Phosphorus in the Thames Catchment

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1. Introduction

In 1994 the River Thames between Day's Lock and Teddington Lock was designated a Sensitive Area under the Urban Waste Water Treatment Directive 91/271/EEC (UWWTD). Article 5 of the Directive requires phosphorus limits to be set on qualifying discharges (sewage treatment works with a population equivalent (PE) exceeding 10,000) unless it can be shown that phosphorus removal will have no effect on eutrophication. In May 1994 the DoE requested the NRA to carry out a catchment study of the Thames to determine whether phosphorus removal would have an effect on eutrophication, and to identify works where it would have the most impact.

The report summarizes a study of the various sources of phosphate in the Thames catchment, and includes predictions of phosphate concentrations that would arise if phosphate stripping was introduced at sewage treatment works (STWs) exceeding 10,000PE. It was not our intention to predict the effects reduced phosphate concentrations would have on eutrophication, ie plant and algae growth, although we do discuss this difficult subject.

To predict river phosphate concentrations a river quality model, TOMCAT, was set up for the entire Thames catchment. TOMCAT is usually used to model carbon, nitrogen and oxygen chemistry in small to medium sized catchments, but can be adapted for other purposes. Section 2 of this report therefore gives a brief overview of phosphorus chemistry in rivers, and identifies general sources of phosphorus in catchments.

Section 3 describes the Thames catchment and looks at phosphorus data in the river Thames, the various sources and their relative contributions. It includes a discussion of algae in the Thames. The section concludes with a simple mass balance estimate of phosphate concentrations, incorporating both agricultural load and river loss. This estimate is useful for comparison with the answers from the more complicated TOMCAT model, which would be expected to be more accurate, but at the same time is prone to calibration difficulties.

Section 4 describes the TOMCAT model, its limitations for modelling phosphate and the simplifying assumptions that have been used to model such a large catchment. Results are included along with recommendations for further modelling work.

Section 5 contains conclusions and recommendations.

2. Phosphorus - General

2.1 Measurement.

Phosphorus in river water exists in one of three chemical fractions: condensed inorganic phosphorus, orthophosphate, and organic phosphorus. Organic phosphorus can be further divided into living and non-living components. The three chemical fractions exist in two physical phases: dissolved (or soluble) and particulate. The dissolved orthophosphate is considered to be the bio-available component of the phosphorus, and is therefore the most important component when discussing eutrophication. Reactive phosphorus consists of orthophosphate and some of the condensed inorganic and organic fractions. This information is summarized in Table 2.1 below.

	Condensed Inorganic Phosphorus	Orthophosphate	Organic Phosphorus	
Dissolved		Bio-available	Dead	
Particulate			Dead	Living

<— Reactive —>

Table 2.1: Aqueous phosphorus species

Orthophosphate is not usually measured directly. Instead reactive phosphorus measurements are used, although this will include other species of phosphorus besides PO_4.

2.2 Sources of River Phosphorus

2.2.1 Natural

Phosphorus occurs naturally in rocks, mainly as the mineral apatite which is a calcium phosphate of variable composition. This form of phosphorus is highly insoluble and the conversion to other forms of inorganic phosphate by weathering and erosion is a slow process, Gymer R.H.(1973). In view of this, the contribution of mineral phosphorus to river concentrations is likely to be extremely small, compared with the man-made production of detergents and fertilizer. Figure 2.1 shows a schematic of the phosphorus cycle in the environment. Phosphorus passes relatively rapidly through river systems to the sea, with residence times of the order of a few weeks or years,, White et al (1992). The return of phosphorus from marine sediment to phosphate rock takes place on geological timescales.

2.2.2 Sewage Treatment Works

An analysis of data from Thames Water Utilities STWs shows that orthophosphate concentrations discharged from STWs averages about 7mg/l (See Section 3.2). There are two principal sources of phosphorus in STW effluent, detergents and metabolic waste products. Work on the Rapid City STW, Harms et al (1978), showed that approximately 82% of the effluent total phosphorus was in the dissolved reactive phosphorus form. They considered this dissolved reactive phosphorus to originate mainly from detergent use, whilst the remainder, the particulate phosphorus, to be mainly due to suspended organic matter. This figure may be too high for UK effluent where about 25% to 40% of the orthophosphate is thought to originate from detergents (Peter Bird, Personal Communication).

2.2.3 Agriculture

Phosphorus is applied to agricultural land in manure and fertilizer. Soluble salts of phosphorus are usually used, such as ammonium phosphate. Church (1981) estimated fertilizer usage for mixed crops to be 28 kgP/ha/year in 1980. The phosphorus quickly becomes bound to the soil matter either through sorption or by forming insoluble precipitates. This reduces the amount of soluble phosphorus run off, though phosphorus is still exported in the particulate form.

A theoretical study of phosphorus loading to an Italian catchment, Marchetti and Verna (1992), estimated 3% of applied phosphorus ends up in the watercourse while plot experiments conducted in America, Klaine et al (1988) showed that a minimum of 2% of applied phosphorus was exported. This work also found that orthophosphate accounted for approximately 7% of the total phosphorus exported from the field, though the experimental plot did experience a high soil loss.

Combining the American figures with those of Church (1981) suggests the total phosphorus entering a river from agricultural sources would be 0.6 kg/ha/year, of which 0.04 kg/ha/year would be orthophosphate. This ties in with values for agricultural phosphorus runoff quoted in SCOPE (1989): 0.2 - 1.2 kg/ha/year total phosphorus, and 0.08 - 0.46 kg/ha/year orthophosphate, although it can be seen that there is considerable variation.

The Ministry of Agriculture, Food, and Fisheries is currently sponsoring research into phosphorus loss from agriculture. Results from various studies so far point to extremely variable losses of phosphorus from agricultural land. Many of the studies are on plots which show that results are heavily site dependant, and much of the work is focused on losses during rainfall events when very heavy losses (18g/ha/hr total phosphorus) have been recorded.

2.2.4 Other sources

Other potential sources of phosphorus include industrial discharges and urban drainage. Thomann and Mueller (1987) quote estimates of urban runoff rates in the USA between 0.1 kgP/ha/year and 10 kgP/ha/year for total phosphorus. The lower end of this range is of the same order as the agricultural runoff quoted above, but the upper end is 10 times larger. Klaine et al (1988) however do not consider urban runoff to be significant.

2.3 Phosphorus in the river

After entering the watercourse phosphorus may interact with either particulate matter, biota or the bed matter. These interactions are summarized in Figure 2.2.

Orthophosphate may become attached to either particulate matter or to the bed sediment, precipitated or be taken up by biota. Condensed phosphate behaves similarly, though before biotic uptake it is usually hydrolysed to orthophosphate. Particulate inorganic phosphorus may settle to the bed or return into solution.

Non-living organic phosphorus will either settle to the bed and/or decay to inorganic phosphorus. Phosphorus may be taken up into the living organic form either via the sediment by attached plants or from the water column by phytoplankton. Brown and Barnwell (1987) estimate the phosphorus content of phytoplankton between 0.1-2.0 mg for every mg of chlorophyll-a.

Fox, Malati and Perry (1989) attribute sorption and desorption rates from river sediment to a number of factors, including temperature, oxygen concentration, pH, and rock type. Removal of phosphorus from bed sediment is increased during scouring events. This leads to increases in both total phosphorus and orthophosphate in the water column. This is particularly so downstream of sewage treatment works where phosphorus tends to accumulate in the sediment, Gymer (1973).

3. The Thames Catchment

The River Thames flows for 240 km from its source in Gloucestershire to Teddington (tidal limit) in West London. Only 126 km are designated as a Eutrophic Sensitive Area, from Day's Lock to Teddington. However, since the Eutrophic Sensitive Area includes the downstream boundary of the catchment, Teddington, all sources of phosphorus in the freshwater catchment will affect the Sensitive Area and need to be considered.

3.1 Measurement

Thames NRA routinely carry out two phosphorus measurements, orthophosphate and total phosphorus. The orthophosphate test measure reactive phosphate, see Section 2.1. Both tests measure dissolved and particulate phosphorus. Orthophosphate measurements are made during routine river monitoring, and from STW effluent. Total phosphorus is only measured at key river sites and provides less data. Appendix 1 gives a regression analysis of orthophosphate against total phosphorus at four sites (Farmoor, Day's, Caversham, and Teddington) on the River Thames. These sites are situated downstream of 4, 13, 19, and 67 STWs exceeding 10,000PE respectively. The analysis shows that orthophosphate makes up between 80% and 90% of the total phosphorus at these sites.

3.2 Phosphorus Sources

3.2.1 Sewage treatment works

There are 67 STWs in the freshwater Thames catchment with a population equivalent of 10,000 or more, which qualify under the UWWTD for nutrient removal, unless it can be shown that phosphorus removal will have no effect on eutrophication. Of these 67 STWs, 4 discharge directly into the River Thames (Cassington, Abingdon, Little Marlow, and Windsor), 14 discharge into small watercourses or rivers that join the River Thames within 5 km of the discharge, and the remaining 49 discharge further up the tributaries. Sixty-six of these works are owned by Thames Water Utilities Limited (TWUL), and one, Aldershot Military is owned by the Crown. These works are listed in Table 3.1 and shown in the map (Figure 3.1). The contribution from a further 240 smaller STWs was included in this study.

Most STWs are sampled by the NRA monthly for orthophosphate. Mean orthophosphate for 1991-1993 from the 67 STWs exceeding 10,000PE is included in Table 3.1. Values range between 3 mgP/l and 15 mgP/l with an average of about 7 mgP/l.

TWUL measure flows at about 80 of their 400 STWs. At present they are only required to provide the NRA with flow returns at 8 of them, although this figure will increase as consents are reviewed. An analysis of flow and orthophosphate data was carried out at 3 STWs where flow data was available. No significant relationship was found between flow and concentration, nor any seasonal differences. The loads appeared to follow an approximately normal distribution. Details are given in Appendix 2. Consents usually state the maximum flow that can be discharged from a STW, although some consents state flows as dry weather flows (DWF). Due to the lack of measurements, estimates of average STW flows were calculated from consented flows in this study. Average flows were assumed to

Table 3.1 : STW's in the Thames Catchment

STW	PE	Flow (Max)	Average Orthophosphate 1991 – 1995 mg/l	(kg/day)	Sum(kg/d)
MAPLE LODGE STW	482508	390000	6.38	1037	1037
READING STW	281500	177275	5.99	443	1480
SLOUGH STW	226402	116480	5.10	248	1728
HOGSMILL VALLEY STW	181909	86400	6.56	236	1964
OXFORD STW	167420	90000	5.59	210	2174
SWINDON STW	157010	132900	6.05	335	2508
CRAWLEY STW	150000	49392	7.75	159	2668
ESHER STW	105300	105600	5.86	258	2926
BLACKBIRDS STW :ALDENHAM	100706	122000	6.44	327	3253
BRACKNELL STW	97500	50114	8.46	177	3430
BASINGSTOKE STW	93600	65000	6.22	168	3598
BANBURY STW	88400	46800	6.21	121	3719
AYLESBURY STW	87000	80325	4.96	166	3885
HIGH WYCOMBE STW	84294	94636	4.84	191	4076
LITTLE MARLOW STW	81758	120900	5.55	279	4355
GUILDFORD STW	74250	67190	5.58	156	4512
CHERTSEY STW	74100	67500	8.27	232	4744
WARGRAVE STW	70550	90000	8.56	321	5065
MAIDENHEAD STW	61000	60000	7.19	180	5245
WOKING STW	58750	80000	6.22	207	5452
NEWBURY STW	57000	63000	4.02	106	5558
CAMBERLEY STW	55500	88800	5.26	195	5752
SANDHURST STW	47200	39000	7.76	126	5878
REIGATE STW	47000	118500	8.07	399	6277
LEATHERHEAD STW	40000	42650	4.30	76	6354
FARNHAM STW	37050	39900	7.27	121	6474
WINDSOR STW	35000	30500	6.49	83	6557
ABINGDON STW	34500	30000	6.69	84	6641
ABINGDON STW (TO THAMES)	34500	10500	5.75	25	6666
BORDON STW	33700	18900	9.19	72	6738
ALTON STW	32000	33909	4.01	57	6795
ALDERSHOT TOWN NORTH STW	31800	29700	6.34	78	6873
BICESTER STW	31300	27000	4.59	52	6925
FLEET STW	31000	23700	7.99	79	7004
DIDCOT STW	30000	15000	4.66	29	7033
GODALMING	28000	15910	7.69	51	7084
CHESHAM STW	29493	43350	6.64	120	7204
HOCKFORD STW :PIRBRIGHT	28000	18823	6.34	50	7253
WANTAGE STW	26000	18750	7.08	55	7309
WITNEY STW	26000	19200	5.08	41	7349
ASCOT STW	25500	23000	7.03	67	7417
WISLEY STW	25450	13500	7.29	41	7458
ASH RIDGE STW :WOKINGHAM	25100	18000	8.87	67	7524
HORLEY STW	24600	19500	6.56	53	7578
ASH VALE STW	24100	16500	2.19	15	7593
CHOLSEY	22900	9600	9.73	39	7632
DORKING STW	22000	18000	6.75	51	7682
CIRENCESTER STW	22000	40000	3.50	58	7741
BERKHAMSTED STW	21783	13636	5.35	30	7771
CASSINGTON STW	17000	12000	5.94	30	7801
LIGHTWATER STW	16650	15600	6.52	42	7843
RIPLEY STW	16400	13000	4.96	27	7870
ARBORFIELD STW	15800	10500	6.65	29	7899
SILCHESTER STW	15600	24000	4.99	50	7949
CARTERTON STW	15450	8700	7.63	28	7976
PRINCES RISBOROUGH STW	15000	11700	6.36	31	8007
WEYBRIDGE STW	14850	30909	9.03	116	8124
HENLEY STW	14100	8850	7.84	29	8153
CRANLEIGH STW	13000	13620	7.80	44	8197
HASLEMERE STW	13000	10837	6.90	31	8228
HARTLEY WINTNEY STW	12900	20500	7.00	60	8288
BURNHAM STW	12406	12273	7.74	40	8327
KIDLINGTON STW	12000	12600	6.50	34	8361
TRING STW	11500	9500	6.27	25	8386
THAME STW	11500	7495	8.10	25	8412
PANGBOURNE STW	10500	7000	9.36	27	8439
110 STWS	1000–10000			1009	9448
131 STWS	>1000			142	9590
TOTAL LOAD					9590

Note loads calculated using consented flow be 1.25 times the DWF, or 0.417 times the maximum flow (standard rules of thumb used by the water industry). Maximum flows (consented or calculated from consented DWF) for the 67 STWs exceeding 10,000PE are given in Table 3.1. A substantial proportion of the flow in the Thames comes from sewage works: the estimated average flow from the 368 STWs upstream of Teddington is 1.5 million cubic metres per day, compared to an average flow over Teddington Weir of about 4 million cubic metres per day (Table 3.4).

Orthophosphate loads were calculated at 300 STWs using average flows estimated from consented flows and measured quality data. Figure 3.2 shows the cumulative load for the years 1991, 1992 and 1993. The STWs are in order of decreasing population equivalence. There is a considerable decrease in the calculated load between years, from 12 tonnes per day in 1991 to 7 tonnes per day in 1993. This decrease may well be due to a decline in phosphate use in detergents, DoE (1994), but the picture is confused by using estimated flows from consents in the calculation: 1991 was a dryer year than 1993, so STW flow would be less than in 1993, but consented flows do not account for this. Hence the difference in loads is likely to be less than that shown.

Figure 3.3 is similar to Figure 3.2 but shows calculated loads averaged over the period 1991-1993. The contribution made by the 67 STWs exceeding 10,000PE and the 110 works with PE between 1000 and 10000 is marked on Figure 3.3. This assumes that there is no loss of phoshorus loads in the tributaries. Approximately 88% of the total STW orthophosphate load originates from the 67 STWs exceeding 10,000PE with another 11% originating from works with PE between 1000 and 10,000. The remaining 131 works contribute just 1%. Average loads for the 67 STWs exceeding 10,000PE are also included in Table 3.1. It can be seen that 1 tonne per day, almost 11% of the total, comes from the largest works, Maple Lodge.

3.2.2 Agriculture

Estimates of agricultural load in the Thames catchment were made using sites upstream of any STW's (see Appendix 3). Orthophosphate measurements at these sites are usually at the limit of detection (0.07mg/l) which indicates a low agricultural loading. Estimates for this loading vary between 0.01 kgP/ha/year - 0.56 kgP/ha/year for orthophosphate, which ties in with literature values (see Section 2.2.2). The mean estimate based on the Thames data is 0.32kgP/ha/year. Table 3.2 gives a list of river sampling points and shows the catchment areas above each one. Agricultural loads above each point are calculated assuming that the whole catchment is agricultural and an average agricultural contribution of 0.25 kgP/ha/year. This figure is a low estimate of agricultural contribution from the literature discussed in Section(2.2.2). Based on these estimates, the agricultural load above Teddington is 680 kgP/day, compared to the STW load of 9590 kgP/day, ie 7% of the total. If the upper figure of 0.56 kgP/ha/year is used instead, the agricultural load comes out at 13% of the total.

Table 3.2: Thames Agricultural Orthophosphate Load

Sample point	Distance from source (km)	Catchment Area (km^2)	Agricultural Load* (kgP/day)
Buscot Intake	40	990	68
Farmoor Intake	73	1600	110
Day's Lock	116	3390	230
Caversham	151	4510	310
Sunnymeads Intake	208	7180	940
Chertsey Intake	221	8190	560
Walton Intake	231	9290	640
Teddington	242	9950	680

* loads calculated assuming P runoff of 0.25 kgP/ha/year

3.2.3 Other Sources

Other sources, such as industrial discharges and urban runoff have not been included in this study. There are in fact very few industrial discharges in the freshwater Thames catchment. We have no direct urban runoff phosphate data although it may be possible to infer loads by studying the data from an urban catchment (eg Blackwater or Hogsmill) in future.

3.3 Phosphorus in the Thames

Orthophosphate is measured at 33 sampling points on the river Thames, shown in Table 3.3. Total phosphorus is measured at 14 of these sites. Figure 3.4 shows mean orthophosphate concentrations along the river Thames for the years 1991, 1992, 1993. Concentrations in 1991 are over 0.5 mgP/l higher than in 1993. This is partly due to the lower flows in 1991, (see Table 3.4) but may also be caused by higher loads discussed in Section 3.2.1. It is interesting to note that in the upper Thames the 1992 concentrations are similar to the 1993 concentrations, whereas in the lower Thames they are much higher. We have not attempted to explain this phenomenon.

Table 3.3 Thames Phosphate Sampling Points.

SITE	URN	GRID_REF	Dist from source(km)
Somerford Keynes Br	PUTR.0104	SU/01809480	8.0
Waterhay Br Ashton K	PUTR.0108	SU/06009330	13.2
Cricklade	PUTR.0091	SU/10309380	19.5
Eysey	PUTR.0093	SU/11309400	20.5
Castle Eaton	PUTR.0090	SU/14409570	25.7
Hannington Br	PUTR.0096	SU/17509610	30.1
Inglesham	PUTR.0097	SU/20409840	35.1
Buscot Intake	PUTR.0107	SU/22909810	39.5
Newbridge	PUTR.0099	SP/40300140	64.6
Farmoor Intake	PTHR.0113	SP/43900640	73.4
Trout Inn Godstow	PTHR.0110	SP/48300920	82.8
Folly Br Oxford	PTHR.0085	SP/51400550	88.4
Donnington Br	PTHR.0186	SP/52400445	89.9
Radley College	PTHR.0098	SU/53809880	96.2
Culham Intake	PTHR.0112	SU/53109720	98.0
Abingdon Weir	PTHR.0077	SU/50609700	101.0
Day's Lock	PTHR.0083	SU/56809350	115.9
Wallingford Br	PTHR.0111	SU/61008950	124.3
Goring Weir	PTHR.0120	SU/59608080	133.9
Caversham	PTHR.0080	SU/72107420	151.3
Sonning Weir	PTHR.0102	SU/75307560	155.6
Henley Br	PTHR.0088	SU/76358260	166.1
Cookham Bridge	PTHR.0082	SU/89808560	185.9
Boveney	PTHR.0079	SU/94407770	199.6
400m d/s Boveney	PTHR.0065	SU/95507770	200.4
Romney Lock	PTHR.0001	SU/96807750	203.5
Sunnymeads Intake	PTHR.0108	SU/99807590	208.1
NSWC Intake Egham	PTHR.0075	TQ/02257182	214.8
NSWC Intake Chertsey	PTHR.0096	TQ/04906790	220.6
Walton	PTHR.0074	TQ/07506590	225.5
MWD Walton Intake	PTHR.0094	TQ/10506810	230.7
Ravens Ait	PTHR.0076	TQ/17406770	238.2
Teddington	PTHR.0107	TQ/17007130	242.5

Table 3.4 Mean Flows in the Thames (Ml/day).

Station name /	code	1991	1992	1993	1991-1993	91-93 Mar-Oct
Buscot	0900	559	836	799	731	499
Eynsham	1200	744	1280	1318	1114	709
Day's	1900	1351	2685	2700	2246	1454
Windsor	2700	3152	4810	5516	4490	3249
Staines	2900	2576	4287	5632	4177	2966
Teddington	3400	2145	4251	5899	4099	2693

In Figure 3.5 mean concentrations from March to October are compared with all year averages for the period 1991-1993 . The summer concentrations are up to 0.3 mgP/l higher than the yearly averages. In this study we have concentrated on year round effects. However, since plant and algae growth occur in the months March to October, we recommend that future work concentrates on spring/summer/autumn orthophosphate levels.

3.4 Eutrophication in the Thames

Figure 3.6 shows chlorophyll levels in the River Thames during a spring diatom bloom: concentrations rise to over 0.3 mg/l in the Sensitive Area. Other species are also involved, both in this bloom and others in the Thames. Figures 3.7 and 3.8 show time series graphs of chlorophyll in the Lower Thames, just above Teddington. The data is fortnightly so it needs to be interpreted carefully. In Figure 3.7 chlorophyll is compared with orthophosphate. It can be seen that orthophosphate levels are about 0.5 mgP/l during the algae bloom of 1993 and the two blooms in 1994. Figure 3.8 shows that the spring chlorophyll peaks coincide with very low silicate levels. It is likely that the diatom concentrations are currently limited by silicate levels, although they may also be light limited. During the summer algae bloom in 1994 there was a decrease in silicate, but not to a limiting extent.

The effects of reduced phosphate levels on the biological effects from eutrophication in the Thames are beyond the scope of this study, although we briefly raise some issues here. Phosphorus stripping is required under the UWWTD unless it has no effect on eutrophication. In lakes limiting values of phosphorus are low: Reynolds (1984) gives a figure of 0.005-0.01 mgP/l. In rivers, however, limiting values are thought to be higher perhaps between 0.1 mgP/l and 0.3 mgP/l. The Toxic and Persistent Substance Centre (TAPS) of the NRA is researching this. Further information is expected to come from a Department of the Environment study into the effects of phosphorus stripping on water quality and river biology downstream of STWs. Within the Thames catchment phophorus stripping will be introduced at 4 STWs (Aldershot, Aldershot Military, Ash Vale, and Alton) by the end of 1998.

It can be seen in Figure 3.5 that the mean orthophosphate concentrations exceed 0.5 mgP/l in all but the top 20 km of the Thames. Furthermore, during summer (March to October) when plant growth occurs, average concentrations are higher than the annual average.

3.5 Impact of phosphorus removal at STW

3.5.1 Previous work

Thames NRA Water Quality Planning team carried out 4 studies between 1990 and 1993 looking at phosphate in the Thames Region. These studies were to ascertain whether phosphorus removal from STWs would reduce river concentrations to below given thresholds. Some of the studies used EC Directive limits (eg Surface Water Abstraction Directive 0.153 mgP/l, Fish Directive 0.065 and 0.13 mgP/l), others used a limiting concentration of 0.1 mgP/l, which was one of the criteria used to assess eutrophication in the

Government's agreed methodology for assessing eutrophic sensitive areas (DOE/MAFF/WO March 1993). It can be seen from Figure 3.5 that around 90% of summer phosphate needs to be removed to meet these limits at Teddington. The studies concluded that even if phosphorus was removed at STWs, phoshorus concentrations in the River Thames from other sources would probably be sufficient to exceed these thresholds.

3.5.2 Quick Estimate

In this study we are trying to ascertain the effects of phosphorus removal on river concentrations, and to identify sites where the impact will be greatest. To do this we have chosen to use a catchment model, discussed in Section 4. In this section we carry out a quick estimate based on annual averages. This estimate provides a figure for comparison with the model.

To do this we first calculated river loads at a number of sites using flows from gauging stations and measured concentrations. The calculation of river loads can be complicated and is discussed further in Appendix 4. Measured river loads were compared with the upstream inputs, calculated by summing the STW loads and the agricultural loads (Table 3.2). The measured loads were found to be smaller than the inputs, due to loss of orthophosphate in the river system. Decay factors were therefore calculated for each site:

decay factor = total load of upstream inputs / load measured in river

Predicted river loads were then obtained by combining reduced input loads with the decay factors:

predicted river load = (reduced STW loads + agricultural loads) * decay factor

Finally, predicted concentrations were calculated by dividing the river loads by the flows. These are shown in Table 3.5 for 80% and 100% orthophosphate removal at the 67 STWs exceeding 10,000PE (ie assuming 80% and 100% of current orthophosphate discharge is removed. This is not necessarily the same as 80% and 100% reduction in total phosphorus between influent and effluent as required by the Directive, though it is not thought to be significantly different). High and low estimates are included. The table also shows the concentrations that are due to agriculture. They indicate that even if all STW orthophosphate was removed, the concentrations in the river would still be at or above 0.1 mgP/l. Table 3.6 shows predicted concentrations using March to October data which are noticeably higher.

Table 3.5 Predicted orthophosphate concentration (mgP/l) in the Thames after P reduction at the 67 STWs exceeding 10,000PE using 1991-1993 data.

Site	Measured concentrations	Agricultural contribution	80% Removal	100% Removal
Buscot	.65	.05-.16	.21-.37	.14-.27
Farmoor	.50	.05-.14	.16-.27	.11-.21
Day's	.63	.06-.14	.23-.33	.16-.26
Windsor	.96	.05-.15	.28-.42	.17-.28
Staines	1.05	.04-.15	.22-.42	.12-.27
Teddington	1.23	.05-.15	.28-.46	.14-.27

Table 3.6 Predicted summer orthophosphate concentration (mgP/l) in the Thames after P reduction at the 67 STWs exceeding 10,000PE using 1991-1993 Mar - Oct data

Site	Measured concentrations	Agricultural contribution	80% Removal	100% Removal
Buscot	.92	.08-.20	.33-.46	.22-.34
Farmoor	.59	.07-.16	.23-.32	.16-.25
Day's	.73	.07-.17	.28-.39	.20-.30
Windsor	1.11	-.18	-.49	-.33
Staines	1.22	.05-.17	.27-.49	.16-.30
Teddington	1.40	.06-.17	.33-.52	.16-.30

Note: Low estimates are calculated using low estimate for river load and low estimate for agricultural load. High estimates are calculated using 'mean' load and high estimate for agricultural load. See Appendix 4 for details.

4. TOMCAT model of Thames Catchment

TOMCAT is a river quality model, normally used for calculating consent conditions. The accompanying leaflet (Appendix 6) explains how it works. It was used in this study, without modification, to model phosphate. There are several advantages of using a catchment model. It is more accurate than the mass balance estimates used in Section 3. It can be used with various levels of sophistication: starting with crude estimates the model can be refined where necessary. Once set up, it is easy to run different scenarios and pinpoint the effect of individual sewage works at different points in the catchment. This section highlights the assumptions involved in using TOMCAT to model phosphate, and recommends possible improvements.

4.1 Modelling phosphorus chemistry

The phosphorus cycle in rivers is a complex process, involving plant growth and water - sediment interactions. In spring and summer, orthophosphate is lost by conversion to organic phosphate in fixed plants and floating phytoplankton. Some of this phosphate will be removed altogether from the river system by grazing of plants by land animals or when the phytoplankton are carried into the estuary. However, much of the organic phosphate will stay in the river, sinking to the bed when the plants and phytoplankton die. This organic material will decay and the phosphate will become available again when the sediments are stirred up by high flows. Thus, in spring and summer there will removal of orthophosphate from the water, but in winter there may well be an addition of orthophosphate. Over time these two terms should balance, unless there is either build up of phosphate in the sediments, or a large amount of phosphate is exported from the river as plant matter.

We have not tried to model these processes in detail. Instead, we have decided to model just one of the phosphorus species, orthophosphate. We have assumed it decays exponentially in the river. The actual rate of decay will vary from river to river depending on, for example, the amount of shading and type of plants present. The advantage of this simple approach is that TOMCAT already uses exponential decay, and that the model is easier to calibrate than a more sophisticated approach. At this stage we have only looked at annual concentrations. In view of the seasonal nature of phosphate decay, discussed above, it would make sense to look at summer and winter phosphates separately. This has not been done here, but it is strongly recommended that seasonal effects be considered in a follow up study. One consequence of only including orthophosphate decay but ignoring 'recharge' from the bed, will be that the model will underestimate winter phosphate concentrations. However, in the Thames, the high phosphates tend to occur in summer, and the low phosphates in winter. Therefore this simple model will still be useful for examining high orthophosphate concentrations.

4.2 Modelling the Thames Catchment

To model decay processes in a river TOMCAT calculates the time it takes the water to flow along the river, and combines this with a decay rate. To calculate times of travel accurately, data from dye tracer studies is needed. These studies have now been carried out by the NRA on many of the tributaries of the Thames, but not all. However, since the orthophosphate decay rates were unknown, and needed to be obtained by trial and error, it was felt that accurate travel times were not necessary. Instead, river velocities were set to be a constant in all rivers, and decay rates adjusted to give a good fit. This approach is fairly quick and easy to implement, but will not allow different travel times for different flow rates. Nor can decay rates be easily compared, since differences that are due to chemistry can not be separated from differences caused by time of travel. It is recommended that realistic velocity flow relationships be used for those catchments where time of travel data exists.

TOMCAT is capable of modelling catchments of great complexity, assuming the user has enough time. By its very size, the Thames model is complex and we have attempted to simplify the structure. Each sub-catchment of the Thames has been modelled as a single river. Discharges have been sited on these rivers based on their distance from the Thames. Sewage treatment works that are far apart and on different tributaries within the same sub-catchment will end up close together if they are a similar distance above the Thames. Figure 4.1 shows a schematic of the model structure. Sub-catchments could be made more complicated (and realistic) by further subdividing them. This would make no difference to the answers unless the decay rates were changed in each tributary of the sub-catchment. Therefore it is recommended that more complex sub-catchments be used only where there are difficulties calibrating the model or where more detailed information is required.

4.3 Calibration

The model was set up for a 2 year period, October 1992 - October 1994, for each sub-catchment of the freshwater Thames. This is a different period from that used in Section 3, because we wanted to avoid the complication of modelling the end of the drought in 1991. STW flows were based on recent measured data where available, otherwise annual average flows for 1989 were used. Upstream river flows were adjusted so the model fitted gauging station data at the confluences with the Thames. For the STWs phosphate concentrations were entered as normal distributions, using measured means: this ensures that the phosphate loads are normal (see Appendix 2). An agricultural load of 0.32 kgP/ha/year was used, catchment areas being obtained from the Institute of Hydrology's Micro Low Flows package. Orthophosphate decay rates were chosen for each catchment to give the best fit at the sampling points above the Thames. The sub-catchment models were then incorporated into a single Thames Catchment model. Runoff was added along the Thames and the large drinking water abstractions were included in the model. Figure 4.2 shows that a good fit was obtained between the flow model and gauging station data.

The phosphate decay rate in the Thames was adjusted to give a good fit with observed data. Figure 4.3 shows a longitudinal plot of mean orthophosphate predicted by the model, compared with observed data. Although the fit is very good, further work is required to understand the processes behind the decay term: for most catchments half the phosphate was removed in 11-280 km. This large range in decay probably reflects the empirical nature of the decay term and variety of tributaries modelled. In the Thames itself the best fit was found using no decay. It may be that summer phosphate loss to the sediments is largely balanced by winter addition from the sediments. Preliminary investigations of seasonal data do indicate that a summer model would need some decay. Another idea is that in the tributaries fresh sediment material is added during runoff. This material adsorbs phosphorus, but as it is carried downstream it becomes more saturated and its ability to adsorb phosphorus is diminished. This would lead to less decay at the downstream end of tributaries and in the Thames itself. This theory has not been verified, but could be tested by modelling some of the larger tributaries in more detail.

4.4 Validation

Once TOMCAT has been calibrated to fit river data, it is advisable to validate it by applying it to another time period. This work has now ben completed and is detailed in appendix 5. The validation procedure worked well in the sub-catchments with all tributaries apart from the Colne validating successfully. It was found necessary though to use decay in the main river Thames particularly between Farmoor and Caversham in order to obtain the best statistical fit between observed and simulated data. The predictions detailed in section 4.5 though were not found to be sensitive to this change, thus allowing confidence in the accuracy of these predictions. Further details may be found in appendix 5.

4.5 Model predictions

4.5.1 Contributions from individual sewage treatment works

The model was run 67 times, switching off the orthophosphate load input from each of the 67 STWs greater then 10,000PE in turn. The results were compared with the model run with all works switched on, the differences being the contribution from the individual works. These are shown in Table 4.1. For example, it can be seen that the most upstream STW, Cirencester, makes a large contribution to the phosphate concentration in the upper Thames (0.26 mg/l), but that this is gradually diluted, so that at the beginning of the Sensitive Area (marked by the dashed line in Table 4.1) its contribution is quite small (0.01 mg/l). On the other hand, Hogsmill, a large London STW, and the furthest STW downstream, makes a significant contribution to the concentration (0.1 mg/l), but only at the bottom of the Thames, at Teddington.

To compare the effects of STWs, there are several factors that need to be taken into account:

1. the river phosphate concentration due to the works;
2. the length of river affected;
3. the residence time: if this is small, then the phosphate is likely to pass out of the river before making a significant contribution to algae growth.

To rank works in order of importance, an index was required that took into account both concentration and the distance affected (residence time being related to distance). We have used a very simple index: the concentration produced by a STW averaged over the length of the Sensitive Area affected.[1] Table 4.2 shows the 67 STWs exceeding 10,000PE ranked in

[1]This index gives the same weight to distance as it does to concentration. For example, a discharge that raises the concentration of 10 km of the Thames by 0.2 mg/l will have the same index as one that raises the concentration of 20km by 0.1 mg/l. The index was calculated by integrating the figures in Table 4.1 and dividing them by the average river concentration. More complex indices could be devised but we feel there is not enough information to justify them.

Table 4.1 UWWTD sewage work contributions to orthophosphate concentration (mg/P/l) at different points in the Thames

Distance (km) from start of model(Ashton Keynes)

	19.	21.	26.	30.	35.	40.	65.	73.	77.	83.	88.	90.	96.	98.	101.	108.	116.	124.	134.	151.	156.	166.	186.	190.	200.	204.	208.	215.	217.	221.	226.	229.	231.	236.	240.
Cirencester	0.26	0.13	0.06	0.06	0.05	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01																		
Swindon			0.71	0.67	0.54	0.33	0.25	0.18	0.18	0.14	0.13	0.10	0.09	0.09	0.09	0.08	0.06	0.06	0.08	0.06	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02
Carterton							0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01															
Witney								0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01															
Cassington										0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01			0.01			
Kidlington											0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01															
Banbury												0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01		0.01	0.01	0.01			0.01			
Bicester												0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0101	0.01	0.01	0.01				0.01							
Oxford													0.12	0.12	0.12	0.11	0.10	0.08	0.08	0.06	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.02	0.02
Wantage																0.03	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Abingdon (to Thames)																0.03	0.03	0.03	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Abingdon																0.01	0.01	0.01	0.01	0.01	0.01														
Didcot																	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01											
Tiling																																			
Aylesbury																		0.06	0.05	0.04	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01
Princes Risborough																		0.01	0.01	0.01	0.01														
Thame																		0.01	0.01	0.01															
Cholsey																			0.01	0.01	0.01	0.01	0.01	0.01				0.01							
Pangbourne																				0.01	0.01	0.01													
Newbury																																			
Silchester																					0.01														
Reading																					0.08	0.07	0.07	0.06	0.06	0.06	0.06	0.06	0.05	0.05	0.05	0.05	0.04	0.04	0.04
Aldershot																																			
Aldershot military																																			
Ash Vale																																			
Camberley																						0.01	0.01	0.01	0.01		0.01	0.01	0.01			0.01			
Basingstoke																						0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01			0.01			
Sandhurst																						0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01		0.01			
Hartley Wintney																																			
Fleet																						0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01			
Arborfield																																			
Ash Ridge																						0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01			
Wargrave																						0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03
Henley																																			
Little Marlow																							0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.02	0.02
High Wycombe																							0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01
Ascot																								0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01			
Bracknell																								0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01
Maidenhead																								0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.02
Burnham																									0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01			
Slough																									0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.02	0.02	0.02
Windsor																												0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Berkhamsted																																			
Blackbirds																													0.02	0.02	0.01	0.01	0.01	0.01	0.01
Chesham																													0.01			0.01			
Maple Lodge																												0.01	0.11	0.12	0.10	0.10	0.10	0.06	0.06
Lightwater																																			
Chertsey																															0.03	0.03	0.03	0.02	0.02
Haslemere																																			
Alton																																			
Bordon																																			
Farnham																																0.01			
Cranleigh																																			
Godalming																															0.01	0.01	0.01	0.01	0.01
Guildford																															0.02	0.02	0.01	0.01	0.01
Hockford																																			
Woking																															0.01	0.01	0.01	0.01	0.01
Ripley																															0.01	0.01	0.01		
Wisley																															0.01	0.01	0.01		0.01
Weybridge																															0.02	0.02	0.02	0.02	0.02
Crawley																																		0.02	0.02
Horley																																		0.01	0.01
Reigate																																		0.04	0.04
Dorking																																		0.01	0.01
Leatherhead																																		0.01	0.01
Esher																																		0.05	0.05
Hogsmill																																			0.10
Other	0.14	0.22	0.20	0.28	0.29	0.22	0.20	0.17	0.17	0.17	0.17	0.16	0.15	0.15	0.15	0.16	0.16	0.20	0.20	0.19	0.18	0.14	0.14	0.13	0.15	0.16	0.15	0.13	0.16	0.15	0.11	0.12	0.18	0.15	0.16
Total	0.40	0.35	0.96	1.01	0.88	0.56	0.60	0.41	0.40	0.36	0.36	0.36	0.46	0.46	0.46	0.51	0.46	0.54	0.55	0.53	0.48	0.62	0.56	0.61	0.65	0.65	0.65	0.67	0.73	0.73	0.76	0.76	0.76	0.82	0.90

Table 4.2 Priority list of STWs

	Sensitive Area Index %	Upper Thames Index %
Oxford STW	8.82	4.84
Reading STW	7.17	0
Swindon STW	6.91	44.27
Aylesbury STW	4.63	0
Wargrave STW	4.43	0
Maple Lodge STW	3.3	0
Little Marlow STW	3.07	0
Abingdon STW (to Thames)	2.77	0.78
Wantage STW	2.19	0.61
Maidenhead STW	1.67	0
Slough STW	1.63	0
High Wycombe STW	1.54	0
Cassington STW	1.38	1.41
Banbury STW	1.28	0.85
Bracknell STW	1.21	0
Bicester STW	1.17	0.78
Didcot STW	1.15	0.12
Cholsey STW	0.99	0
Princes Risborough STW	0.93	0
Abingdon STW	0.88	0.25
Windsor STW	0.85	0
Ash Ridge STW	0.79	0
Witney STW	0.76	1.19
Kidlington STW	0.76	0.61
Carterton STW	0.76	2
Fleet STW	0.74	0
Pangbourne STW	0.71	0
Thame STW	0.7	0
Sandhurst STW	0.7	0
Basingstoke STW	0.62	0
Camberley STW	0.61	0
Chertsey STW	0.57	0
Cirencester STW	0.57	6.37
Silchester STW	0.54	0
Weybridge STW	0.48	0
Hartley Wintney STW	0.47	0
Blackbirds STW	0.46	0
Ascot STW	0.45	0
Tring STW	0.4	0
Esher STW	0.37	0
Burnham STW	0.34	0
Newbury STW	0.34	0
Guildford STW	0.33	0
Arborfield STW	0.33	0
Reigate STW	0.32	0
Henley STW	0.32	0
Woking STW	0.28	0
Aldershot STW	0.23	0
Crawley STW	0.17	0
Godalming STW	0.16	0
Chesham STW	0.15	0
Wisley STW	0.13	0
Ripley STW	0.13	0
Berkhamsted STW	0.12	0
Hogsmill STW	0.11	0
Farnham STW	0.1	0
Ash Vale STW	0.09	0
Hockford STW	0.08	0
Bordon STW	0.08	0
Cranleigh STW	0.08	0
Leatherhead STW	0.07	0
Aldershot military STW	0.07	0
Dorking STW	0.05	0
Lightwater STW	0.04	0
Horley STW	0.04	0
Alton STW	0.03	0
Haslemere STW	0.03	0
Other	26.32	35.94
Total	100	100

order of the index. The index is expressed as a percentage. It can be seen that Oxford contributes nearly 9% of the phosphate concentration in the Sensitive Area. We have also included a second index, based on the percentage contribution to the orthophosphate in the Thames upstream of the Sensitive Area. Thus Swindon which contributes 7% of the phosphate in the Sensitive Area, also contributes 44% of the phosphate in the Thames above Day's Lock. This is of interest since the upper Thames is a candidate for designation as a Sensitive Area. However, it should not be forgotten that in future other tributaries may be designated and some of the works that only have a small effect on the Thames may make significant contribution to these tributaries.

Several other points are worth noting:

1. The large upstream works (Swindon, Oxford and Reading) all appear near the top of the list. However, large downstream works, such as Esher and Hogsmill, appear in the bottom half of the list.
2. The top eight STWs, Oxford, Reading, Swindon, Aylesbury, Wargrave, Maple Lodge, Little Marlow and Abingdon (Old and New) contribute 42% of the phosphate concentration. The next eight STWs contribute a further 12%, while the remaining 50 works contribute 20%.
3. Agriculture and small STWs contribute 26%. This can also be seen in Table 4.1 where their contribution is between 0.1 - 0.2 mgP/l.

4.5.2 Effects of phosphate stripping

Table 4.3 shows the various phosphate standards that apply for STWs discharging to Sensitive Areas. Works must either meet a total phosphorus concentration limit, the value depending on the population equivalence, or remove 80% of the incoming phosphorus. We do not know the total phosphorus concentrations entering STWs, but a quick estimate based on Table 3.1 suggests it will be around 10 mgP/l. In this case the 80% reduction figure would imply a discharge of 2mg/l total phosphorus. Therefore, we have chosen 2 mg/l as a representative figure for effluent phosphate concentration after phosphorus removal.

Table 4.3 UWWTD standards for discharges to Sensitive Areas

Population Equivalent	Concentration of Total Phosphorus (mgP/l)	Percentage reduction
10,000 - 100,000	2	80%
> 100,000	1	80%

TOMCAT was therefore run to see what would happen to phosphate levels if all 67 STWs exceeding 10,000PE discharge at 2 mgP/l orthophosphate[2]. The concentrations in the

[2]TOMCAT was set up to reproduce accurate STW phosphate loads, rather than accurate flows and accurate concentrations. More consideration may need to be given to the best way of modelling given effluent concentrations.

Thames are shown in Figure 4.4, compared with current levels. The model predicts concentrations around 0.3 mgP/l compared with current levels around 0.6 mgP/l.

TOMCAT was also run to see what would happen if phosphorus stripping was introduced only at the top eight sewage works in the priority list (Table 4.2). The results are again shown in Figure 4.4: concentrations are reduced to around 0.4 mgP/l.

4.5.3 Comparison with quick estimate

In Section 3.5.2 the contribution of small works and agriculture to orthophosphate concentrations in the Thames was estimated to be around 0.2 mgP/l. (Table 3.5, 100% removal). This is comparable with the estimate from TOMCAT (Table 4.1, penultimate line.) In Section 3.5.2 we used a quick estimate to predict the effects of removing 80% of the effluent orthophosphate. In Section 4.5.2 we used TOMCAT to estimate the effects of the major works discharging at 2 mgP/l which we felt was roughly equivalent to removing 80% of influent phosphorus. Although these two scenarios are not quite the same, it can be seen that the upper range of figures in Table 3.5 agree well with the TOMCAT estimate shown in Figure 4.4.

5. Conclusion and Recommendations

TOMCAT has been set up to predict orthophosphate concentrations in the River Thames. The calibration has been successful and the model agrees well with earlier work and quick estimates carried out here. A better understanding of phosphorus in STWs and the river environment would remove some of the uncertainties, and recommendations for further literature searches and data collection are included in Section 5.1. In Section 5.2 we recapitulate the recommendations made in Section 4 on improvements to the model. Recommendations on phosphate stripping, based on the model's predictions, are made in Section 5.3.

5.1 Data requirements

The following data and information would give improved predictions:

1. Check literature for fractionization of STW influent and effluent. Possibly carry out further analysis on local STW effluent. Total phosphorus, dissolved phosphorus, orthophosphate, dissolved orthophosphate, inorganic phosphorus and dissolved inorganic phosphorus could all be measured.
2. Estimate proportion of phosphorus bound to particulate matter in the Thames.
3. Estimate which phosphorus fractions are present. Check literature or take measurements of sediment phosphorus. Check seasonal variation of phosphorus species.
4. Estimate phosphorus load from CSOs and urban runoff by investigating watercourses in urban drainage areas (eg Blackwater, Hogsmill).
5. Better estimates of stw flows.

5.2 Improvements to the model

The following recommendations are made for improving the model accuracy:

1. Seasonal effects should be modelled.
2. More complex sub-catchments could be used where there are difficulties calibrating the model or where more detailed information is required. The Colne and Ginge Brook are two such sub-catchments.
3. A dynamic tributary model including all phosphorus fractions needs constructing to better understand the empirical decay term used in the model.
4. Improve the main river Thames flow model.
5. Further investigation of decay in the main river Thames.

Model improvements are further discussed at the end of appendix 5

5.3 Phosphorus removal

It is not clear yet what phosphate limit should be used as a guide for assessing eutrophication, although work being carried out by the NRA as well as the study of phosphorus removal at works within the catchment will give a clearer picture. Earlier studies carried out on the Thames showed that phosphate removal at STWs would not bring river phosphate levels below 0.1 mgP/l. This study confirms the earlier work. The results of the TOMCAT model show that phosphorus stripping at 8 STWs would reduce river concentrations to about 0.4 mgP/l, while stripping at all works exceeding 10,000 PE would reduce river concentrations to about 0.3 mgP/l. Further work can be carried out to estimate the accuracy of these figures, and to improve it. If further reductions in river phosphate were required then a combination of stricter standards at the large sewage works, phosphorus removal at smaller works and changes to agricultural practices might be needed. In recent years the use of phosphate in detergents has declined and this will have a knock on effect on rivers.

If it is decided that the phosphate concentrations of 0.3 - 0.4 mgP/l would reduce the level of eutrophication, then the next question is which STWs should be targeted first. We have proposed a simple index and ranked the Thames STWs accordingly (Table 4.2). Phosphorus stripping would have most effect at those work near the top of the list. We suggest a pilot scheme should contain at least the top 8 works: Oxford, Swindon, Reading, Wargrave, Aylesbury, Maple Lodge, Little Marlow and Abingdon (Old and New). On the other hand there would be little benefit to the Thames in removing phosphorus from works at the bottom of the list, although it would benefit some of the tributaries. The 4 works in the catchment where phosphorus removal is being carried out, Aldershot, Aldershot Military, Ash Vale and Alton, will reduce the phosphorus concentrations in the tributaries (Blackwater and Wey North Sensitive Areas), but will have very little effect on the Thames.

In this report we have pointed out the seasonal fluctuations in river phosphate concentration as well as the seasonal growth of plants and algae. Phosphorus stripping may not be necessary during the winter (November to February), and it might be worth examining the economics of seasonal stripping. However, consideration should be given to whether phosphate would be stored in river sediments during the winter, and then released during the summer.

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Phosphorus in the Thames Catchment

Figures

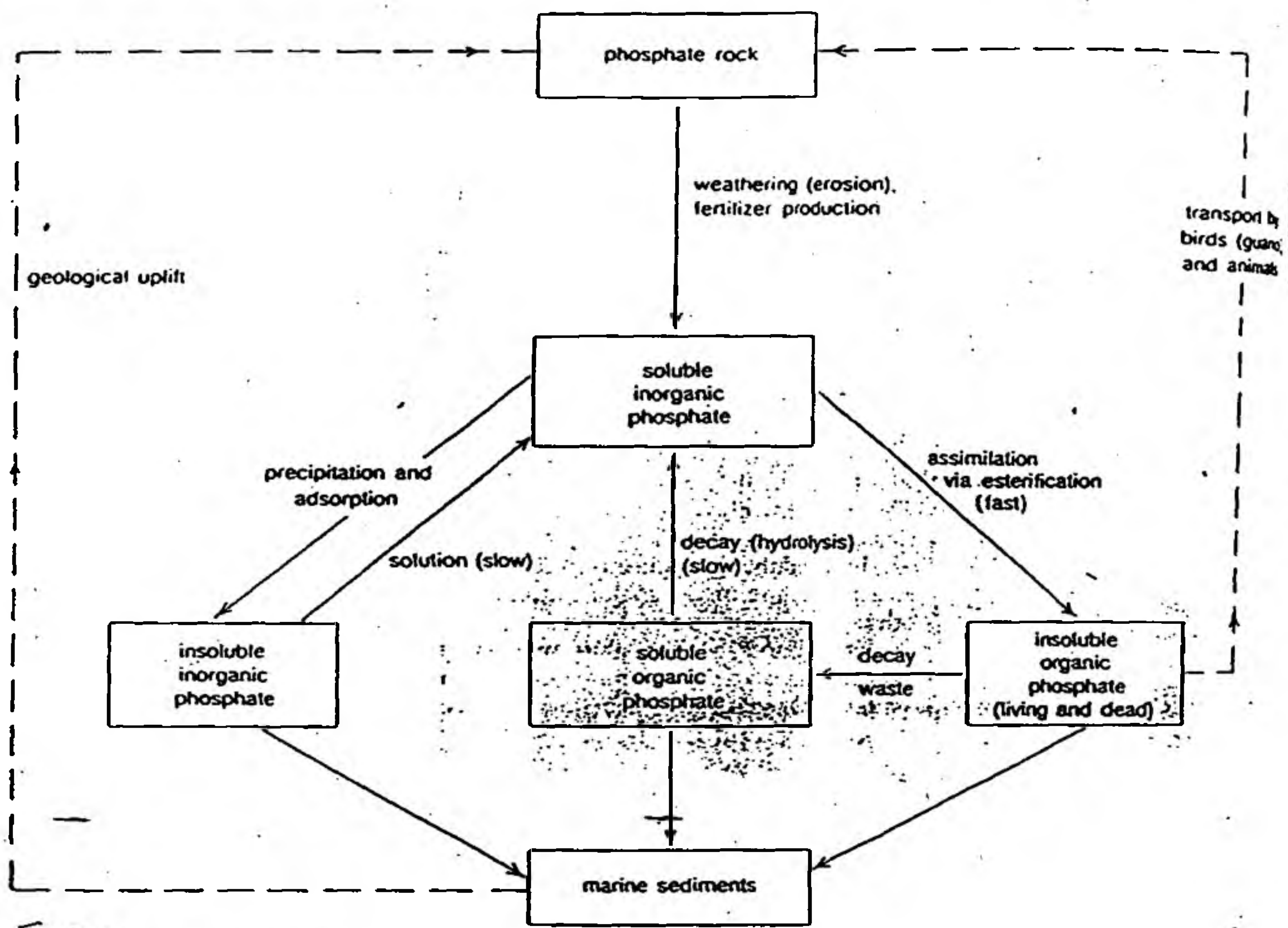


Fig 2.1 The phosphorus cycle.
Dashed arrows indicate minor phosphorus transportation pathways.

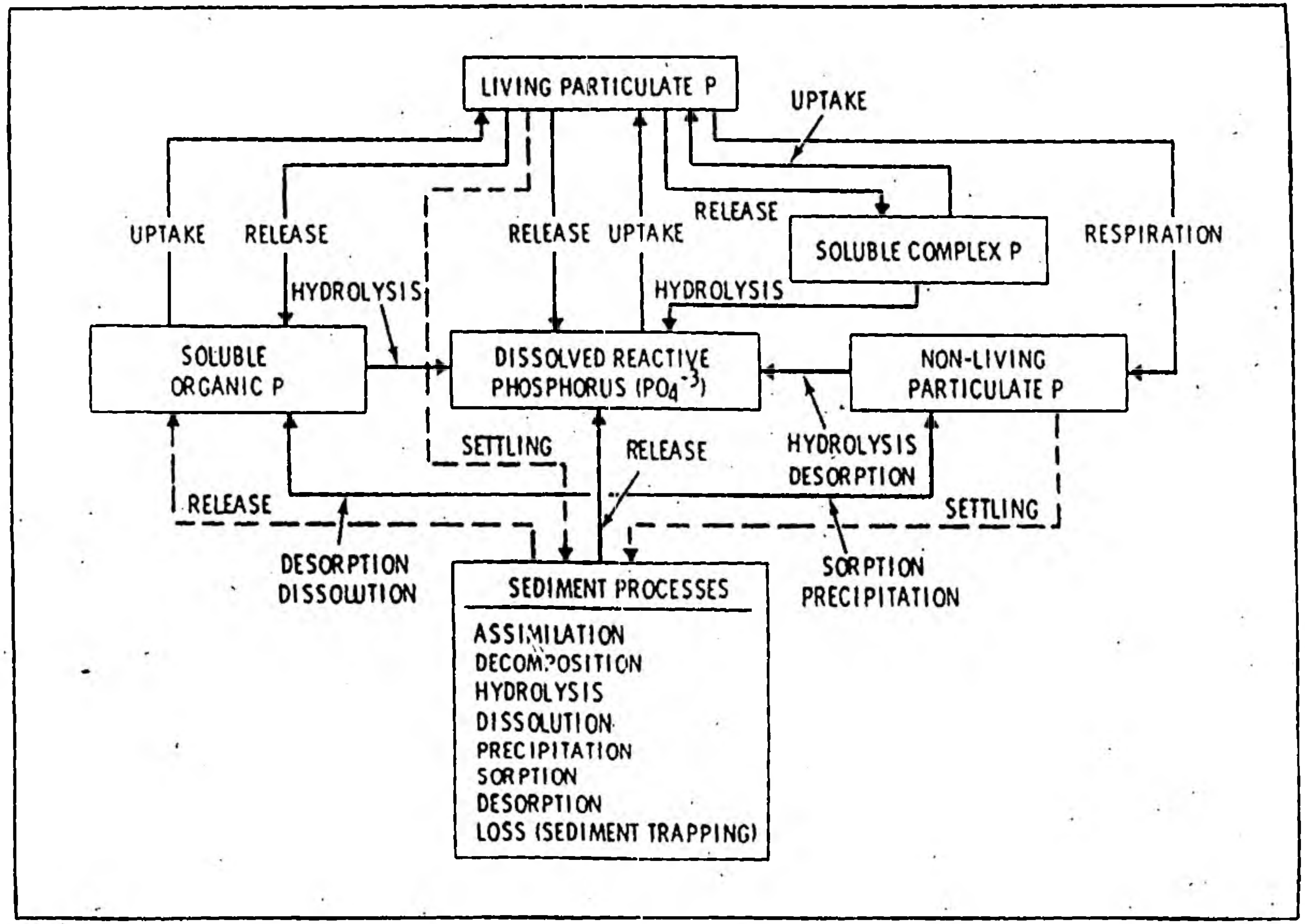


Figure 2.2 Phosphorus cycle (from Baca and Arnett, 1976).

Key to Figure 3.1

1	Cirencester	SU 0330 9690
2	Swindon	SU 1271 8580
3	Carterton	SP 2802 0485
4	Witney	SP 3480 0860
5	Cassington	SP 4660 1010
6	Kidlington	SP 4910 1240
7	Banbury	SP 4695 3972
8	Bicester	SP 5786 2120
9	Oxford	SP 5420 0220
10	Wantage	SU 4075 9171
11	Abingdon (New)	SU 4985 9523
12	Abingdon	SU 4910 9510
13	Didcot	SU 5210 9140
14	Tring	SP 9240 1330
15	Aylesbury	SP 7890 1480
16	Princes Risborough	SP 7980 0380
17	Thame	SP 7120 0690
18	Cholsey	SU 5914 8723
19	Pangbourne	SU 6440 7660
20	Newbury	SU 4989 6671
21	Silchester	SU 6220 6100
22	Reading	SU 7110 7090
23	Basingstoke	SU 6800 5520
24	Aldershot	SU 8835 5036
25	Aldershot Military	SU 8840 5270
26	Ash Vale	SU 8851 5411
27	Camberley	SU 8587 5948
28	Sandhurst	SU 8370 6098
29	Hartley Wintney	SU 7666 5808
30	Fleet	SU 8040 5640
31	Arborfield	SU 7677 6739
32	Ash Ridge	SU 8122 7008
33	Wargrave	SU 7788 7759
34	Henley	SU 7605 8418
35	Little Marlow	SU 8772 8696
36	High Wycombe	SU 8850 9200
37	Ascot	SU 8910 6820
38	Bracknell	SU 8530 7210
39	Maidenhead	SU 8950 8060
40	Burnham	SU 9190 8080
41	Slough	SU 9430 7920
42	Windsor	SU 9968 7510
43	Berkhamsted	TL 0140 0680
44	Blackbirds	TL 1370 0110
45	Chesham	SU 9807 9952
46	Maple Lodge	TQ 0420 9200
47	Lightwater	SU 9390 6216
48	Chertsey	TQ 0148 6774
49	Haslemere	SU 8790 3250
50	Bordon	SU 8030 3620
51	Alton	SU 7290 3980
52	Farnham	SU 8526 4738
53	Godalming	SU 9940 4570
54	Cranleigh	TQ 0396 3948
55	Guidlford	TQ 0030 5160
56	Hockford	SU 9603 5425
57	Woking	TQ 0320 5720
58	Ripley	TQ 0450 5745
59	Wisley	TQ 0610 5990
60	Weybridge	TQ 0660 6320
61	Crawley	TQ 2880 4020
62	Horley	TQ 2671 4367
63	Reigate	TQ 2695 4805
64	Dorking	TQ 1770 5040
65	Leatherhead	TQ 1470 5810
66	Esher	TQ 1340 6660
67	Hogsmill	TQ 1919 6858

Fig 3.1 Location of Large Sewage Treatment Works that Discharge Directly or Indirectly into the Thames Eutrophic Sensitive Area.

Fig 3.2

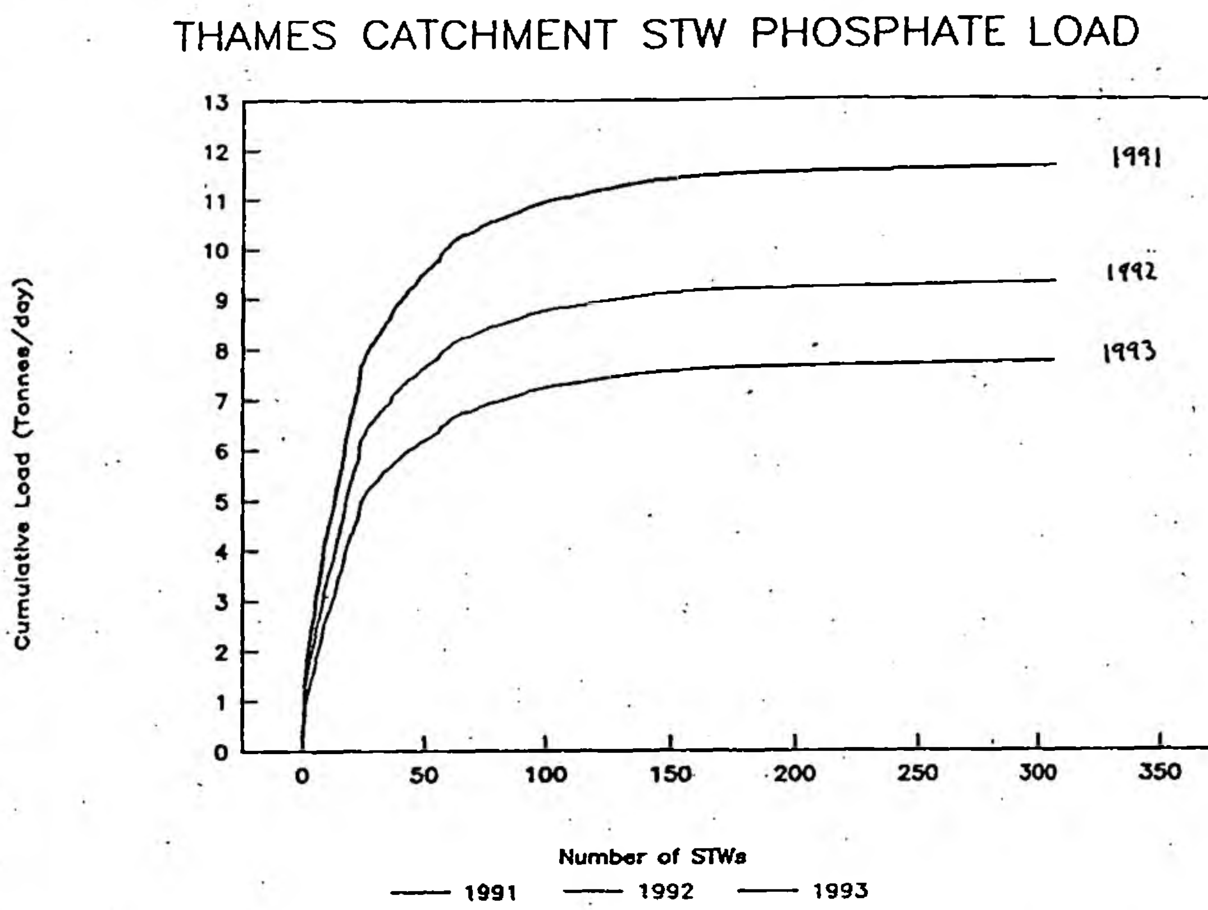

THAMES CATCHMENT STW PHOSPHATE LOAD
Cumulative Load (Tonnes/day)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
1991
1992
1993
0
50
100
150
200
250
300
350
Number of STWs
1991
1992
1993

Fig 3.3

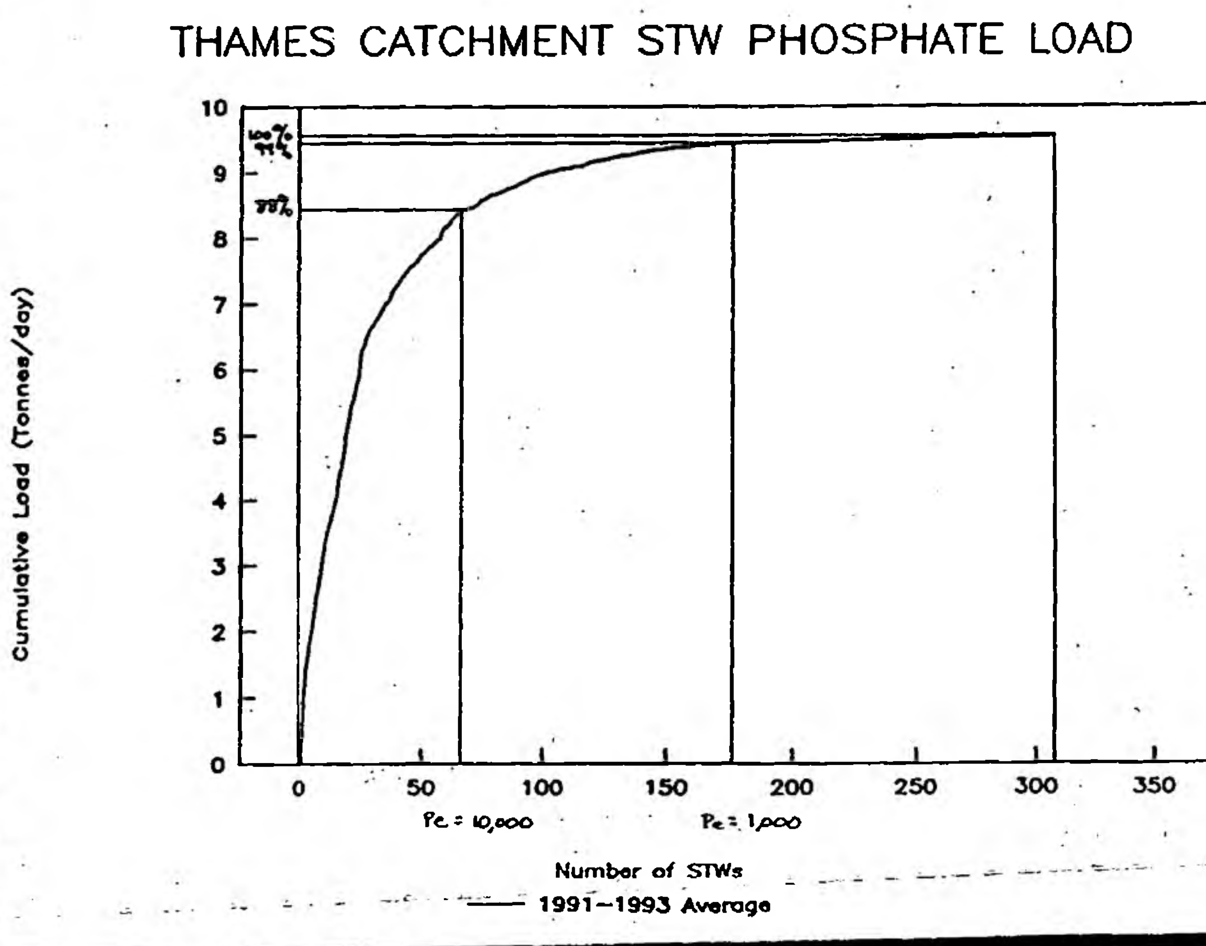

THAMES CATCHMENT STW PHOSPHATE LOAD
Cumulative Load (Tonnes/day)
0
1
2
3
4
5
6
7
8
9
10
100%
99%
88%
0
50
100
150
200
250
300
350
Pe = 10,000
Pe = 1,000
Number of STWs
1991–1993 Average

Fig 3.4

Mean Orthophosphate Concentrations

River Thames

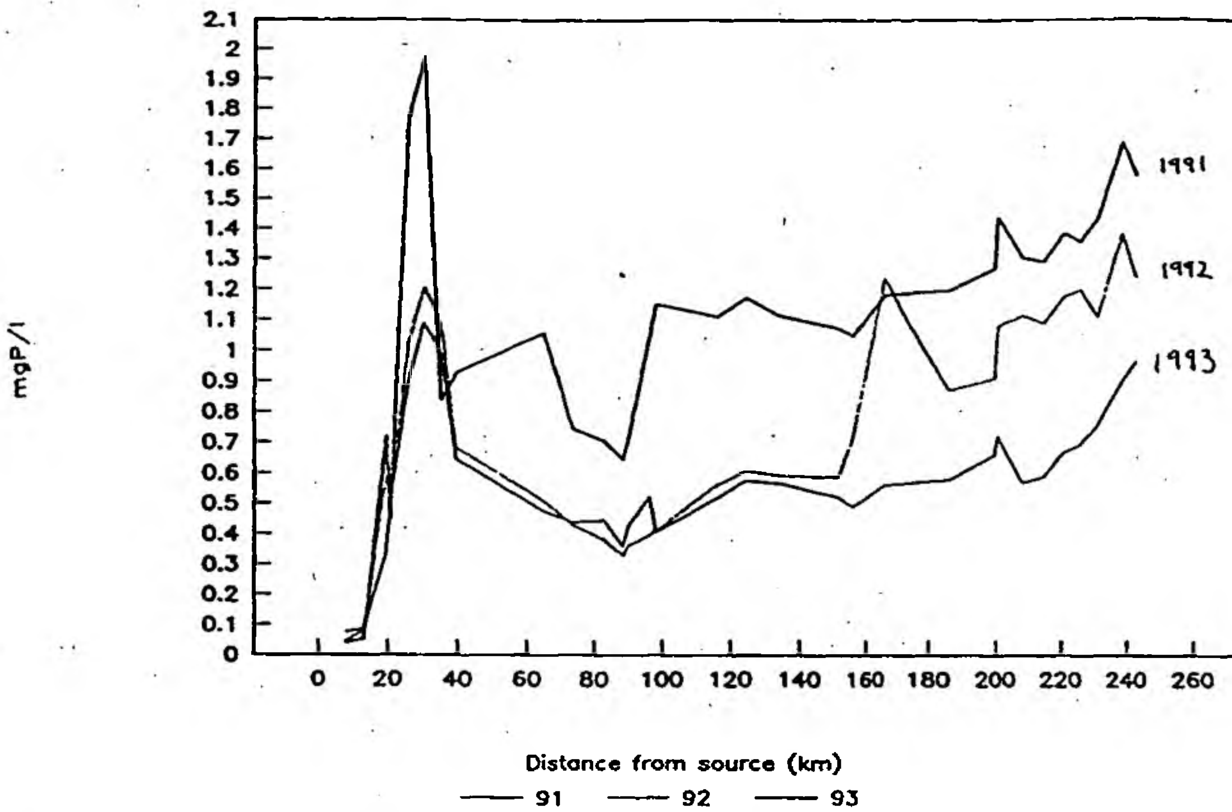
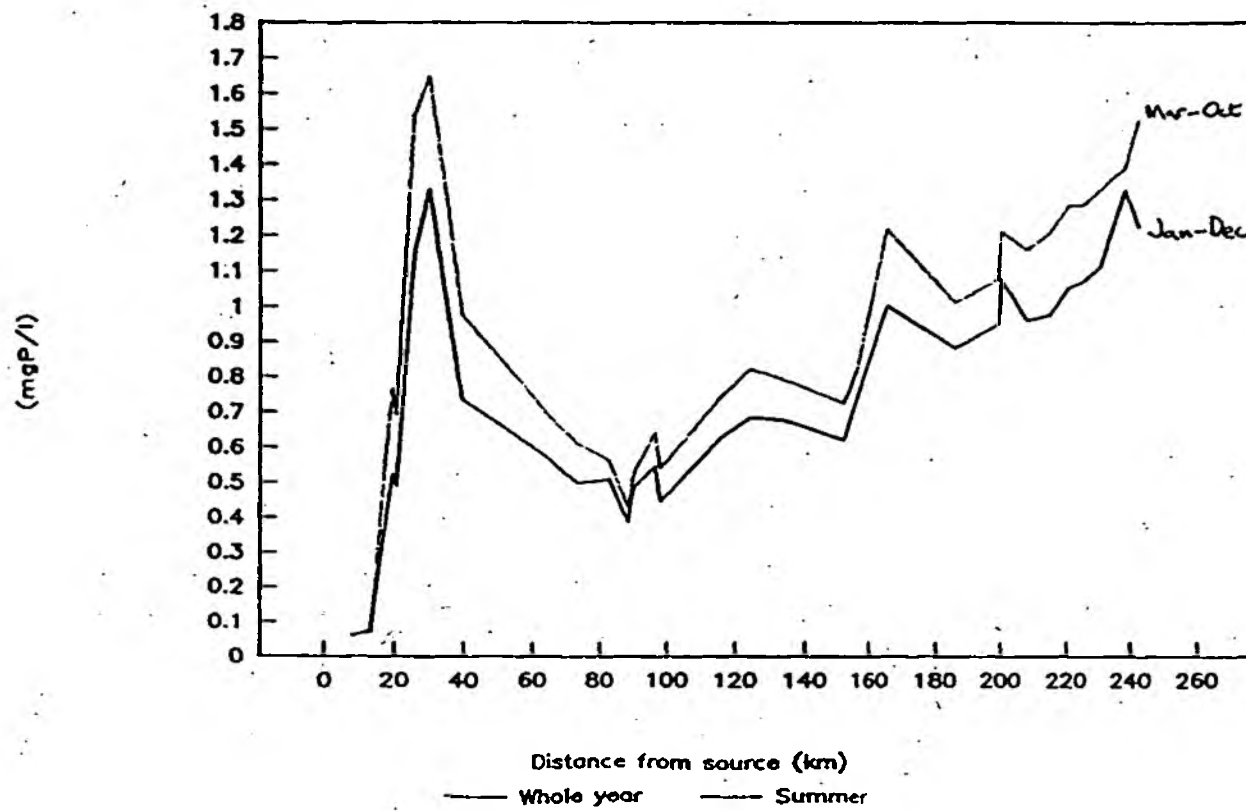


Fig 3.5

Mean Orthophosphate Concentrations

River Thames 1991–1993



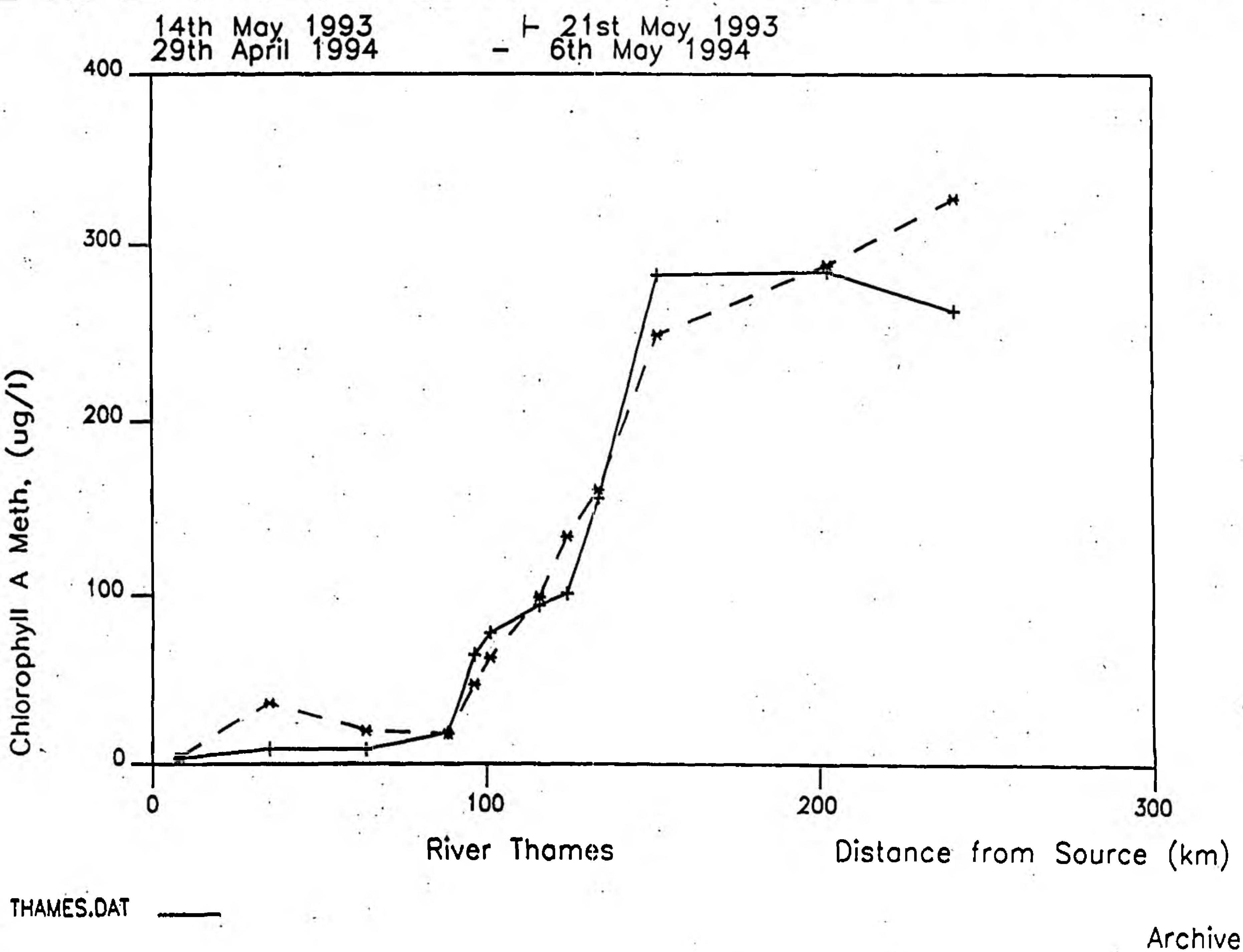

14th May 1993
21st May 1993
29th April 1994
6th May 1994
400
300
200
100
0
Chlorophyll A Meth. (ug/l)
0
100
200
300
River Thames
Distance from Source (km)
THAMES.DAT
Archive data

Fig 3.7

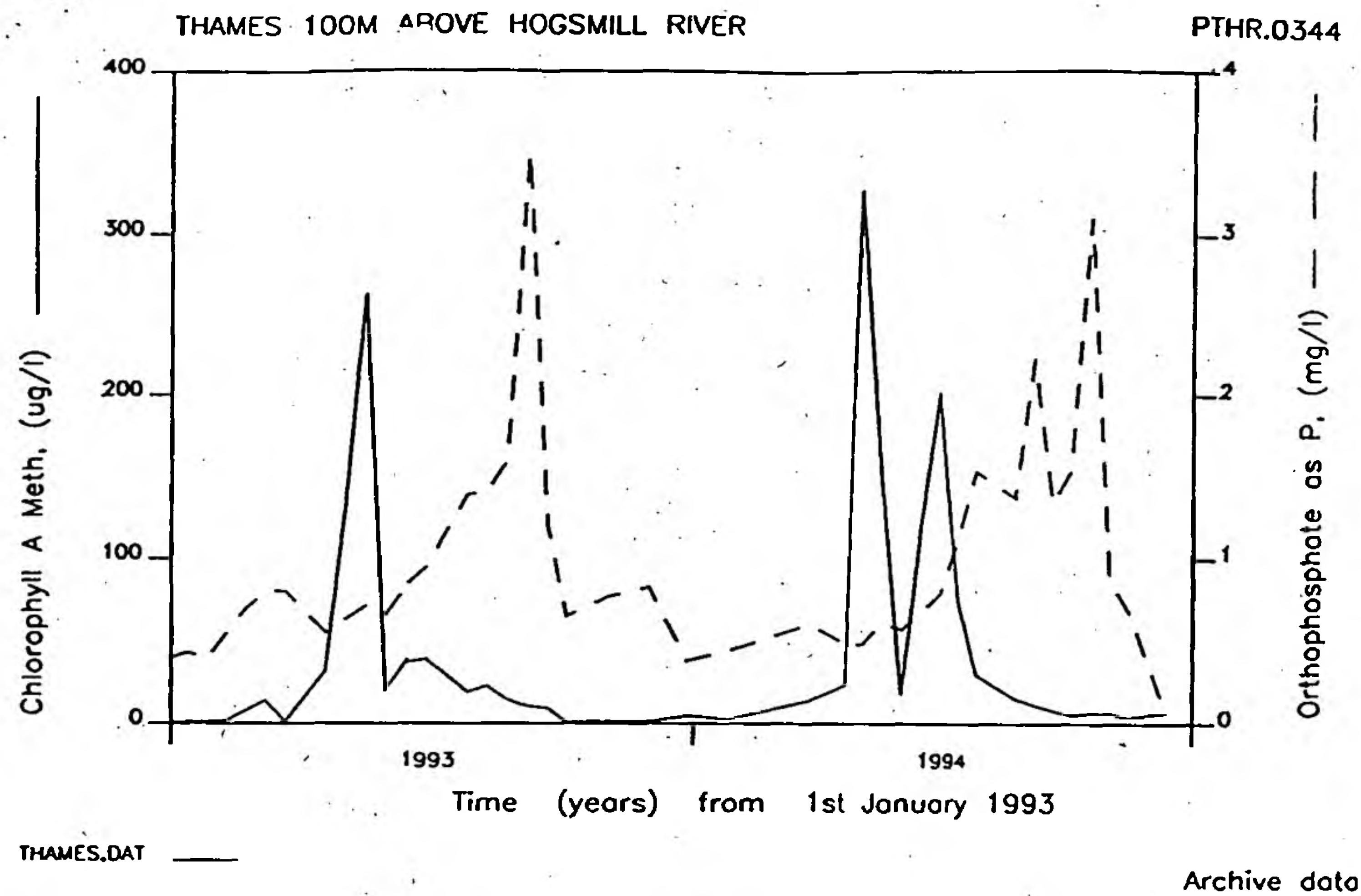

THAMES 100M ABOVE HOGSMILL RIVER
PTHR.0344
400
300
200
100
0
4
3
2
1
0
Chlorophyll A Meth. (ug/l)
Orthophosphate as P. (mg/l)
1993
1994
Time (years) from 1st January 1993
THAMES.DAT
Archive data

Fig 3.8

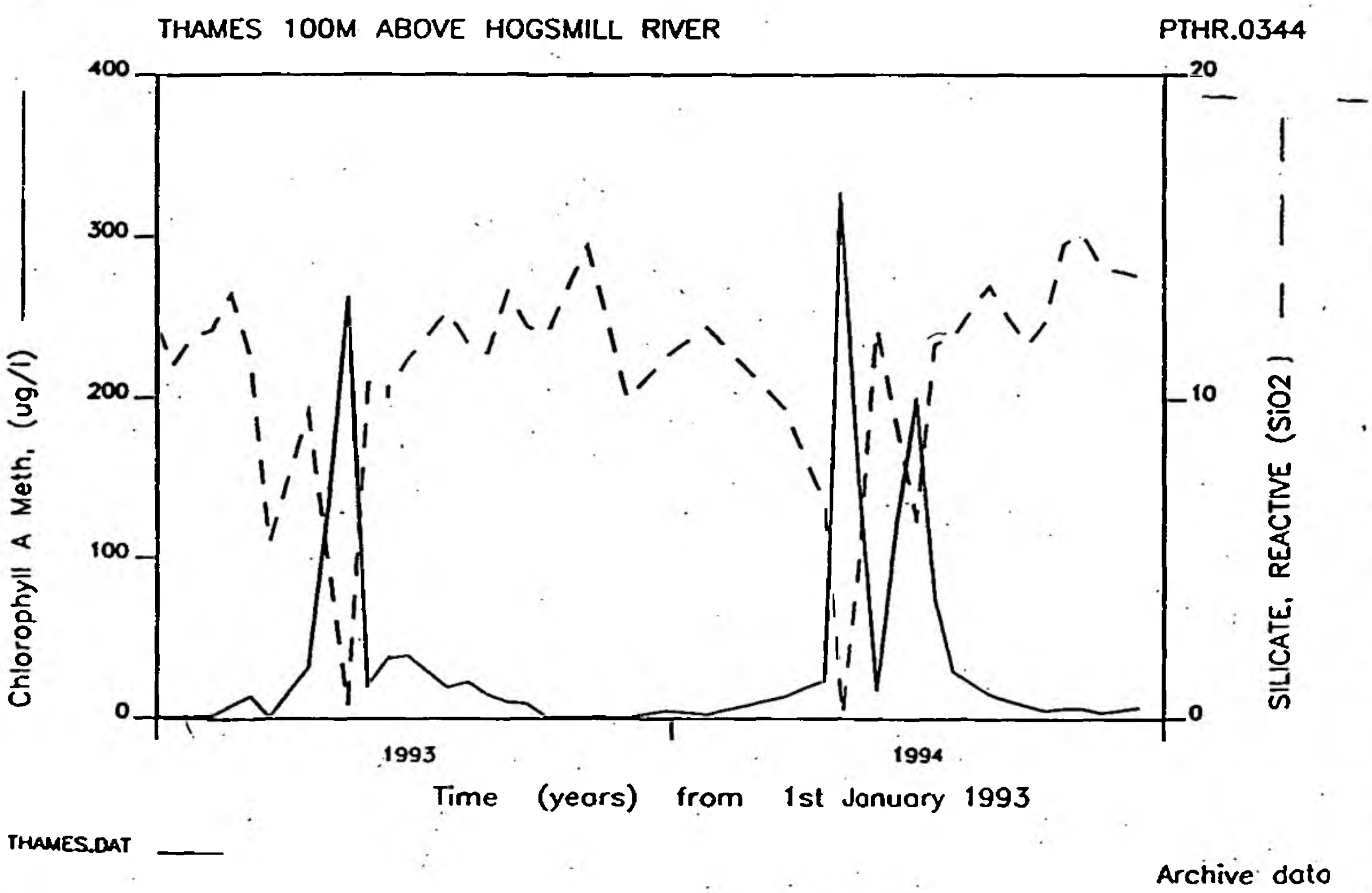

THAMES 100M ABOVE HOGSMILL RIVER
PTHR.0344
400
300
200
100
0
20
10
0
Chlorophyll A Meth. (ug/l)
SILICATE, REACTIVE (SiO2)
1993
1994
Time (years) from 1st January 1993
THAMES.DAT
Archive data

Fig. 4.1.

TOMFRONT (C) NRA Thames Region 1994

Schematic of Tomcat file: TOFU
produced on: Wednesday, 22 November 1995

THAMES PHOSPHATE MODEL - TOPHOO

Distances in km

```
         *                                          River Thames
 13.2    -                                          Model start
         |<---                                      Ashton Keynes stw (eff)
         |
         |          *                               Cerney Wick Brook
         |          |<---                           Cirencester stw
         |          x                               Cerney Wyck Brook Spine Rd : PUTR.0009
         |     6.2  |                               Confluence - Cerney Wyck
 16.1    |----------|
 19.4    -                                          Cricklade : PUTR.0091 (GS 0190)
         |<---                                      Churn (eff)
         |<---                                      Cricklade Stw
         |<---                                      Key (eff)
         |<---                                      Ampney Bk tributary (eff)
 20.5    -                                          Eysey : PUTR.0093
         |
         |          *                               Wiltshire Ray tributary
         |          |<---                           Wroughton Stw
         |          |<---                      ---> Swindon
         |          x                               Seven Br. Criclade: PUTR.0071
         |    20.9  |                               Confluence - Wiltshire Ray
 21.6    |----------|
 25.7    -                                          Castle Eaton : PUTR.0090
         |<---                                      Share ditch (eff)
 30.0    -                                          Hannington Bridge : PUTR.0096
         |<---                                      Bydemill brook (eff)
         |
         |          *                               Cole tributary
         |          |<---                           Wanborough Stw
         |          |<---                           Bourton Stw
         |          |<---                           Shrivenham Stw
         |          x                               Coleshill PUTR.0025
         |    27.6  |                               Confluence - Cole
 34.1    |----------|
 35.1    -                                          Inglesham : PUTR.0097
         |<---                                      Coln(eff)
         |<---                                      Leach (eff)
 39.5    -                                          Buscot Intake : PUTR.0107 (GS 0900)
         |<---                                      Faringdon Bk (eff)
         |<---                                      Wadley Stream (eff)
         |
         |          *                               Great Brook Tributary
         |          |<---                           Brize Norton stw
         |          |<---                           Carterton stw
         |          |<---                           Bampton stw
         |          x                               Chimney Lane : PUTR.0051
         |    11.9  |                               Confluence - Great Bk
 61.0    |----------|
 64.6    -                                          Newbridge : PUTR.0099
         |
         |          *                               Windrush tributary
         |          |<---                           Bourton-on-the-Water
         |          |<---                           Burford
```

```
        |               |<---              Witney
        |               |<---              Standlake
        |               x                  Newbridge: PWRR.0021
        |      73.3     |                  Confluence - Windrush
64.6    |---------------|
        |--->                              Farmoor abstraction
73.3    -                                  Farmoor : PTHR.0113
        x                                  Eynsham : GS 1200
        |<---                              Eynsham Wharf Stream (eff)
        |
        |               *                  Evenlode tributary
        |               |<---              Moreton-in-the-Marsh
        |               |<---              Broadwell Stw
        |               |<---              Chipping Norton Stw
        |               |<---              Milton-under-Wychwood
        |               |<---              Chadlington
        |               |<---              Enstone
        |               |<---              Charlbury
        |               |<---              Middle Barton
        |               |<---              Finstock Stw
        |               |<---              Combe
        |               |<---              Woodstock Stw
        |               |<---              Church Hanbouruggh Stw
        |               x                  B449 Cassington PEVR.0006
        |      67.5     |                  Confluence - Evenlode
78.5    |---------------|
        |<---                              Cassington Stw
82.8    -                                  Trout Inn Godstow : PTHR.0110
        |<---                              Kidlington stw (via Castle Mill Stream)
88.4    -                                  Folly Bridge : PTHR.0085
        |
        |               *                  Cherwell tributary
        |               |<---              Byfield Stw
        |               |<---              Culworth Stw
        |               |<---              Chipping W
        |               |<---              Cropedy
        |               |<---              Shutford
        |               |<---              Chacombe Stw
        |               |<---              Hook Norton Stw
        |               |<---              Greatworth Stw
        |               |<---              Braughton Stw
        |               |<---              Banbury Stw
        |               |<---              Bloxham Stw
        |               |<---              Kings Sutton Stw
        |               |<---              Heyfords
        |               |<---              Grendon Underwood
        |               |<---              Launton
        |               |<---              Marsh Gibbon Stw
        |               |<---              Tackley Stw
        |               |<---              Bicester Stw
        |               |<---              Bletchingdon Stw
        |               |<---              Islip Stw
        |               x                  Marston Road : PCHR.0016
        |      96.4     |                  Confluence - Cherwell
89.2    |---------------|
90.0    -                                  Donnington Bridge : PTHR.0186
        |
        |               *                  Northfield Brook
        |               |<---              Oxford stw
        |               x                  Northfield Bk at Sandford : PTHR.0048
        |      1.8      |                  Confluence - Northfield Bk
93.5    |---------------|
96.2    -                                  Radley College : PTHR.0098
98.0    -                                  Culham Intake : PTHR.0112
```

```
101.0  -                              Abingdon Weir : PTHR.0077
       |
       |            .                 Ock tributary
       |            |<---             Uffington Stw
       |            |<---             Stanford-in-the-Vale Stw
       |            |<---             Kingston Bagpuize Stw
       |            |<---             Wantage Stw
       |            |<---             Appleton Stw
       |            |<---             Gozzards Ford Stw
       |            x                 U\S Thames POCR.0013
       |     37.2   |                 Confluence - Ock
102.1  |------------|
       |<---                          Abingdon Stw (to Thames)
       |
       |            .                 Ginge tributary - Sutton Courtney Weir pool
       |            |<---             Drayton stw
       |            |<---             Abingdon stw
       |            x                 Ginge bk u/s Thames : PTHR.0028
       |     13.0   |                 Confluence - Ginge Bk
105.5  |------------|
       |--->                          Didcot abstraction
105.9  -                              Sutton Courtney GS 1800
       |<---                          Didcot return
       |
       |            .                 Moor Ditch tributary
       |            |<---             Harewell stw
       |            |<---             Didcot stw
       |            x                 Moor ditch Appleford : PTHR.0043
       |     9.2    |                 Confluence - Moor Ditch
109.6  |------------|
       |<---                          Clifton Hampden Ditch (eff)
15.9   -                              Days Lock : PTHR.0083 (GS 1900) <---
       |
       |            .                 Thame tributary
       |            |<---             Tring Stw
       |            |<---             Wingrave Stw
       |            |<---             Weedon Stw
       |            |<---             Waddesdon Stw
       |            |<---             Aylesbury Stw
       |            |<---             Princes Risborough Stw
       |            |<---             Stone Stw
       |            |<---             Chinnor Stw No. 2
       |            |<---             Chinnor Stw
       |            |<---             Haddenham Stw
       |            |<---             Long Crendon
       |            |<---             Thame Stw
       |            |<---             WormingHall Stw
       |            |<---             Watlington Stw
       |            |<---             Wheatley Stw
       |            |<---             Chalgrove Stw
       |            x                 Dorchester Bridge : PTAR.0022
       |            |<---             Dorchester Stw
       |     76.9   |                 Confluence - Thame
117.3  |------------|
       |<---                          Benson Works via Howberry Dtch - poorly entered
   .3  -                              Wallingford Bridge : PTHR.0111
       |<---                          Bradford Brook (eff)
       |
       |            .                 Cholsey Bk tributary
       |            |<---             Cholsey stw
       |            x                 d/s Cholsey stw : PTHR.0016
       |     6.4    |                 Confluence (Cholsey Bk)
2?.0   |------------|
       |<---                          Goring Stw
```

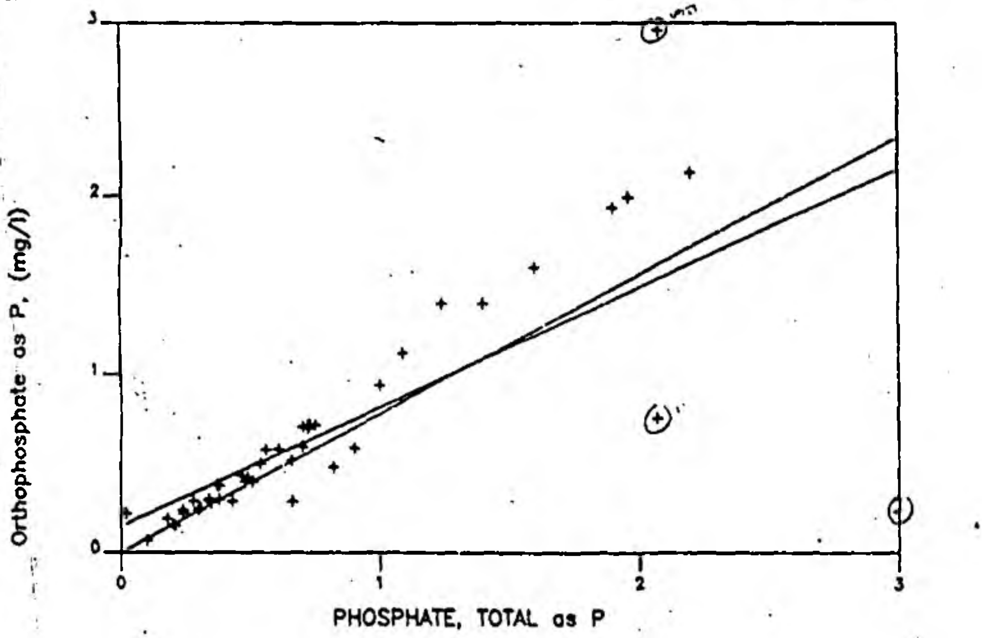
```
133.9  -                                          u/s Goring Weir : PTHR.0120
       |<---                                      Pang (eff)
       |
       |          *                               Sul tributary
       |          |<---                           Pangbourne stw
       |          X                               Saltney Mead : PPSR.0007
       |     6.1  |                               Confluence (Sul)
141.8  |----------|
151.4  -                                          Caversham : PTHR.0080 (GS 2200)
       |
       |          *                               Kennet tributary
       |          |<---                           Fyfield stw
       |          |<---                           Marlborough stw
       |          |<---                           Romsbury stw
       |          |<---                           Great Bedwyn stw
       |          |<---                           Hungerford
       |          |<---                           East Shefford
       |          |<---                           Chievely stw
       |          |<---                           Kintbury stw
       |          |<---                           Washwater
       |          |<---                           Greenham Common
       |          |<---                           Kingsclere stw
       |          |<---                           Newbury stw
       |          |<---                           Woolhampton stw
       |          |<---                           Silchester stw
       |          |<---                           Stratfield stw
       |          |<---                           Burghfield stw
       |          |<---                           Reading stw
       |          X                               U/s Thames : PKER.0025
       |    98.8  |                               Confluence (Kennet)
152.6  |----------|
155.6  -                                          Sonning Weir : PTHR.0102
       |
       |          *                               Loddon tributary
       |          |<---                           Aldershot stw
       |          |<---                           Aldershot military stw
       |          |<---                           Ash Vale stw
       |          |<---                           Sherborne stw
       |          |<---                           Camberley stw
       |          |<---                           Basingstoke stw
       |          |<---                           Sandhurst stw
       |          |<---                           Crondal stw
       |          |<---                           Sherfield stw
       |          |<---                           East Hampstead stw
       |          |<---                           Hartley Wintney stw
       |          |<---                           Fleet stw
       |          |<---                           Arborfield stw
       |          |<---                           Ash Ridge stw
       |          |<---                           Wargrave stw
       |          X                               Loddon Drive Wargrave : PLDR.0032
       |    50.0  |                               Confluence - Loddon
160.5  |----------|
166.1  -                                          Henley Bridge : PTHR.0088
       |<---                                      Henley stw (eff) scaled by Farley Crt str
       |<---                                      Bisham Bk (eff)
       |<---                                      Little Marlow stw
       |
       |          *                               Wye tributary
       |          |<---                           High Wycombe stw
       |          X                               Hedsor GS : PWYR.0015
       |    17.6  |                               Confluence - Wye
184.8  |----------|
       |<---                                      Cookham stw (eff)
185.8  -                                          Cookham Bridge : PTHR.0082
```

```
        |
        |          •            Cut tributary
        |          |<---        Ascot stw
        |          |<---        Bracknell stw
        |          |<---        White Waltham stw
        |          |<---        Maidenhead stw
        |          X            Cut at Cannon Hill
        |    23.7  |            Confluence - Cut
195.3   |----------|
199.1   -                       Bovney : PTHR.0079
        |
        |          •            Bovney ditch tributary
        |          |<---        Burnham stw
        |          |<---        Slough stw
        |          X            Bovney ditch u/s Thames : PTHR.0008
        |    7.0   |            Confluence - Bovney Dtch
99.8    |----------|
00.3    -                       400m d/s Bovney : PTHR.0065
203.4   -                       Romney Lock : PTHR.0001 (Windsor GS 2700)
        |--->                   Datchet abstraction(T10)
8.1     -                       Sunnymeads Intake : PTHR.0108
        |--->                   Sunnymeads abstraction
        |<---                   Windsor stw
        |--->                   Egham NSWC abstraction
        |
        |          •            Colne(Brook) tributary
        |          |<---        Markyate stw
        |          |<---        Berkhamsted stw
        |          |<---        Blackbirds stw
        |          |<---        Chesham stw
        |          |<---        Maple Lodge stw
        |          X            Denham GS : PCNR.0027
        |          |---•        Colne\Colne Brook bifurcation
        |    51.8  -            Colne Brook Reach
        |          |<---        Iver North stw
        |          |<---        Iver South stw
        |          X            Colne Brook u/s of Thames : PCNR.0039
        |    66.8  |            Confluence - Colne Brook
214.4   |----------|
215.0   -                       u/s Egham : PTHR:0075
        |
        |          •            Colne Tributary
        |          |<---        Misbourne (eff)
        |          |<---        Accretion flow (eff)
        |          X            Colne u/s of Thames : PCNR.0025
        |    18.0  |            Confluence - Colne
16.1    |----------|
        X                       Staines : GS 2900
        |--->                   Littleton abstraction(T14)
20.8    -                       Chertsey Intake : PTHR.0096
        |--->                   NSWC Chertsey abstraction
        |
        |          •            Chertsey Bourne tributary
        |          |<---        Lightwater stw
        |          |<---        Chobham stw
        |          |<---        Chertsey stw
        |          X            Bourne u\s Thames : PBNR.0005
        |    25.0  |            Confluence - Bourne
.4      |----------|
        |
        |          •            Wey tributary
        |          |<---        Haslemere stw
        |          |<---        Alton stw
        |          |<---        Bentley stw
```

```
       |           |<---                              Bordon stw
       |           |<---                              Farnham stw
       |           |<---                              Elstead stw
       |           |<---                              Cranleigh stw
       |           |<---                              Shamley stw
       |           |<---                              Godalming stw
       |           |<---                              Guildford stw
       |           |<---                              Hockford stw
       |           |<---                              Woking stw
       |           |<---                              Ripley stw
       |           |<---                              Wisley stw
       |           |<---                              Weybridge stw
       |           x                                  Wey u/s Thames : PWER.0030
       |     87.0  |                                  Confluence - Wey
225.5  |-----------|
225.7  -                                              u/s Walton : PTHR.0074
       |--->                                          NSWC Walton abstraction
228.7  -                                              Walton GS 3100
       |<---                                          Ash tributary - eff
230.8  -                                              Walton Intake : PTHR.0094
       |--->                                          Walton abstraction(T15)
       |--->                                          Hampton abstraction(T22,T23)
       |
       |           *                                  Mole tributary
       |           |<---                              Merstham stw
       |           |<---                              Crawley
       |           |<---                              Burstow stw
       |           |<---                              Horley stw
       |           |<---                              Holmwood stw
       |           |<---                              Reigate stw
       |           |<---                              Dorking stw
       |           |<---                              Leatherhead stw
       |           |<---                              Esher stw
       |           x                                  U\s Thames
       |     80.2  |                                  Confluence - Mole
236.0  |-----------|
238.4  -                                              Ravens AIT : PTHR.0076
       |
       |           *                                  Hogsmill tributary
       |           |<---                              Hogsmill stw
       |           x                                  Hogsmill u/s Thames : PHMR.0010
       |      2.4  |                                  Confluence - Hogsmill
240.0  |-----------|
       x                                              Teddington : PTHR.0107 (GS 3400)
242.6  #
```

End of report

[redacted] [redacted]HAM[redacted] WAT[redacted]TAKE, [redacted]MOOR[redacted] PTHR.0113

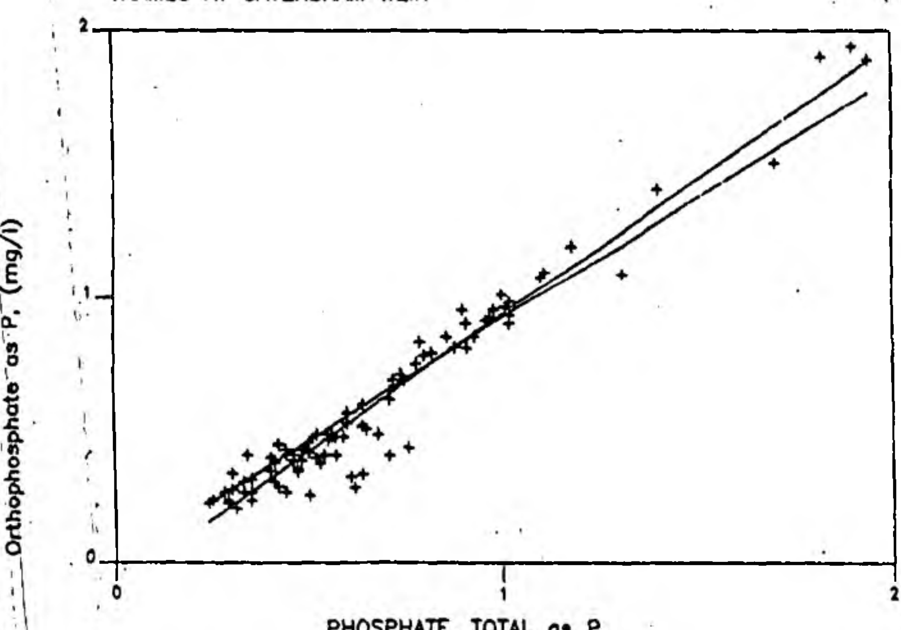


ALISON.DAT ++++++

Archive data

Fig A1.3

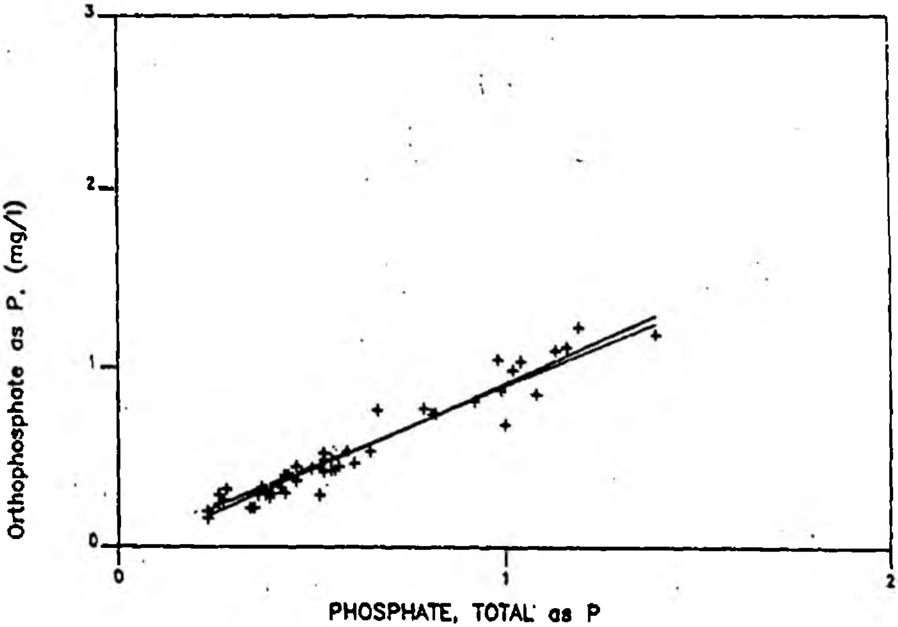
THAMES AT CAVERSHAM WEIR PTHR.0080



ALISON.DAT ++++++

Archive data

THAMES AT DAYS LOCK PTHR.0083

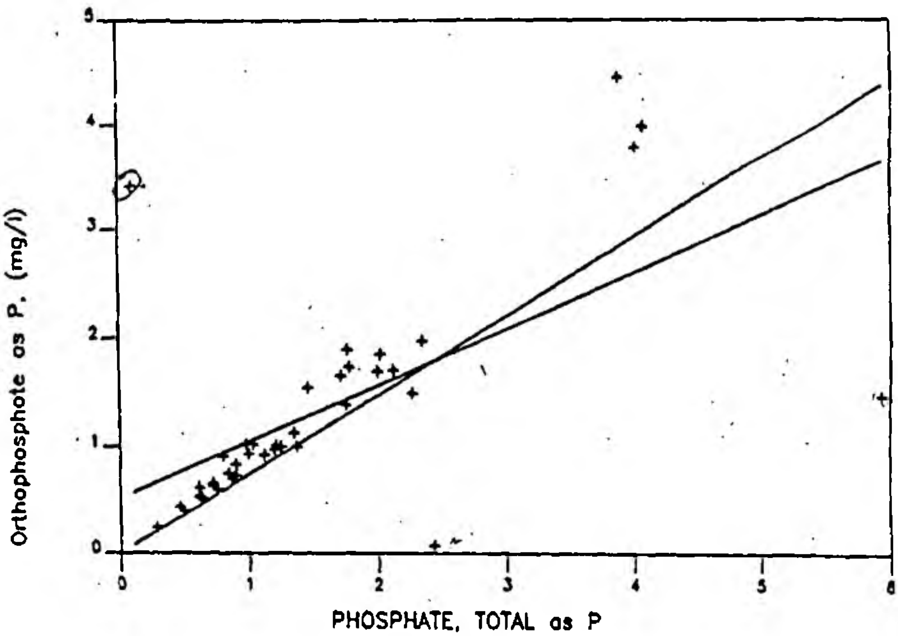


ALISON.DAT ++++++

Archive data

Fig AI.4

THAMES AT TEDDINGTON WEIR PTHR.0107



ALISON.DAT ++++++

Appendix 2. Variation in loads from STWs.

In order to construct a model of STW loads the relationship between flow and orthophosphate concentration was examined as well as the winter/summer variation in load.

Daily flow data (between Jan 1991 - Oct1994) from three Thames STWs Reading, Blackbirds and Godalming was plotted against corresponding quality data. It was found not possible to fit a significant regression line to these data sets using either raw or logged data. Also no significant difference between winter and summer loads from each works was found when using a ttest to compare the summer mean and winter mean. This is surprising because since no seasonal variation has been found in the load data it might have been expected that a flow vs quality relationship would have been found. The reason that this has not occured is probably due to the fact that different statistical tests were used to investigate the different relationships.

The variation of load from these works was next investigated using histogram plots. These appeared approximately normal with coefficient of variations of 0.24 at Reading, 0.27 at Blackbirds and 0.10 at Godalming.

It was decided to use a non-seasonal, normally distributed load model for orthophosphate in TOMCAT. This was achieved by using a constant STW flow and using a normally distributed concentration. Since no relationship could be found between shapes of the quality and load distributions for the three STW under study it was decided to fix the coefficient of variation of the quality distribution at 0.25 for all STWs. During calibration of the tributaries in TOFU, this value was varied between 0.1 and 0.4 and the model was found not to be sensitive to it.

Appendix 3. Thames agricultural phosphorus load.

Agricultural loads of orthophosphate may be calculated by assuming that all of the land upstream of a particular sampling point is agricultural land and then using an estimate of the average load per hectare per year. Literature values for agricultural load vary considerably. They are summarized by SCOPE 1989 who give between 0.08kg/ha/yr and 0.46kg/ha/yr for orthophosphate and between 0.2kg/ha/yr and 1.2kg/ha/yr for total phosphorous, on agricultural land.

In order to estimate the agricultural load in the Thames catchment a number of sites upstream of any point source discharges were selected. Mean orthophosphate concentrations were then calculated for October 1992 to September 1994 data using zero and face value for less than values. These figures are shown below in table A3.1.

Also shown are equivalent agricultural loads calculated by using the Institute of Hydrology's Micro Low Flow package to estimate the flow and upstream land area at the sample point. It should be noted though that these agricultural estimates are for net loading after loss in the watercourse. The figures quoted above are for loads before loss in the watercourse.

Table A3.1
Orthophosphate concentrations upstream of STW discharges.

River	Drainage area ha	Concentration mg/l	Equivalent agri load(kg/ha/yr)
Thames	-	0.01-0.07	-
Churn	1930	0.00-0.07	0.01-0.27
W. Ray	550	0.04-0.07	0.29-0.56
Ampney Bk	4550	0.01-0.07	0.02-0.2
Leach	7600	0.01-0.07	0.04-0.29
O. Ray	-	1.38-1.38	-
Charlton Bk	-	0.04-0.09	-
Tadmarton Str	-	0.02-0.08	-
Og*	6300	0.03-0.07	0.14-0.32
Loddon**	4530	0.00-0.06	0.01-0.29

* 1 data point removed
** 2 data points removed

The average upper estimate for agricultural load from the figures above is 0.32kg/ha/yr. This value was used in TOFU to estimate the agricultural load.

Appendix 4. Calculation of river loads.

The load in the river may be calculated using one of three techniques

1. mean (flow * concentration for day matched data)
2. mean (concentration * mean monthly flow)
3. mean concentration * mean flow .

Gauged flows are available at 11 sites along the river Thames. These are shown in Table A4.1 along with the sampling point which best represents the quality at the site. There is a poor data set at Ewen. Mean flows at six of these gauging sites are shown in table A4.2, and mean loads are shown in table A4.3.

It may be seen that these different methods produce considerably different results. Method 1 may be used as a low estimate of the load whilst method 3 as a high estimate.

An improvement on the above methods for calculating river load is explained by Ferguson 1986. This method regresses the flow against the concentration and then uses a correction factor to remove bias introduced during the regression. This method has not been further investigated in this study owing to time constraints but any further work could consider using this method.

Reference.

1. Ferguson R.I. January 1986. River loads underestimated by Rating Curves. Water Resources Research Vol 22 pp 74-76.

Table A4.1.
Flow Gauging Stations on the Thames.

Name	No.	First year	Nearest Sample Point	URN
Ewen	0130	1979	Somerford Keynes	PUTR.0104
Cricklade	0190	1971	Cricklade	PUTR.0091
Buscot	0900	1979	Buscot Intake	PUTR.0107
Eynsham	1200	1951	Farmoor	PTHR.0113
Sutton Courteney	1800	1973	----------------	--------
Days	1900	1938	Days	PTHR.0083
Caversham	2200	8.1992	Caversham	PTHR.0080
Royal Windsor	2700	1978	Sunnymeads Intake	PTHR.0108
Staines	2900	10.1990	Chertsey Intake	PTHR.0096
Walton	3100	8.1991	u\s Walton	PTHR.0074
Teddington	3400	1882	Teddington	PTHR.0107

Table A4.2
Mean Yearly Flows in the Thames 1991 - 1993 (Ml/day).

Station name	Station No.	91	92	93	91-93	91-93 Mch-Oct	91-93 Apr-Sept
Buscot	0900	559	836	799	731	499	442
Eynsham	1200	744	1280	1318	1114	709	600
Eynsham(nat)	11200	876	1407	1449	1244	838	725
Days	1900	1351	2685	2700	2246	1454	1228
Days(nat)	11900	1393	2725	2759	2293	1488	1259
Windsor	2700	3152	4810	5516	4490	3249	2908
Staines	2900	2576	4287	5632	4177	2966	2528
Staines(nat)					5041	3830	3392
Teddington	3400	2145	4251	5899	4099	2693	2177
Teddington(nat)	13400	4205	6334	7707	6082	4574	4085

nat - natural flow

Table A4.3.
Mean Phosphate loads in the Thames 1991-1993(kgP/day).

Station Name	1	2	3	4	5	6
Buscot	368	356	538	383	458	432
Eynsham	394	420	553	361	420	366
Eynsham(nat)	441	470	619	427	496	442
Days	1119	1182	1414	895	1063	915
Days(nat)	1141	1206	1442	916	1088	938
Windsor	3278	3126	4314	284	3606	3370
Staines	3063	3102	4402	2284	3619	3246
Staines(nat)	3697	3743	5313	2949	4673	4483
Teddington	3392	4047	5033	2654	3743	3322
Teddington(nat)	5033	6004	7467	4508	6358	6236

Notes.

1 = mean (conc * flow on day of conc measurement)
2 = mean (conc * mean monthly flow)
3 = mean conc * mean flow
4 = as 1 but for March - October of each year
5 = as 3 but using March - October data
6 = as 3 but using april - Sept data

Natural loads are calculated by scaling the measured loads by (mean natural flow / mean gauged flow) from table A4.2.

Appendix 5. Calibration and validation of Thames phosphate model.

Introduction.

This appendix contains a brief overview of the Tomcat model set up and discusses the calibration and validation results. It should be read in conjunction with section 4 of the main report.

The conceptual design of the Tomcat model has been developed in the main report section 4.1,4.2. It is summarized here.

The water chemistry of phosphorus is too complicated and too little data is available for a full phosphorus model to be currently created. Instead a simplified approach has been taken with only orthophosphate having been modelled. Also because of the unavailability of time of travel data for many of the tributaries it was decided to use an empirical approach, with the decay of orthophosphate been an exponential function of distance. This approach should therefore be considered an improved mass balance estimate.

Model set up.

The model has been set up for calibration using October 1992 to September 1994 data. The model spans the Thames between Ashton Keynes and Teddington. The validation model was set up using January 1982 to December 1983 data spanning between Cricklade and Teddington. Cricklade is 19km downstream of Ashton Keynes and downstream of the first major STW discharge from Cirencester. No data was available for the 1982/1983 time period upstream of Cricklade.

The validation time period has on average lower STW and river flows than during the calibration time period. STW and river orthophosphate concentrations are higher. This is demonstrated in figure A5.1 where main river mean concentrations for the two time periods are plotted with average river concentrations changing from 0.9mg/l during 1982/1983 to 0.5mg/l during 1992/1994.

STW's and Tributaries.

There are 67 STW's with population equivalents exceeding 10,000 in the calibration model and 65 in the validation model. Abingdon New and Cirencester are not included in the validation model. There are also 240 minor STW's. In order to simulate the loading of orthophosphate from STW's (see appendix 2) actual mean STW flows are used wherever they are available and mean orthophosphate concentrations with a coefficient of variation of 0.25. Where actual flows are not available, the nearest available years flow is used and where no flows are available consented flows are used instead.

Each tributary is modelled as a single river. STW discharging via a tributary are sited at their total distance upstream of the Thames on the tributary. Branches in tributaries are therefore not modelled. When no major STW occurs on a tributary the tributary is treated as an effluent discharging directly to the main river using sample point data from the bottom of the tributary. Thus minor STW's occurring on these types of tributaries are modelled implicitly.

Flows in tributaries were calculated using gauging station information when it existed or Micro Low Flow estimates combined with another watercourse's (of similar geological make up) gauged flow when it didn't.

Agriculture.

Tomcat models accretion load by adding a volume per km per day to a watercourse, with an associated concentration. For each tributary the area of the tributary was known and the estimated agricultural load of 0.32kg/ha/yr could then be converted into an accretion loading.

Calibration of tributaries.

Most tributaries entering the river Thames have sample point data just upstream of the confluence with the Thames. This data was used for calibrating each tributary. The decay term was adjusted until the statistical tests used in TOMCAT were passed.

During validation of the model the decay used during calibration of a tributary was used in the validation model of the tributary. If the fit was poor an attempt was made for each tributary to find a common decay term which allowed both time period models to pass the statistical tests.

Calibration of the model was generally successful though poor fits were found in the Colne and Hogsmill. The half life for decay in the tributaries varied between 11km and 270km. This high range probably reflects the variety of tributaries modelled and the empirical nature of the decay term. The decay term blankets many physical and chemical processes (see section 4.1) and in order to better understand this high range more detailed modeling work on a variety of tributaries needs to be conducted.

Validation of the model was again mainly successful with common decay terms been found in all tributaries apart from the river Colne and Ginge Brook. The operating scheme of Abingdon STW has changed between the two time periods which is likely why validation was not successful. A poor statistical fit was also found again in the Hogsmill.

Calibration and validation were often found to be very sensitive to STW flow. If more detailed modelling work is required on any tributary, better STW flow estimates must be obtained.

Main river calibration.

Cricklade gauging station was used to calculate the upstream flow in the main river. Accretion was then added to make up any missing flow at the gauging stations downstream towards Teddington. Accretion concentration was adjusted to account for any land area agricultural load not already included in the tributary flows. Mean flow simulation was good (see fig 4.2 main report - calibration, fig A5.2 - validation) but even though flow correlation was used throughout the model it was found that main river 5th and 95th percentile flow modelling was poor. No attempt was made to improve this simulation due to restrictions in time. This is an area which could be further investigated, though since only mean orthophosphate concentrations are of interest it may not lead to any significant improvements in model predictions.

32 sampling points are available for calibration on the main Thames for the calibration time period. No decay was required to obtain the best statistical fit in the main river Thames. Results of the statistical comparison between the modelled and simulated data sets are shown in table A5.1. It may be seen that all tests are passed at most sites. Figure A5.1 shows the actual and simulated data plotted longitudinally down the river Thames.

For the validation time period 18 sample points are available for comparison. Decay was required along the whole river though mostly the decay required was very small with a half life greater than 500km. A higher decay was required between Farmoor and Caversham with a half life of 277km though this is still small in comparison to the decay required in most of the tributaries. Statistical comparison between modelled and observed data are shown in table A5.2. The decay was adjusted so as to give the best statistical fit. Figure A5.1 shows the actual and simulated data plotted longitudinally down the river Thames.

The difference in decay between the two time periods is of concern. Technically this means that the model has failed to validate. In order therefore to determine the usefulness of the model, the sensitivity of the model predictions to the variability in decay was examined. This is discussed in the next section.

Sensitivity of predictions.

The calibration and validation models were run with and without decay in the main river Thames in order to estimate the sensitivity of the phosphate index(see section 4.5.1). It was discovered that the ranked order of STW changed very little for the top 15 or so works. Table A5.3 and A5.4 show this. Table A5.3 is the ranked works for zero decay in the Thames during the validation period. Table A5.4 is for the same model but with main river decay. It can be seen that apart from a little shuffling the top 15 works are the same with or without decay. The stability of the model to this decay allows us to be confident about our ranking table. It may be seen that after about the 15th works the table order does become sensitive to the decay and therefore the predictions become unreliable. The same behaviour is shown for the calibration period. Comparison of table 4.2 in the main report with table A5.5 shows a similar stability in the top 15 works.

The other effect the model is examining is post removal concentrations. Fig A5.3 shows pre and post removal concentrations down the main river Thames for both the validation and calibration time periods for the model run both with and without decay. It may be seen that the inclusion of decay has decreased post removal river concentrations of orthophosphate from around 0.3mg/l to 0.25mg/l for the calibration time period and from around 0.4mg/l to 0.35mg/l for the validation time period.

Conclusions.

Tributary validation has proven to be successful apart from in the river Colne sub catchment. Main river validation has not been so successful though the model still appears a useable tool for ranking the impact of STW on river orthophosphate concentrations and for estimating post STW removal river orthophosphate concentrations.

If more detailed results are required from the model I recommend that the following work should be considered:-

1. Improvement to the main river Thames flow model.

2. Obtain better STW flow estimates from all STW under consideration.

3. Ginge Brook(Abingdon STW) and the Colne sub-catchment need closer investigation.

4. A better understanding of the processes that our empirical decay term is blanketing needs to be gained. This could be carried out by setting up a time series model of a tributary using phosphorus fraction data collected during special surveys. High flow, storm flow and low flow events would all be worthy of modelling.

5. Seasonal modelling should be conducted.

6. Variability in the Thames decay term should be investigated.

Table A5.1 – Statistical comparison of observed to simulated data.
Calibration time period no decay.

Site name	ttst	mw	ks
Cricklade : PUTR.0091	pass	accept	accept
Eysey : PUTR.0093	pass	accept	reject
Castle Eaton : PUTR.0090	pass	accept	accept
Hannington Bridge : PUTR.0096	pass	accept	accept
Inglesham : PUTR.0097	pass	accept	accept
Buscot Intake : PUTR.0107	pass	accept	accept
Newbridge : PUTR.0099	pass	reject	reject
Farmoor : PTHR.0113	pass	accept	accept
Trout Inn Godstow : PTHR.0110	pass	accept	accept
Folly Bridge : PTHR.0085	pass	accept	accept
Donnington Bridge : PTHR.0186	pass	accept	accept
Radley College : PTHR.0098	pass	accept	accept
Abingdon Weir : PTHR.0077	pass	accept	accept
Days Lock : PTHR.0083	pass	accept	accept
Wallingford Bridge : PTHR.0111	pass	accept	accept
u/s Goring Weir : PTHR.0120	pass	accept	accept
Caversham : PTHR.0080	pass	accept	accept
Sonning Weir : PTHR.0102	pass	accept	accept
Henley Bridge : PTHR.0088	pass	accept	accept
Cookham Bridge : PTHR.0082	pass	accept	accept
Bovney : PTHR.0079	pass	accept	accept
400m d/s Bovney : PTHR.0065	pass	accept	accept
Romney Lock : PTHR.0001	pass	accept	accept
Sunnymeads Intake : PTHR.0108	pass	accept	accept
u/s Egham : PTHR.0075	pass	accept	reject
Chertsey Intake : PTHR.0096	pass	accept	accept
u/s Walton : PTHR.0074	pass	accept	accept
Walton Intake : PTHR.0094	pass	accept	accept
Ravens AIT : PTHR.0076	pass	accept	accept
Teddington : PTHR.0107	pass	accept	accept

Table A5.2 – Statistical comparison of observed to simulated data.
Validation time period with decay.

Site name	ttst	mw	ks
Eysey : PUTR.0093	pass	accept	accept
Hannington Bridge : PUTR.0096	pass	accept	reject
Buscot Intake : PUTR.0107	pass	accept	reject
Farmoor : PTHR.0113	pass	accept	accept
Culham Intake : PTHR.0112	pass	accept	accept
Abingdon Weir : PTHR.0077	pass	accept	reject
Days Lock : PTHR.0083	pass	accept	reject
Wallingford Bridge : PTHR.0111	pass	accept	accept
u/s Goring Weir : PTHR.0120	pass	accept	accept
Caversham : PTHR.0080	pass	accept	reject
Sonning Weir : PTHR.0102	pass	accept	accept
Henley Bridge : PTHR.0088	pass	accept	accept
Cookham Bridge : PTHR.0082	pass	accept	accept
Bovney : PTHR.0079	pass	accept	accept
u/s Egham : PTHR.0075	pass	accept	accept
Walton Intake : PTHR.0094	pass	accept	accept
Ravens AIT : PTHR.0076	pass	reject	reject
Teddington : PTHR.0107	pass	accept	reject

Key to tables A5.1 and A5.2

ttest – ttest performed at 95% confidence level
mw – Mann Whitney test performed at 5 % confidence level
ks – Kolmogorov Smirnov performed at 90% confidence level

Table A5.3 – Prioritory list of STWs for validation time period with no decay in the model

	Sensitive Area Index %	Upper Thames Index %
Oxford STW	13.29	9.54
Swindon STW	8.38	47.86
Reading STW	8.28	0
Maple Lodge STW	3.62	0
Aylesbury STW	3.54	0
Wargrave STW	2.89	0
Little Marlow STW	2.38	0
Slough STW	2.33	0
Abingdon STW	2.3	0.35
Wantage STW	1.75	0.26
Kidlington STW	1.62	1.13
High Wycombe STW	1.61	0
Bracknell STW	1.6	0
Bicester STW	1.51	1.05
Cholsey STW	1.33	0
Didcot STW	1.23	0.17
Newbury STW	1.16	0
Maidenhead STW	1.09	0
Witney STW	1.09	2.34
Basingstoke STW	1.06	0
Pangbourne STW	0.95	0
Ash Ridge STW	0.87	0
Cassington STW	0.87	0.6
Windsor STW	0.84	0
Princes Risborough STW	0.82	0
Camberley STW	0.8	0
Sandhurst STW	0.7	0
Fleet STW	0.69	0
Thame STW	0.66	0
Silchester STW	0.64	0
Carterton STW	0.57	1.3
Banbury STW	0.57	0.39
Tring STW	0.53	0
Henley STW	0.52	0
Esher STW	0.49	0
Chertsey STW	0.48	0
Ascot STW	0.45	0
Blackbirds STW	0.44	0
Arborfield STW	0.4	0
Guildford STW	0.36	0
Woking STW	0.36	0
Burnham STW	0.32	0
Hartley Wintney STW	0.3	0
Aldershot STW	0.29	0
Ash Vale STW	0.26	0
Weybridge STW	0.23	0
Chesham STW	0.18	0
Crawley STW	0.14	0
Reigate STW	0.13	0
Wisley STW	0.12	0
Ripley STW	0.12	0
Hockford STW	0.12	0
Farnham STW	0.12	0
Godalming STW	0.12	0
Cranleigh STW	0.11	0
Lightwater STW	0.11	0
Bordon STW	0.11	0
Berkhamsted STW	0.11	0
Leatherhead STW	0.09	0
Hogsmill STW	0.09	0
Dorking STW	0.08	0
Aldershot military STW	0.05	0
Horley STW	0.05	0
Haslemere STW	0.04	0
Alton STW	0.04	0
Other	21.61	35.02
Total	100	100

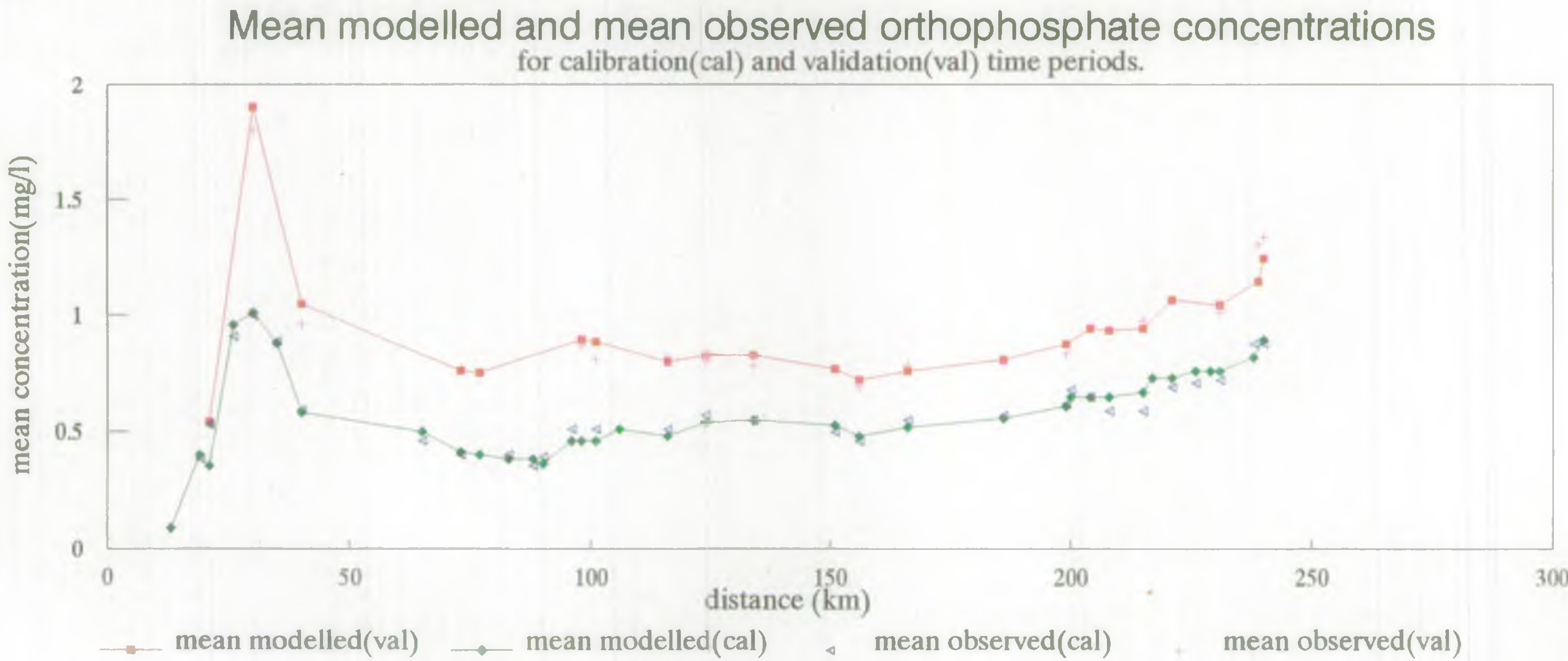
Table A5.4 – Prioritory list of STWs for validation time period with decay in the model

	Sensitive Area Index %	Upper Thames Index %
Oxford STW	12.71	9.6
Reading STW	8.88	0
Swindon STW	7.25	47.83
Maple Lodge STW	3.88	0
Aylesbury STW	3.57	0
Wargrave STW	3.08	0
Little Marlow STW	2.64	0
Slough STW	2.52	0
Abingdon STW	2.29	0.35
Wantage STW	1.74	0.26
Bracknell STW	1.73	0
High Wycombe STW	1.7	0
Kidlington STW	1.55	1.13
Bicester STW	1.44	1.04
Cholsey STW	1.37	0
Newbury STW	1.28	0
Maidenhead STW	1.14	0
Basingstoke STW	1.12	0
Didcot STW	1.08	0.18
Ash Ridge STW	1.02	0
Pangbourne STW	0.97	0
Camberley STW	0.92	0
Witney STW	0.85	2.32
Windsor STW	0.81	0
Princes Risborough STW	0.74	0
Sandhurst STW	0.73	0
Fleet STW	0.73	0
Cassington STW	0.72	0.58
Silchester STW	0.7	0
Thame STW	0.63	0
Ascot STW	0.54	0
Henley STW	0.52	0
Banbury STW	0.5	0.39
Esher STW	0.5	0
Tring STW	0.49	0
Carterton STW	0.49	1.29
Chertsey STW	0.48	0
Blackbirds STW	0.37	0
Guildford STW	0.35	0
Woking STW	0.35	0
Arborfield STW	0.34	0
Hartley Wintney STW	0.32	0
Burnham STW	0.31	0
Aldershot STW	0.27	0
Ash Vale STW	0.22	0
Crawley STW	0.15	0
Reigate STW	0.15	0
Godalming STW	0.13	0
Wisley STW	0.13	0
Ripley STW	0.13	0
Hockford STW	0.13	0
Weybridge STW	0.13	0
Farnham STW	0.13	0
Leatherhead STW	0.1	0
Hogsmill STW	0.1	0
Bordon STW	0.09	0
Lightwater STW	0.09	0
Aldershot military STW	0.08	0
Dorking STW	0.06	0
Horley STW	0.05	0
Cranleigh STW	0.01	0
Chesham STW	0.01	0
Alton STW	0	0
Berkhamsted STW	0	0
Haslemere STW	0	0
Other	22.5	35.03
Total	100	100

Table A5.5 – Priority list of STWs for calibration time period with decay in the model

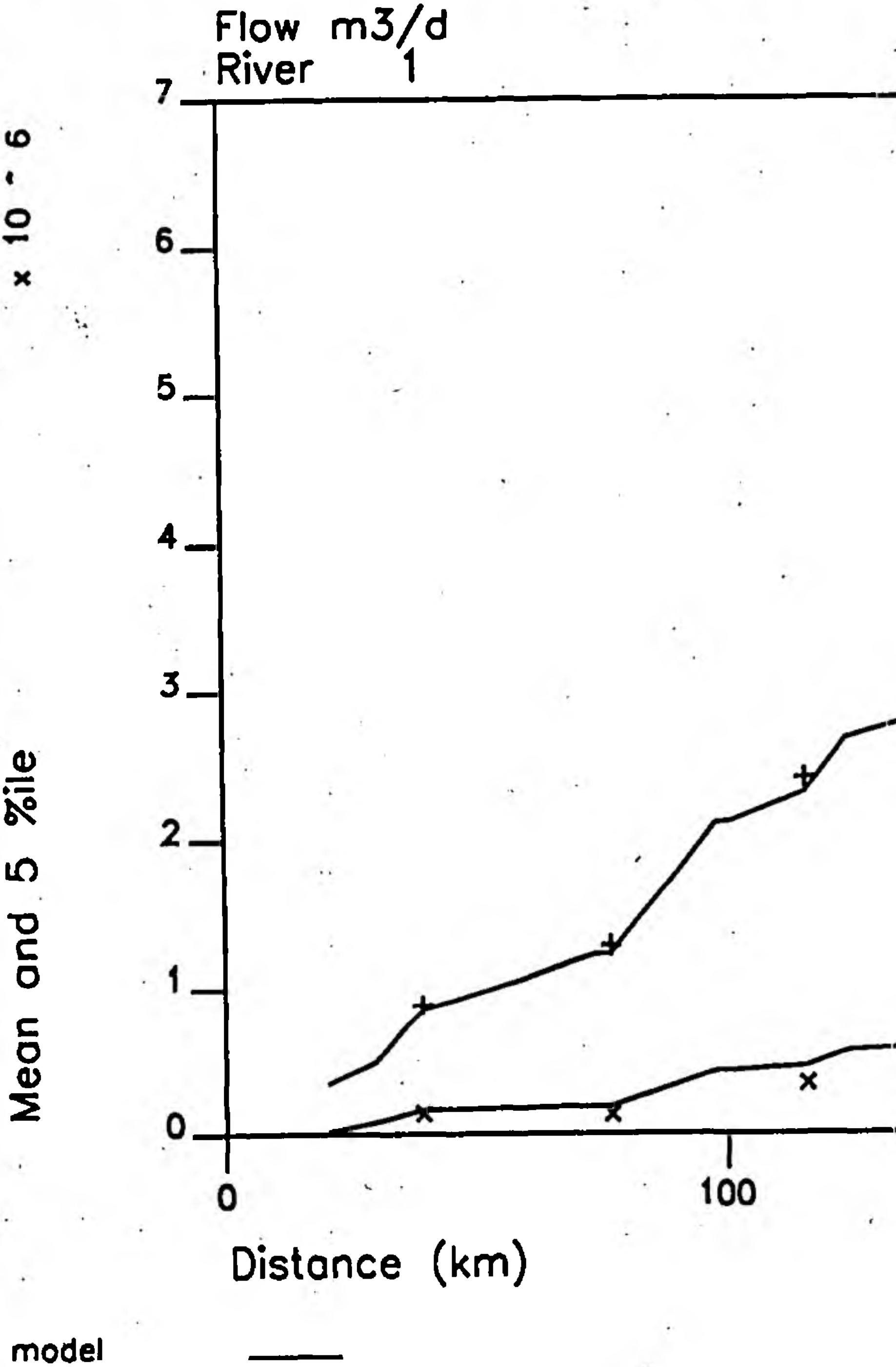
	Sensitive Area Index %	Upper Thames Index %
Oxford STW	8.42	4.89
Reading STW	7.71	0
Swindon STW	5.87	44.13
Wargrave STW	4.78	0
Aylesbury STW	4.7	0
Maple Lodge STW	3.41	0
Little Marlow STW	3.33	0
Abingdon STW (to Thames)	2.72	0.79
Wantage STW	2.11	0.64
Maidenhead STW	1.8	0
Slough STW	1.77	0
High Wycombe STW	1.67	0
Bracknell STW	1.31	0
Cassington STW	1.27	1.39
Banbury STW	1.19	0.85
Didcot STW	1.14	0.13
Bicester STW	1.1	0.76
Cholsey STW	1.03	0
Princes Risborough STW	0.93	0
Windsor STW	0.91	0
Abingdon STW	0.85	0.27
Ash Ridge STW	0.84	0
Fleet STW	0.8	0
Pangbourne STW	0.75	0
Sandhurst STW	0.73	0
Kidlington STW	0.72	0.61
Witney STW	0.7	1.16
Thame STW	0.67	0
Basingstoke STW	0.67	0
Carterton STW	0.63	1.98
Camberley STW	0.63	0
Chertsey STW	0.62	0
Silchester STW	0.59	0
Weybridge STW	0.52	0
Cirencester STW	0.49	6.48
Hartley Wintney STW	0.49	0
Ascot STW	0.48	0
Tring STW	0.42	0
Esher STW	0.4	0
Blackbirds STW	0.4	0
Newbury STW	0.38	0
Henley STW	0.36	0
Guildford STW	0.36	0
Burnham STW	0.36	0
Reigate STW	0.35	0
Arborfield STW	0.35	0
Woking STW	0.31	0
Aldershot STW	0.24	0
Crawley STW	0.18	0
Godalming STW	0.17	0
Wisley STW	0.14	0
Ripley STW	0.12	0
Hogsmill STW	0.12	0
Chesham STW	0.12	0
Hockford STW	0.09	0
Farnham STW	0.09	0
Berkhamsted STW	0.08	0
Ash Vale STW	0.08	0
Bordon STW	0.08	0
Cranleigh STW	0.07	0
Leatherhead STW	0.07	0
Aldershot military STW	0.06	0
Dorking STW	0.06	0
Horley STW	0.05	0
Lightwater STW	0.03	0
Haslemere STW	0.02	0
Alton STW	0.02	0
Other	26.07	35.91
Total	100	100

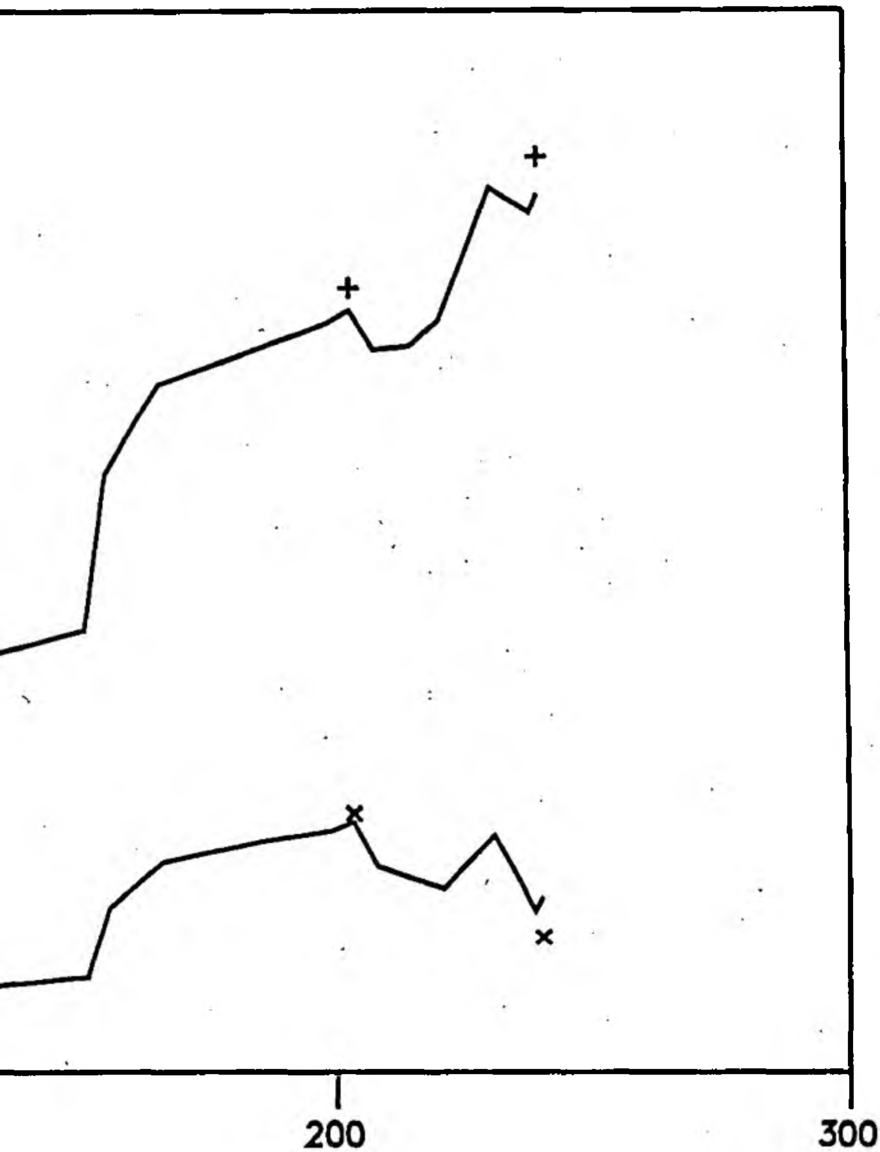
Figure A5.1



Mean modelled and mean observed orthophosphate concentrations
for calibration(cal) and validation(val) time periods.
mean concentration(mg/l)
2
1.5
1
0.5
0
0
50
100
150
200
250
300
distance (km)
mean modelled(val)
mean modelled(cal)
mean observed(cal)
mean observed(val)

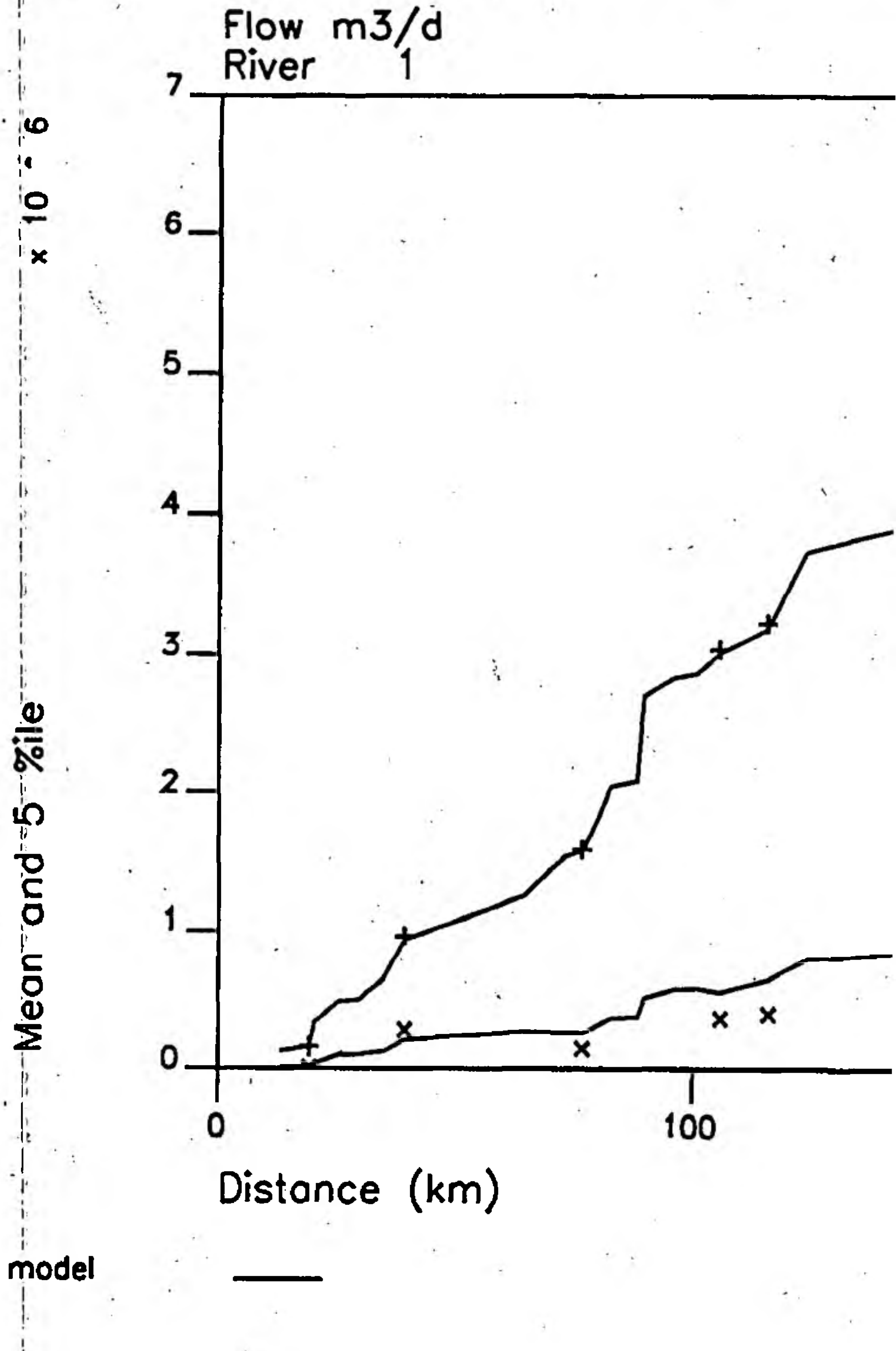
Fig [redacted] 2. [redacted]



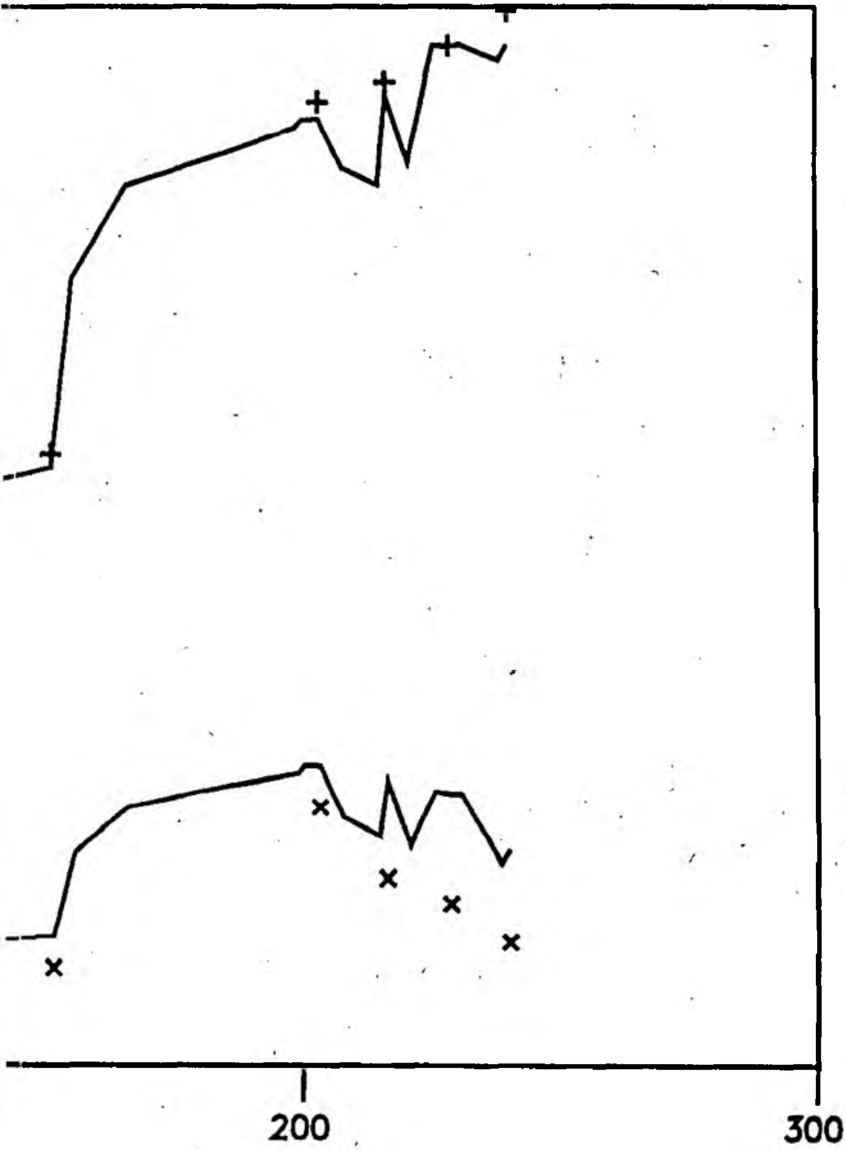


Mean ++++++ Percentile xxxxxx

[redacted] Fig. 2 [redacted] F [redacted] C [redacted] at [redacted] in [redacted] ain [redacted] ive [redacted] l he [redacted]



[redacted]



Mean ++++++ Percentile xxxxxx

Figure 4.3

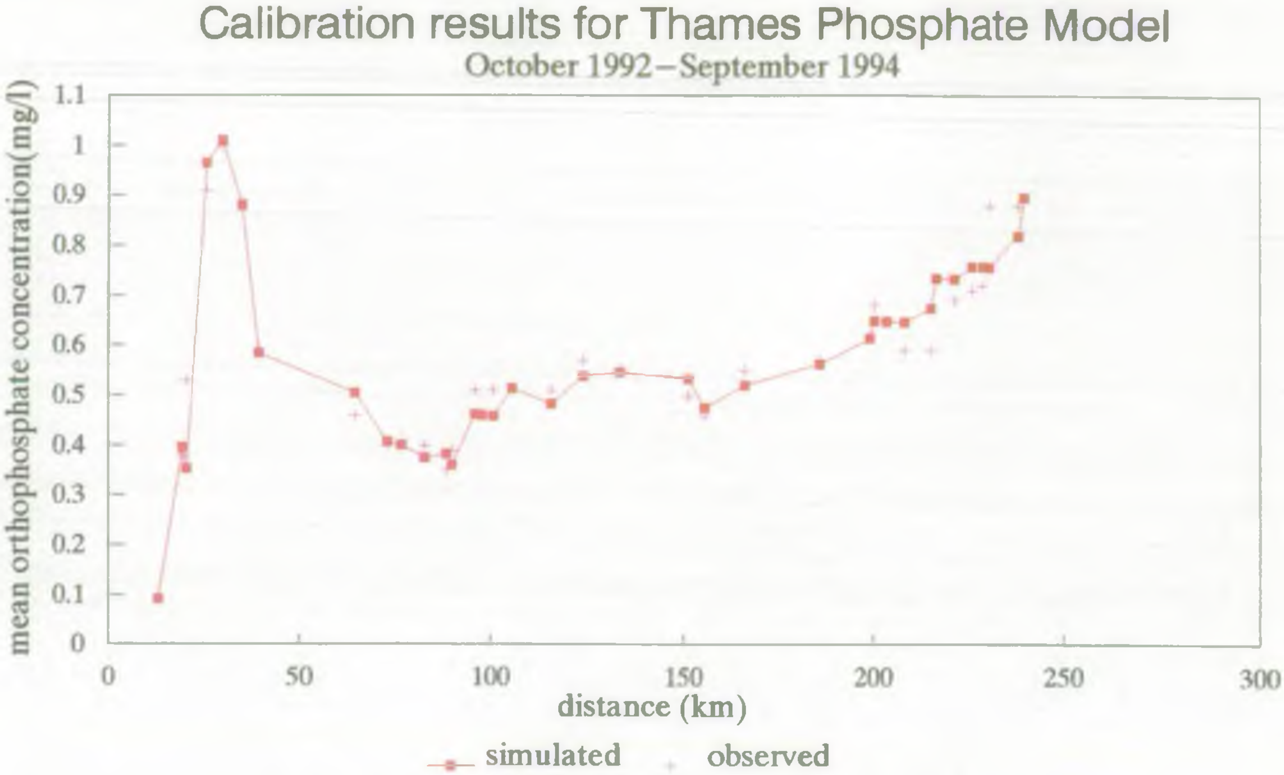


Figure 4.4

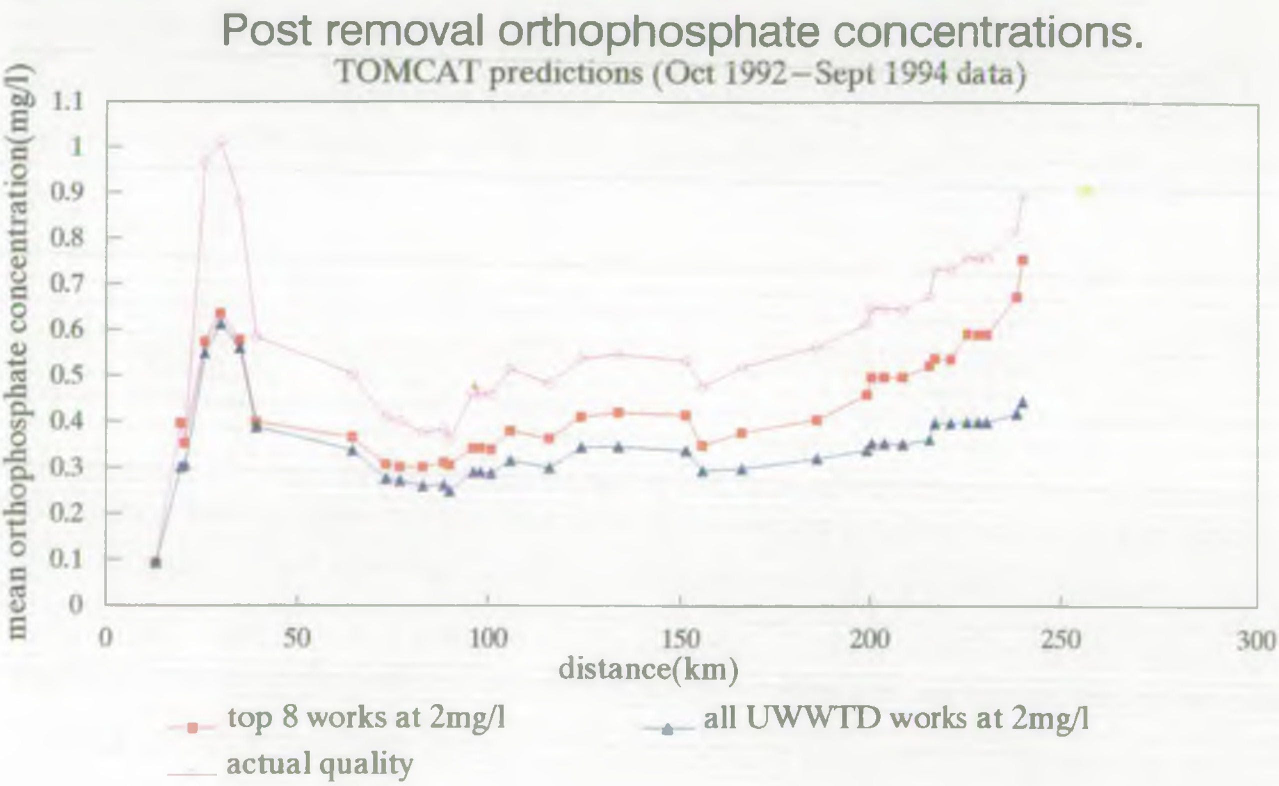
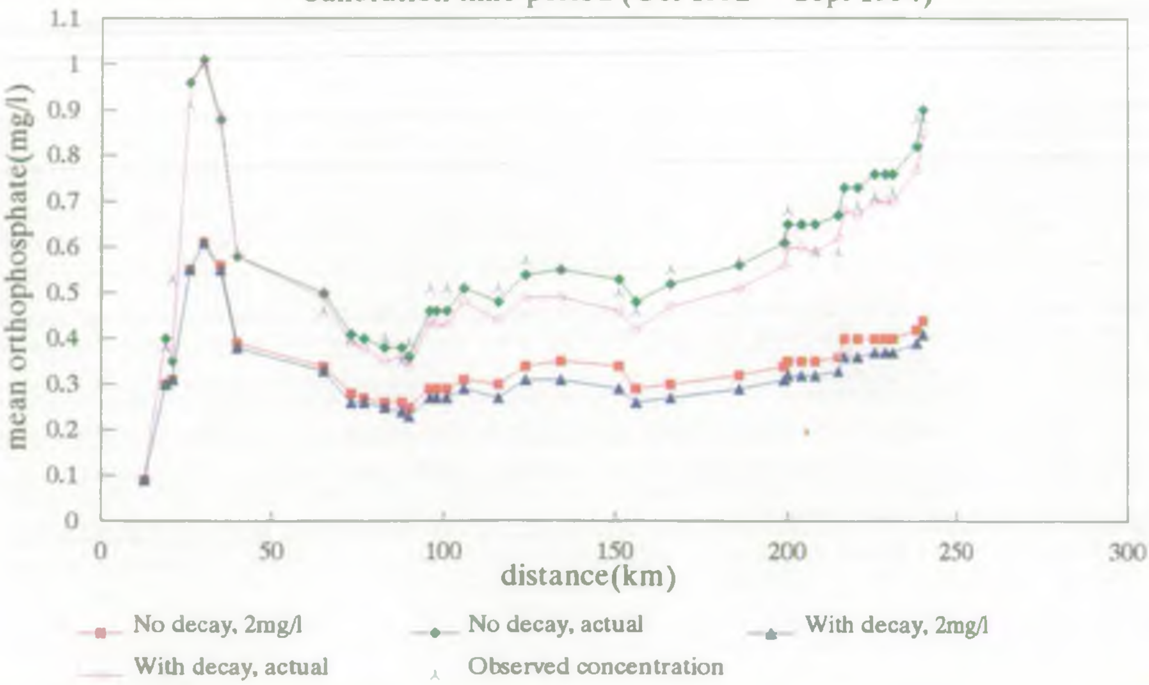


Figure A5.3

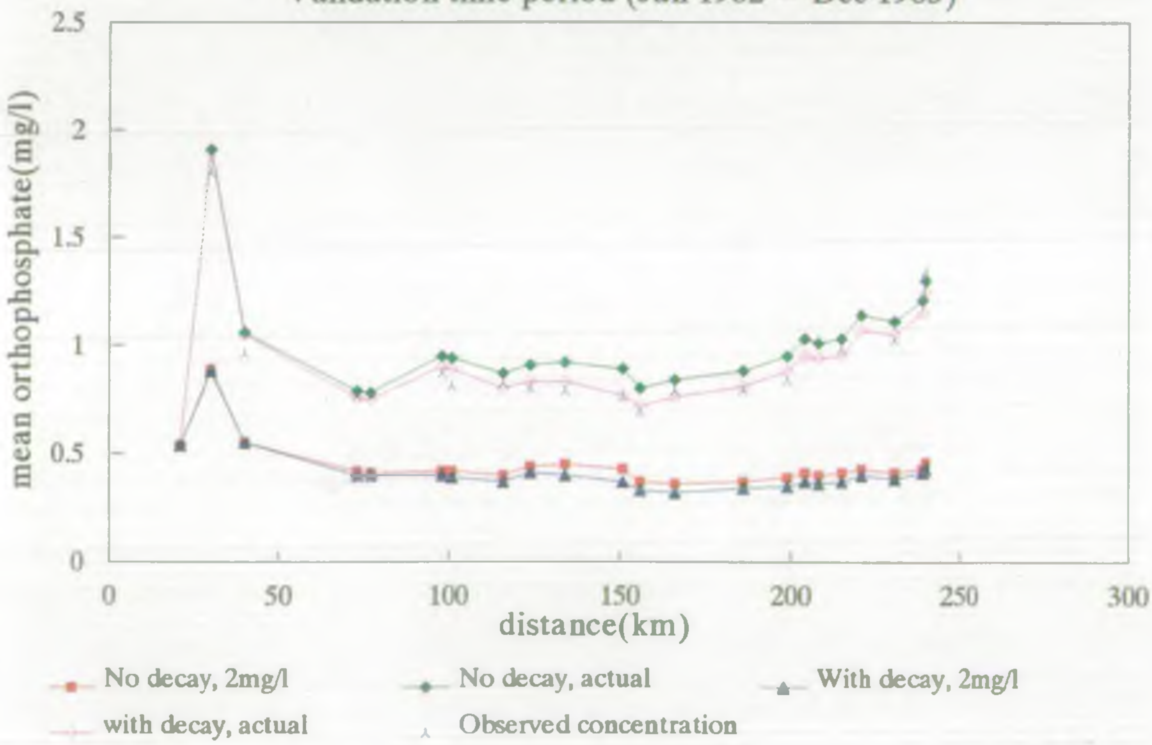
Phosphate removal at UWWTD works using 2 model scenarios.

Calibration time period (Oct 1992 – Sept 1994)



Phosphate removal at UWWTD works using 2 model scenarios.

Validation time period (Jan 1982 – Dec 1983)



TOMCAT

NRA
Thames Region

TOMCAT is a river quality model. It was created in 1982 by the Thames Water Authority to model the impact of sewage treatment works on water quality, and to guide investment. Today it is an essential tool for calculating consent standards for effluent discharges in catchments where there might be several works affecting the river quality, or where it is important to predict dissolved oxygen levels. Users include the National Rivers Authority (NRA), water companies, industry and consultants, both in the UK and abroad. This leaflet explains briefly how the model works and describes the enhancements that are being carried out by the Thames Region of the NRA.

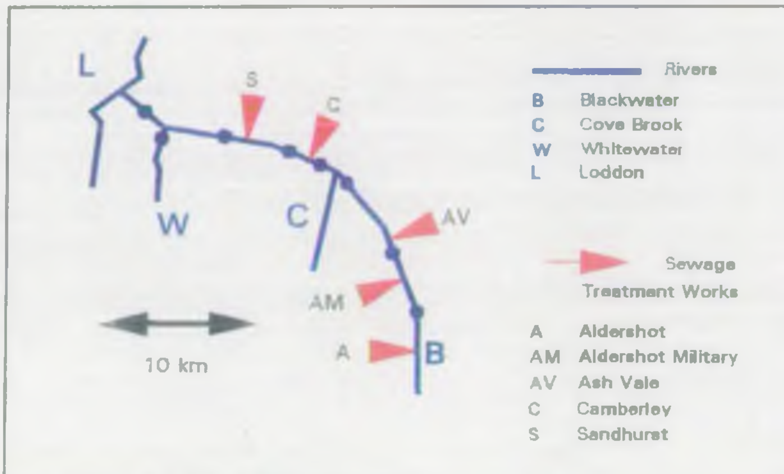


Fig. 1: The Blackwater Catchment

TOMCAT uses a simple flow model that can be applied to quite complex catchments. The model has a modular structure which allows various events to be easily added or removed. Events include tributaries, bifurcations, discharges and abstractions. Accretion flows (from groundwater or runoff) can also be included. Figure 1 shows part of the Blackwater catchment that has been modelled using TOMCAT. Velocities are calculated from flows, either using Manning's equation, or a velocity-flow relationship.

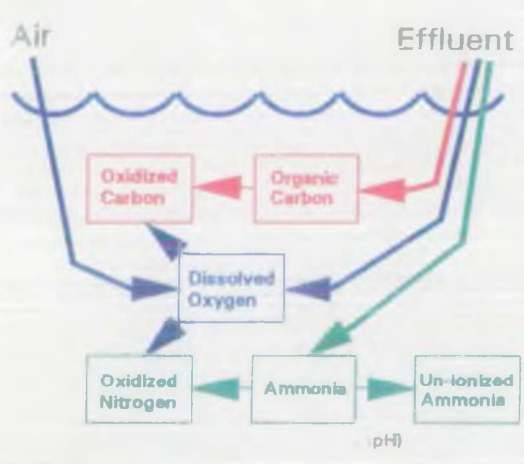


Fig. 2: Chemical system

TOMCAT models the determinands biochemical oxygen demand (BOD), ammonia, dissolved oxygen and un-ionized ammonia. These determinands are inter-linked, as shown in Figure 2. Temperature is also modelled since it controls the biochemical reaction rates. Conservative determinands (such as chloride) can be included in the model. These are useful for checking the flow model.

In England and Wales, the NRA samples many sewage treatment works and river sites only 12 times a year. This does not provide enough data to run a normal time-series model, since there will be considerable variation in quality between samples. However, several years data can be grouped together to give a good picture of the distributions of quality in the effluent and the river. TOMCAT uses these distributions to generate its own data set. This has monthly and hourly components, allowing for variation seasonally and within a day. A separate program, MARIGOLD has been written to convert raw data into distributions for TOMCAT. It uses analysis of variance (ANOVA) to detect the seasonal and hourly components of the data, leaving cumulative frequency distributions of the residuals. If there is very little raw data, or perhaps none at all, TOMCAT can use standard distributions, such as a normal or lognormal with a user specified mean and standard deviation.

TOMCAT uses a Monte-Carlo process to generate its data. For example, it calculates the flow and concentration at the top of a river, by adding the seasonal and hourly components to random values selected from the residual distributions. It does this for a number of 'shots' each representing a different combination of season and hour. The time of travel to the next downstream event is calculated from the flow equations for each shot. To model the mixing of an effluent with the river, flows and concentrations are calculated for the effluent using the Monte-Carlo process, shots from the river are matched for date and time with data from the effluent and the mass balance equation is used to calculate downstream values for each shot. Biochemical decay is incorporated in the model by reducing the river concentrations between events by appropriate amounts depending on the time of travel and decay rates fixed by the user.

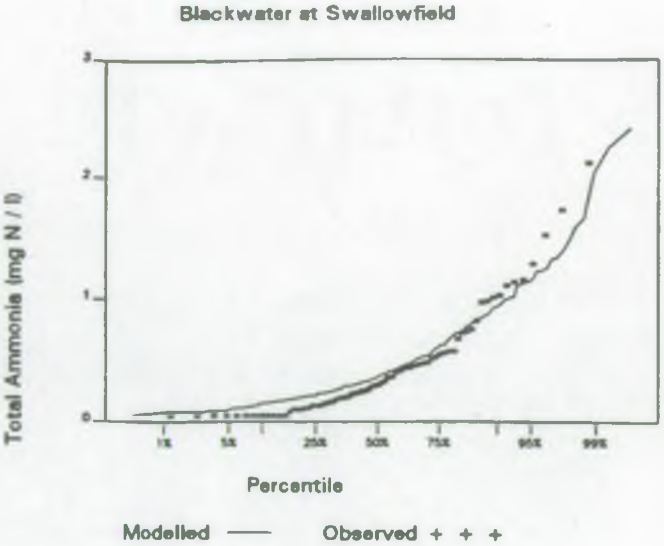


Fig. 3: Probability Plot

The downstream data is output in a number of ways: as statistical distributions, in both tabular and graphical form (Figure 3), as longitudinal profiles (Figure 4) or as time series data for graphical analysis or use in another TOMCAT model. If observed downstream data exists TOMCAT performs statistical comparisons between it and the model output: a t-test on the means; a Mann-Witney test on the medians; and a Kolmogorov-Smirnov test on the shape of the distributions. Because TOMCAT keeps track of the month and time of day for each shot, it is easy to output data and statistics for a particular season or for a particular time of day (eg sampling hours).

Water quality standards in England and Wales are defined in terms of percentiles of concentrations. The statistical output from TOMCAT is particularly suited to predicting whether these standards will be met. Consent conditions for effluent discharges can be calculated by adjusting scaling factors until downstream standards are met. Where there is more than one discharge into a catchment, there will usually be a number of different combinations of consent conditions that will meet the objectives. Deciding on the optimal solution - which may depend on maximizing environmental benefit, or perhaps minimizing costs - is a complicated task that can not be done automatically.

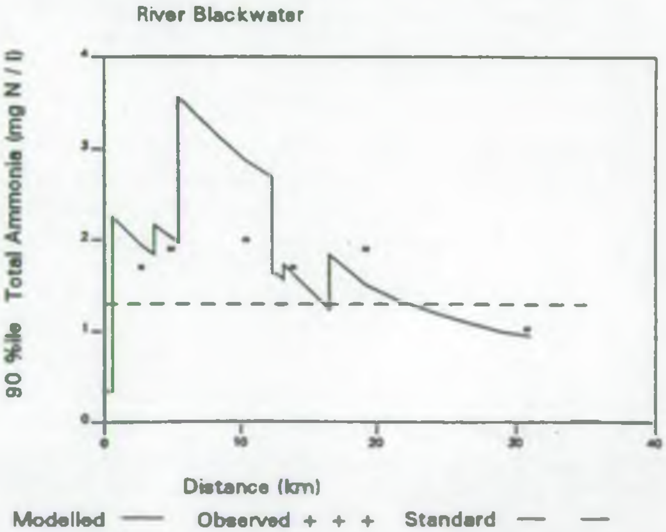


Fig. 4: Longitudinal Plot

Figure 2 showed only some of the processes affecting river quality. In nutrient rich rivers, the growth of plants and algae cause fluctuations in dissolved oxygen, as well as contributing to the BOD load. These conditions can not be modelled using the current version of TOMCAT. However Thames NRA are now testing a version of the model that takes into account these processes.

TOMCAT is written in standard FORTRAN 77 and can be run on any machine with a FORTRAN compiler. A compiled version is available for IBM-PCs that have a 386 or better chip. Other programs, designed to make it easy to use TOMCAT, including the data analysis package MARIGOLD, a menu driven front end called TOMFRONT, and two graphics programs, have also been written to run on IBM-PCs. These programs and further information can be obtained from:

Water Quality Planning, NRA Thames Region, Kings Meadow House, Kings Meadow Road, Reading, RG1 8DQ. Tel: 01734 535316.