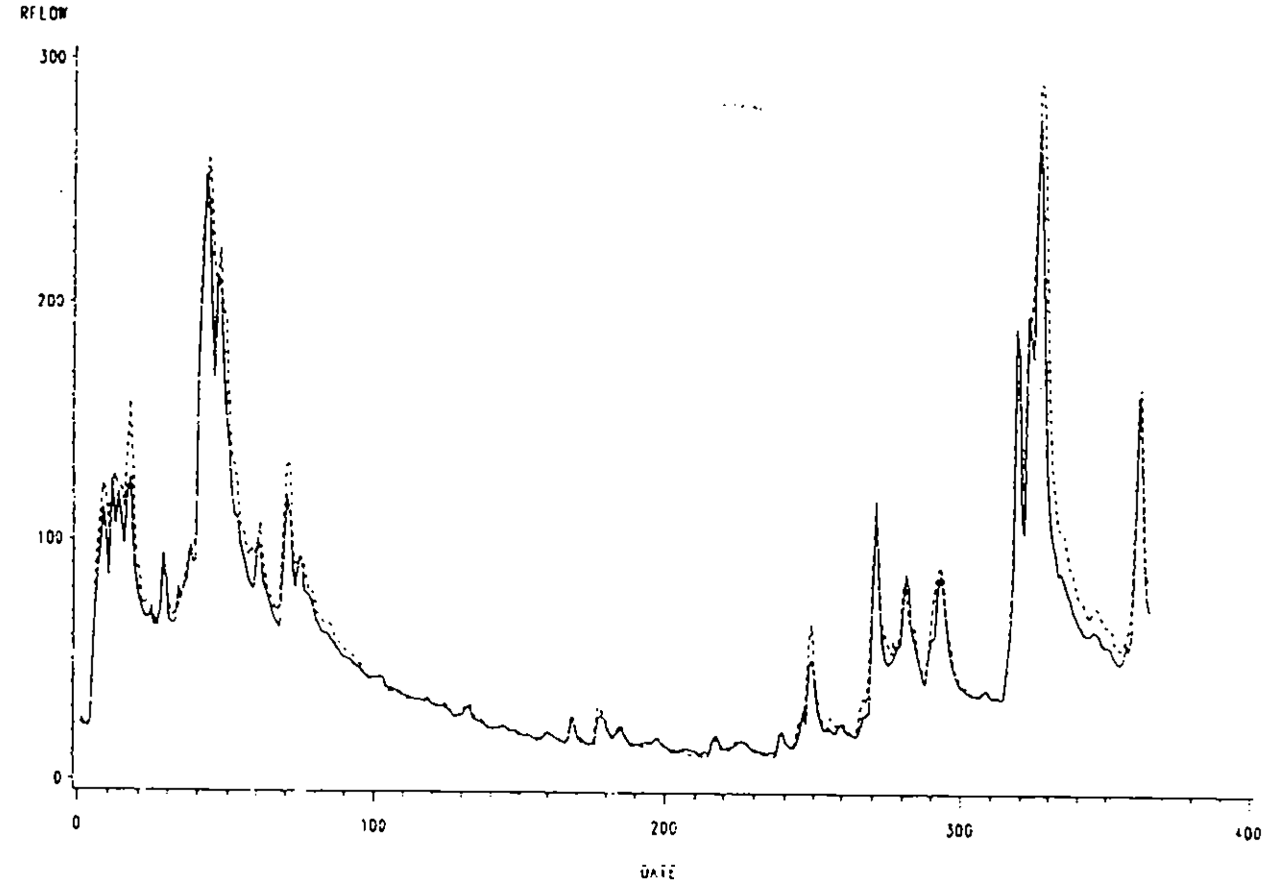
Observed is the dotted line
Modelled is the solid line



Cookham 1974 Flow

Observed is the dotted line
Modelled is the solid line

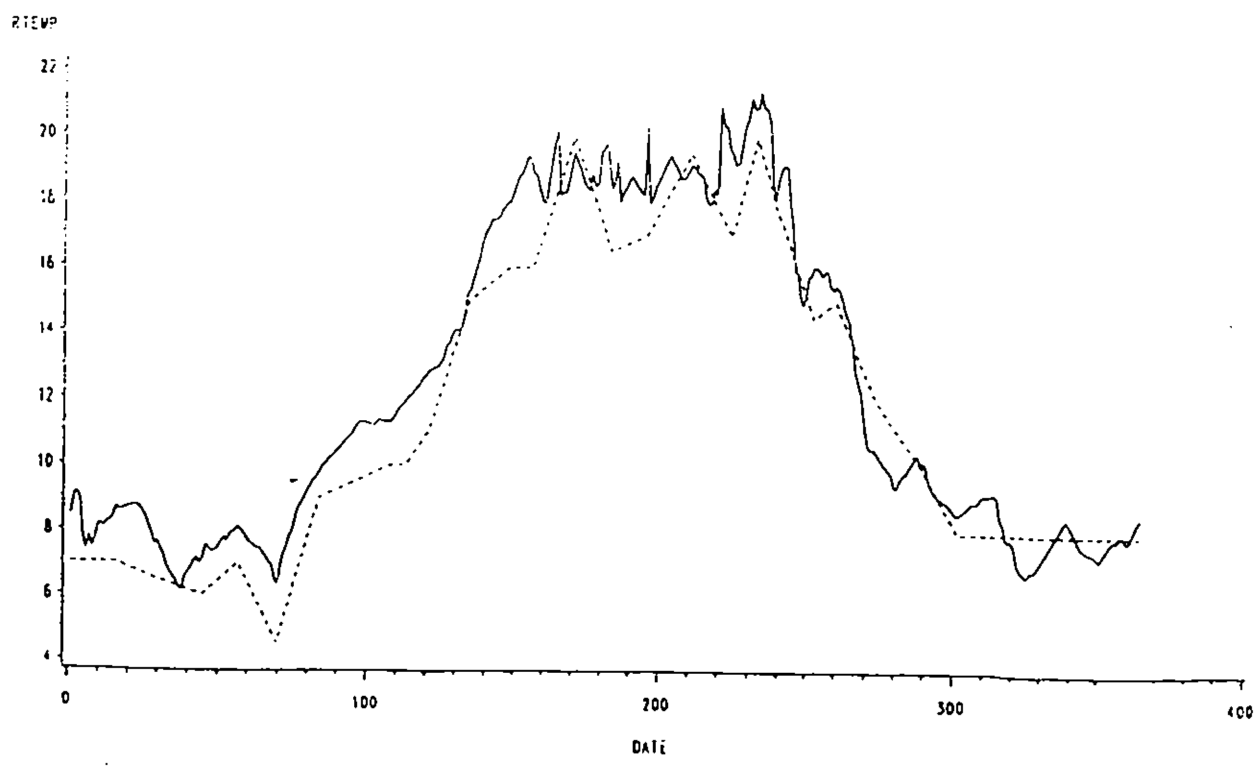
Figure B.4



Days 1974 TEMP

Observed is the dotted line
Modelled is the solid line

Figure B.5

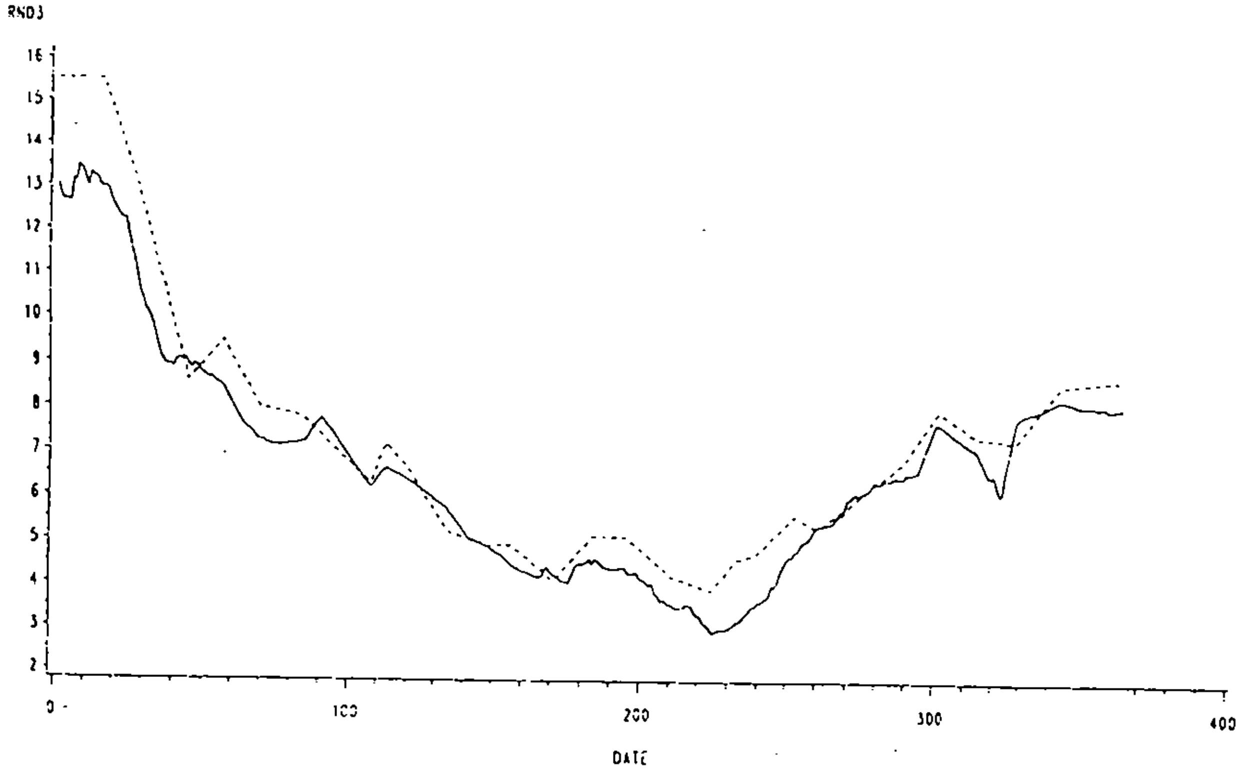


Days 1974 NO3

Observed is the dotted line
Modelled is the solid line

Figure B.6

Initial algae data, no concentration



Days 1974 NO3

Observed is the dotted line
Modelled is the solid line

Figure B.7

New algae data, full concentration

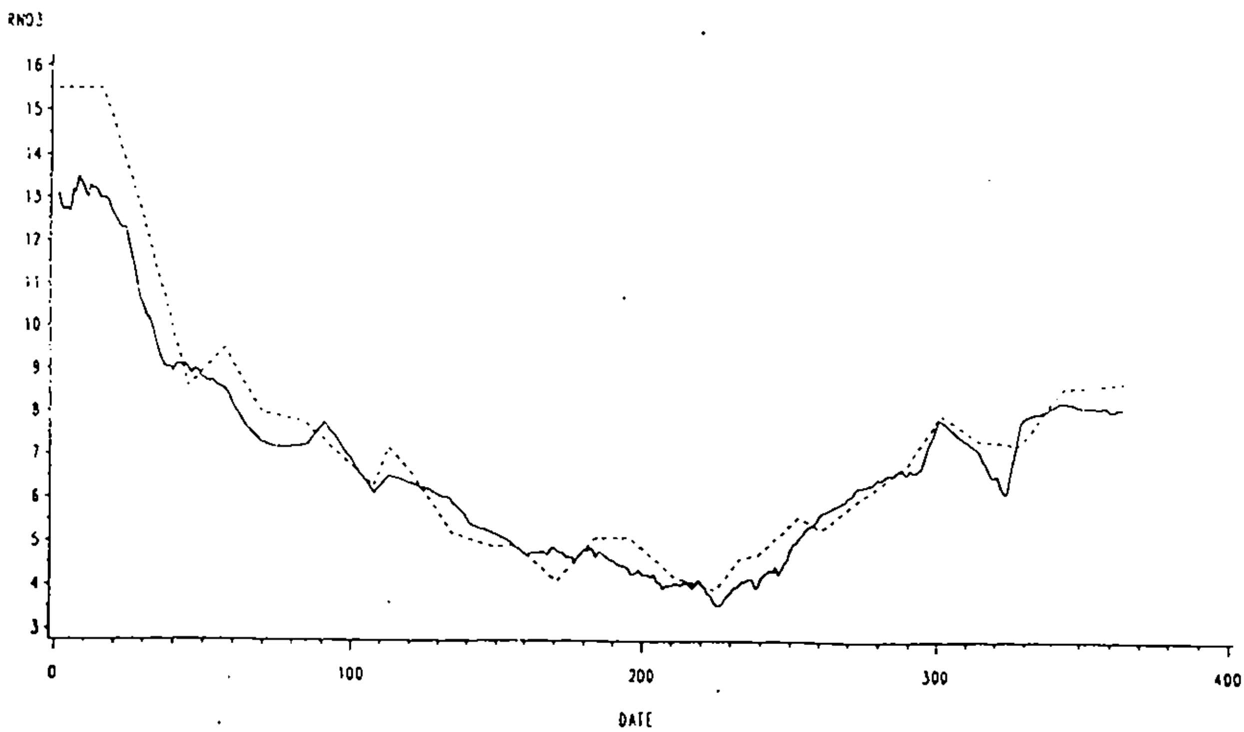


Figure B.8

Initial algae data, no concentration

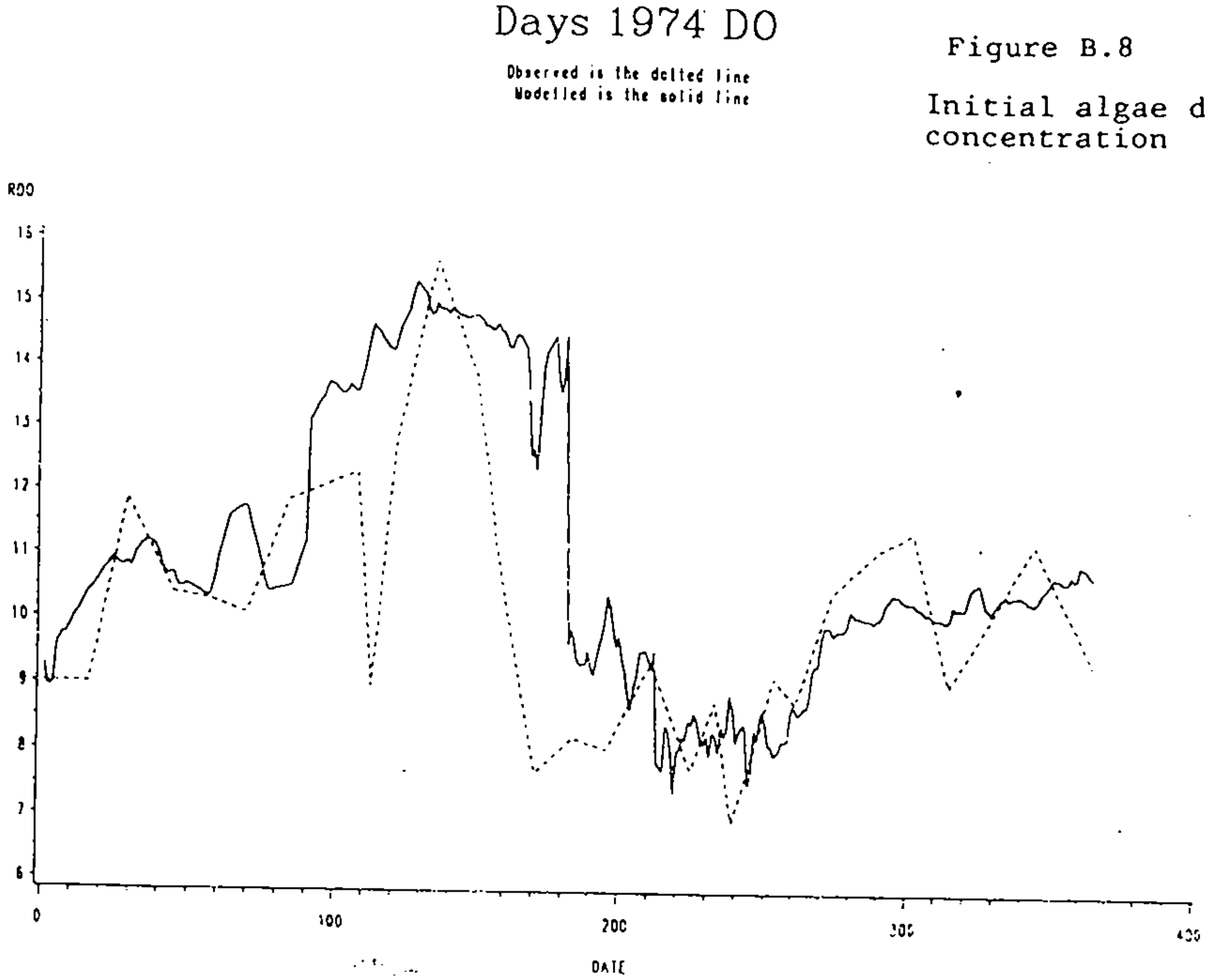
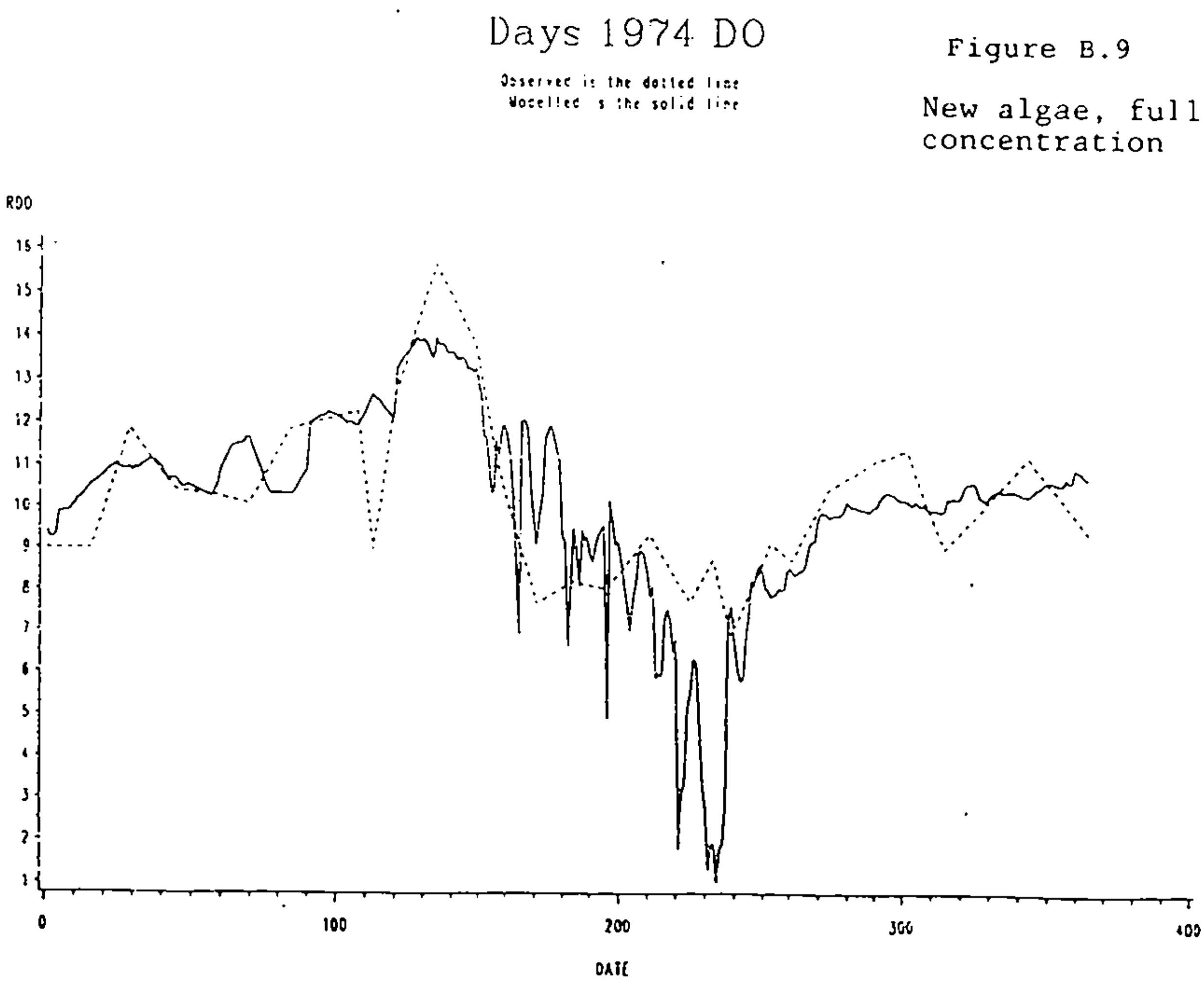


Figure B.9

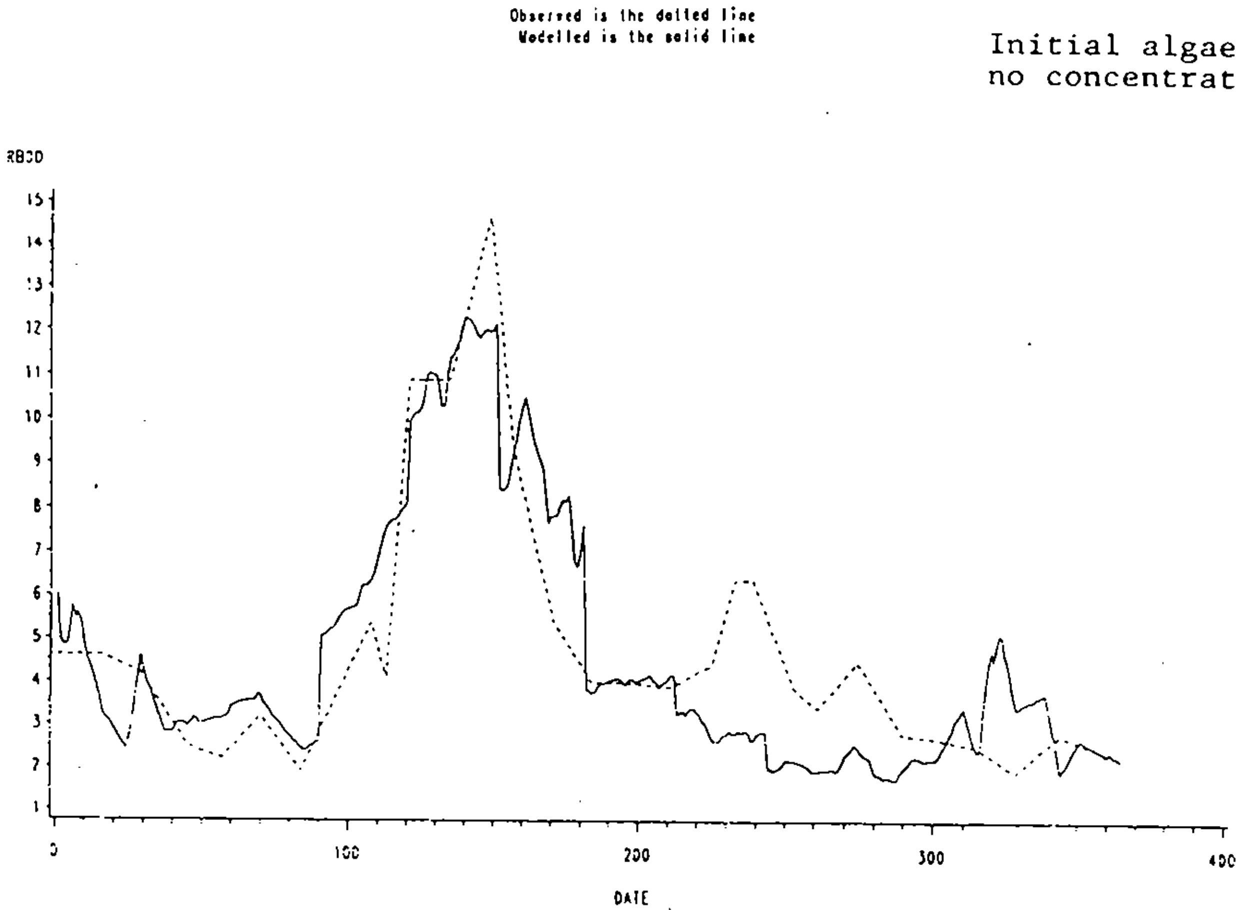
New algae, full concentration



Days 1974 BOD

Figure B.10

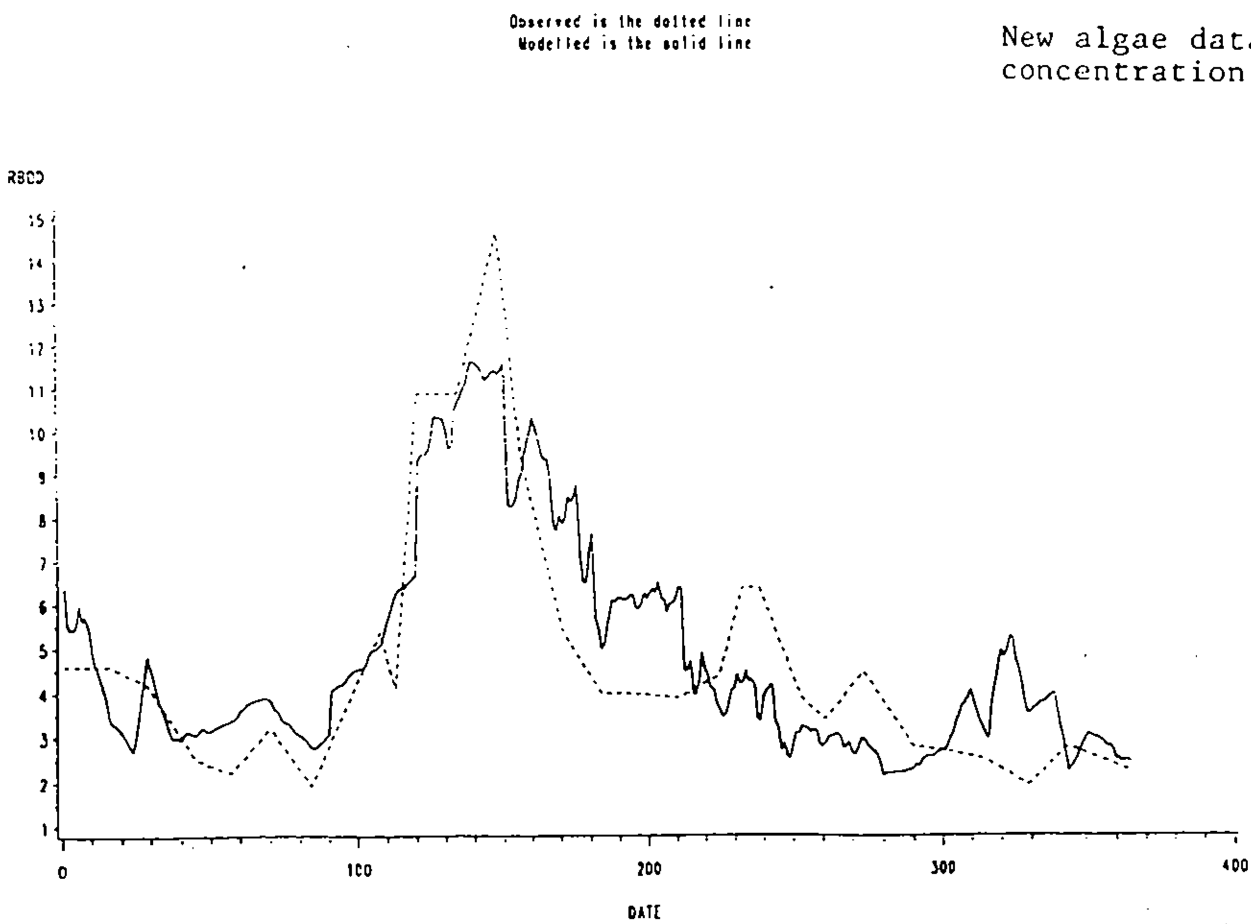
Initial algae data, no concentration



Days 1974 BOD

Figure B.11

New algae data, full concentration

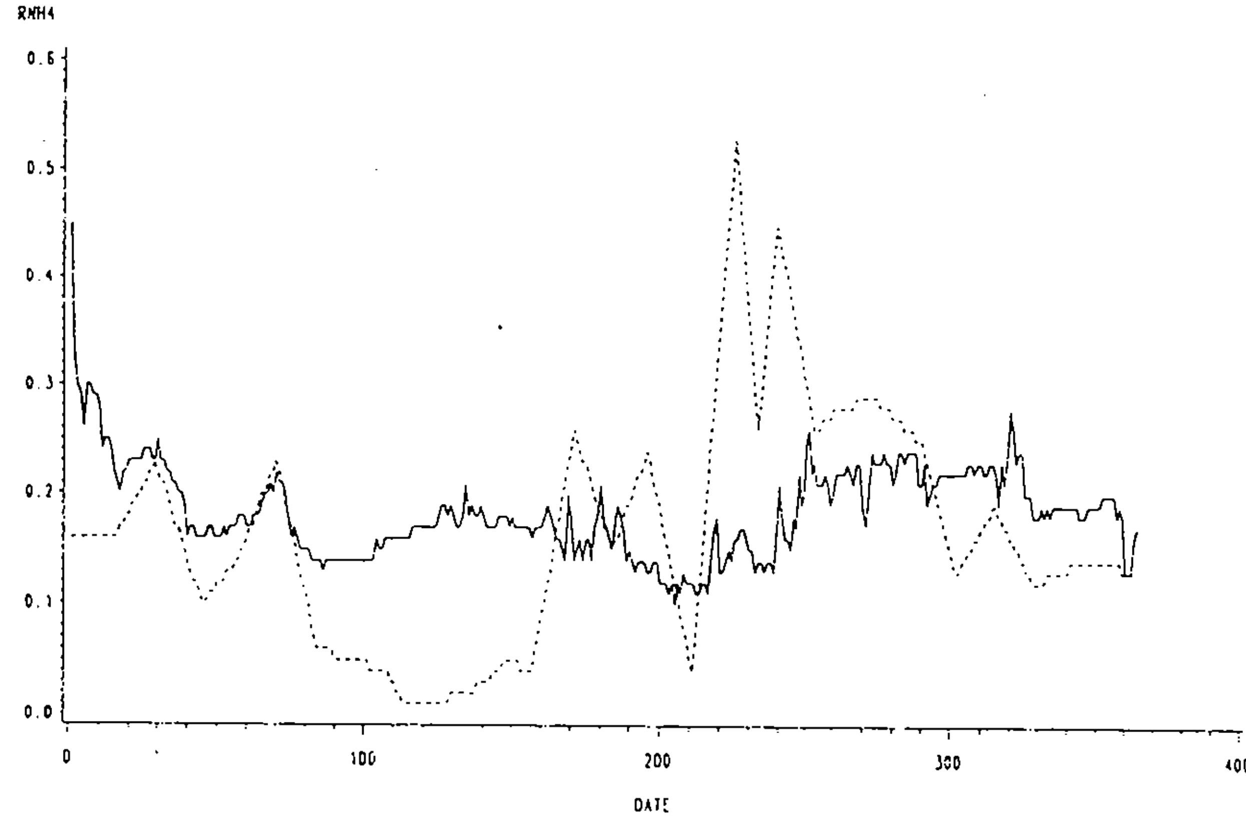


Days 1974 NH4

Observed is the dotted line
Modelled is the solid line

Figure B.12

Initial algae data, no concentration



Days 1974 NH4

Observed is the dotted line
Modelled is the solid line

Figure B.13

New algae data, full concentration

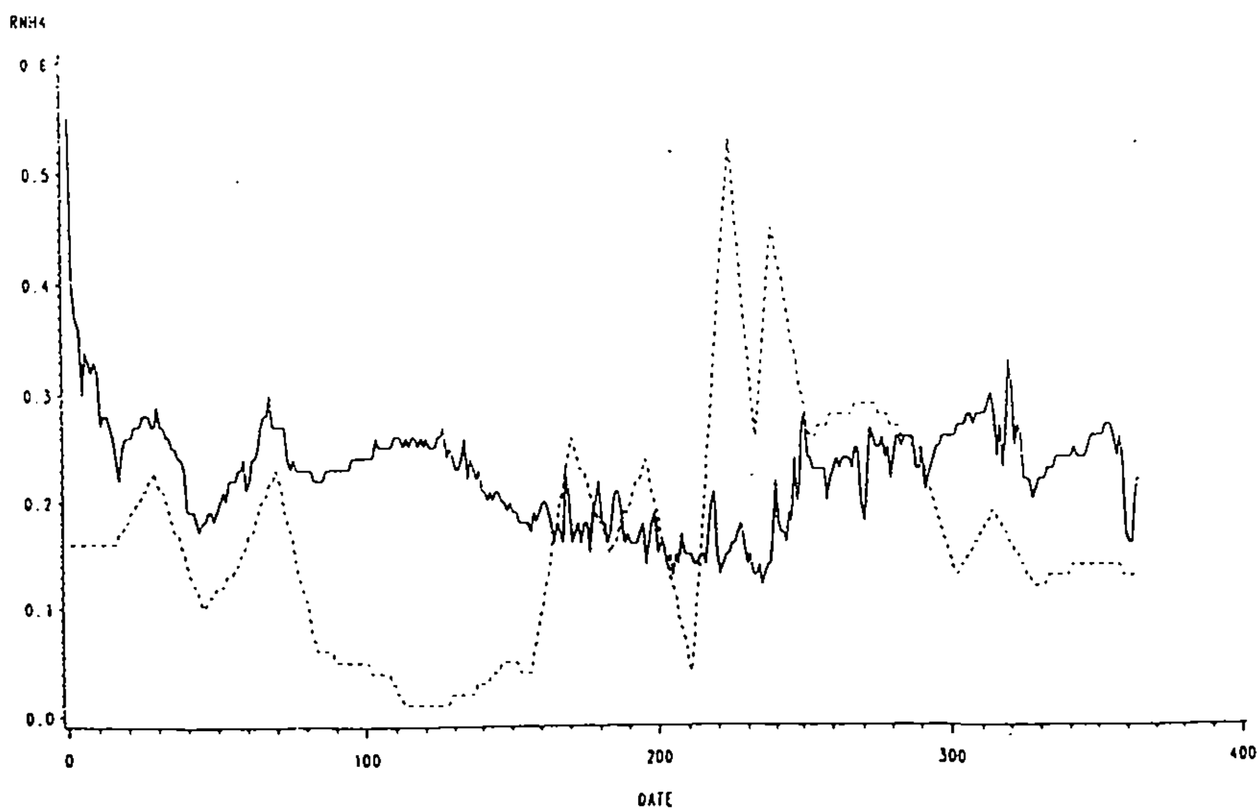


Figure B.14

Initial algae data, no concentration

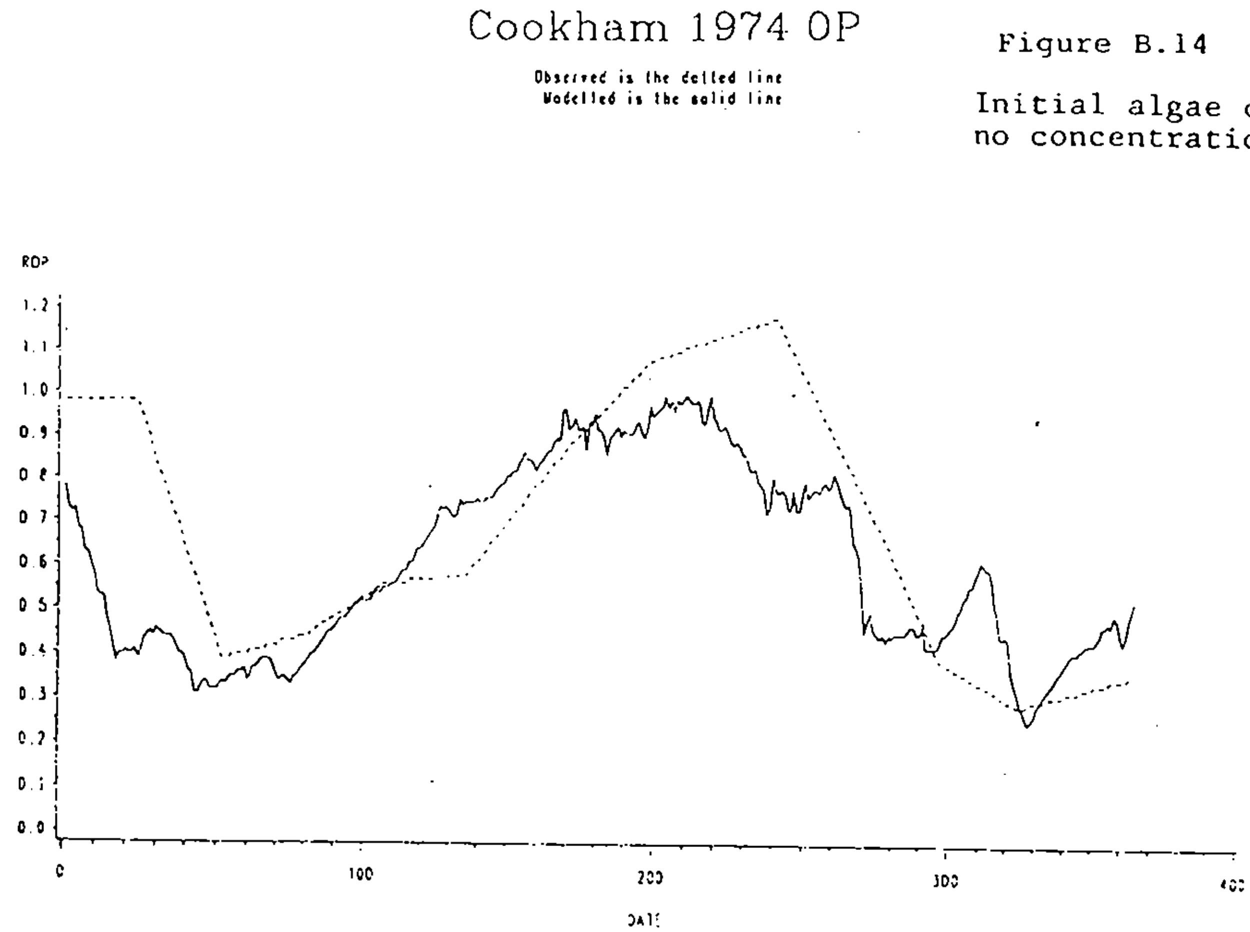
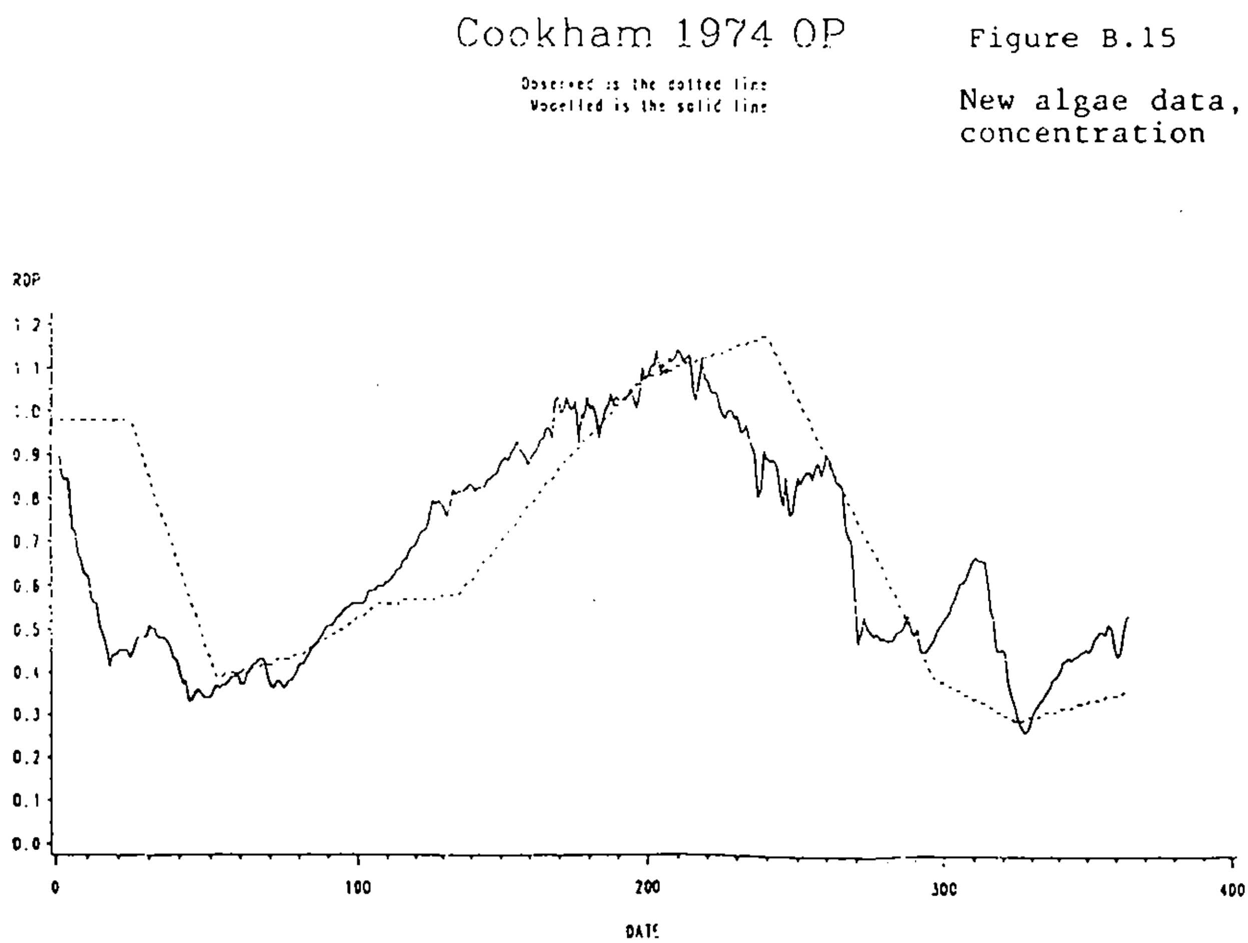


Figure B.15

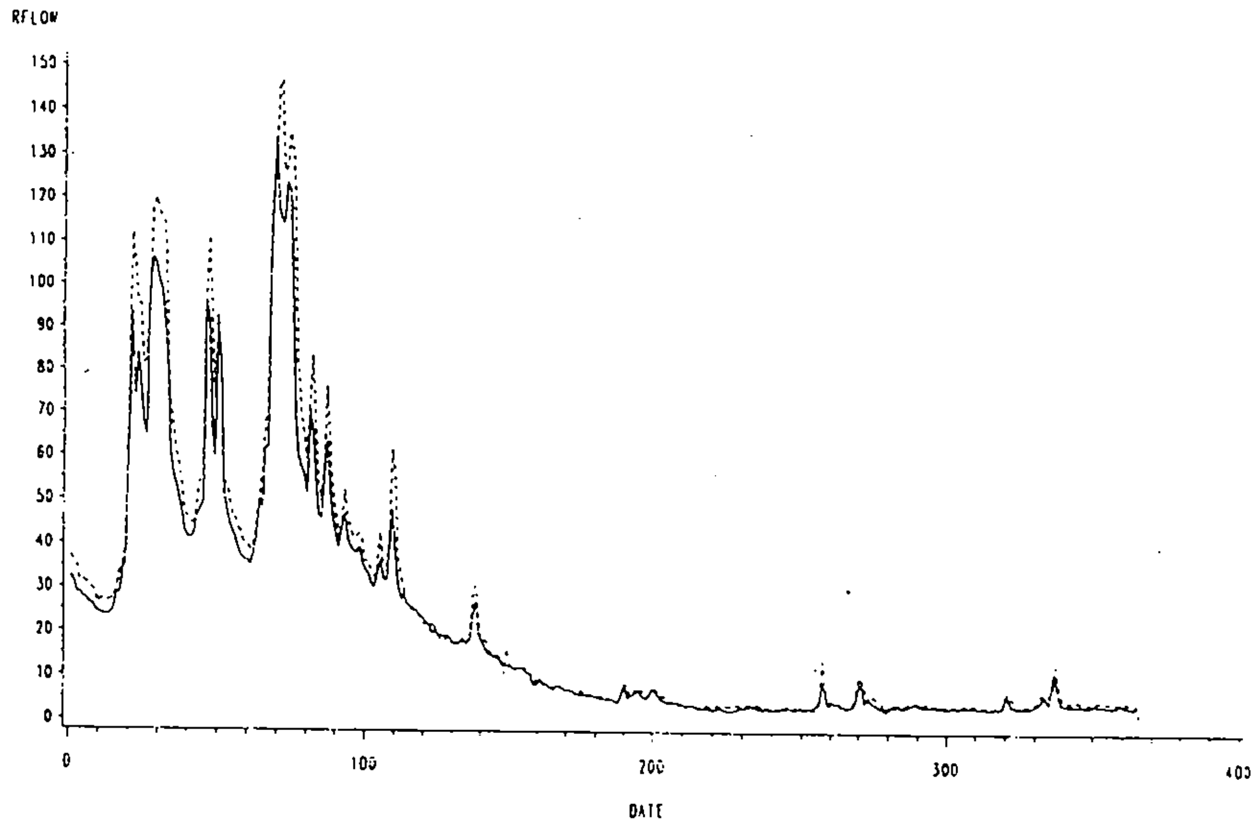
New algae data, full concentration



Days 1975 Flow

Observed is the dotted line
Modelled is the solid line

Figure B.16



Days 1975 TEMP

Observed is the dotted line
Modelled is the solid line

Figure B.17

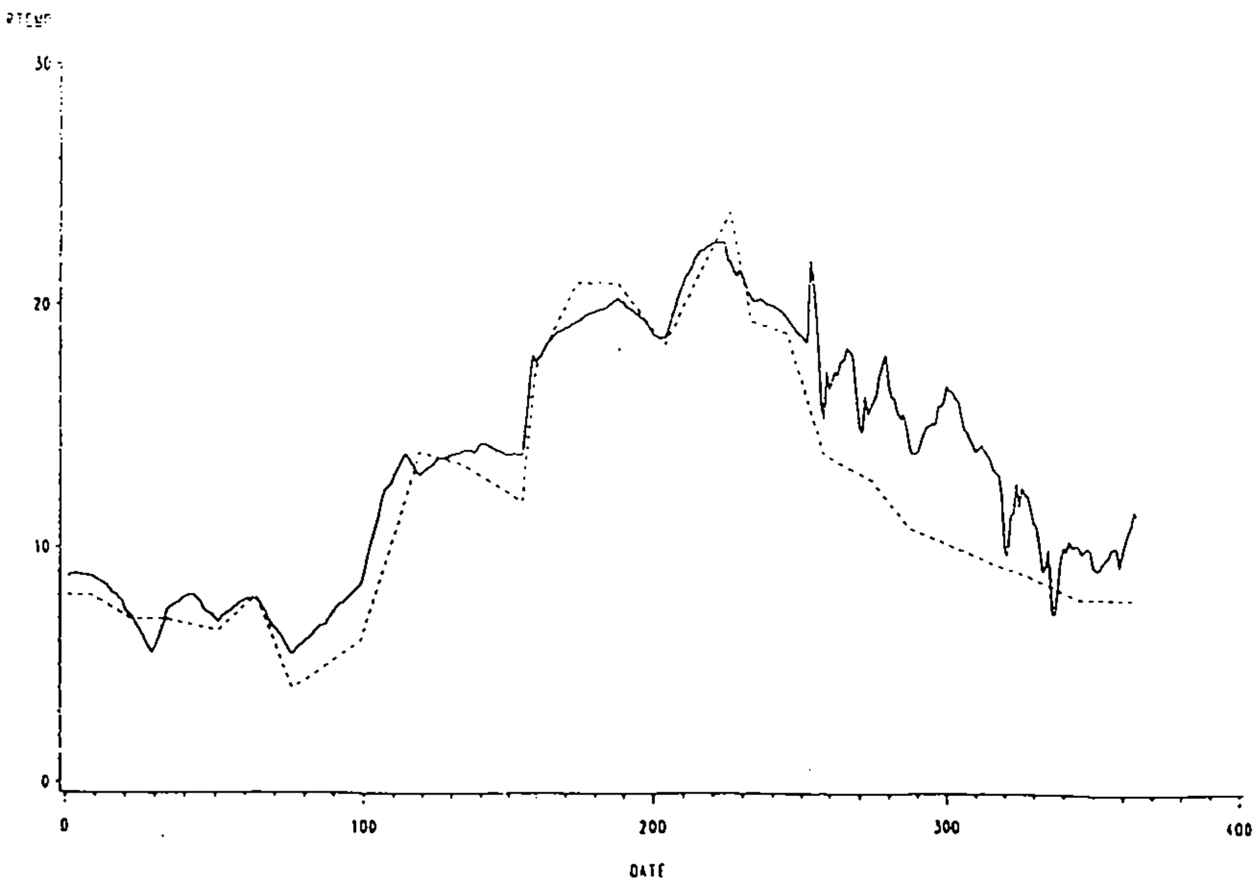


Figure B.18
Initial algae data, no concentration

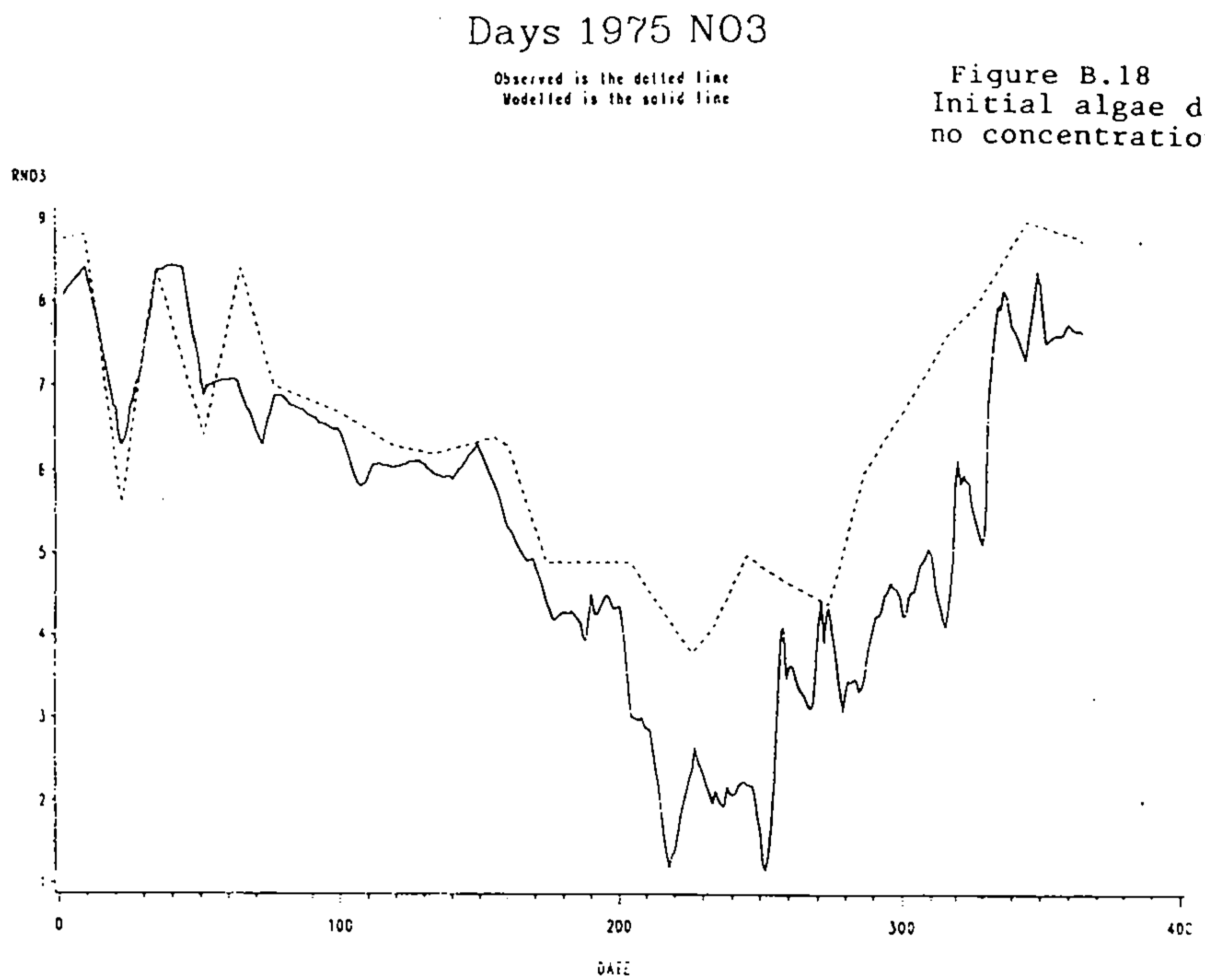
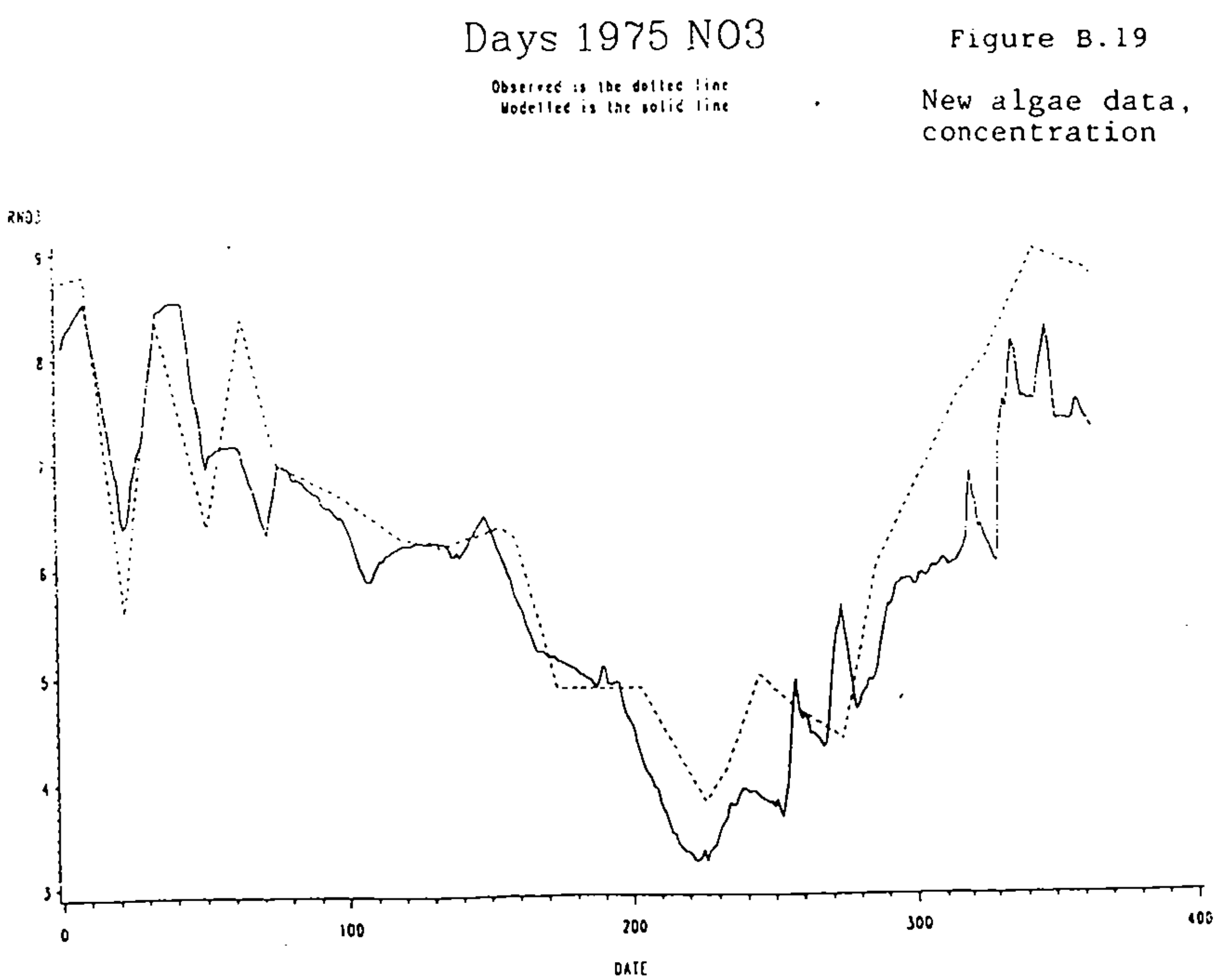


Figure B.19

New algae data, full concentration

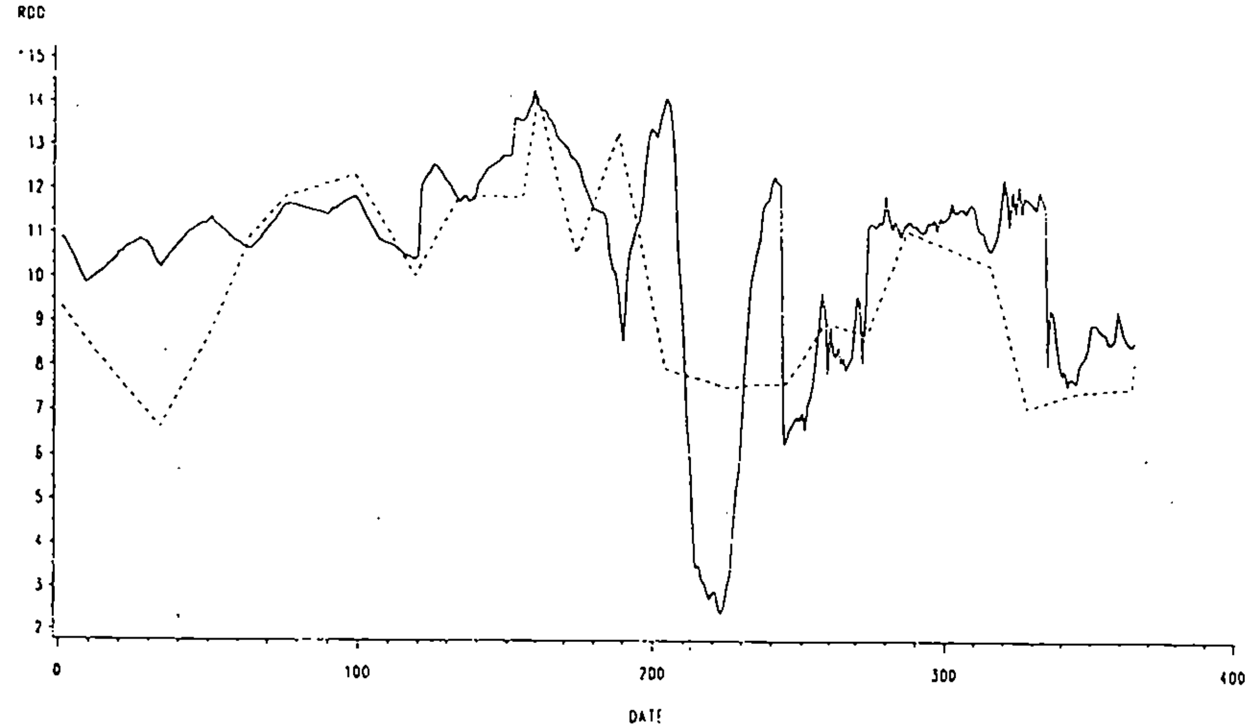


Days 1975 DO

Observed is the dotted line
Modelled is the solid line

Figure B.20

Initial algae data, no concentration



Days 1975 DO

Observed is the dotted line
Modelled is the solid line

Figure B.21

New algae data, full concentration

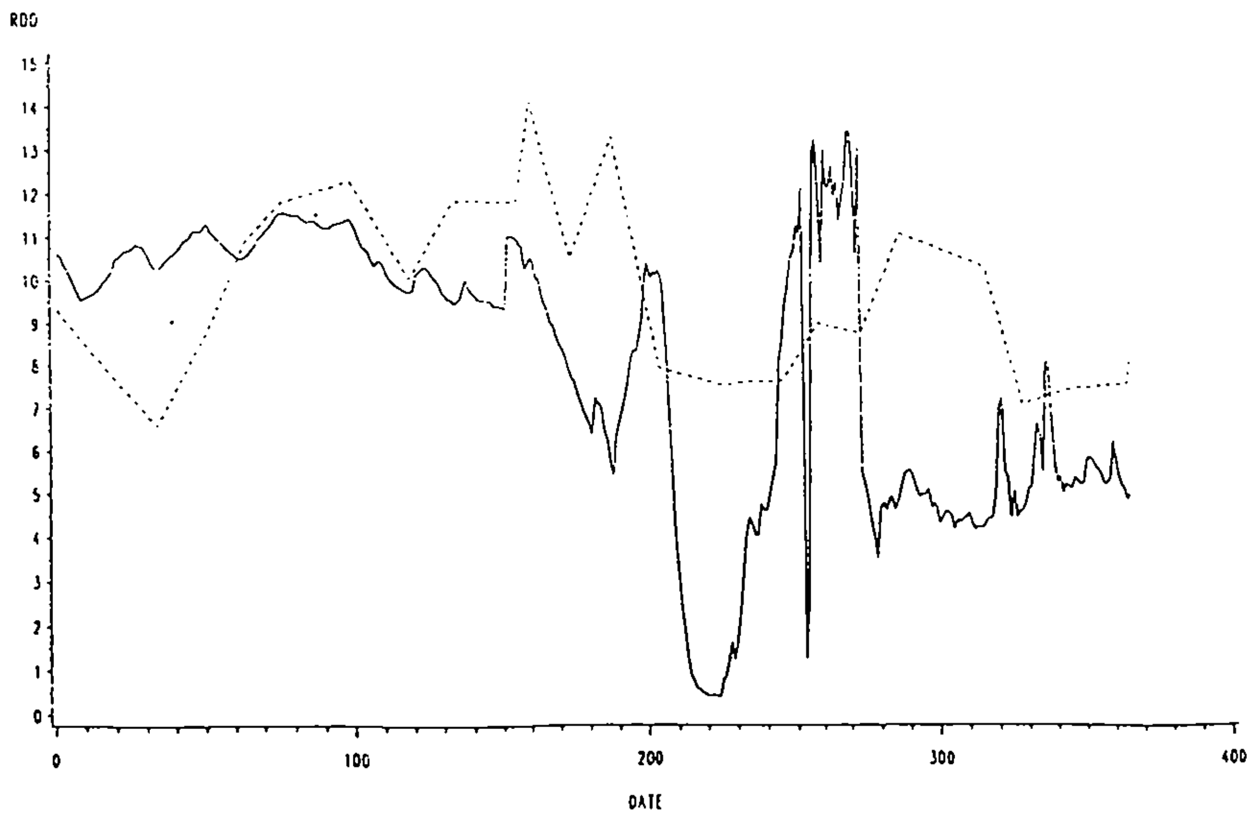


Figure B.22

Initial algae data, no concentration

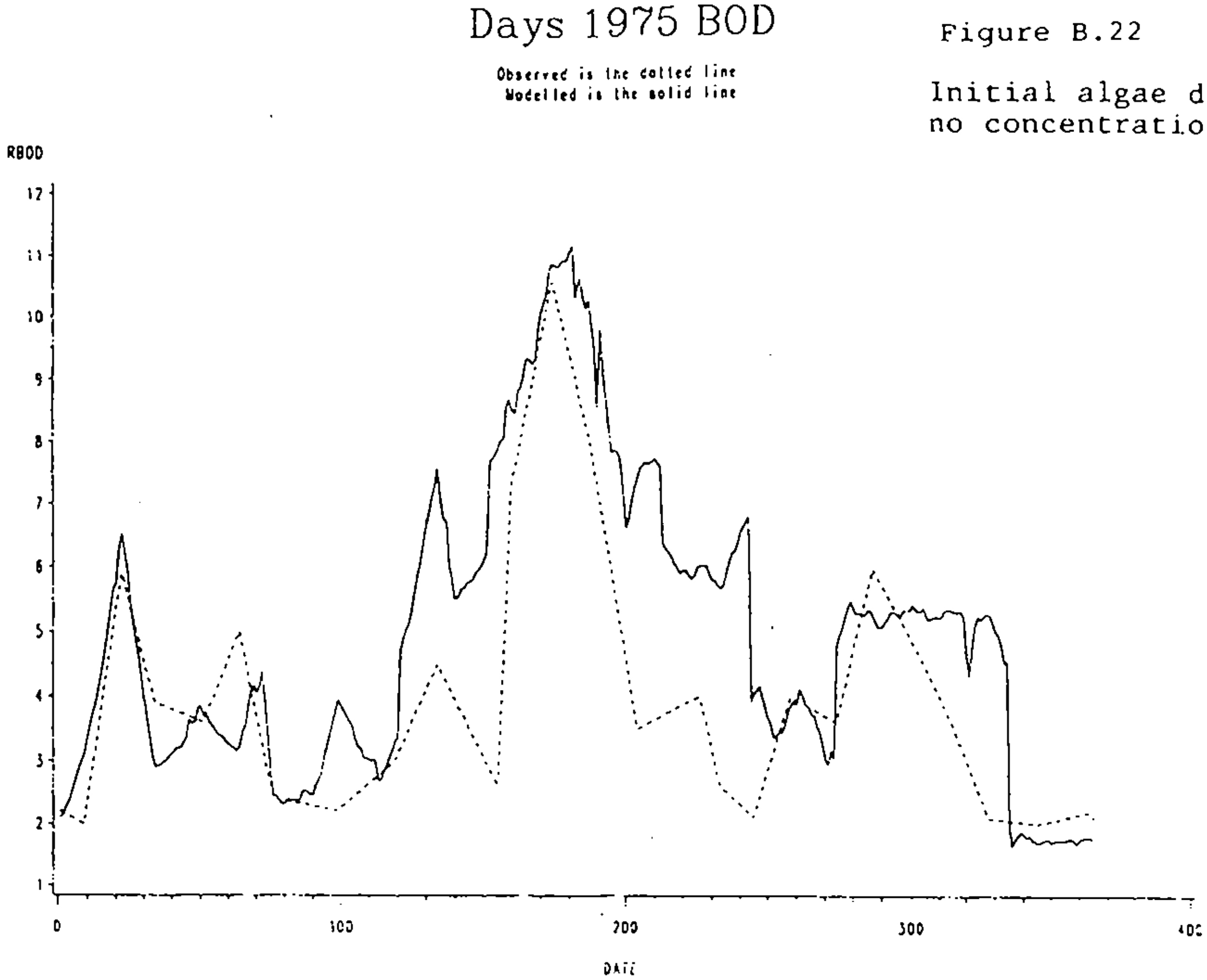
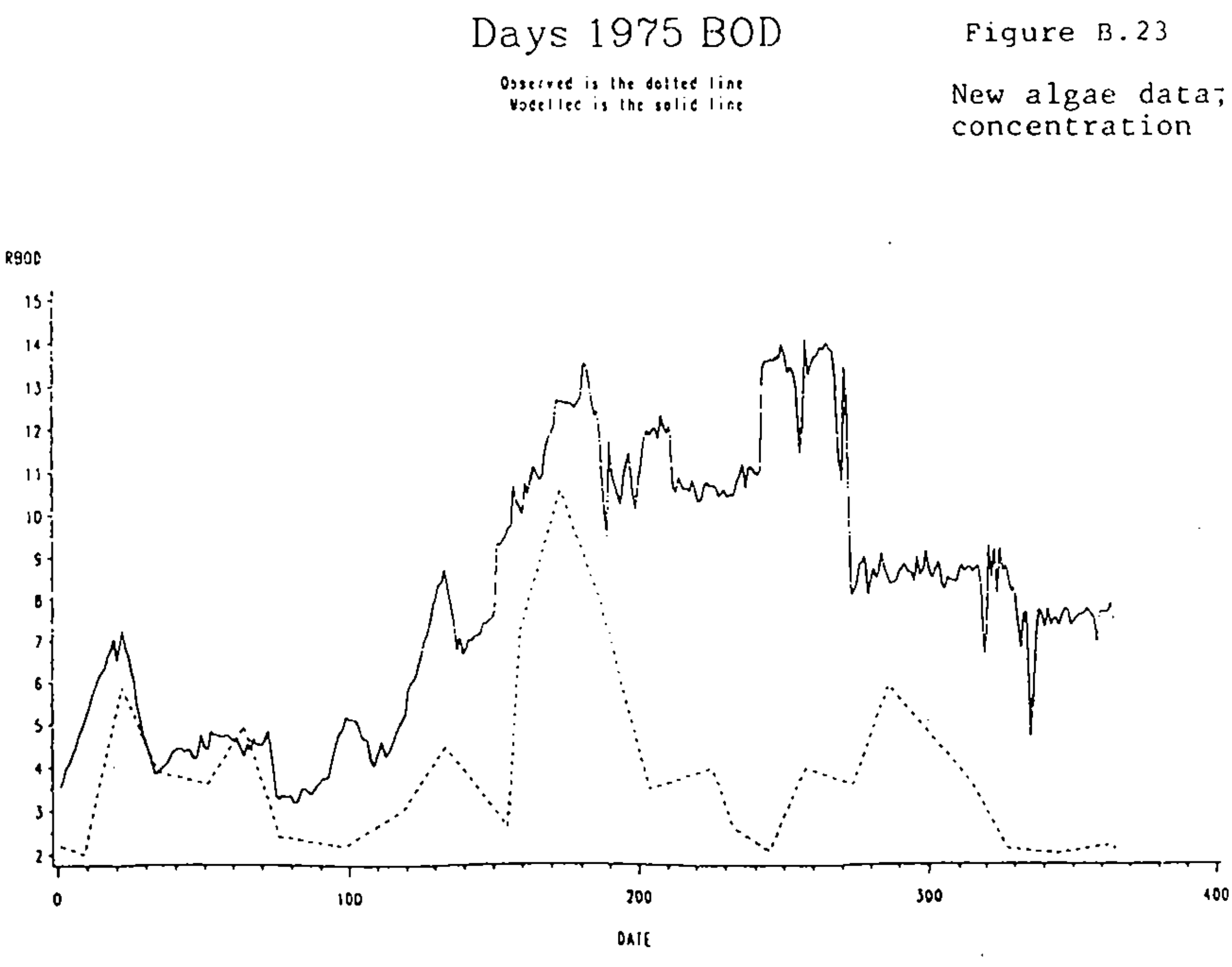


Figure B.23

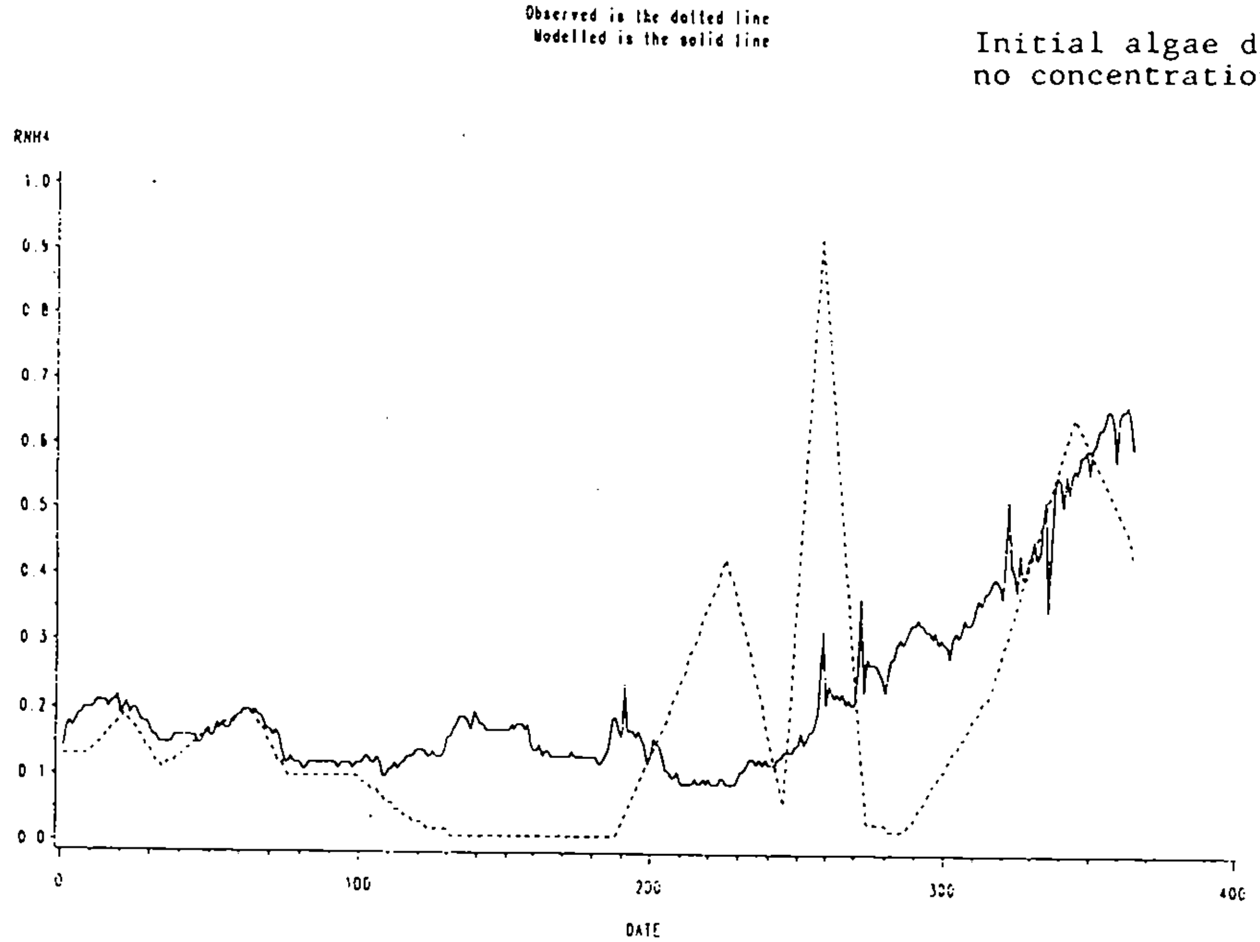
New algae data; full concentration



Days 1975 NH4

Figure B.24

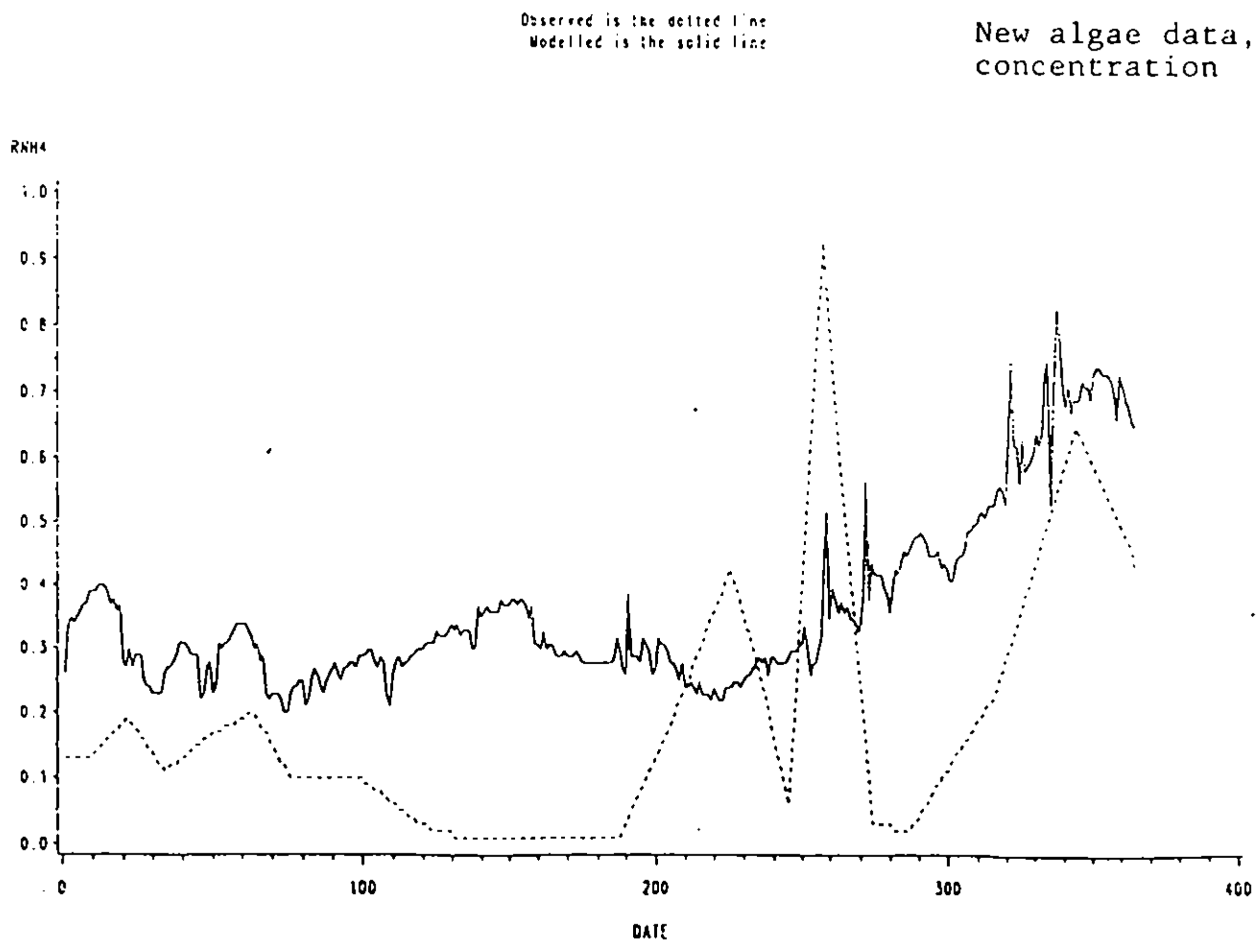
Initial algae data, no concentration



Days 1975 NH4

Figure B.25

New algae data, full concentration

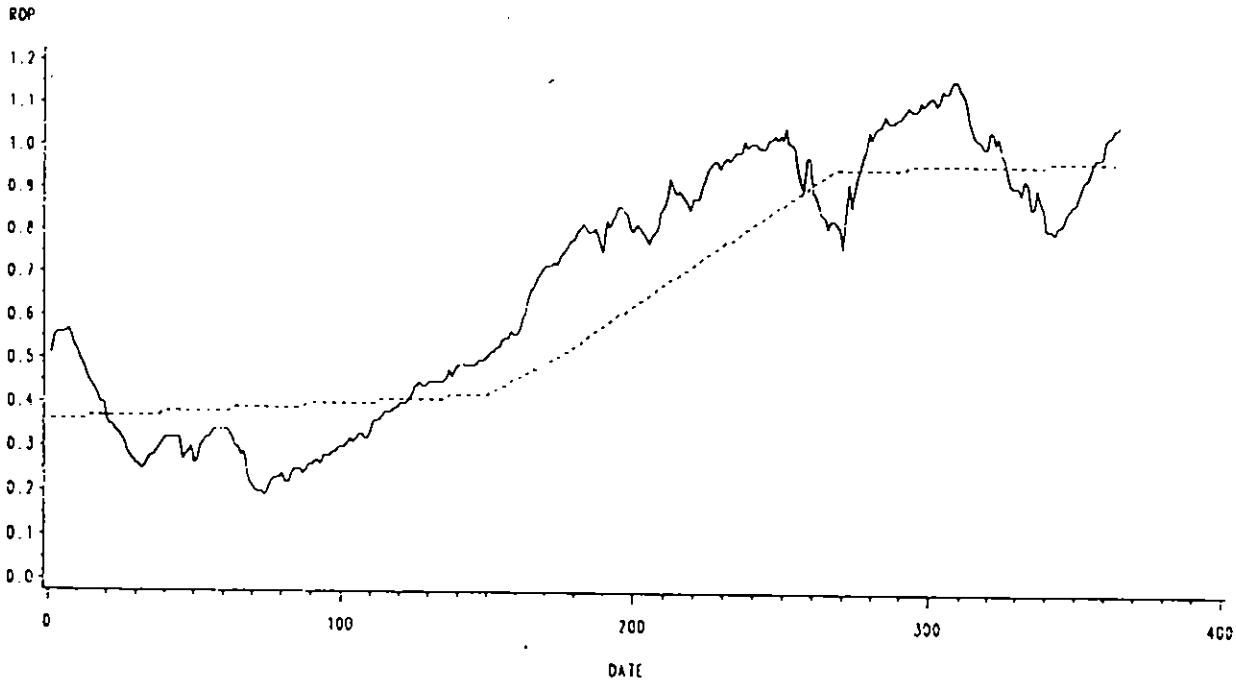


Cookham 1975 OP

Observed is the dotted line
Modelled is the solid line.

Figure B.26

Initial algae data, no concentration



Cookham 1975 OP

Observed is the dotted line
Modelled is the solid line

Figure B.27

New algae data, full concentration