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EAST ANGLIA RIVER TIMES OF TRAVEL PROJECT CM97/1A

Final Report to The Environment Agency

University of Huddersfield
and
The Nottingham Trent University

FEBRUARY 2000

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EXECUTIVE SUMMARY

The Environment Agency let a research contract in April 1997 to Dr Jill Labadz (University of Huddersfield) and Professor Dave Butcher (Nottingham Trent University) to investigate travel times on four rivers in the East Anglian region; the Gipping, Waveney, Bure and Wensum. The methodology utilised for these experiments involved the injection of Rhodamine WT and the tracing of that dye downstream at specified locations using Turner 10-AU fluorimeters.

Three tracer experiments were carried out on the Waveney, Bure and Wensum, and four on the Gipping, across as great a range of discharges as was possible during the time span of the study. Additionally, one experiment was completed on the Wendling Beck and one on the lower Gipping from Sproughton to Horseshoe Sluices. The sites for injection and sampling were identified by discussion with the Environment Agency and reflected points where spillages might be likely to occur, together with intake locations. The final selection was made taking into account the practicalities of access and the security and safety of equipment and staff.

The methodology used was generally successful, although it proved necessary to subdivide some of the traces on the Wensum and the Waveney as a result of the slow river velocities and long travel times. One trace on the River Waveney was repeated because of the failure of the water company's intake pump at Shipmeadow.

Travel time predictions have been calculated based on the empirical data to allow calculation of the time of arrival, time of peak concentration, through time, and the concentration unitised peak for pollution spillages across a broad range of discharges for all rivers. The production methodology is derived from the work of Kilpatrick and Taylor (1986) and was used successfully by the authors for a similar study on rivers in the Yorkshire region (Wilson *et al*, 1997, 2000).

A summary of the observed travel times is shown in Table ES.1. Overall the results reveal very slow travel times in comparison to other rivers in the UK, particularly at low discharges. The travel time of the River Waveney at low flow was the longest recorded in the UK in such an experiment. This result in particular reflected the very low discharges in the summer of 1997 when the low flow traces were completed.

Table ES.1 Travel Times and Peak concentrations

River Gipping

Stowmarket to Sproughton

Trace Mean Discharge (cumecs)	Time to Arrival (Hours)	Time to Peak (hours)
0.548	106.75	114.25
0.708	75.25	79.5
0.998	68.25	75.5
0.410	195.00	226.25

River Waveney

Diss to Shipmeadow

Trace Mean Discharge (cumecs)	Time to Arrival (Hours)	Time to Peak (hours)
0.420	427.75	559.00
1.134	98.00	111.25
0.477	278.75	390.50

River Bure

Saxthorpe to Belaugh

Trace Mean Discharge (cumecs)	Time to Arrival (Hours)	Time to Peak (hours)
0.543	156.5	170
1.152	66	55.58
1.261	54.5	48.25

River Wensum

Sculthorpe to Costessey

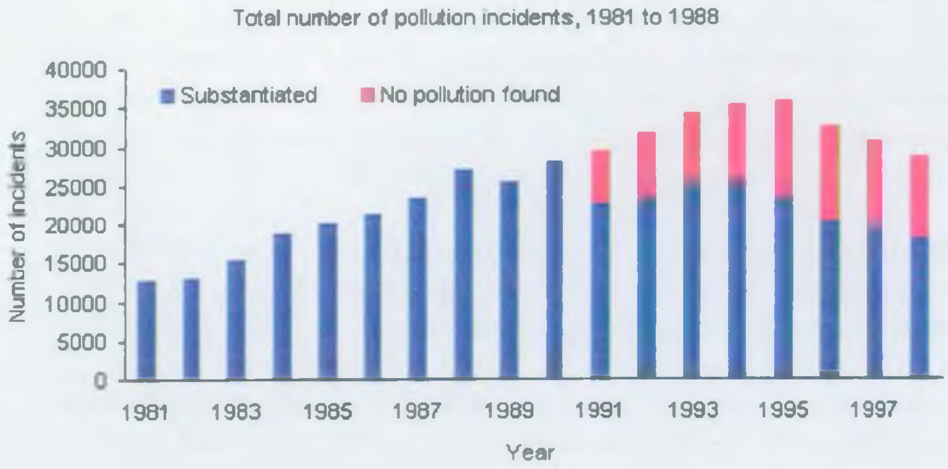
Trace Mean Discharge (cumecs)	Time to Arrival (Hours)	Time to Peak (hours)
1.027	162.75	203.75
3.852	55.5	57.75
8.736	32.17	36.71

Plate 1 : River Waveney upstream of Needham GS ....still waters

1. INTRODUCTION AND RATIONALE

Surface water resources, which account for over 55% of the potable abstraction in the UK, are increasingly being utilised to address the escalating demand for water supplies. This brings with it a need for increased awareness about the sources of pollution which threaten these resources. The duty of the water supply companies for the provision of 'wholesome' water to the consumer's tap is offset against the necessity to maintain the traditional usage of fluvial channels for irrigation, waste disposal and recreation. With regional potable water forecasts predicting significant increases in demand, particularly in the south of England, the pressure on the available resources is intensifying. The role of the Environment Agency (EA) in planning and managing water resources has been furthered through the preparation and implementation of catchment management plans (CMPs) and LEAPs.

The total number of reported pollution incidents in inland waters rose more or less continuously between 1981 and 1995. This is considered to be partly due to an increased public awareness of water quality issues. A freephone number has been available since 1994 to enable the public to report pollution incidents; the line is staffed 24 hours a day. Many of the incidents are relatively minor and some cannot subsequently be substantiated by direct investigation. Since 1990, therefore, the number of substantiated pollution incidents have been separately recorded. In 1998 there were over 28,000 reports of water pollution, of which nearly 18,000 were subsequently substantiated. In terms of the total number of substantiated pollution incidents in 1998, industrial sources, including the water industry, predominated. In terms of polluting materials, where these could be identified, oil predominated followed by sewage and organic wastes; only 8% were defined as being caused by specific chemicals or groups of chemicals. Figure 1.1 shows the pattern of incidents per year and table 1.1 shows the breakdown of types of incident for the Anglian region of the Environment Agency.



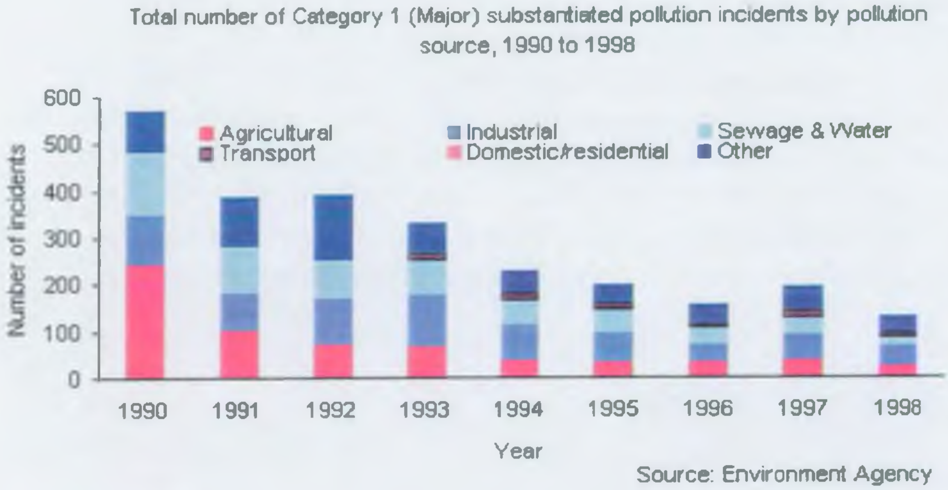


Figure 1.1 Pollution Incidents in the UK (Source: Environment Agency)

Table 1.1 Total number of substantiated incidents by incident category (1998) Anglian region

Category 1	Category 2	Category 3
7	132	2024

The increasing pressure on the fluvial environment has led in recent years to a steady increase in the number and severity of pollution incidents. Whilst the implementation of licence and consent systems to regulate abstraction and effluent discharge within river systems manages overall pollution levels, unintentional releases from consented sources and accidental releases cannot effectively be controlled.

A need has been identified to develop simple and robust methodologies to predict the downstream impact of pollution incidents, particularly the time of first arrival, the time to peak concentration and the total throughput time for the pollutant plume. This information is vital to the management and protection of potable water intakes in order to reduce the deleterious impact of pollution incidents on sensitive downstream users. A number of Environment Agency regions have commissioned research into travel times in rivers. Results from a study in Yorkshire (Wilson *et al*, 1997) have shown that direct measurements of travel times can be more effective than predictions based on more theoretical models.

Extensive recent research (Kirkpatrick and Taylor, 1986; Wilson, 1997; Wilson *et al.*, 1997) using conservative tracers to simulate pollutants has demonstrated that simple mathematical relationships, derived from time of travel experiments, can be used to provide accurate predictions of downstream time and concentration parameters given a satisfactory range of information. The quality of such predictions is mainly dependent on the range of flows at which time of travel studies are conducted.

2. METHODOLOGY

2.1 Introduction

The programme for the development of this project encompassed a series of planning and consultation procedures prior to field investigations.

- The determination of potential sources of pollution together with the major points of abstraction was carried out in collaboration with the Environment Agency. A repertoire of potential sites for injection and sampling was identified for consideration by field visit.

- Site inspections of selected field locations were carried out in order to assess the suitability of the chosen points against criteria concerning channel morphology, river conditions, safety, access and security.

- Negotiations with riparian land owners and existing users of the river corridor to obtain rights of access were completed, to develop an acceptable practice and notification system. This included discussions with licensed abstractors for agreement about dye concentrations and operational practices during experiments. In particular, agreement was reached with Anglian Water and with Essex and Suffolk Water with regard to maximum acceptable concentrations of dye at all abstraction points. During these discussions it was agreed that the concentration of dye would not exceed 0.2 $\mu g\ l^{-1}$ above background levels at the river intakes

- The methodology used for the experiments was similar to that employed successfully for a similar time of travel study in the Yorkshire region, carried out by the authors. Rhodamine WT was used to simulate a conservative pollutant in the river system; the progress of the tracer was monitored down the river system using two Turner Designs 10-AU field fluorimeters which are 'leapfrogged' downstream with the dye.

2.2 Choice of Tracer

Tracers may be used to measure travel times and to predict downstream concentrations of pollutants; they are usually either radioisotopes or fluorescent dyes. Bacteriophage tracers have also been employed, but the difficulty of assay and their variability of survival limit their effectiveness. The use of radioisotopes such as ^{82}Br is considered safe, but the essential requirement of public acceptability make their use undesirable. Fluorescent dyes such as fluorescein and pyramine exhibit much longer half lives with only slight photochemical decay. Rhodamine WT is one of the most resistant of these fluorescent dyes with very little decay.

Rhodamine WT is considered to be the most appropriate agent for long reach tracing studies (Wilson, 1997). Rhodamine WT has low toxicity, suffers little photochemical decay, and can be measured accurately at low concentrations (Leibundgut and Hadi; 1997). The ability to operate at very low concentrations makes Rhodamine WT an acceptable tracer for use at potable abstractions and is generally acceptable to most of the major water companies. The specific advantage of Rhodamine WT for these studies is the comparatively low chemical adsorption onto sediments and vegetation. This is particularly important for the rivers in the study which have significant amounts of channel vegetation. The basic properties of Rhodamine WT are outlined in Table 2.1.

Rhodamine WT

Generic Name	C.I. Basic Red 388
Acute Oral Toxicity (LD_{50}) - in rats	> 25000 mg/kg
Maximum excitation (nm)	555
Maximum emission (nm)	580
Minimum detectability (mgl^{-1})	0.013
Photochemical Decay Coefficients (6 hours, Sunny)	$< 1.0 \times 10^4$
% dye recovery in a peaty stream	86

(Smart and Laidlaw, 1977; COSHH Data Sheets; Smart, 1984.)

Table 2.1 Basic Properties of Rhodamine WT

The Rhodamine WT used in this study was supplied as a 20% solution by weight by Town End Chemical Works Ltd. of Bramley, Leeds. The receipt for the purchase of the dye used in the current experiments is shown in Appendix B.

The initial dye volume was calculated in all cases using the equation developed by Church (1974),(equation 2.1).

$$W = 3.8C_p\left(\frac{QL}{u}\right)^{0.93}$$ Equation 2.1

where:-

W = mass of 20% solution of Rhodamine WT (mg)
Cp = peak concentration ($\mu g\ l^{-1}$)
Q = discharge ($m^3.sec^{-1}$)

L = length of reach (m)
u = mean velocity ($m.sec^{-1}$)

The discharge level used in this equation was that obtained from the Environment Agency control room immediately prior to the injection and reflected the river discharge at injection. In a few cases, where the telemetry system had failed, the most recent discharge level available from the Environment Agency was used. A value for mean velocity was estimated on the basis of previous experience.

This volume of dye was then introduced into the river as a 'gulp' injection as close to the centre of the main flow as is practicable. In most cases the dye was injected late in the evening so that the initial colouration of the river was less visible and this also allowed the dye to become invisible to the naked eye by the morning. Plate 2.1 shows the injection site at Sculthorpe.

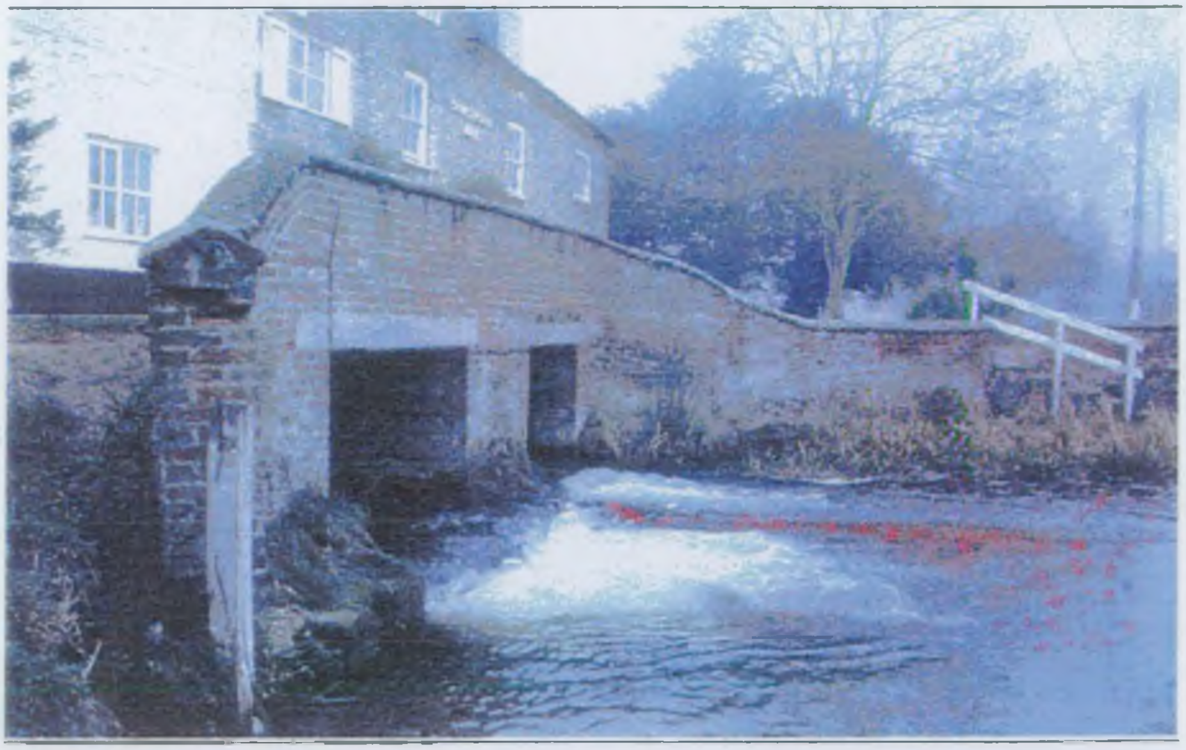


Plate 2.1 Sculthorpe Mill Injection Site

Plate 2.2 shows a dye injection at Swanton Morley on the River Wensum

Plate 2.2 Dye Injection at Swanton Morley on the River Wensum

At individual sites downstream a submersible sampling pump was positioned close to the thalweg, and secured with a large weight. A flexible hose connected the pump to the fluorimeter, passing a sample of river water to the measuring equipment, before returning it downstream via a second pipe. The fluorimeters were powered either using 12v batteries or alternately a 240v mains supply. The instruments took continuous fluorescence readings, logging the average value every minute. They proved to be capable of storing over 20 days worth of information before being downloaded.

The fluorimeters were installed and run in advance of the tracer plume to establish base line conditions and then remained constantly logging during the passage of the tracer. When the tracer concentration fell to a baseline level or within the prescribed proportion of the peak, (for these experiments 20%), the machine was relocated to the next available D/S site. Using two fluorimeters it proved possible to 'leapfrog' between sites in order to set up the equipment prior to the arrival of the dye.

At some sites Rock and Taylor and EPIC water samplers were used in parallel with or as a substitute for the fluorimeters. This generally occurred where 3 sites were being sampled or in locations where security was a problem. Water samples were taken at intervals ranging between 15 minutes and 2 hours depending on the dye concentration. In some cases a fluorimeter was recalibrated for the testing of discrete samples.

The results from the fluorimeters were downloaded directly to a PC either in the field or later in the laboratory. The stored data was compensated for temperature and then processed to produce travel time information. The baseline of background fluorescence was removed and then the important features of each tracer curve were identified. The final results are presented in 15 minute intervals, expressed from the time of injection.

2.3 Quality Assurance - calibration

The need for regular and repeated calibration of fluorimeters is paramount. Whilst both the fluorimeters were serviced by the suppliers at the outset of the contract, there is always likely to be some drift in the results as a result of variation in the bulb or in the filters. One particular problem that became apparent during the course of this contract was a build up of algae on the flew cell of a continuous fluorimeter at Shipmeadow on the River Waveney. This caused a decay in the base concentration which required calibration before and after any measurements at that site.

Where possible machines were run in tandem at a single site in order to assess the comparability of readings; however, since the fluorimeters are also calibrated in tandem prior to their use in the field, the differences between individual machines have in the past been found to be very small. In practice the fluorimeters were recalibrated against a suite of standards at regular intervals; the results for January 1998 are shown below in table 2.2 for illustration.

Table 2.2 Results of fluorimeter calibration, January 1998

29th January 1998	Standard concentration = -0.0537 + 0.959 Fluor1	$R^2 = 0.9993$
	Standard concentration = -0.038 + 1.013 Fluor2	$R^2 = 0.9998$

3. INJECTION AND SAMPLING SITES

The identification of sites for injection and sampling was carried out initially through discussion with the Environment Agency. The sites were selected on a number of criteria.

(a) The sites for injection were placed as far upstream in the river system as possible but also reflected locations where spillages were likely or had occurred in the past.

(b) Sampling sites were identified using a number of other criteria:-

(i) the need to sample at water intakes or at sites where pollution monitoring takes place;

(ii) the need to allow a sufficient distance from the injection site to the first sampling site to allow sufficient mixing of the dye to occur. This is generally in the order of a minimum of 5 km;

(iii) the requirement for an adequate distance between sampling sites to allow the wave of dye to pass;

(iv) The need for some overlap between sampling sites and river gauging stations. This allows more accurate calculations of factors such as dye recovery;

(v) practical constraints of access, safety, security and mains power.

In practice Environment Agency flow gauging and pollution monitoring sites were chosen wherever possible, together with water company intake structures. These offered secure locations with mains power for the fluorimeters.

During the course of the study some changes did take place to the initial site selection.

(a) Given the extremely long duration of a number of traces, sites where equipment could be locked securely were used in preference to more exposed locations. Thus the sampling site at Needham, which was originally to have been located upstream of the gauging station, was relocated to the gauging station itself. This new position had the further advantage of mains power.

(b) For the final trace on the River Waveney, the Environment Agency flow gauging station at Ellingham was used in preference to the water company intake at Shipmeadow. This was the result of failure of the water company's pumping system at Shipmeadow.

The final selection of sites used for the dye traces is shown in table 3.1 and in summary in Table 3.1.

Table 3.1 Final sampling sites by River

	RIVER GIPPING DYE TRACE SITE LOCATIONS	NGR	REACH LENGTH (km)	CUMULATIVE REACH LENGTH (km)
INJECTION	Station Road, Stowmarket	TM 051588	-	-
POINT 1	Gypsy Lane (Needham Mkt)	TM 086560	5.4 km	5.4 km
POINT 2	Claydon Bridge	TM 128501	8.8 km	14.2 km
POINT 3	Sproughton Intake	TM 130448	6.6 km	20.8 km
POINT 4*	Horseshoe Weir	TM 149448	2.6 km	23.4 km

* High Flow Only

	RIVER WAVENEY DYE TRACE SITE LOCATIONS	NGR	REACH LENGTH (km)	CUMULATIVE REACH LENGTH (km)
INJECTION	Denmark Bridge, Diss	TM 111794	-	-
POINT 1	Billingford Gauging Station	TM 168782	6 km	6 km
POINT 2	Needham Gauging Station	TM 228812	9.0 km	15.0 km
POINT 3	Wortwell, (Homersfield Sluices)	TM 285846	8.3 km	23.3 km
POINT 4	Shipmeadow Intake	TM 385907	26.85 km	50.15 km
POINT 4*	Ellingham	TM 364917	24.25 km	47.55 km

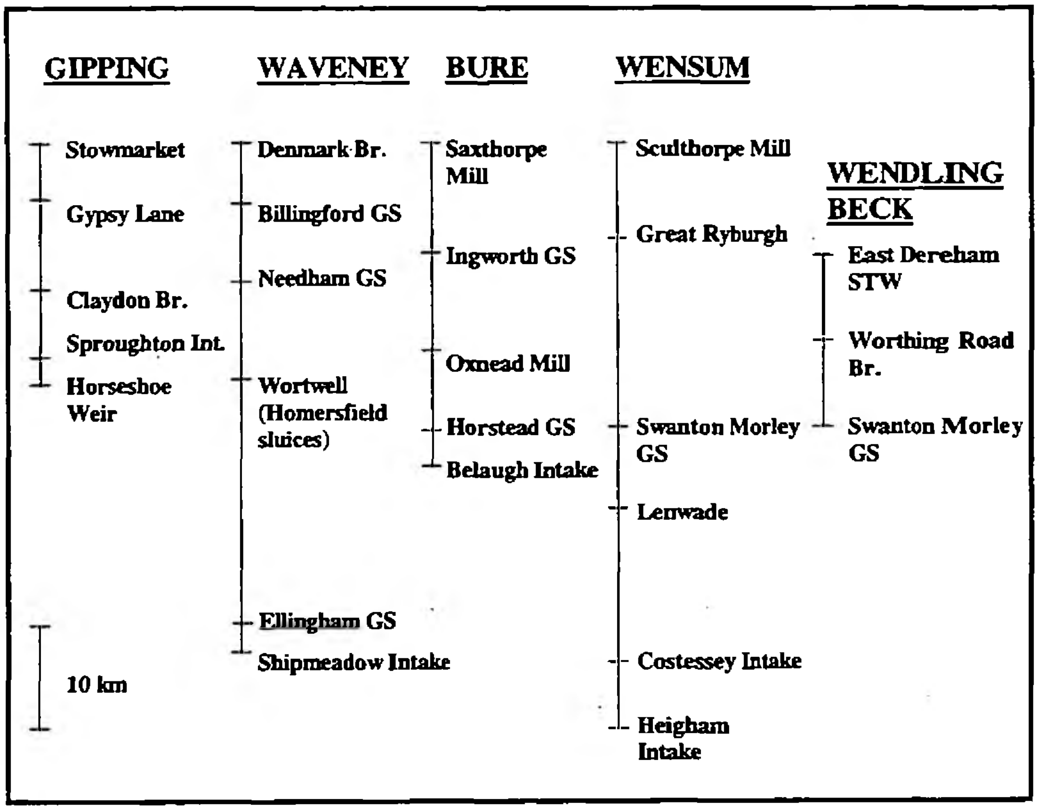
* This site was used as an alternative to Shipmeadow Intake for the final trace.

	RIVER BURE DYE TRACE SITE LOCATIONS	NGR	REACH LENGTH (km)	CUMULATIVE REACH LENGTH (km)
INJECTION	Saxthorpe Mill	TG 115303	-	-
POINT 1	Ingworth Gauging Station	TG 192296	10.7 km	10.7 km
POINT 2	Oxnead Mill Bridge	TG 232238	9.5 km	20.2 km
POINT 3	Horstead Gauging Station	TG 267194	9.6 km	29.8 km
POINT 4	Belaugh Intake	TG 288187	3.4 km	33.2 km

	RIVER WENSUM DYE TRACE SITE LOCATIONS	NGR	REACH LENGTH (km)	CUMULATIVE REACH LENGTH (km)
INJECTION	Sculthorpe Mill Road Bridge	TF 893304	-	-
POINT 1	Great Ryburgh Bridge	TF 964274	9.35 km	9.35 km
POINT 2	Swanton Morley GS	TG 022185	15.8 km	23.15 km
POINT 3	Lenwade	TG 103185	14.1 km	39.25 km
POINT 4	Costessey Pits Intake	TG 165132	13.5 km	52.75 km
POINT 5	Heigham Intake	TG 210097	6.5 km	59.25 km

	WENDLING BECK DYE TRACE SITE LOCATIONS	NGR	REACH LENGTH (km)	CUMULATIVE REACH LENGTH (km)
INJECTION	Sewage Outfall East Dereham STW	TF 976137	-	-
POINT 1	Road Bridge, Worthing.	TF 998201	8.3 km	8.3 km
POINT 2	Swanton Morley GS	TG 022185	4.0 km	12.3 km

Figure 3.1 Summary of Injection and Sampling Sites



4. DYE MASSES AND DISCHARGE LEVELS

The choice of flow at which the dye traces took place was governed by the requirement to cover as wide a range of flows as possible whilst using only 3 traces and providing at least one week's notice to the water company concerned.

The dye masses injected and the flow levels quoted by the control room of the Environment Agency are shown in Table 4.1. Two injections were used on the River Wensum and on the River Waveney. This was the result of four factors:

- the significant length of the river traces;
- the extremely long travel times recorded;
- the requirement by water companies to maintain low dye concentrations at intakes;
- the requirement that high visible concentrations of dye should not be apparent for long periods in the upper reaches of the river after injection.

Table 4.1 Dye masses and quoted discharge at time of injection

	Date of experiment	Dye mass injected (g) @20% solution	Discharge ($m^3\ sec^{-1}$) (value quoted by EA at time of injection)	Gauging Station
Gipping 1	30/6/97	30	1.00	Bramford
Gipping 2	30/11/97	35	0.46	Bramford
Gipping 3	28/02/98	25	0.44	Bramford
Gipping 4 (Horseshoe Weir)	28/04/98	20		
Gipping 5	31/07/99	25	0.274	Bramford
Waveney Upper 1	31/8/97	55	0.495	Needham
Waveney Lower 1	5/10/97	60	0.70	Needham
Waveney 2	29/01/98	150	1.44	Needham
Waveney Upper 3	12/05/98	60	0.580	Needham
Waveney Lower 3	04/06/98	40	0.540	Needham
Waveney Lower 4	02/07/98	78.4	0.560	Needham
Bure 1	31/8/97	40	0.616	Ingworth
Bure 2	12/12/97	70	1.422	Ingworth
Bure 3	12/03/98	75	1.47	Ingworth

	Date of experiment	Dye mass injected (g) @20% solution	Discharge ($m^3 sec^{-1}$) (value quoted by EA at time of injection)	Gauging Station
Wensum Upper 1	27/7/97	40	0.387	Swanton 3A
Wensum Lower 1	17/8/97	25	0.277	Swanton 3A
			0.510	Swanton 2A
Wensum Upper 2	04/01/98	150	4.736	Swanton 3A
			3.251	Swanton 2A
Wensum Lower 2	06/01/98	100	4.736	Swanton 3A
			3.251	Swanton 2A
Wensum 3	05/04/98	80	2.76	Swanton (comb)
Wendling Beck	13/7/97	15	0.300 *	Worthing
			0.550	Swanton 3A
			0.756	Swanton 2A

* discharge at Worthing Bridge by flowmeter gauging

The amount of dye injected was calculated using Church's equation so that the agreed maximum of 0.2 $\mu g\ l^{-1}$ at water company intakes would not be exceeded. In practice the dye volume injected was calculated to give a peak of only 0.1 $\mu g\ l^{-1}$ at the intake in order to give a margin of safety. Table 4.2 shows the peak concentrations of dye recorded at water company intakes:

Table 4.2 Peak concentrations recorded at water company intakes

River	Intake	Agreed maximum (μg l⁻¹)	Trace	Actual peak concentration (μg l⁻¹)
Gipping	Sproughton	0.2	1	0.103
			2	0.076
			3	0.101
			5	0.067
Waveney	Shipmeadow	0.2	1	0.031
			2	0.267
			3	*
	(Ellingham)		4	0.119 **
Bure	Belaugh	0.2	1	0.064
			2	0.113
			3	0.158
Wensum	Costessey	0.2	1	0.070
			2	0.121
			3	0.129
	Heigham	0.2	1	not detectable
			2	0.043
			3	0.111

* Dye not recorded at Shipmeadow due to failure of water company intake pump
** Data recorded at Ellingham due to pump failure at Shipmeadow

As may be seen Church's equation proved to be extremely effective in predicting the final peak with the actual values all close to 0.1 ($\mu g\ l^{-1}$). The variations in the actual peak values are likely to be the result of a number of factors:-

- lack of accurate data in some cases about discharges at the time of injection. This occurred where, due to failures in the telemetry system, the control room were not able to supply a recent discharge value;

- changes in discharge during the course of the dye trace. The extreme length of the traces necessarily involved some variation in discharge during the course of the trace;

- the velocity component of Church's equation can only be an estimate, particularly for the first trace on any river.

The one instance where the peak dye concentration recorded was outside of the agreed specification occurred at Shipmeadow on 03/02/98 and 04/02/98 when concentrations slightly exceeded 0.2 μg l^{-1} for a period of 10 hours. This was the first trace completed on this river using only one injection with a distance of 47.55 km. Clearly, for the first trace on such a long river, it proved to be extremely difficult to estimate the velocity component of Church's equation. Only when a number of traces have been completed can this be estimated with a greater degree of assurance.

5. RESULTS OF DYE TRACE EXPERIMENTS

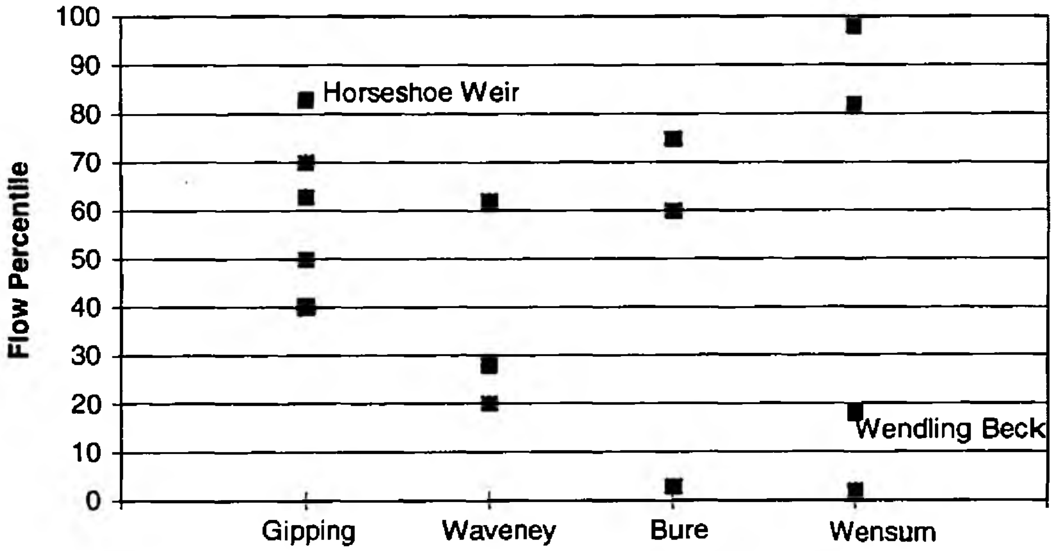
5.1 Tracer Experiments and flow coverage

The series of tracer experiments were undertaken between June 1997 and July 1998. Overall there were very few problems experienced in what was a major fieldwork element. Table 5.1 and Figure 5.1 show the range of flows which were covered. To enable comparisons to be made between rivers, the flow percentiles have been used. The flow percentile is derived from the long term flow record and indicates the discharge which is not exceeded for a given percentage of time for the total record. The percentages are derived from the regional river flow statistics from October 1966 to September 1995. There is clearly an excellent coverage of the flows of the Bure and the Wensum, but the flows on the Gipping are dominated by the higher flows. The flow percentiles for the period of the dye tracing experiments have also been calculated because the study period proved to be one characterised by extremely low flows.

Table 5.1 Mean trace Discharges and Flow Percentiles

	Date of experiment	Mean Trace Discharge	Flow Percentile (1969 -1995)	Gauging Station
Gipping 1	30/6/97	0.708	63	Bramford
Gipping 2	30/11/97	0.998	70	Bramford
Gipping 3	28/02/98	0.548	50	Bramford
Gipping 4 (Horseshoe Weir)	28/04/98	1.834	83	Bramford
Gipping 5	31/07/99	0.410	40	Bramford
Waveney Upper 1	31/8/97	0.420	20	Needham
Waveney Lower 1	5/10/97	0.641	43	Needham
Waveney 2	29/01/98	1.134	62	Needham
Waveney Upper 3	12/05/98	0.477	28	Needham
Waveney Lower 3	04/06/98	0.448	29	Needham
Waveney Lower 4	02/07/98	0.416	20	Needham
Bure 1	31/8/97	0.534	3	Ingworth
Bure 2	12/12/97	1.152	60	Ingworth
Bure 3	12/03/98	1.261	75	Ingworth
Wensum Upper 1	27/7/97	0.379	2	Swanton 3A
Wensum Lower 1	17/8/97	0.641	2	Swanton (comb.)
Wensum Upper 2	04/01/98	8.736	98	Swanton (comb.)
Wensum Lower 2	06/01/98	8.677	98	Swanton (comb.)
Wensum 3	05/04/98	3.852	82	Swanton (comb.)
Wendling Beck	13/7/97	1.312	18	Swanton (comb.)

Figure 5.1 Flow values for travel time experiments



(Flow percentiles based on 1969-1995 data set)

It was originally envisaged that one tracer experiment would be completed within the flow percentiles 0-25%, 26-55% and >55%. This was achieved for the Bure, Wensum and Waveney but not for the Gipping. Despite the exact number of experiments desired within each flow banding not being achieved for logistical reasons, it is evident that good coverage of flows was attained from the experiments.

This spread is very important as it allowed interpolations to be made within the range of flows covered, rather than needing to extrapolate outside of the range with the attendant reduction of confidence in the predictions made. Much of this wide range was achieved as a result of the lack of rainfall and resultant sustained low flows during the summer of 1997; this enabled the lower extreme of the range to be sampled.

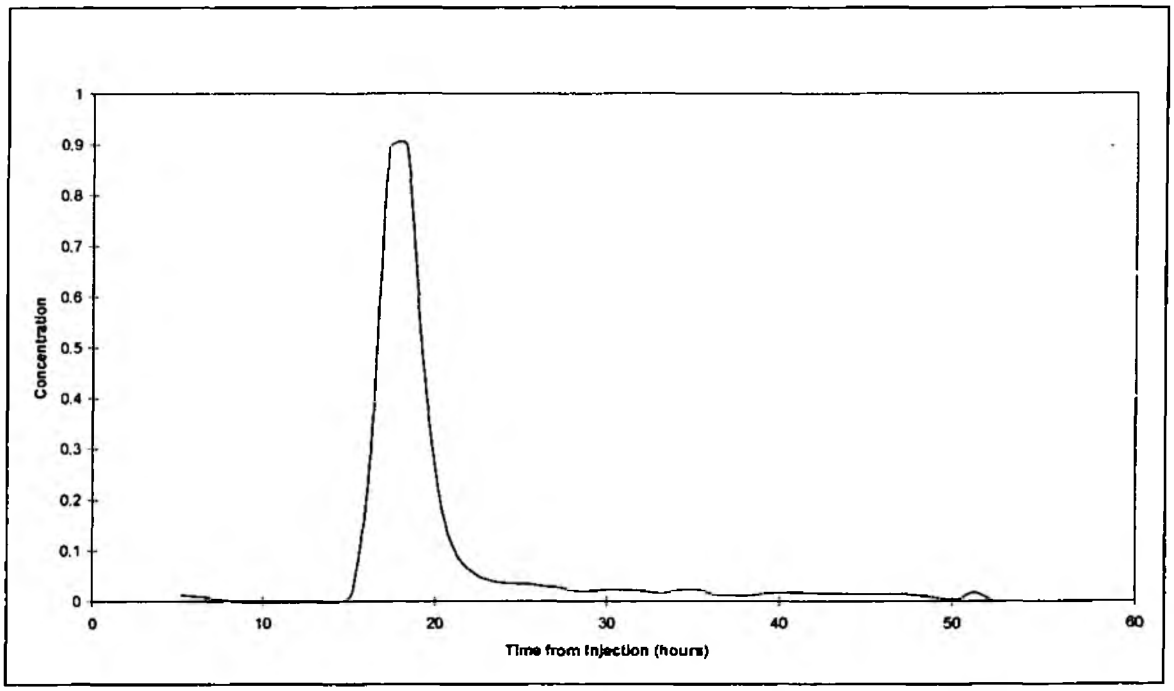
The 19 sampling sites within the study areas were used on over 65 occasions. All sites on the major rivers were monitored at least three times, with the exception of Ellingham which was monitored only once. The initial arrival and peak times were obtained at all sites and through times for all of the sites to an acceptable level.

5.2 Dye Response Curves

5.2.1 Characteristic Response Curves of the Rivers under study

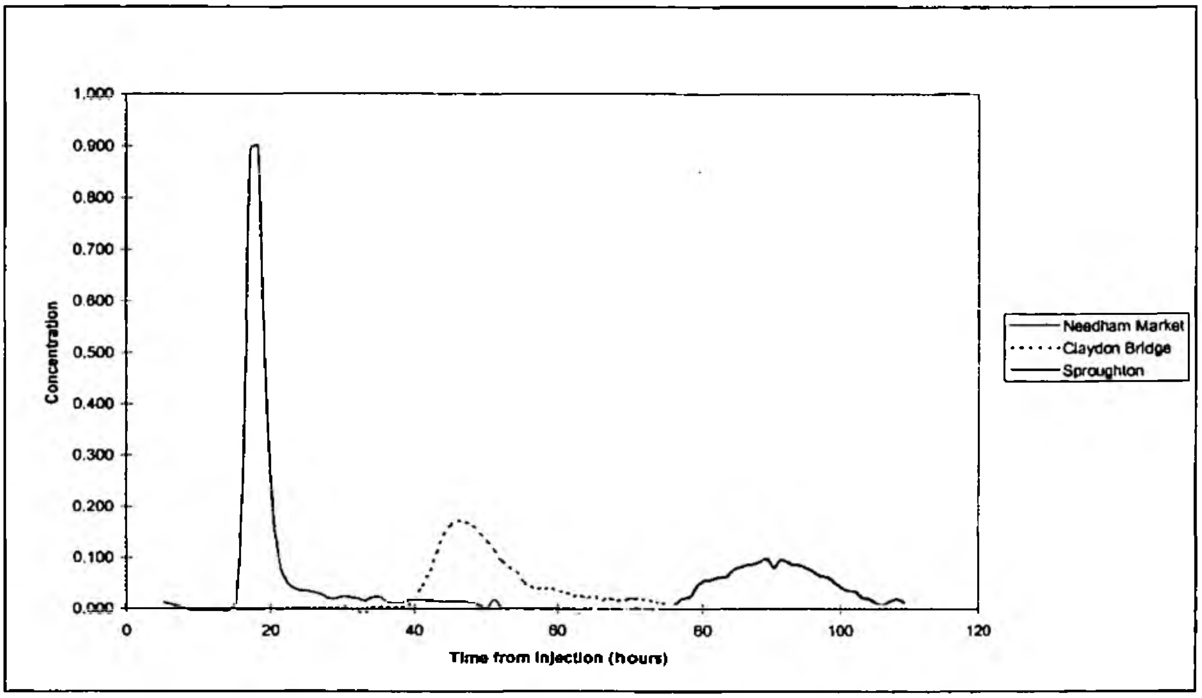
The response curves of the Rivers Gipping, Bure and Waveney demonstrate the classic skewed shape that has been described by workers such as Kilpatrick and Taylor (1986). Figure 5.2 shows the response curve at Gypsy Lane in Needham Market to an injection of dye at Stowmarket, 5 km upstream.

Figure 5.2 Concentration - Time Distribution for River Gipping at Gypsy Lane (Needham Market) 30/06/97 (time in hours, concentration in $\mu g.l^{-1}$)



The peak at Gypsy Lane is rapidly reduced as the dye peak moves downstream. This is shown in Figure 5.3. This pattern of response is repeated in the dye traces of the Rivers Bure and Waveney.

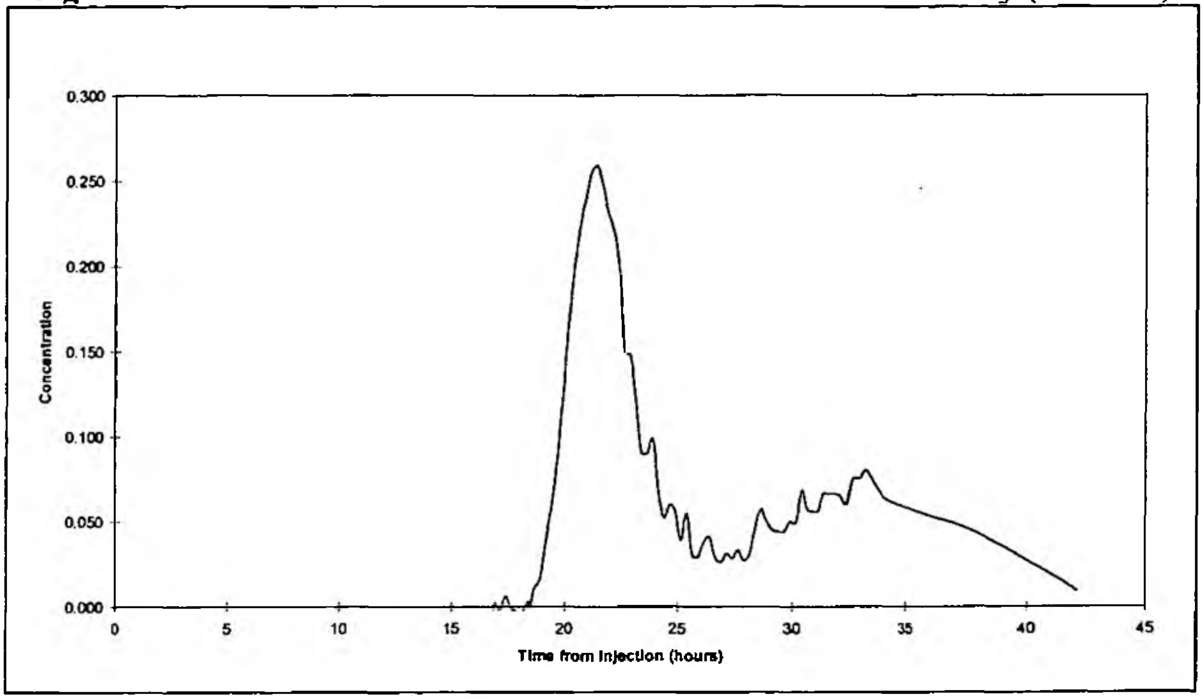
Figure 5.3 Concentration - Time Distribution for River Gipping for trace beginning 30/06/97



5.2.2 Variations in the characteristic response curves

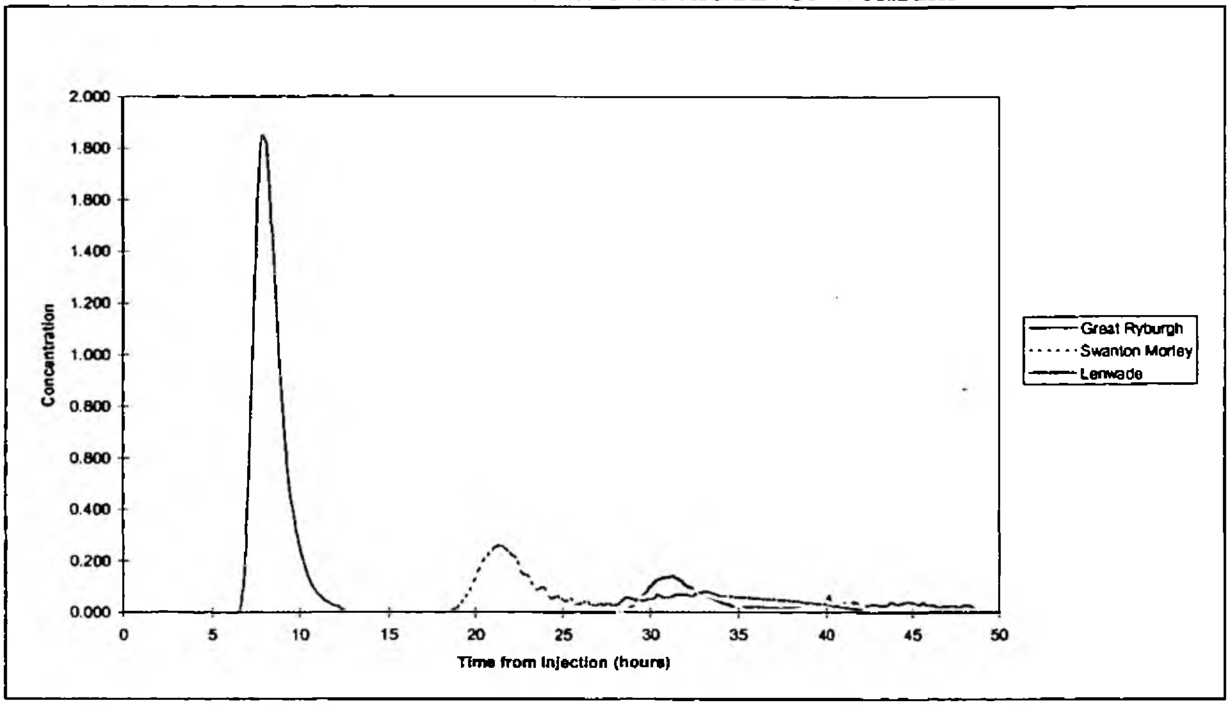
The most striking variation in the response pattern is that which occurs on the River Wensum, which demonstrates a secondary peak on the recession limb of the primary pulse. The pattern is shown clearly in Figure 5.4 which shows the dye concentration at Swanton Morley.

Figure 5.4 Concentration - Time Distribution at Swanton Morley (05/01/98)



This peak becomes more significant in relation to primary peak as the dye moves downstream from Great Ryburgh to Swanton Morley. This is shown in Figure 5.5.

Figure 5.5 Concentration - Time Distribution for the Trace Beginning 04/01/98 on the River Wensum



The origin of this phenomenon appears to lie in the reach between Sculthorpe and Great Ryburgh. It was not found in the results of the Wendling Beck study. The cause is likely to be related to a retention of water and, therefore, dye in a major dead zone for a period of some hours. This may be the result of a diversion of some or all of the river's flow into a feature such as a quarry. The significance of the double peak is to reduce the concentration of the primary peak but to enlarge the through time downstream. This is particularly true at the two abstraction points at Costessey and Heigham, where the dye takes a particularly long time to pass.

5.3 Analysis of Response Curves

Table 5.2 summarises the dye response curves obtained for the tracer experiments. The following characteristics are identified:

Q	=	mean discharge (cumecs) at gauging station during trace, calculated from daily mean flows.
Time to Arrival	=	Time from dye injection to first discernible rise in concentration observed at the site (hours)
Time to Peak	=	Time from dye injection to peak concentration at the site (hours)
Peak	=	Maximum concentration recorded (µg l^{-1} above background level)

Table 5.2 Principal Characteristics of the Dye Response Curves

River Gipping Injection at Stowmarket	Trace	Time to Arrival (Hours)	Time to Peak (Hours)	Through Time (15% peak) (Hours)	Peak Concentration µg l^{-1}
Gypsy Lane	# 1	14.92	17.75	5.81	1.00
Claydon Bridge	30/06/97	39.5	46	22.55	0.172
Sproughton	Q = 0.708	75.25	79.5	29.5	0.103
Gypsy Lane, Needham Market	# 2	16.42	20.25	8.81	0.883
Claydon Bridge	30/11/97	49.5	55.25	11.82	0.215
Sproughton	Q = 0.998	68.25	75.5	13.75	0.076
Gypsy Lane, Needham Market	# 3	26.5	32	10.25	1.038
Claydon Bridge	28/02/98	70	77.5	18.5	0.238
Sproughton	Q = 0.548	106.75	114.25	22.5	0.101
Gypsy Lane	#5	57.5	67.5	25.75	0.238
Claydon Bridge	31/07/99	114	141.75	>40.25	0.147
Sproughton	Q = 0.410	195	226.25	-	0.067

River Bure Injection at Saxthorpe	Trace	Time to Arrival (Hours)	Time to Peak (hours)	Through Time (15% peak) (Hours)	Peak Concentration µg l-1
Ingworth	# 1	19.75	29	16.24	0.575
Oxnead	31/08/97	66.75	76.5	24.64	0.152
Horstead Mill	Q = 0.543	101.5	119.25		0.068
Belaugh		156.5	170		0.064
Ingworth	# 2	13.83	11.66	5.53	0.994
Oxnead	12/12/97	32.24	28.08	11.22	0.390
Horstead Mill	Q=1.152	48.08	43.08	13.23	0.142
Belaugh		66	55.58		0.113
Ingworth	# 3	11.46	10.25	2.92	1.930
Oxnead	12/03/98	27.93	24.75	8.78	0.628
Horstead Mill	Q = 1.261	41.83	37	11.39	0.302
Belaugh		54.5	48.25	15.81	0.158

River Wensum Injection at Sculthorpe	Trace	Time to Arrival (Hours)	Time to Peak (hours)	Through Time (15% peak) (Hours)	Peak Concentration µg l-1
Great Ryburgh	#1 Upper	34	48.5	28.89	0.479
Swanton Morley	Q = 0.379	70	95.5	61.7	0.088
Lenwade	# 1 Lower	63.25	72.13	20.86	0.094
Costessey	Q = 0.641	92.75	108.25		0.070
Great Ryburgh 2	# 2 Upper	6.51	7.92	3.42	1.846
Swanton Morley	Q = 8.736	18.5	21.42	6.67	0.259
Lenwade		28.3	31.33	8.2	0.139
Lenwade	# 2	6.17	8.79	6.26	0.226
Costessey	Lower	13.67	15.29	4.84	0.121
Heigham	Q = 8.677	19.80	20.50		0.043
Great Ryburgh	# 3	9.75	11.38	3.78	2.130
Swanton Morley		28	31.18	9.58	0.358
Lenwade	Q = 3.852	48	50.25	18.71	0.153
Costessey		55.5	57.75	16.73	0.129
Heigham		57.25	66.22	37.59	0.111

River Waveney Injection at Diss	Trace	Time to Arrival (Hours)	Time to Peak (hours)	Through Time (15% peak) (Hours	Peak Concentration $\mu g\ l^{-1}$
Billingford	# 1 (Upper)	110.0	136.0	120.0	0.412
Needham Mill	31/08/97	239.25	292.75	-	0.046
Wortwell	# 1 (Lower)	64.82	76.83	27.10	0.417
Shipmeadow	05/10/97	188.50	212.75	49.09	0.031
Billingford	# 2	15.75	19.0	7.68	3.476
Needham Mill	29/01/98	43.25	50.0	15.5	1.049
Wortwell	Q = 1.134	67.25	74.75	17.33	0.603
Shipmeadow		98	111.25	35	0.267
Billingford	# 3 (Upper)	37.50	44.25	16.5	1.842
Needham Mill	12/05/98	110.75	129.75	68.5	0.268
Wortwell	Q = 0.477	184.75	224.74	90.0	0.099
Wortwell	# 3 (Lower)	61.5	72.0	22.3	0.124
	04/06/98				
Wortwell	# 4 (Lower)	66.0	77.0	28.0	0.368
Shipmeadow	02/07/98	168.0	241.75	156.0	0.119

A more complete summary of each dye trace, together with the complete dye trace results, may be found in Appendix C.

5.3 Recovery rates for injected dye

Recovery rates for injected dye are a valuable indicator of the efficiency of the methodology used. The amount of dye not recorded in the tracer experiments should always be taken into account when using the trace results for further predictive studies. The recovery rate for injected dye is normally expressed in percentage terms based on the amount of dye passing a sampling point. It is crucial that an accurate measure of discharge is available at that point and thus recovery rates are normally only expressed where a dye sampling point is coincident with a flow gauging station.

Church (1974) outlines four possible areas where the accuracy of predictions based on dye traces may occur. These are:-

- non representative sampling due to incomplete mixing of the dye at the monitoring site. This commonly occurs at the first monitoring site downstream of the injection if this site has been located too close to the injection;

- loss of dye through sorption onto material in the river, particularly where the river has large amounts of vegetation;

- dye loss through water seepage through the river bed;

- inaccuracies in the equipment used for measurement of the dye concentrations. The recovery rates for the dye traces undertaken in this study are shown in table 5.3.

There is also the likelihood of some photochemical decay (see section 2.2).

Table 5.3 Recovery rates of injected dye

	Monitoring site	Gauging station	Dye trace	% Dye recovery
Gipping	Claydon Bridge	Bramford GS*	1 30/06/97	97.73
			2 30/11/97	67.7
			3 28/02/98	111.68
			5 31/07/99	87.80
Waveney	Needham	Billingford GS	1 21/08/97	62.51
		Needham GS	2 29/01/98	125.14
		Needham GS	3 12/05/98	124.78
Bure	Ingworth	Ingworth GS	1 31/08/97	95.36
			2 12/12/97	99.21
			3 12/03/98	106.3
Wensum	Swanton Morley	Swanton Morley GS	1 27/07/97	91.84
			2 04/01/98	**
			3 05/04/98	**
Wendling Beck	Swanton Morley	Swanton Morley GS	1 13/07/98	99.87

* no gauging station coincident with sampling points
** not calculated - flows suspect

The rivers where the recovery rates were least satisfactory appear to be the Gipping and the Waveney:

- There was no gauging station coincident with the sampling points on the River Gipping and thus the calculation of dye recovery is necessarily a flawed exercise. During the second trace, for example, the dye concentration peaked at 2am at Claydon Bridge, but daily mean flows are reported as 0.8 cumecs at Bramford until 9am and 1.6 cumecs thereafter. The lack of temporal resolution, in combination with the spatial incongruity, may help to explain the apparently poor dye recovery.

- In the case of the first trace on the River Waveney, the low recovery is also due to Suffolk County Council, without notice to the authors, diverting the entire flow of the river away from the gauging station two weeks after commencement of the trace but long before the dye concentrations had returned to background. Although good data was obtained for times of arrival and peak, the through times and total dye recovery were significantly affected by this event.

- Variations in flow during long traces, such as those on the Waveney, may lead to fluctuations in background fluorescence as a result of changes in sediment transport and water quality. This may result in apparent dye recoveries above or below the true value.

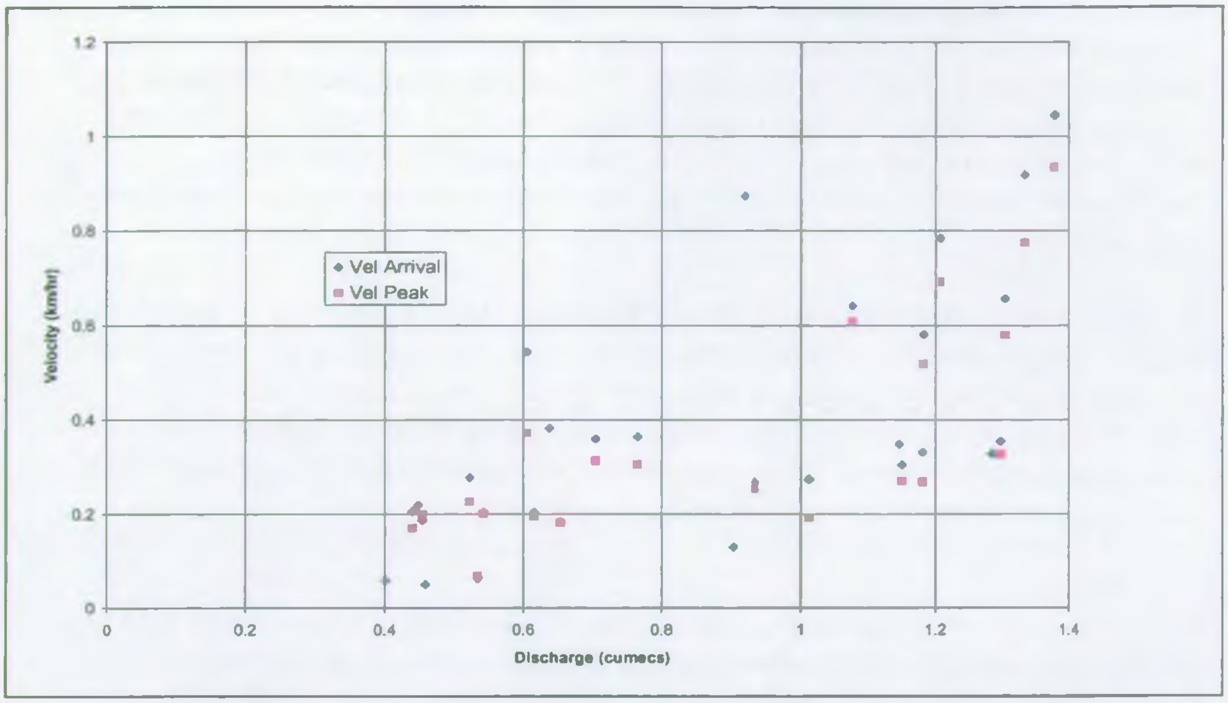
5.4 Travel Times and Velocities : comparisons with other UK studies

Figure 5.6 summarises the velocities of the injected dye to arrival and to peak concentration. Two facets of this diagram are apparent:-

- above 1.0 cumecs velocities increase with discharge;

- below 1.0 cumecs the velocities are highly variable and less predictable - it is likely that these are more influenced by factors other than discharge. These factors are likely to include the degree of within channel vegetation and the management of weirs and sluices.

Figure 5.6 East Anglian Rivers - Velocities of Arrival and Peak



Figures 5.7 and 5.8 show a comparison of velocities in the East Anglian study and that of the Yorkshire region study (Wilson, 1997; see also Wilson *et al*, 1997, in Appendix A). The velocity expressed is that of reach velocity compared with the discharge of that reach when the dye was present. It is apparent that the lower discharges of the East Anglian rivers result in slower velocities but those velocities are significantly lower than would have been predicted on the basis of the Yorkshire study.

Figure 5.7 Velocity of dye arrival - Yorkshire and East Anglian Rivers

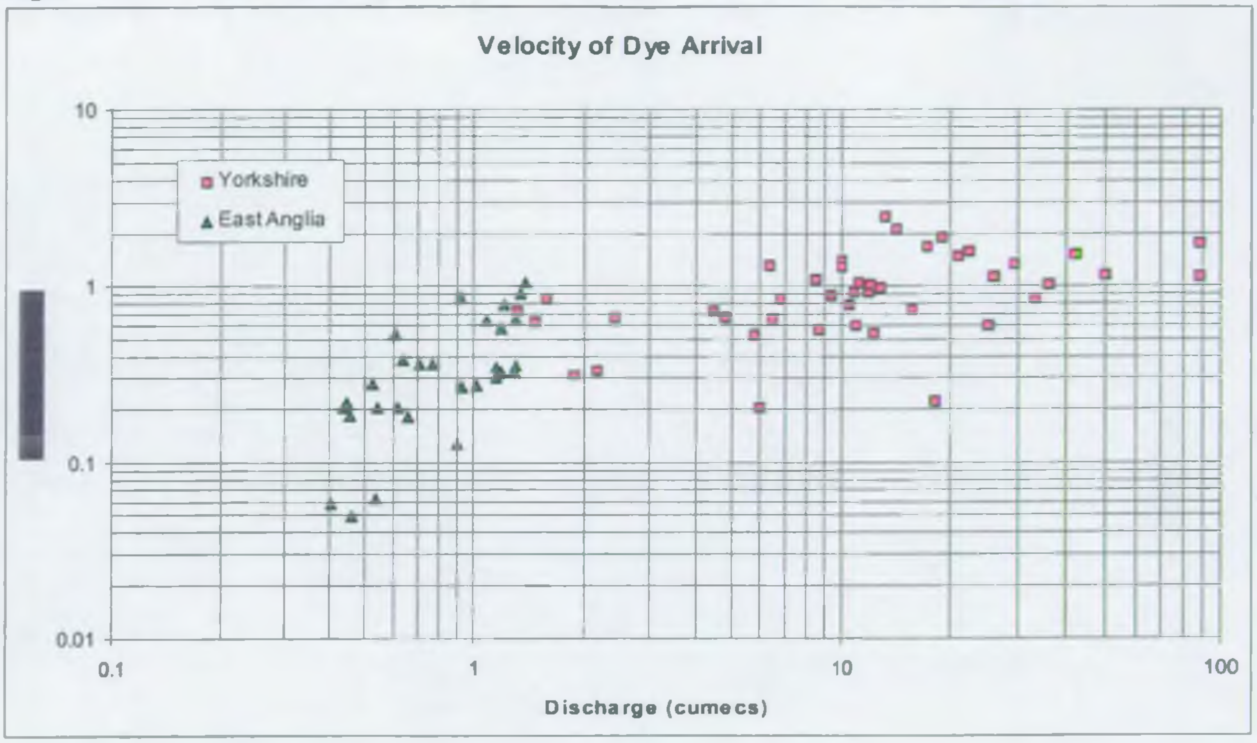
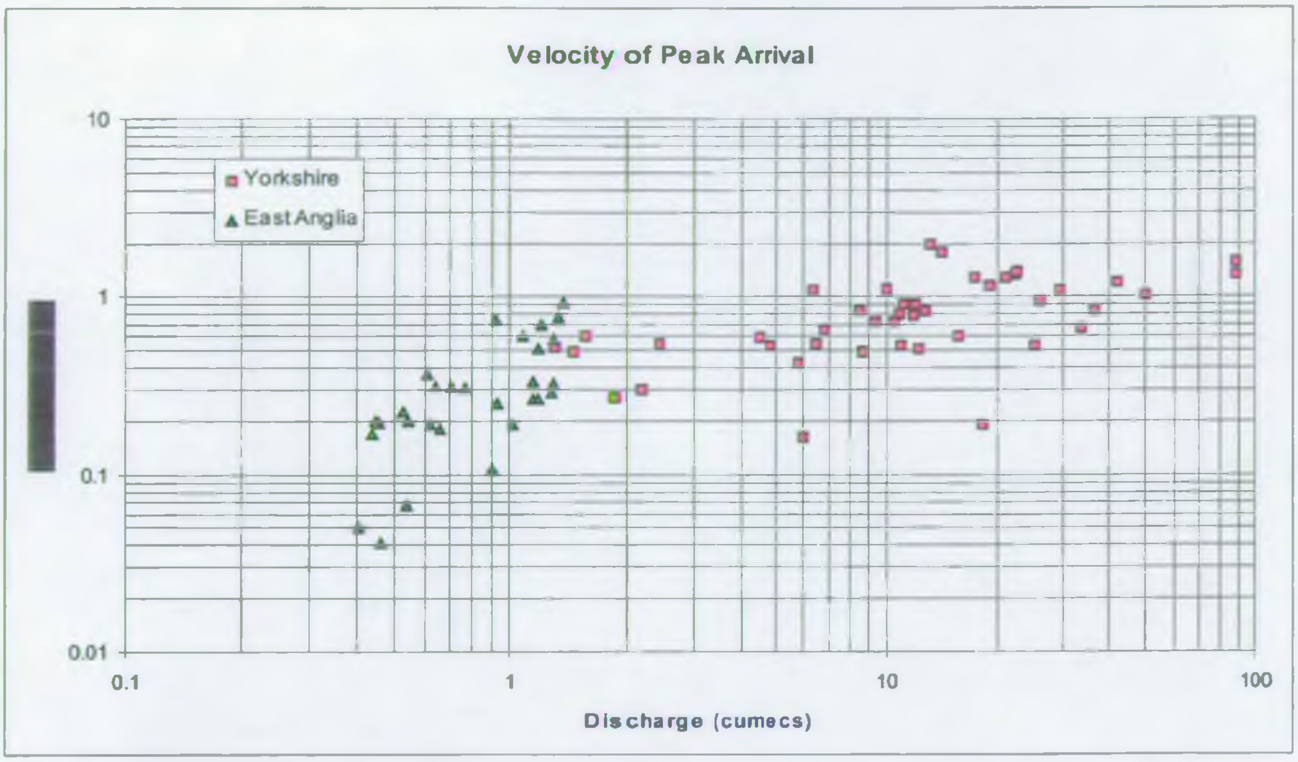


Figure 5.8 Velocity of Peak Arrival - Yorkshire and East Anglian Rivers



6. PREDICTIONS OF TRAVEL TIMES IN EAST ANGLIAN RIVERS

6.1 Approaches to travel time predictions

The essential requirement for travel time predictions is that of a simple robust strategy that will quickly allow accurate predictions, often in emergency situations. The aim of this section is to develop the results of the dye trace experiments into such a strategy. There has been a great deal of previous research into pollution incidents, but much of it has used a theoretical basis with little regard to the collection of field data, particularly at a scale appropriate to an operational context. Much of the research has focused on the development of mathematical models, often based on extremely limited data sets.

The two principal contemporary approaches to the field of pollution incident modelling are the Advective Dispersion Equation (ADE) and the Aggregated Dead Zone model (ADZ): other approaches tend to be derived from, or variants of these.

6.1.1 Advective Dispersion Equation

Early prediction of pollution travel times was predominantly based on the ADE, developed by Taylor in 1954, an approach that was subsequently further developed by Fischer (1967):

$$\frac{\partial c}{\partial t} = -\overline{u}\frac{\partial c}{\partial x} + D\frac{\partial^2 c}{\partial x^2} \qquad \text{Equation 6.1}$$

where:- c = solution concentration
$\overline{u}$ = mean water velocity
D = dispersion coefficient

The model is based on Fickian diffusion theory and the dispersion coefficient is estimated by calculation. It is based on the assumptions that the turbulence is statistically stationary in time and the velocity steady. It also assumes constant flow cross-section; a particular problem for application to the East Anglian rivers in this study.

The ADE is a one-dimensional equation discarding transverse and vertical dispersion. It is not applicable to the early convective stages of mixing but assumes that, after this initial distance when mixing has occurred throughout the channel cross section, the distribution will become Gaussian as described by the equation. In some of the early studies, which first proposed the ADE as a possible approach, there are data sets which clearly exhibit non-Gaussian distributions. Further studies demonstrated this persistent skewness (Sabol and Nordin. 1978). The skewed nature of the typical distribution are particularly evident in the results of this study.

The skewed nature of the concentration in time was first attributed to dead zones by Hays and his co-workers in 1966. Dead zones include eddies, meanders, vegetated areas, bridge pillars and areas above weirs and locks. The highly controlled nature of the rivers in East Anglia cause most of the dead zones to be the results of locks and weirs; indeed at low flows it may well be that the whole river system consists of a series of inter-connected dead zones controlled by a series of weirs and sluices.

6.1.2 Aggregated Dead Zones

With the widening acceptance that the ADE did not accurately reflect the real world, work began in the 1980s to include the effects of dead zones in models. The most successful approach was to aggregate the effects of all of the individual dead zones in a stretch of channel (Beer and Young, 1983). This aggregated dead zone (ADZ) model was based on the assumption that most of the dispersion of the ADE was the result of dead zone effects. In order to use this model an "effective dead zone volume" is determined from field observation of tracer concentration profiles (Young and Wallis, 1993) to determine the Dispersive Fraction, which is the ratio of pollution residence time in the aggregated dead zone to that in the river as a whole (Wilson, 1997). It has been argued, however, that whilst the simplification of the complexities of the river inherent to the ADZ approach has in some respects been beneficial, the disregard of the processes occurring within the river system has also been detrimental. This is particularly the case where the overall river system contains an uneven distribution of significant dead zone features; for example where the lower reaches of the river have more control structures. A further problem of the ADZ approach relates to the requirement for substantial data sets for ADZ calibration. These data sets have been collected over short river reaches due to time and cost constraints, limiting its applicability for larger rivers where drinking water abstraction takes place.

6.1.3 Empirical Approaches

More recently increasing attention has been focused on more simple empirical techniques where dye tracing results for individual rivers are used for general predictions based on discharge. Kilpatrick and Taylor (1986) describe a means of normalising results of tracer studies for use in pollutant travel time predictions. Fundamental to this approach is the ability to compare data obtained at different discharges and concentrations, using the concept of the concentration unitised peak (cup). This allows the results from different experiments to be made comparable by taking account of:

(a) the amount of tracer used;

(b) any tracer lost through the course of an experiment; and

(c) the discharge at which the experiment was completed.

The resulting term is known as the unit concentration (Cu) which is the concentration that would be observed having injected one kilogram of dye into a stream flowing at one cumec. Kilpatrick and Taylor then used this approach to consider the unit concentrations for the peak.

Francois and Calmels (1997) also describe empirical approaches, with the aim of focusing on ease of understanding and practicality of use. If it can provide a useable model with sufficient accuracy for the objectives a simple model is seen as far more appropriate for the use of agencies such as the Environment Agency, who may be obliged to defend their decisions in a legal context.

6.2 Empirical approaches to travel time prediction for East Anglian rivers

The methodology adopted for this study has been based on the empirical approach derived from the work of Wilson et al (1997) and Kilpatrick and Taylor (1986). The fundamental basis of the approach has been to identify 4 facets of the pollution plume. These are:

Te	:	time from injection to arrival (hours)
Tp	:	time from injection to peak concentration (hours)
td	:	through time (hours)
Cup	:	concentration unitised peak (µg/litre/gramme injected)

These facets are a function of:

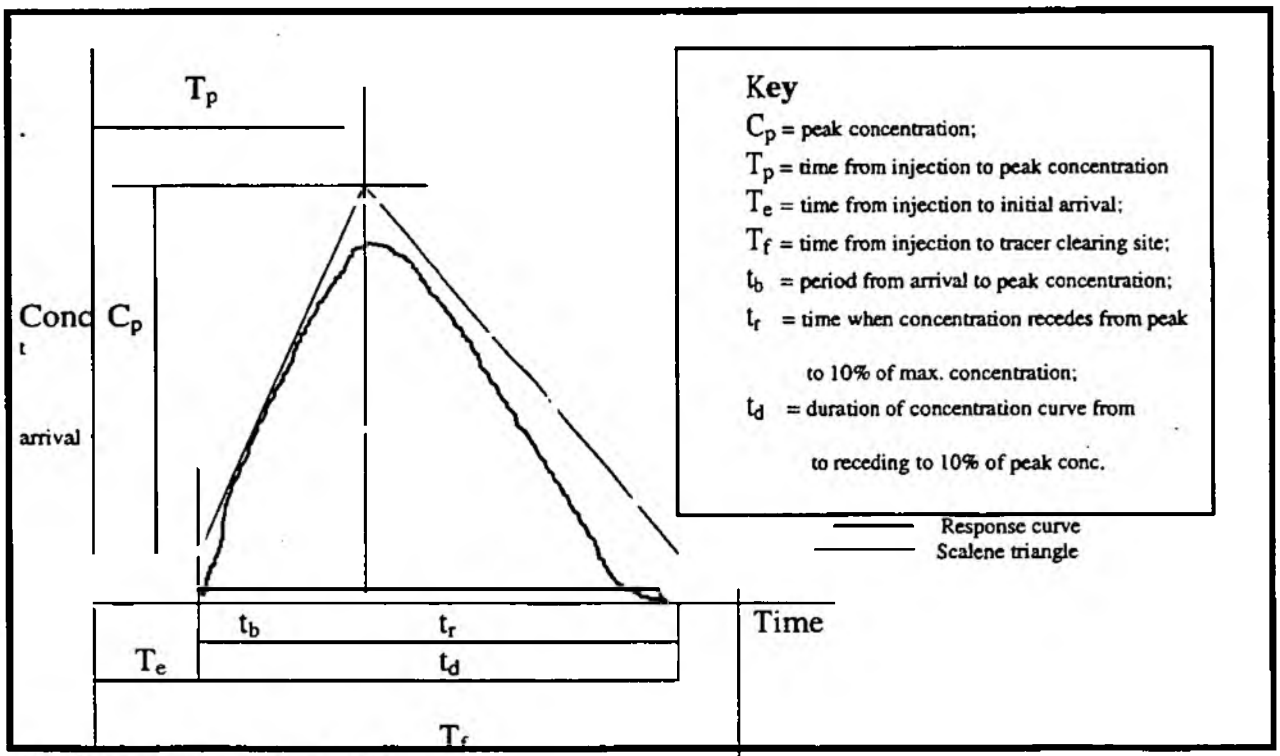
x	:	distance from injection and
Q	:	discharge

These particular elements of the time concentration-time distribution are shown in Figure 6.1. Kilpatrick and Taylor (1986) used a Scalene triangle (three unequal length sides) as an analogy for the response curve. The intention of this was to simplify the more complex response curve and allow predictions to be made based on this simpler form. The main features of the curve (arrival time, peak concentration and through time) form the triangle.

The use of a concentration – unitised peak (cup in mg/l per g of dye injected) allows the prediction by simple multiplication of peak concentration for a pollution incident of any magnitude, provided that:-

a) mass of pollution is known;
b) spillage is instantaneous;
c) the pollutant is a chemically conservative solute.

Figure 6.1 Features of concentration distribution, with scalene triangle overlaid



(based on Kilpatrick and Taylor, 1986)

The characteristic shape of the classic concentration-time distribution is a fairly rapid rise from the leading edge to the peak concentration followed by a more gradual recession to the trailing edge, and this shape is maintained as the plume moves downstream. Kilpatrick and Taylor (1986) used the scalene triangle as an analogy for the response curve. The intention of this was to simplify the more complex response curve and allow predictions to be made based upon this simpler form. Testing of this analogy was undertaken using 184 data sets collected by the U.S. Geological Survey from all over the United States. The main features of the curve i.e. arrival time, peak time, peak concentration, and through time were used to form the triangle. The area of the triangle was then compared to that of the original response curve. Log-linear regression analysis of the two areas yields an expression for the area of the scalene triangle (A_Δ) which is:

$$A_\Delta = 1.024\left(A_c\right)^{1.006} \qquad \text{Equation 6.2}$$

where:- A_c = area under concentration-time distribution.

The approaches set out by Kilpatrick and Taylor are in quite stark contrast to much of the other work which has been completed in this field. The essence of this lies in the fact that the process of making predictions relies heavily upon the acquisition and use of suitable data. Data are used from experiments which cover very long lengths of river channel. The river networks studied were often more complex than simple linear systems, with a number of individual branches being covered. In addition, a large number of sets of tracer results are used for the development of interrelations. The attempt to make some links between the characteristics of the channel and the behaviour of the pollutant plume moves away from the tendency to aggregate the processes occurring in the channel. The predictive techniques are not process-based, but the coefficients derived can be used to make connections between plume behaviour and channel attributes.

There are a number of problems that have been identified by researchers such as Wilson *et al.* (1997) associated with the work of Kilpatrick and Taylor:-

- the calculation of unitised concentrations as they suggest necessitates the availability of river gaugings for each monitoring site utilised. Whilst an attempt was made to link sampling sites with gauging stations in this study and there was at least one gauging station used on all rivers except the Gipping, the use of gauging stations as sampling sites is not always appropriate to the time of travel experiment;

- no indication is given of the accuracy of the relationships which are put forward or the predictions which are derived from them;

- the use of non-S.I. units makes comparison of the relationships with other data sets with metric measurements problematic.

Despite these drawbacks the techniques outlined appear to be robust given the large amount of data upon which they are based. The consistency and regularity of the relationships observed would also appear to indicate that they are reproducible and form the basis for predictive systems for regulatory bodies such as the Environment Agency.

6.3 Joining dye trace data from the same river

As already discussed, on the Rivers Waveney and Wensum it proved necessary to divide the overall trace into two sections at the lower flows. Clearly for the estimation of overall travel times in these rivers it is necessary for there to be some overlap between the points at which data are collected rather than simply joining two separate experiments. For the River Waveney this overlap occurred at Wortwell and for the Wensum the site at Lenwade was used on the second pair of traces. This overlap allows some evaluation of the procedure for joining the two traces.

Clearly the results from the two parts of the trace cannot simply be conflated; the through time and the time to peak in the lower reaches of the river are a function of the advection and dispersion process taking place in the whole river. Therefore these values should take account of the results of the upper trace and the these values must be adjusted. The procedure for this was as follows:

(i) the values for the upper section of the trace are used without adjustment;

(ii) the values of time to arrival from injection in the lower section of the trace represent the advection of tracer with no delay and, therefore, can be added incrementally to time of arrival at the lower injection site of the tracer (from the upper injection);

(iii) as a first approximation the time to peak concentration at the first site of the lower trace is calculated by adding the observed time to peak at that site to the time from arrival to peak at the last site of the upper trace;

(iv) The through time at the first site of the lower trace was increased by the addition of the through time at the last site on the upper trace;

After these calculations have been carried out they may be validated by a comparison with the site measured on both the upper and lower traces. This is illustrated for the first dye trace carried out on the River Wensum in Table 6.1:

Table 6.1 Predicted and Actual values at Lenwade

Predicted values at Lenwade

Time of Arrival	Time to Peak	Through Time
24.67	30.21	11.93

Actual Values at Lenwade

Time of Arrival	Time to Peak	Through Time
28.3	31.33	8.2

The methodology appears to be extremely effective at predicting the time to arrival and the time to peak but is less effective at predicting the through time. This is likely to be partly the result of the development of the secondary peak in the concentration curve on the River Wensum.

6.4 Prediction of time to peak concentration

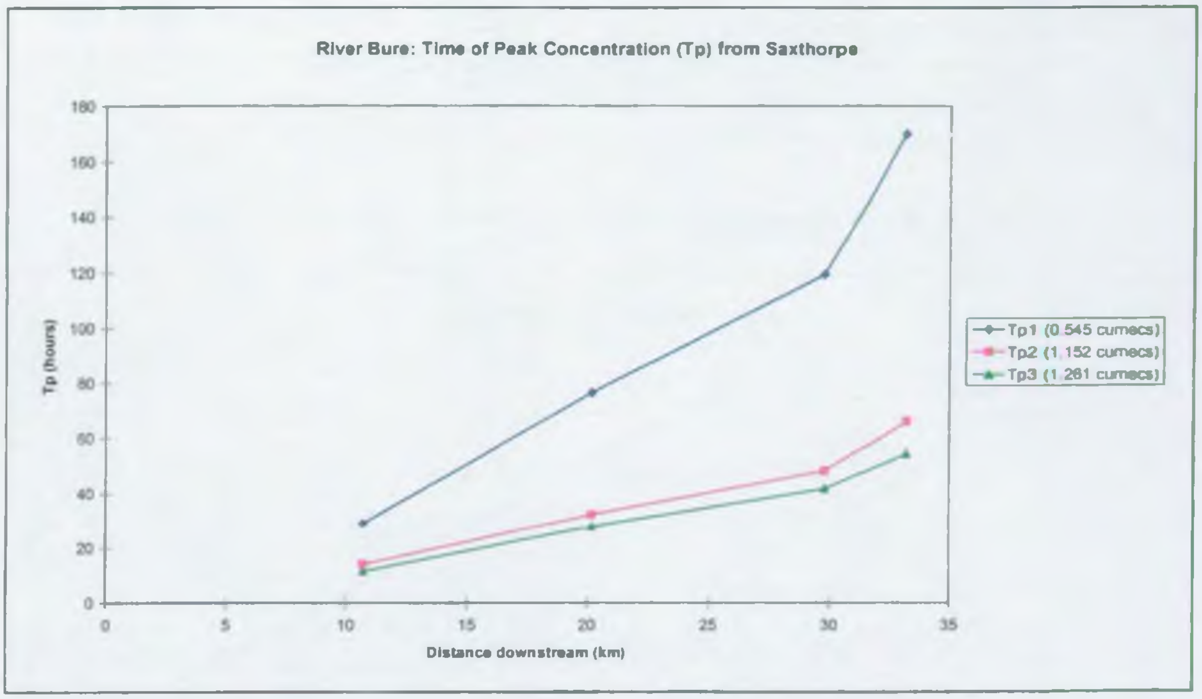
Wilson *et al* (1997) have demonstrated a consistent relationship between distance and the time to peak concentration at different discharge levels. This pattern is demonstrated for the River Bure in Figure 6.2 and is made of 3 distinct elements:-

(a) the time of peak concentration increases as the distance downstream increases;

(b) the rate of this increase becomes more significant as discharge decreases;

(c) the time to peak at the initial monitoring site is inversely related to discharge.

Figure 6.2 River Bure: Time of Peak Concentration (Tp) from Saxthorpe



The approach adopted to predict Tp from discharge and discharge downstream is completed in 2 stages:

(i) The data for all of the rivers demonstrate a very high correlation between time of peak concentration and discharge. Therefore for the initial monitoring site a relationship is established between discharge and time of peak concentration. This relationship is demonstrated for the River Bure in Figure 6.3. Thus it is possible to predict the time of peak concentration from discharge for the initial monitoring site.

(ii) A further relationship is then calculated between the discharge level and the gradient of the slope of the relationship between distance from injection and time to peak. The nature of this relationship for the River Bure is shown in Figure 6.4.

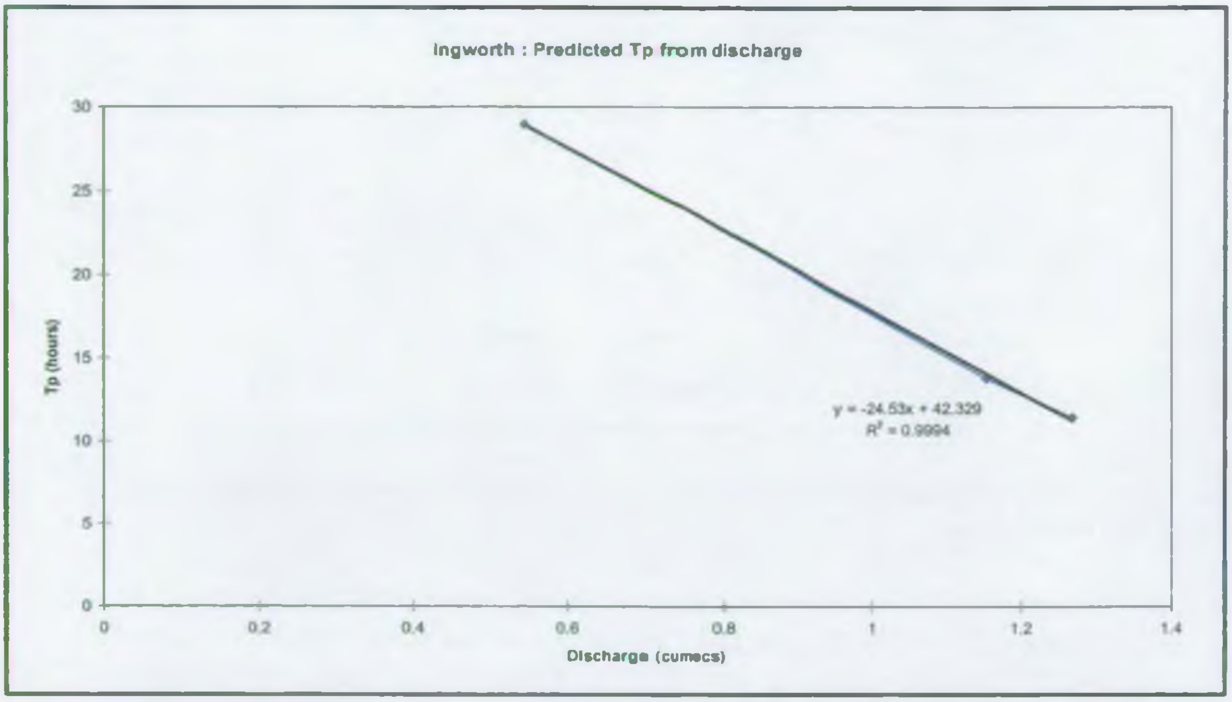
The final relationship between Tp, distance from injection (spillage) may be summarised:

$$Tp = A + Bx \qquad \text{Equation 6.3}$$

where A = Tp for initial monitoring site relative to discharge
B = the gradient of Tp against distance from injection, relative to discharge

This methodology may be exemplified by reference to the River Bure. The first component of the overall prediction involves the prediction of the time to peak at the first site (Figure 6.3). On the River Bure the first site is at Ingworth. The coefficient of determination for the relationship between discharge (measured at Ingworth itself) and time to peak concentration is 0.9994.

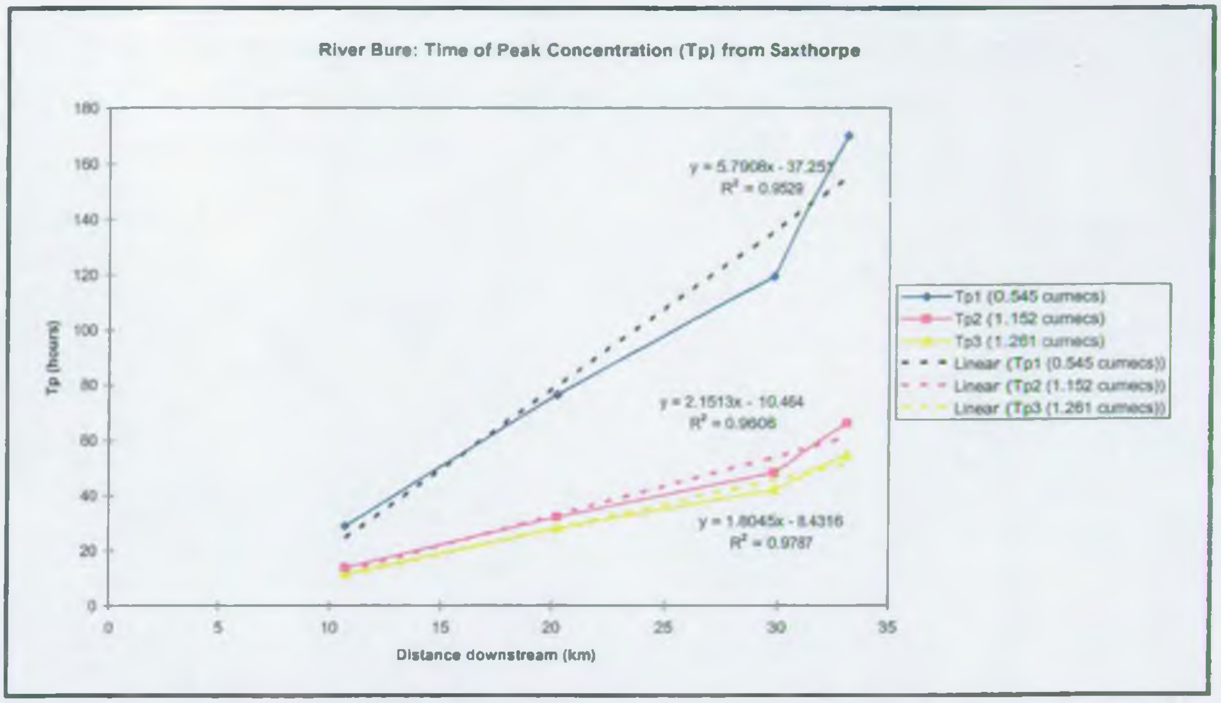
Figure 6.3 River Bure at Ingworth: Predicted Tp from discharge



The resulting regression relationship was then used to predict the arrival time of the dye at any given discharge. Clearly the use of only 3 data points, the product of 3 dye traces, represents the absolute minimum necessary for this approach, but the high cost of dye tracing and the high coefficient of determination resulting from the regression render the outcome more than satisfactory.

The second component of the analysis involves the calculation of the gradients of the regression lines fitted to the Tp data for all of the sites. The data for the River Bure are shown in Figure 6.4.

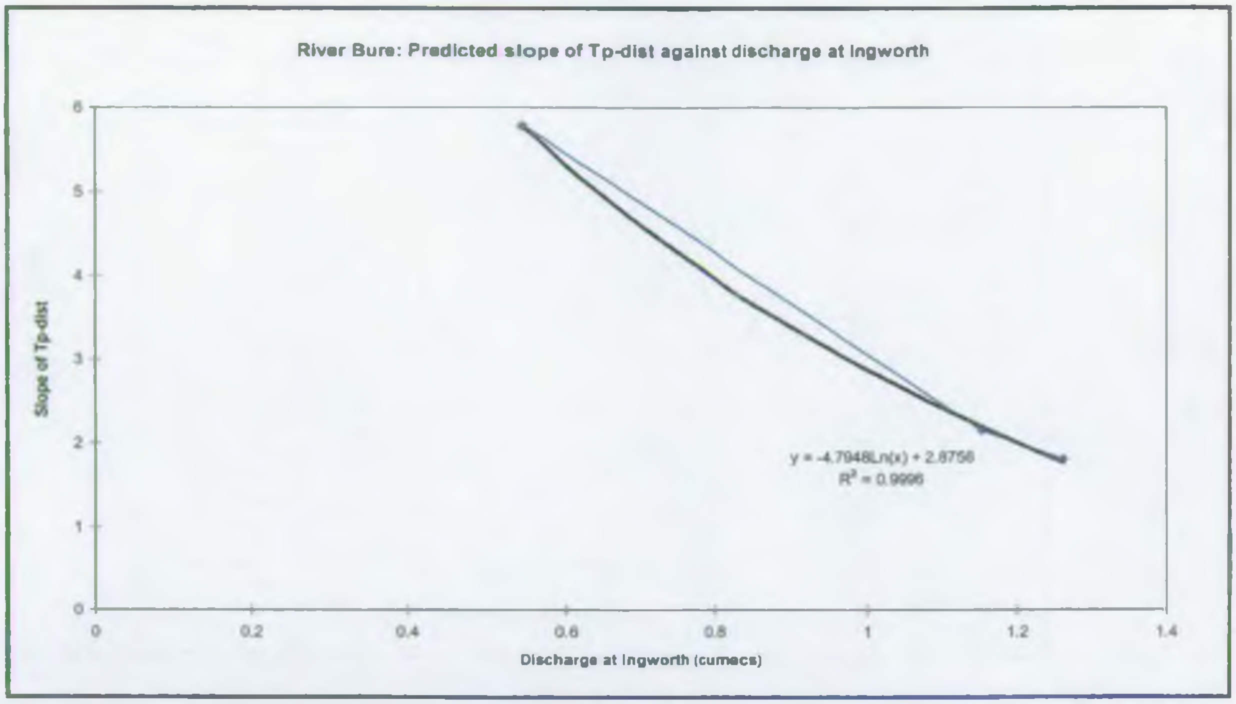
Figure 6.4 River Bure: Time of Peak Concentration (Tp) from Saxthorpe



The coefficients of determination for the regression lines indicate how well the points used to calculate the gradient are described by a straight line. The error that does occur in the regression relationship would appear to be a product of a slight increase in the time to peak at the last site (Belaugh). Nevertheless the regression relationship errs on the conservative side predicting a slightly earlier time to peak than actually occurs. This would appear to be an acceptable error.

The next stage involves the description of the increase in the gradient of the Tp - Distance relationship. It is clear from the figure above that this increase is a function of the increasing discharge and it is therefore possible to establish a relationship between discharge and the gradient of the Tp-distance relationship. Figure 6.5 shows this relationship.

Figure 6.5 River Bure: Predicted slope of Tp-dist against discharge at Ingworth



The equation gives an coefficient of determination of 0.9996 between the observed and predicted values, giving an excellent description of the relationship.

Thus the overall equation to predict Tp is given by:

$$Tp = A + Bx \qquad \text{Equation 6.4}$$

where : A is Tp for the initial monitoring site relative to discharge
B is the gradient of Tp against distance relative to discharge.

The overall relationship gives an excellent prediction of the Tp for the River Bure. Table 6.2 shows the predictions for Tp for the River Bure. The only data requirements to predict the time of peak are distance and discharge. Obviously it would be desirable to use a greater number of data points to characterise the relationships more accurately, and to reserve further data sets for model validation, but this was not possible within the terms of the contract.

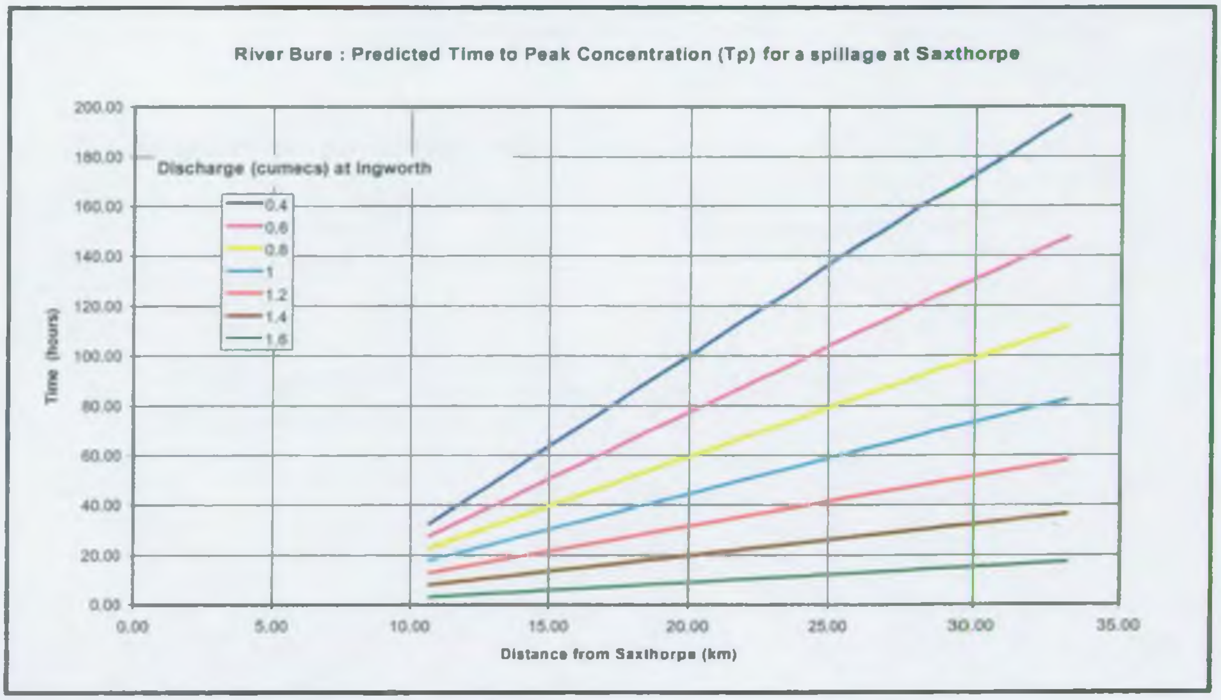
Table 6.2 River Bure: Predicted Time of Peak Concentration (hours from injection) from a spillage at Saxthorpe

		Discharge (cumecs)						
		0.4	0.6	0.8	1	1.2	1.4	1.6
Distance from Saxthorpe (km)								
(Ingworth)	**10.70**	32.52	27.61	22.71	17.80	12.89	7.99	3.08
	11.00	34.70	29.21	23.89	18.66	13.49	8.37	3.27
	11.20	36.15	30.27	24.68	19.24	13.89	8.62	3.39
	11.70	39.79	32.94	26.65	20.67	14.89	9.25	3.70
	12.20	43.42	35.60	28.62	22.11	15.90	9.88	4.01
	12.70	47.06	38.26	30.60	23.55	16.90	10.51	4.33
	13.20	50.69	40.92	32.57	24.99	17.90	11.14	4.64
	13.70	54.32	43.59	34.54	26.43	18.90	11.77	4.95
	14.20	57.96	46.25	36.51	27.86	19.90	12.40	5.26
	14.70	61.59	48.91	38.49	29.30	20.90	13.04	5.57
	15.20	65.23	51.57	40.46	30.74	21.90	13.67	5.88
	15.70	68.86	54.24	42.43	32.18	22.90	14.30	6.19
	16.20	72.50	56.90	44.41	33.61	23.90	14.93	6.50
	16.70	76.13	59.56	46.38	35.05	24.90	15.56	6.81
	17.20	79.77	62.22	48.35	36.49	25.90	16.19	7.12
	17.70	83.40	64.89	50.32	37.93	26.90	16.82	7.44
	18.20	87.03	67.55	52.30	39.37	27.90	17.45	7.75
	18.70	90.67	70.21	54.27	40.80	28.90	18.09	8.06
	19.20	94.30	72.87	56.24	42.24	29.90	18.72	8.37
	19.70	97.94	75.54	58.21	43.68	30.91	19.35	8.68
(Oxnead)	**20.20**	101.57	78.20	60.19	45.12	31.91	19.98	8.99
	20.70	105.21	80.86	62.16	46.56	32.91	20.61	9.30
	21.20	108.84	83.52	64.13	47.99	33.91	21.24	9.61
	21.70	112.48	86.18	66.11	49.43	34.91	21.87	9.92
	22.20	116.11	88.85	68.08	50.87	35.91	22.50	10.23
	22.70	119.75	91.51	70.05	52.31	36.91	23.13	10.55
	23.20	123.38	94.17	72.02	53.74	37.91	23.77	10.86
	23.70	127.01	96.83	74.00	55.18	38.91	24.40	11.17
	24.20	130.65	99.50	75.97	56.62	39.91	25.03	11.48
	24.70	134.28	102.16	77.94	58.06	40.91	25.66	11.79
	25.20	137.92	104.82	79.92	59.50	41.91	26.29	12.10
	25.70	141.55	107.48	81.89	60.93	42.91	26.92	12.41
	26.20	145.19	110.15	83.86	62.37	43.91	27.55	12.72
	26.70	148.82	112.81	85.83	63.81	44.92	28.18	13.03

		Discharge (cumecs)						
		0.4	0.6	0.8	1	1.2	1.4	1.6
Distance from Saxthorpe (km)								
	27.20	152.46	115.47	87.81	65.25	45.92	28.81	13.34
	27.70	156.09	118.13	89.78	66.68	46.92	29.45	13.66
	28.20	159.73	120.80	91.75	68.12	47.92	30.08	13.97
	28.70	163.36	123.46	93.72	69.56	48.92	30.71	14.28
	29.20	166.99	126.12	95.70	71.00	49.92	31.34	14.59
(Horstead)	**29.70**	170.63	128.78	97.67	72.44	50.92	31.97	14.90
	30.20	174.26	131.45	99.64	73.87	51.92	32.60	15.21
	30.70	177.90	134.11	101.62	75.31	52.92	33.23	15.52
	31.20	181.53	136.77	103.59	76.75	53.92	33.86	15.83
	31.70	185.17	139.43	105.56	78.19	54.92	34.49	16.14
	32.20	188.80	142.10	107.53	79.62	55.92	35.13	16.45
(Belaugh)	**32.70**	192.44	144.76	109.51	81.06	56.92	35.76	16.77
	33.20	196.07	147.42	111.48	82.50	57.92	36.39	17.08

These values are shown diagramatically in Figure 6.6.

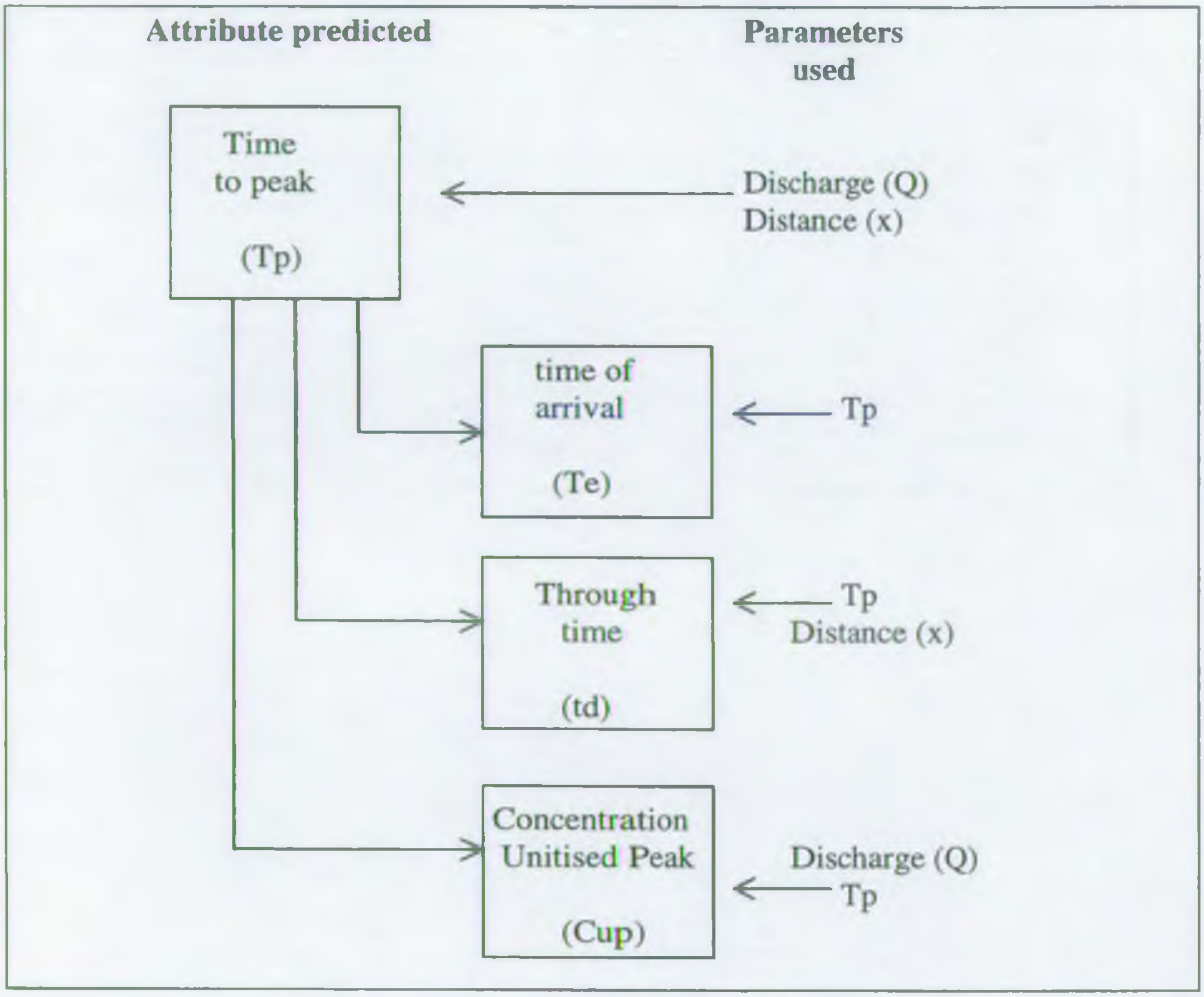
Figure 6.6 River Bure: Predicted Time to Peak Concentration (Tp) for a spillage at Saxthorpe



6.5 Prediction of the time of arrival (Te), through time (td) and concentration unitised peak (Cup)

Having predicted the time to peak as a function of discharge and distance downstream the other facets of the scalene triangle are calculated from the time to peak, as shown in figure 6.7.

Figure 6.7 Steps taken to predict elements of concentration distribution



The principal characteristics of this approach are:

- Strong interrelations have been shown to exist between different elements of tracer distribution curves in the field experiments, both within individual data sets and between them. These relationships are used to generate predictions about the behaviour of pollutant plumes with a high level of accuracy.

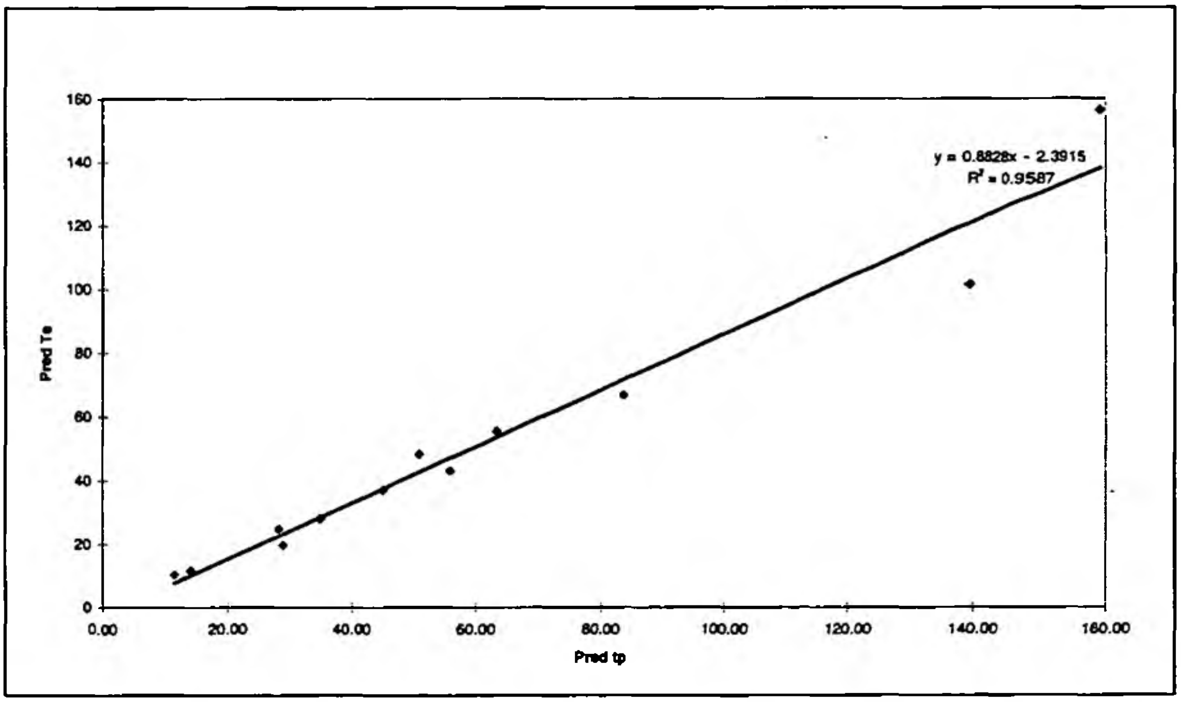
- The approach taken allows the river stretches studied to be viewed as a whole instead of as individual reaches. The effect of this is that, when making predictions, errors are not accumulated as they can be when separate reaches are modelled and the resulting predictions added together.

- It is possible to link the predictive equations derived from tracer experiments on one river with those from another confluent river. This allows complex networks to be covered, but without the requirement for long traces with all their attendant problems. This is particularly useful in the case of the Wendling Beck, a tributary of the Wensum.

- The technique uses readily available and understandable parameters as variables for calculations. In an emergency situation the ability to make a rapid assessment of the likely effects of a pollution incident is vital.

- The relationship between time of arrival and time to peak for the River Bure is shown in Figure 6.8. The regression relationship is then used to calculate the time of arrival.

Figure 6.8 River Bure: Relationship between Time of Arrival and Time to Peak



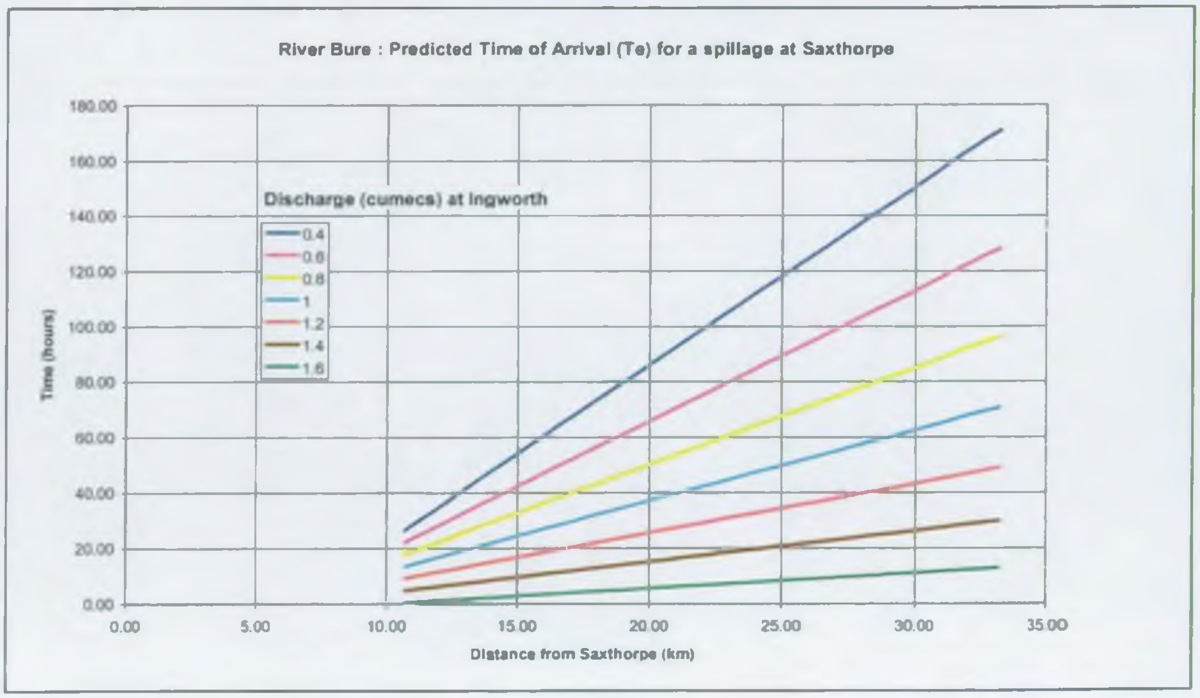
6.5.1 Prediction of the time of arrival

Table 6.3 River Bure: Predicted Time of First Arrival (hours from injection) from a spillage at Saxthorpe

Distance from Saxthorpe (km)		Discharge (cumecs) 0.4	0.6	0.8	1	1.2	1.4	1.6
(Ingworth)	**10.70**	26.31	21.98	17.65	13.32	8.99	4.66	0.33
	11.00	28.24	23.39	18.70	14.08	9.52	4.99	0.49
	11.20	29.52	24.33	19.39	14.59	9.87	5.22	0.60
	11.70	32.73	26.68	21.14	15.86	10.76	5.77	0.88
	12.20	35.94	29.03	22.88	17.13	11.64	6.33	1.15
	12.70	39.15	31.39	24.62	18.40	12.52	6.89	1.43
	13.20	42.36	33.74	26.36	19.67	13.41	7.45	1.70
	13.70	45.57	36.09	28.10	20.94	14.29	8.00	1.98
	14.20	48.77	38.44	29.84	22.21	15.17	8.56	2.25
	14.70	51.98	40.79	31.58	23.48	16.06	9.12	2.52
	15.20	55.19	43.14	33.33	24.75	16.94	9.67	2.80
	15.70	58.40	45.49	35.07	26.01	17.82	10.23	3.07
	16.20	61.61	47.84	36.81	27.28	18.71	10.79	3.35
	16.70	64.82	50.19	38.55	28.55	19.59	11.35	3.62
	17.20	68.03	52.54	40.29	29.82	20.47	11.90	3.90
	17.70	71.23	54.89	42.03	31.09	21.36	12.46	4.17
	18.20	74.44	57.24	43.78	32.36	22.24	13.02	4.45
	18.70	77.65	59.59	45.52	33.63	23.13	13.57	4.72
	19.20	80.86	61.94	47.26	34.90	24.01	14.13	5.00
	19.70	84.07	64.29	49.00	36.17	24.89	14.69	5.27
(Oxnead)	**20.20**	87.28	66.64	50.74	37.44	25.78	15.25	5.55
	20.70	90.49	68.99	52.48	38.71	26.66	15.80	5.82
	21.20	93.69	71.34	54.23	39.98	27.54	16.36	6.09
	21.70	96.90	73.69	55.97	41.25	28.43	16.92	6.37
	22.20	100.11	76.04	57.71	42.52	29.31	17.47	6.64
	22.70	103.32	78.39	59.45	43.78	30.19	18.03	6.92
	23.20	106.53	80.74	61.19	45.05	31.08	18.59	7.19
	23.70	109.74	83.09	62.93	46.32	31.96	19.15	7.47
	24.20	112.95	85.44	64.67	47.59	32.84	19.70	7.74
	24.70	116.15	87.80	66.42	48.86	33.73	20.26	8.02
	25.20	119.36	90.15	68.16	50.13	34.61	20.82	8.29
	25.70	122.57	92.50	69.90	51.40	35.49	21.37	8.57
	26.20	125.78	94.85	71.64	52.67	36.38	21.93	8.84

Distance from Saxthorpe(km)		Discharge 0.4	0.6	0.8	1	1.2	1.4	1.6
	26.70	128.99	97.20	73.38	53.94	37.26	22.49	9.11
	27.20	132.20	99.55	75.12	55.21	38.14	23.05	9.39
	27.70	135.41	101.90	76.87	56.48	39.03	23.60	9.66
	28.20	138.61	104.25	78.61	57.75	39.91	24.16	9.94
	28.70	141.82	106.60	80.35	59.02	40.79	24.72	10.21
	29.20	145.03	108.95	82.09	60.29	41.68	25.27	10.49
	29.70	148.24	111.30	83.83	61.55	42.56	25.83	10.76
	30.20	151.45	113.65	85.57	62.82	43.44	26.39	11.04
	30.70	154.66	116.00	87.31	64.09	44.33	26.95	11.31
	31.20	157.87	118.35	89.06	65.36	45.21	27.50	11.59
	31.70	161.07	120.70	90.80	66.63	46.09	28.06	11.86
	32.20	164.28	123.05	92.54	67.90	46.98	28.62	12.13
	32.70	167.49	125.40	94.28	69.17	47.86	29.17	12.41
(Belaugh)	33.20	170.70	127.75	96.02	70.44	48.74	29.73	12.68

Figure 6.9 River Bure: Predicted Time of Arrival (Te) for a spillage at Saxthorpe



6.5.2 Prediction of Through Time

Figure 6.10 River Bure: Relationship between Through Time and Time to Peak

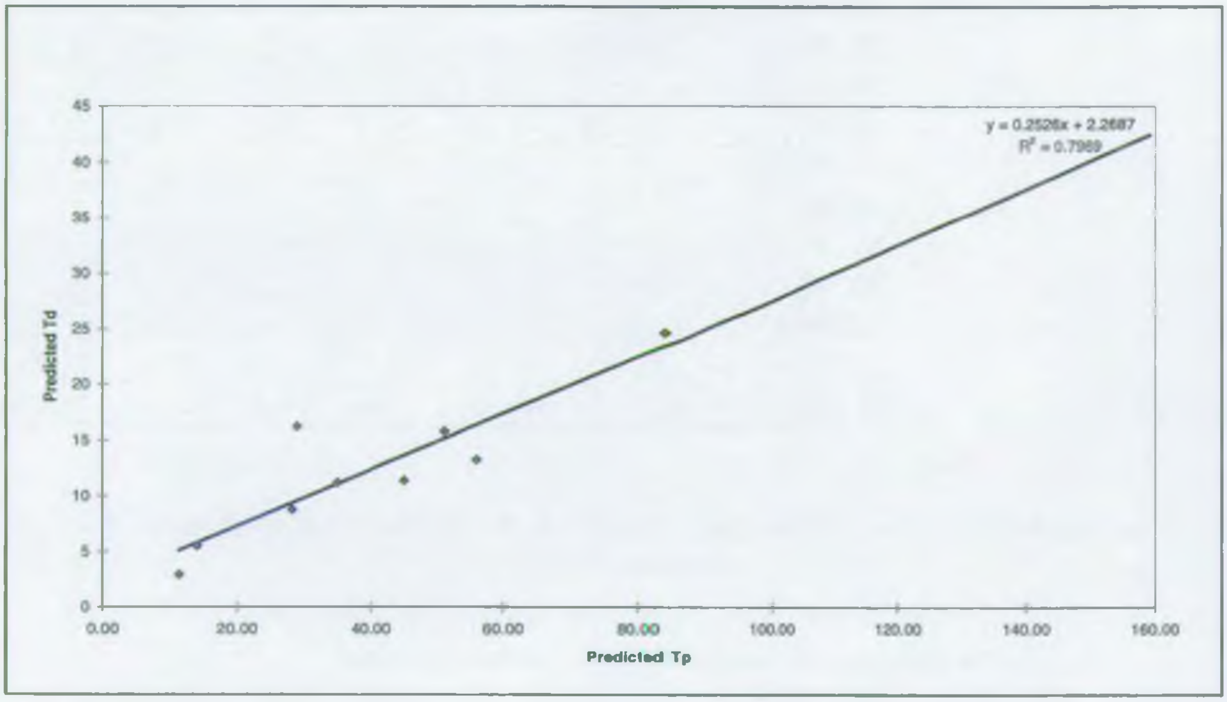


Table 6.4 River Bure: Predicted Through Time from a spillage at Saxthorpe (hours from arrival at site)

Distance from Saxthorpe (km)		Discharge (cumecs) 0.4	0.6	0.8	1	1.2	1.4	1.6
(Ingworth)	**10.70**	10.48	9.24	8.00	6.76	5.53	4.29	3.05
	11.00	11.03	9.65	8.30	6.98	5.68	4.38	3.09
	11.20	11.40	9.92	8.50	7.13	5.78	4.45	3.13
	11.70	12.32	10.59	9.00	7.49	6.03	4.61	3.20
	12.20	13.24	11.26	9.50	7.85	6.28	4.76	3.28
	12.70	14.15	11.93	10.00	8.22	6.54	4.92	3.36
	13.20	15.07	12.61	10.50	8.58	6.79	5.08	3.44
	13.70	15.99	13.28	10.99	8.94	7.04	5.24	3.52
	14.20	16.91	13.95	11.49	9.31	7.29	5.40	3.60
	14.70	17.83	14.62	11.99	9.67	7.55	5.56	3.68
	15.20	18.75	15.30	12.49	10.03	7.80	5.72	3.75
	15.70	19.66	15.97	12.99	10.40	8.05	5.88	3.83
	16.20	20.58	16.64	13.49	10.76	8.31	6.04	3.91
	16.70	21.50	17.31	13.98	11.12	8.56	6.20	3.99
	17.20	22.42	17.99	14.48	11.49	8.81	6.36	4.07
	17.70	23.34	18.66	14.98	11.85	9.06	6.52	4.15
	18.20	24.25	19.33	15.48	12.21	9.32	6.68	4.23
	18.70	25.17	20.00	15.98	12.58	9.57	6.84	4.30
	19.20	26.09	20.68	16.48	12.94	9.82	7.00	4.38
	19.70	27.01	21.35	16.97	13.30	10.08	7.16	4.46
(Oxnead)	**20.20**	27.93	22.02	17.47	13.67	10.33	7.32	4.54
	20.70	28.84	22.69	17.97	14.03	10.58	7.47	4.62
	21.20	29.76	23.37	18.47	14.39	10.83	7.63	4.70
	21.70	30.68	24.04	18.97	14.75	11.09	7.79	4.78
	22.20	31.60	24.71	19.47	15.12	11.34	7.95	4.85
	22.70	32.52	25.38	19.96	15.48	11.59	8.11	4.93
	23.20	33.43	26.06	20.46	15.84	11.84	8.27	5.01
	23.70	34.35	26.73	20.96	16.21	12.10	8.43	5.09
	24.20	35.27	27.40	21.46	16.57	12.35	8.59	5.17
	24.70	36.19	28.07	21.96	16.93	12.60	8.75	5.25
	25.20	37.11	28.75	22.46	17.30	12.86	8.91	5.33
	25.70	38.02	29.42	22.95	17.66	13.11	9.07	5.40
	26.20	38.94	30.09	23.45	18.02	13.36	9.23	5.48
	26.70	39.86	30.76	23.95	18.39	13.61	9.39	5.56
	27.20	40.78	31.44	24.45	18.75	13.87	9.55	5.64

		Discharge (cumecs)						
		0.4	0.6	0.8	1	1.2	1.4	1.6
Distance from Saxthorpe (km)								
	27.70	41.70	32.11	24.95	19.11	14.12	9.71	5.72
	28.20	42.62	32.78	25.45	19.48	14.37	9.87	5.80
	28.70	43.53	33.45	25.94	19.84	14.63	10.03	5.88
	29.20	44.45	34.13	26.44	20.20	14.88	10.18	5.95
(Horstead)	**29.70**	45.37	34.80	26.94	20.57	15.13	10.34	6.03
	30.20	46.29	35.47	27.44	20.93	15.38	10.50	6.11
	30.70	47.21	36.14	27.94	21.29	15.64	10.66	6.19
	31.20	48.12	36.82	28.44	21.66	15.89	10.82	6.27
	31.70	49.04	37.49	28.93	22.02	16.14	10.98	6.35
	32.20	49.96	38.16	29.43	22.38	16.39	11.14	6.43
	32.70	50.88	38.83	29.93	22.75	16.65	11.30	6.50
(Belaugh)	**33.20**	51.80	39.51	30.43	23.11	16.90	11.46	6.58

Figure 6.11 River Bure: Predicted Through Time (td) for a spillage at Saxthorpe

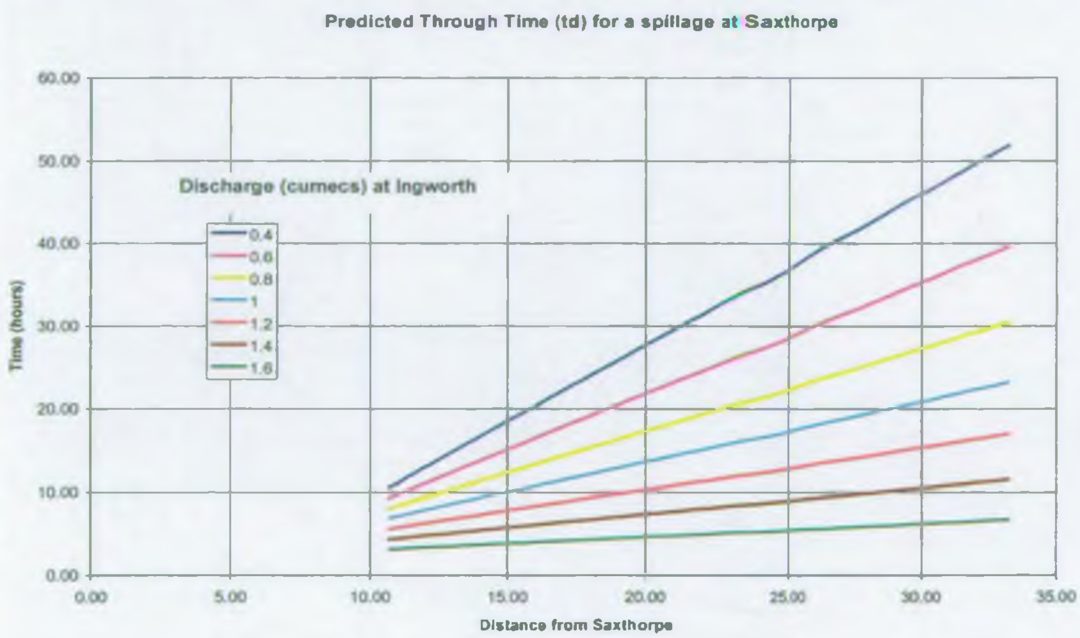
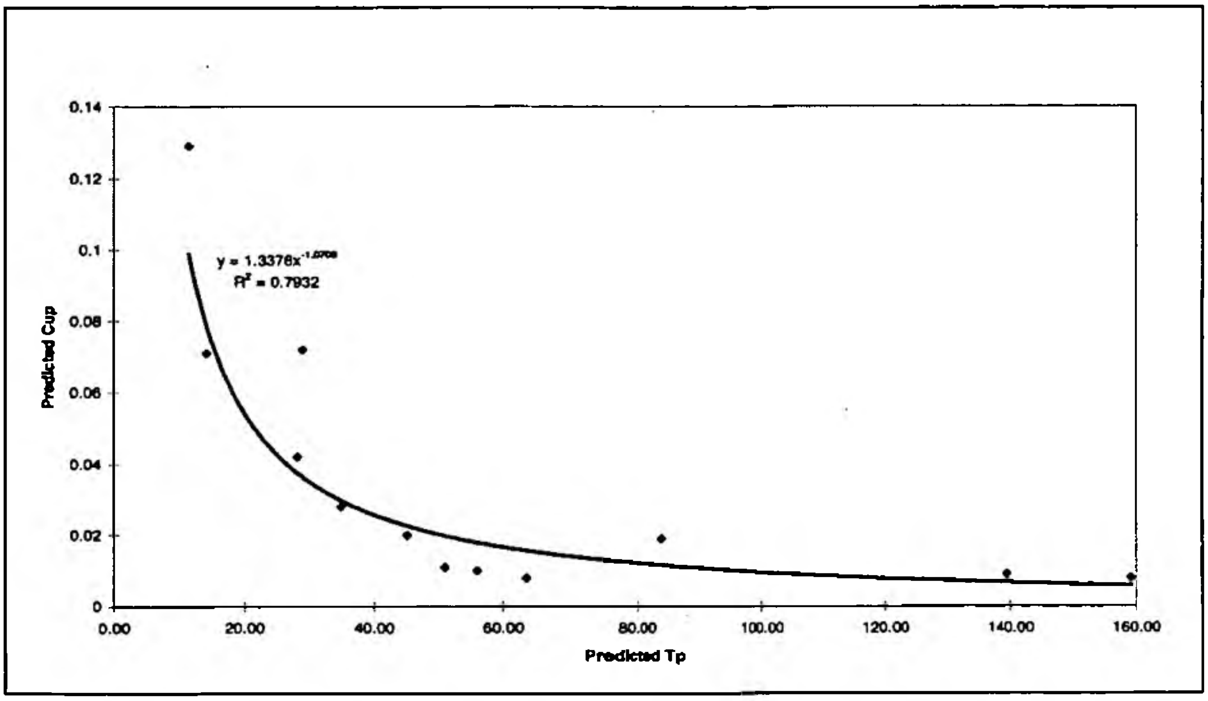


Table 6.5 River Bure: Predicted Concentration Unitised Peak from a spillage at Saxthorpe (μg l^{-1} per g of dye injected)

	Distance from Saxthorpe (km)	Discharge (cumecs) 0.4	0.6	0.8	1	1.2	1.4	1.6
(Ingworth)	**10.70**	0.031	0.037	0.046	0.060	0.085	0.143	0.401
	11.00	0.029	0.035	0.043	0.057	0.081	0.136	0.376
	11.20	0.028	0.034	0.042	0.055	0.078	0.131	0.361
	11.70	0.025	0.031	0.039	0.051	0.073	0.122	0.328
	12.20	0.023	0.028	0.036	0.047	0.068	0.113	0.301
	12.70	0.021	0.026	0.033	0.044	0.063	0.106	0.277
	13.20	0.019	0.024	0.031	0.041	0.059	0.099	0.257
	13.70	0.018	0.023	0.029	0.039	0.056	0.094	0.240
	14.20	0.017	0.021	0.027	0.037	0.053	0.089	0.224
	14.70	0.016	0.020	0.026	0.035	0.050	0.084	0.211
	15.20	0.015	0.019	0.025	0.033	0.048	0.080	0.199
	15.70	0.014	0.018	0.023	0.031	0.046	0.076	0.188
	16.20	0.013	0.017	0.022	0.030	0.043	0.072	0.178
	16.70	0.012	0.016	0.021	0.029	0.042	0.069	0.169
	17.20	0.012	0.015	0.020	0.027	0.040	0.066	0.161
	17.70	0.011	0.015	0.019	0.026	0.038	0.064	0.154
	18.20	0.011	0.014	0.019	0.025	0.037	0.061	0.147
	18.70	0.010	0.014	0.018	0.024	0.035	0.059	0.141
	19.20	0.010	0.013	0.017	0.023	0.034	0.057	0.136
	19.70	0.009	0.012	0.017	0.023	0.033	0.055	0.130
(Oxnead)	**20.20**	0.009	0.012	0.016	0.022	0.032	0.053	0.125
	20.70	0.009	0.012	0.015	0.021	0.031	0.051	0.121
	21.20	0.008	0.011	0.015	0.020	0.030	0.049	0.117
	21.70	0.008	0.011	0.014	0.020	0.029	0.048	0.113
	22.20	0.008	0.010	0.014	0.019	0.028	0.046	0.109
	22.70	0.008	0.010	0.014	0.019	0.027	0.045	0.106
	23.20	0.007	0.010	0.013	0.018	0.026	0.044	0.102
	23.70	0.007	0.010	0.013	0.018	0.026	0.043	0.099
	24.20	0.007	0.009	0.012	0.017	0.025	0.041	0.096
	24.70	0.007	0.009	0.012	0.017	0.024	0.040	0.094
	25.20	0.007	0.009	0.012	0.016	0.024	0.039	0.091
	25.70	0.006	0.009	0.011	0.016	0.023	0.038	0.088
	26.20	0.006	0.008	0.011	0.015	0.022	0.037	0.086
	26.70	0.006	0.008	0.011	0.015	0.022	0.036	0.084

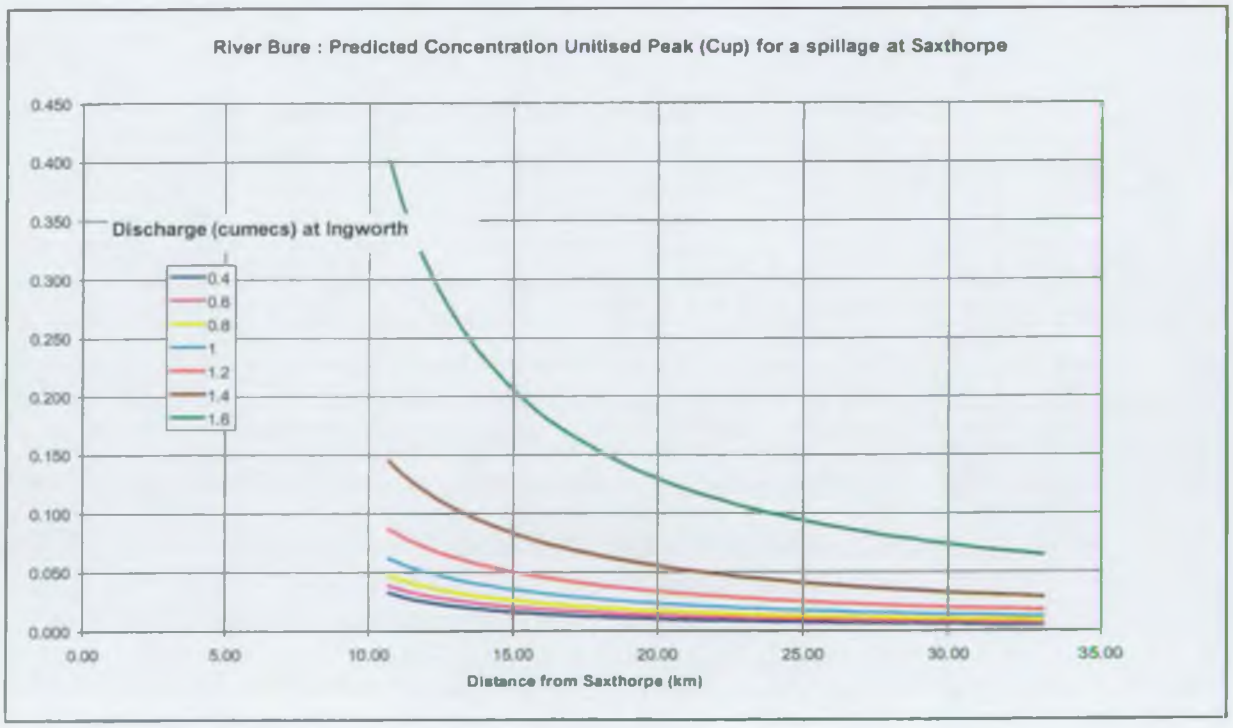
6.5.3 Prediction of Concentration Unitised Peak

Figure 6.12 River Bure: Relationship between Cup and Time to Peak



Distance from Saxthorpe (km)		Discharge (cumecs) 0.4	0.6	0.8	1	1.2	1.4	1.6
	27.20	0.006	0.008	0.011	0.015	0.021	0.035	0.082
	27.70	0.006	0.008	0.010	0.014	0.021	0.035	0.080
	28.20	0.006	0.008	0.010	0.014	0.020	0.034	0.078
	28.70	0.005	0.007	0.010	0.014	0.020	0.033	0.076
	29.20	0.005	0.007	0.010	0.013	0.020	0.032	0.074
(Horstead)	29.70	0.005	0.007	0.009	0.013	0.019	0.032	0.073
	30.20	0.005	0.007	0.009	0.013	0.019	0.031	0.071
	30.70	0.005	0.007	0.009	0.013	0.018	0.030	0.069
	31.20	0.005	0.007	0.009	0.012	0.018	0.030	0.068
	31.70	0.005	0.006	0.009	0.012	0.018	0.029	0.067
	32.20	0.005	0.006	0.009	0.012	0.017	0.029	0.065
	32.70	0.005	0.006	0.008	0.012	0.017	0.028	0.064
(Belaugh)	33.20	0.004	0.006	0.008	0.011	0.017	0.028	0.063

Figure 6.13 River Bure: Predicted Concentration Unitised Peak (Cup) for a spillage at Saxthorpe ($\mu g\ l^{-1}$ per g of dye injected)



6.5.4 Evaluation of Predictions

Table 6.6 River Bure: Comparison of observed and predicted characteristics of pollution plume

Site	Measured Tp	Pred. Tp	Measured Te	Pred. Te	Measured td	Pred. td	Measured Cup	Pred. Cup
Ingworth	29	28.96	19.75	23.17	16.24	9.58	0.072	0.036
Oxnead	76.5	83.93	66.75	71.70	24.64	23.47	0.019	0.012
Horstead Mill	119.25	139.47	101.5	120.73	-	-	0.009	0.007
Belaugh	170	159.14	156.5	138.10	-	-	0.008	0.006
Ingworth	13.83	14.07	11.66	10.03	5.53	5.82	0.071	0.079
Oxnead	32.24	34.94	28.08	28.46	11.22	11.10	0.028	0.030
Horstead Mill	48.08	56.04	43.08	47.08	13.23	16.42	0.01	0.018
Belaugh	66	63.51	55.58	53.67	-	-	0.008	0.016
Ingworth	11.46	11.40	10.25	7.67	2.92	5.15	0.129	0.099
Oxnead	27.93	28.15	24.75	22.46	8.78	9.38	0.042	0.038
Horstead Mill	41.83	45.08	37	37.41	11.39	13.66	0.02	0.023
Belaugh	54.5	51.08	48.25	42.70	15.81	15.17	0.011	0.020

6.5.5 Summary of River Bure travel time predictions

Table 6.7 River Bure Predictive Equations

Variable	Equation	R^2	Equation No
Ingworth Tp	- 24.53Q + 42.329	0.9994	6.5
Slope Tp-dist	= - 4.7948(Log Q) + 2.8756	0.9996	6.6
Tp	= Ingworth Tp + [x (slope Tp-dist)]		6.7
Te	= 0.8828 Tp + 2.3915	0.9587	6.8
Td	= 0.2526 Tp + 2.2687	0.7969	6.9
Cup	$= 1.3376\ Tp^{-1.0706}$	0.7932	6.10

where Q = Discharge at Ingworth (cumecs)
x = Distance downstream from Ingworth (km)
Tp = Time to peak concentration (hours from injection)
Te = Time to arrival (hours from injection)
Td = Through time (hours from arrival)
Cup = Concentration Unitised Peak ($\mu g.l^{-1}$ per g of dye injected)

6.6 Travel Time Predictions for the Rivers Gipping, Wensum and Waveney

A similar approach to that adopted for the River Bure was used for the other rivers in the study. The summary equations are presented in this section together with the graphs. The full data sets and tables are presented in Appendix B

6.6.1 River Gipping

Table 6.8 River Gipping Predictive Equations

Variable	Equation	R^2	Equation No
Gypsy Lane Tp	$= 11.142\ Q^{-1.3305}$	0.9762	6.11
Slope Tp-dist	$= 2.4619Q^{-0.9334}$	0.9989	6.12
Tp	= Gypsy Lane Tp + [x (slope Tp-dist)]		6.13
Te	= 0.9262 Tp	0.9699	6.14
Td	= 0.1509 Tp + 8.1087	0.3247	6.15
Cup	$= 0.1024\ TP^{-0.5297}$	0.1195	6.16

where
- Q = Discharge at Bramford (cumecs)
- x = Distance downstream from Gypsy Lane (km)
- Tp = Time to peak concentration (hours from injection)
- Te = Time to arrival (hours from injection)
- td = Through time (hours from arrival)
- Cup = Concentration Unitised Peak ($\mu g\ l^{-1}$ per g of dye injected)

Table 6.9 River Gipping: Time to Peak Concentration from spillage at Stowmarket (hours from injection)

Distance from Stowmarket (km)		Discharge (cumecs) 0.2	0.4	0.6	0.8	1	1.2	1.4	1.6
(Needham Market)	**5.40**	94.83	37.71	21.99	14.99	11.14	8.74	7.12	5.96
	5.50	95.94	38.29	22.38	15.30	11.39	8.95	7.30	6.12
	6.00	101.46	41.18	24.36	16.81	12.33	9.99	8.20	6.24
	6.50	106.99	44.08	26.35	18.33	13.56	11.03	9.10	6.46
	7.00	112.52	46.97	28.33	19.84	14.79	12.06	10.00	6.67
	7.50	118.05	49.87	30.31	21.36	16.02	13.10	10.90	6.87
	8.00	123.58	52.76	32.30	22.88	17.25	14.14	11.80	7.05
	8.50	129.11	55.66	34.28	24.39	18.48	15.18	12.70	7.23
	9.00	134.64	58.55	36.26	25.91	19.72	16.22	13.60	7.39
	9.50	140.17	61.45	38.25	27.42	20.95	17.26	14.49	7.56
	10.00	145.70	64.34	40.23	28.94	22.18	18.29	15.39	7.71
	10.50	151.23	67.24	42.21	30.46	23.41	19.33	16.29	7.86
	11.00	156.76	70.13	44.19	31.97	24.64	20.37	17.19	8.01
	11.50	162.29	73.03	46.18	33.49	25.87	21.41	18.09	8.15
	12.00	167.81	75.92	48.16	35.00	27.10	22.45	18.99	8.29
	12.50	173.34	78.82	50.14	36.52	28.33	23.49	19.89	8.43
	13.00	178.87	81.71	52.13	38.04	29.56	24.52	20.79	8.56
	13.50	184.40	84.61	54.11	39.55	30.79	25.56	21.69	8.69
(Claydon Bridge)	**14.00**	189.93	87.50	56.09	41.07	32.02	26.60	22.59	8.82
	14.50	195.46	90.40	58.08	42.58	33.26	27.64	23.49	8.94
	15.00	200.99	93.29	60.06	44.10	34.49	28.68	24.39	9.06
	15.50	206.52	96.19	62.04	45.62	35.72	29.72	25.28	9.18
	16.00	212.05	99.09	64.02	47.13	36.95	30.75	26.18	9.30
	16.50	217.58	101.98	66.01	48.65	38.18	31.79	27.08	9.41
	17.00	223.11	104.88	67.99	50.16	39.41	32.83	27.98	9.53
	17.50	228.63	107.77	69.97	51.68	40.64	33.87	28.88	9.64
	18.00	234.16	110.67	71.96	53.20	41.87	34.91	29.78	9.75
	18.50	239.69	113.56	73.94	54.71	43.10	35.95	30.68	9.85
	19.00	245.22	116.46	75.92	56.23	44.33	36.98	31.58	9.96
	19.50	250.75	119.35	77.90	57.74	45.57	38.02	32.48	10.06
	20.00	256.28	122.25	79.89	59.26	46.80	39.06	33.38	10.17
	20.50	261.81	125.14	81.87	60.78	48.03	40.10	34.28	10.27
(Sproughton)	**21.00**	267.34	128.04	83.85	62.29	49.26	41.14	35.18	10.37

Figure 6.14 River Gipping: Predicted Time to Peak Concentration (Tp) for a spillage at Stowmarket

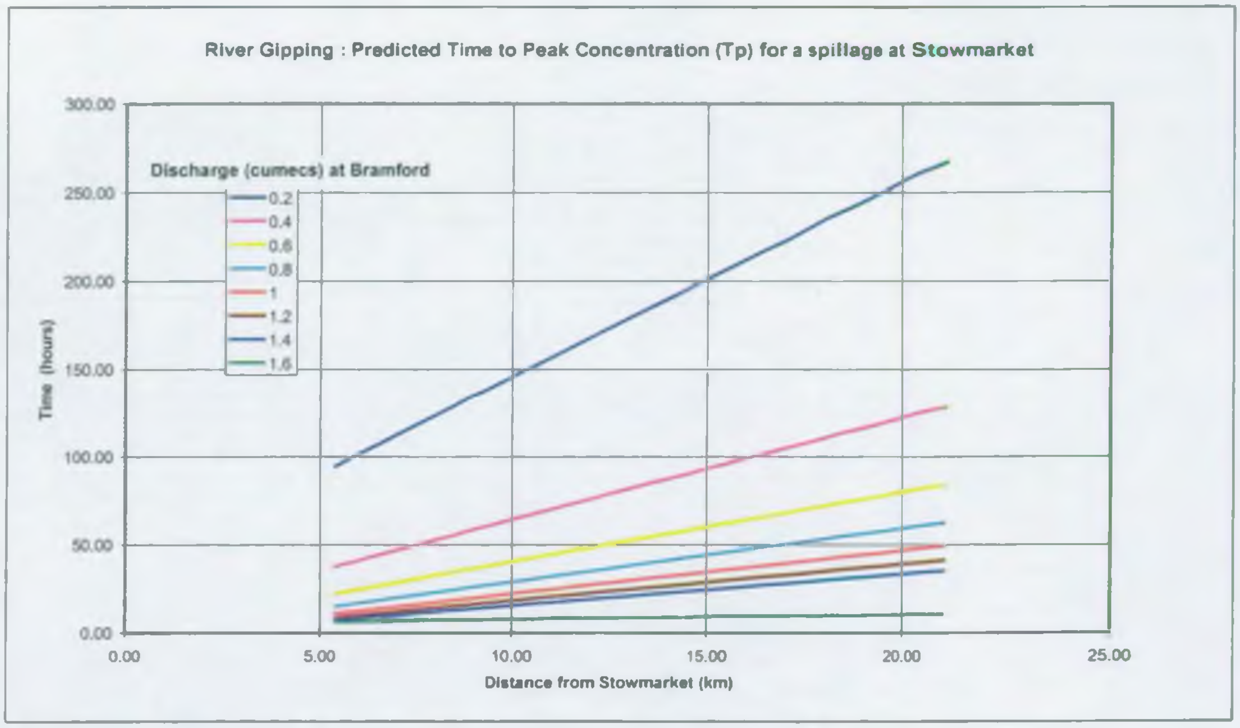


Table 6.10 River Gipping: Predicted time to arrival from spillage at Stowmarket (hours from injection)

Distance from Stowmarket (km)		Discharge (cumecs) 0.2	0.4	0.6	0.8	1	1.2	1.4	1.6
(Needham Market)	**5.40**	87.83	34.92	20.36	13.89	10.32	8.10	6.60	5.52
	5.50	88.86	35.46	20.73	14.17	10.55	8.29	6.76	5.67
	6.00	93.98	38.14	22.57	15.57	11.42	9.25	7.59	5.78
	6.50	99.10	40.82	24.40	16.98	12.56	10.21	8.43	5.98
	7.00	104.22	43.51	26.24	18.38	13.70	11.17	9.26	6.18
	7.50	109.34	46.19	28.08	19.78	14.84	12.14	10.09	6.36
	8.00	114.46	48.87	29.91	21.19	15.98	13.10	10.93	6.53
	8.50	119.58	51.55	31.75	22.59	17.12	14.06	11.76	6.69
	9.00	124.70	54.23	33.59	24.00	18.26	15.02	12.59	6.85
	9.50	129.82	56.91	35.42	25.40	19.40	15.98	13.42	7.00
	10.00	134.95	59.59	37.26	26.80	20.54	16.94	14.26	7.14
	10.50	140.07	62.28	39.10	28.21	21.68	17.91	15.09	7.28
	11.00	145.19	64.96	40.93	29.61	22.82	18.87	15.92	7.42
	11.50	150.31	67.64	42.77	31.02	23.96	19.83	16.76	7.55
	12.00	155.43	70.32	44.61	32.42	25.10	20.79	17.59	7.68
	12.50	160.55	73.00	46.44	33.83	26.24	21.75	18.42	7.81
	13.00	165.67	75.68	48.28	35.23	27.38	22.71	19.25	7.93
	13.50	170.79	78.37	50.12	36.63	28.52	23.68	20.09	8.05
(Claydon Bridge)	**14.00**	175.91	81.05	51.95	38.04	29.66	24.64	20.92	8.16
	14.50	181.04	83.73	53.79	39.44	30.80	25.60	21.75	8.28
	15.00	186.16	86.41	55.63	40.85	31.94	26.56	22.59	8.39
	15.50	191.28	89.09	57.46	42.25	33.08	27.52	23.42	8.50
	16.00	196.40	91.77	59.30	43.65	34.22	28.48	24.25	8.61
	16.50	201.52	94.45	61.14	45.06	35.36	29.45	25.08	8.72
	17.00	206.64	97.14	62.97	46.46	36.50	30.41	25.92	8.82
	17.50	211.76	99.82	64.81	47.87	37.64	31.37	26.75	8.93
	18.00	216.88	102.50	66.65	49.27	38.78	32.33	27.58	9.03
	18.50	222.00	105.18	68.48	50.67	39.92	33.29	28.42	9.13
	19.00	227.13	107.86	70.32	52.08	41.06	34.25	29.25	9.22
	19.50	232.25	110.54	72.16	53.48	42.20	35.22	30.08	9.32
	20.00	237.37	113.22	73.99	54.89	43.34	36.18	30.91	9.42
	20.50	242.49	115.91	75.83	56.29	44.48	37.14	31.75	9.51
(Sproughton)	**21.00**	247.61	118.59	77.67	57.70	45.62	38.10	32.58	9.60

Figure 6.15 River Gipping Predicted Time of Arrival (Te) for a spillage at Stowmarket

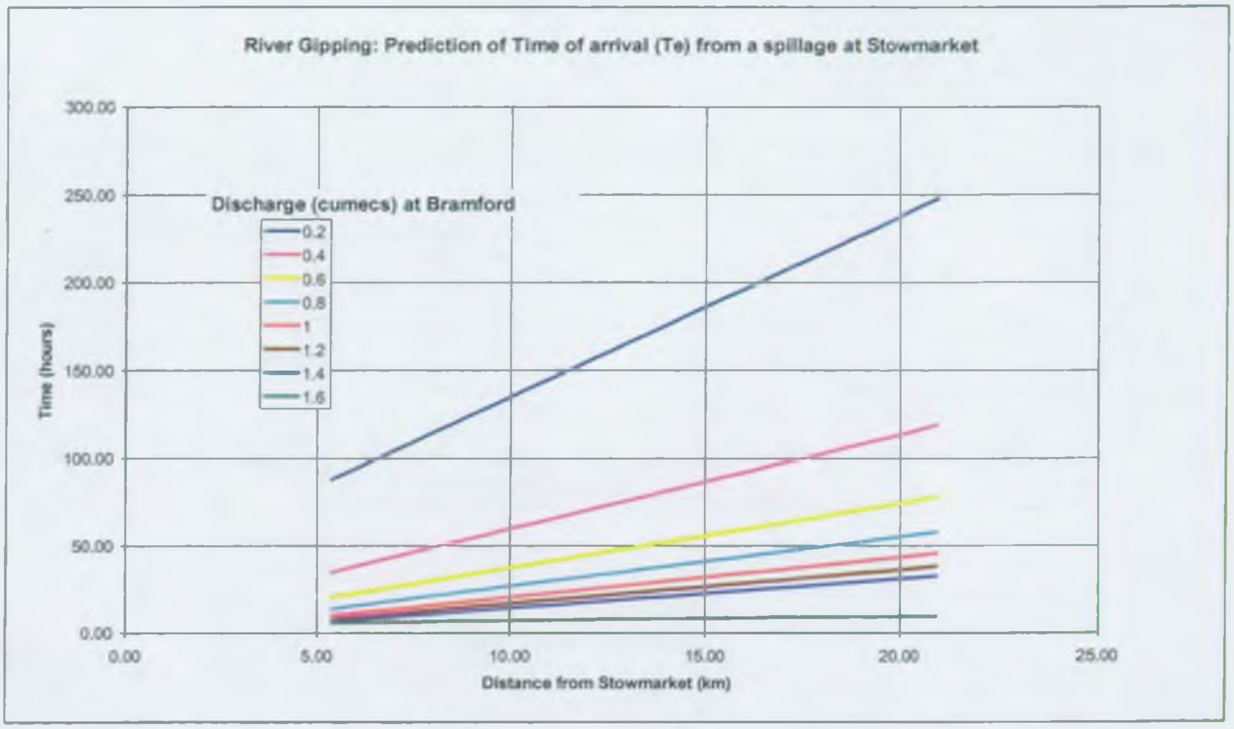


Figure 6.16 River Gipping: Predicted through time (td) for spillage at Stowmarket

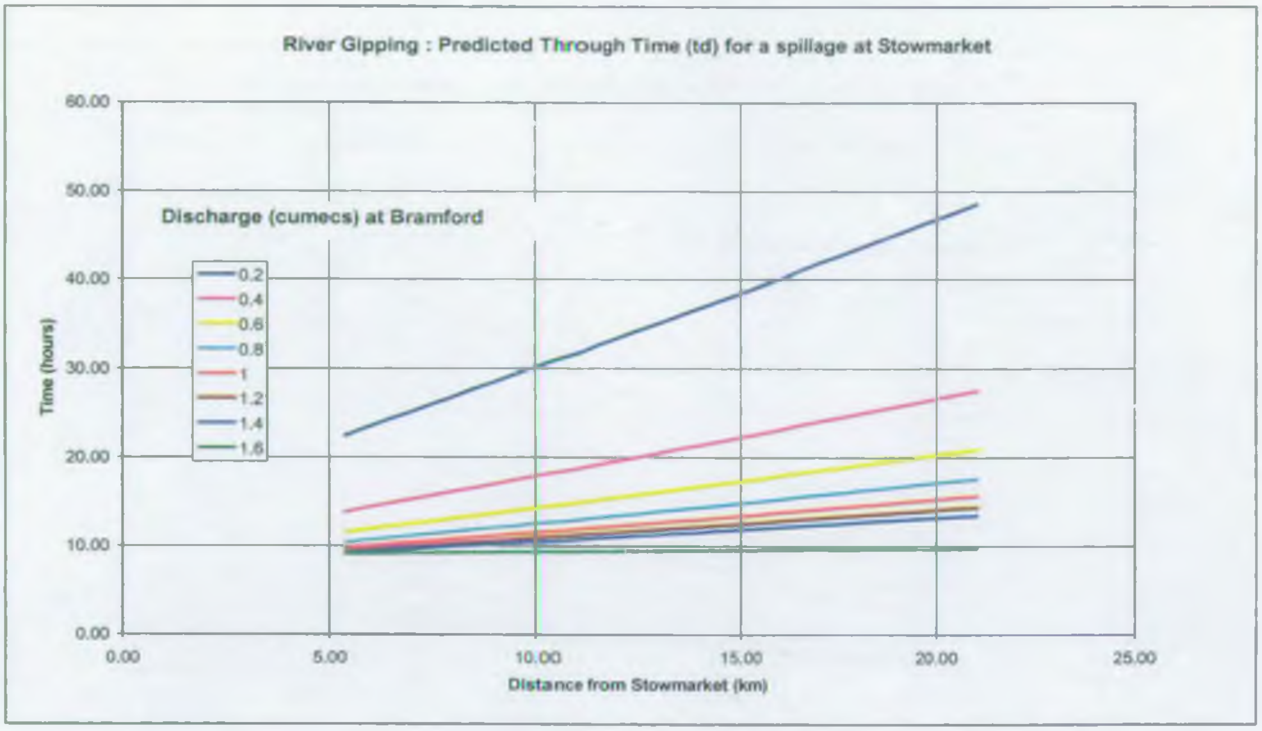
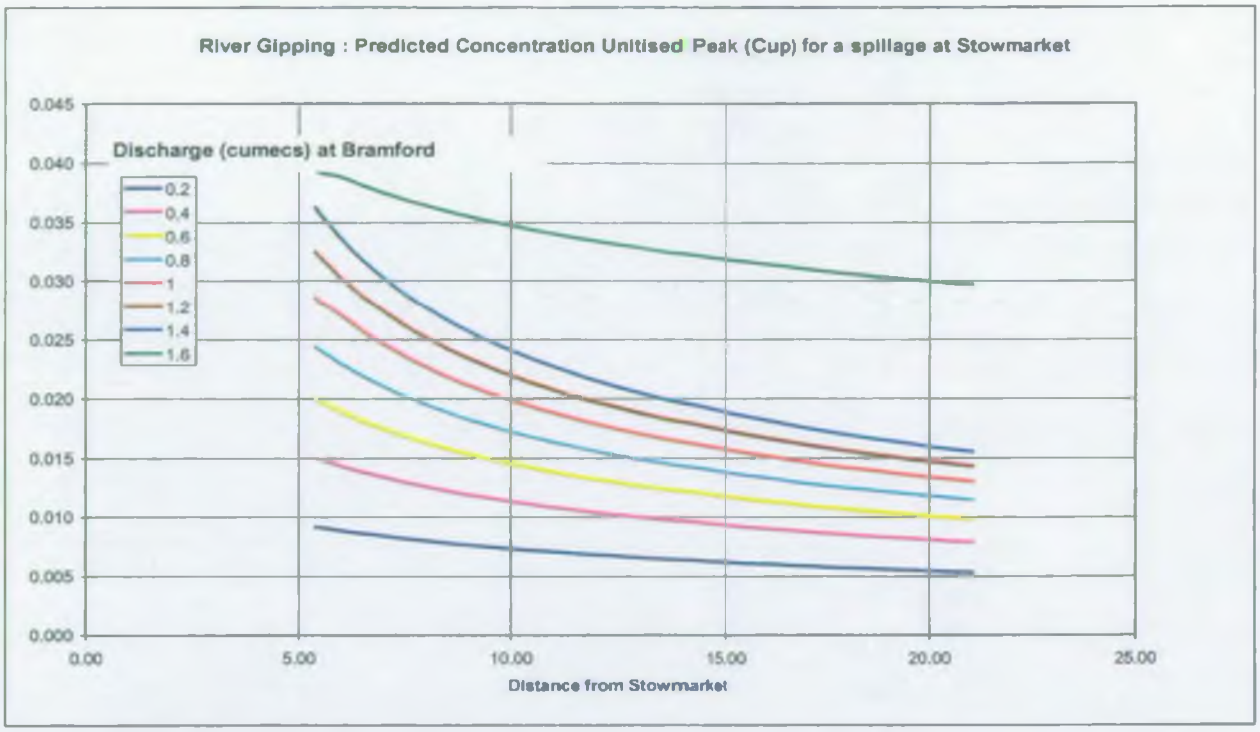


Table 6.12 River Gipping: Predicted Cup from a spillage at Stowmarket ($\mu g\ l^{-1}$ per g of dye injected)

Distance from Stowmarket (km)		Discharge (cumecs) 0.2	0.4	0.6	0.8	1	1.2	1.4	1.6
(Needham Market)	**5.40**	0.009	0.015	0.020	0.024	0.029	0.032	0.036	0.040
	5.50	0.009	0.015	0.020	0.024	0.028	0.032	0.036	0.039
	6.00	0.009	0.014	0.019	0.023	0.027	0.030	0.034	0.039
	6.50	0.009	0.014	0.018	0.022	0.026	0.029	0.032	0.038
	7.00	0.008	0.013	0.017	0.021	0.025	0.027	0.030	0.037
	7.50	0.008	0.013	0.017	0.020	0.024	0.026	0.029	0.037
	8.00	0.008	0.013	0.016	0.020	0.023	0.025	0.028	0.036
	8.50	0.008	0.012	0.016	0.019	0.022	0.024	0.027	0.036
	9.00	0.008	0.012	0.015	0.018	0.021	0.023	0.026	0.035
	9.50	0.007	0.012	0.015	0.018	0.020	0.023	0.025	0.035
	10.00	0.007	0.011	0.014	0.017	0.020	0.022	0.024	0.035
	10.50	0.007	0.011	0.014	0.017	0.019	0.021	0.023	0.034
	11.00	0.007	0.011	0.014	0.016	0.019	0.021	0.023	0.034
	11.50	0.007	0.011	0.013	0.016	0.018	0.020	0.022	0.034
	12.00	0.007	0.010	0.013	0.016	0.018	0.020	0.022	0.033
	12.50	0.007	0.010	0.013	0.015	0.017	0.019	0.021	0.033
	13.00	0.007	0.010	0.013	0.015	0.017	0.019	0.021	0.033
	13.50	0.006	0.010	0.012	0.015	0.017	0.018	0.020	0.033
(Claydon Bridge)	**14.00**	0.006	0.010	0.012	0.014	0.016	0.018	0.020	0.032
	14.50	0.006	0.009	0.012	0.014	0.016	0.018	0.019	0.032
	15.00	0.006	0.009	0.012	0.014	0.016	0.017	0.019	0.032
	15.50	0.006	0.009	0.012	0.014	0.015	0.017	0.019	0.032
	16.00	0.006	0.009	0.011	0.013	0.015	0.017	0.018	0.031
	16.50	0.006	0.009	0.011	0.013	0.015	0.016	0.018	0.031
	17.00	0.006	0.009	0.011	0.013	0.015	0.016	0.018	0.031
	17.50	0.006	0.009	0.011	0.013	0.014	0.016	0.017	0.031
	18.00	0.006	0.008	0.011	0.012	0.014	0.016	0.017	0.031
	18.50	0.006	0.008	0.010	0.012	0.014	0.015	0.017	0.030
	19.00	0.006	0.008	0.010	0.012	0.014	0.015	0.016	0.030
	19.50	0.005	0.008	0.010	0.012	0.014	0.015	0.016	0.030
	20.00	0.005	0.008	0.010	0.012	0.013	0.015	0.016	0.030
	20.50	0.005	0.008	0.010	0.012	0.013	0.014	0.016	0.030
(Sproughton)	**21.00**	0.005	0.008	0.010	0.011	0.013	0.014	0.016	0.030

Figure 6.17 River Gipping: Predicted Concentration Utilised Peak (Cup) for a spillage at Stowmarket ($\mu g\ l^{-1}$ per g of dye injected)



6.6.2 River Waveney

Table 6.13 River Waveney Predictive Equations

Variable	Equation	R^2	Equation No
Tp	$= 21.6310\ Q^{-1.8321}$	0.9002	6.23
Slope Tp-dist	$= -8.3447Q + 11.525$	0.9875	6.24
Tp	= Billingford Tp + [x (slope Tp-dist)]		6.25
Te	$= 0.9164\ Tp$	0.8472	6.26
Td	$= 0.4311\ Tp + 19.026$	0.7585	6.27
Cup	$= 0.831\ Tp+^{-1.2697}$	0.4208	6.28

where
Q = Discharge at Needham
x = Distance from Billingford (km)
Tp = Time to peak concentration (hours from injection)
Te = Time to arrival (hours from injection)
Td = Through time (hours from arrival)
Cup = Concentration Unitised Peak ($\mu g\ l^{-1}$ per g of dye injected)

Table 6.14 Predicted time to Peak Concentration from spillage at Diss (hours from injection)

		Discharge (cumecs) 0.4	0.6	0.8	1	1.2
Distance from Diss (km)						
(Billingford)	**6.00**	115.92	55.15	32.56	21.63	15.49
	7.00	124.10	61.67	37.41	24.81	17.00
	8.00	132.29	68.19	42.26	27.99	18.51
	9.00	140.48	74.71	47.11	31.17	20.03
	10.00	148.67	81.22	51.96	34.36	21.54
	11.00	156.86	87.74	56.81	37.54	23.05
	12.00	165.04	94.26	61.66	40.72	24.56
	13.00	173.23	100.78	66.51	43.90	26.07
	14.00	181.42	107.30	71.36	47.08	27.59
(Needham Mill)	**15.00**	189.61	113.82	76.21	50.26	29.10
	16.00	197.80	120.34	81.06	53.44	30.61
	17.00	205.99	126.86	85.91	56.63	32.12
	18.00	214.17	133.38	90.76	59.81	33.64
	19.00	222.36	139.90	95.61	62.99	35.15
	20.00	230.55	146.42	100.46	66.17	36.66
	21.00	238.74	152.94	105.31	69.35	38.17
	22.00	246.93	159.45	110.16	72.53	39.69
(Homersfield Sluices)	**23.00**	255.11	165.97	115.01	75.71	41.20
	24.00	263.30	172.49	119.86	78.89	42.71
	25.00	271.49	179.01	124.71	82.08	44.22
	26.00	279.68	185.53	129.56	85.26	45.74
	27.00	287.87	192.05	134.41	88.44	47.25
	28.00	296.05	198.57	139.26	91.62	48.76
	29.00	304.24	205.09	144.11	94.80	50.27
	30.00	312.43	211.61	148.96	97.98	51.79
	31.00	320.62	218.13	153.81	101.16	53.30
	32.00	328.81	224.65	158.66	104.34	54.81
	33.00	337.00	231.17	163.51	107.53	56.32
	34.00	345.18	237.68	168.36	110.71	57.83
	35.00	353.37	244.20	173.21	113.89	59.35
	36.00	361.56	250.72	178.06	117.07	60.86
	37.00	369.75	257.24	182.91	120.25	62.37
	38.00	377.94	263.76	187.76	123.43	63.88
	39.00	386.12	270.28	192.61	126.61	65.40
	40.00	394.31	276.80	197.46	129.80	66.91
	41.00	402.50	283.32	202.31	132.98	68.42

Distance from Diss (km)		Discharge (cumecs) 0.4	0.6	0.8	1	1.2
	42.00	410.69	289.84	207.16	136.16	69.93
	43.00	418.88	296.36	212.01	139.34	71.45
	44.00	427.06	302.88	216.86	142.52	72.96
	45.00	435.25	309.40	221.71	145.70	74.47
	46.00	443.44	315.91	226.57	148.88	75.98
(Ellingham)	47.00	451.63	322.43	231.42	152.06	77.50
	48.00	459.82	328.95	236.27	155.25	79.01
	49.00	468.00	335.47	241.12	158.43	80.52
(Shipmeadow)	50.00	476.19	341.99	245.97	161.61	82.03
	51.00	484.38	348.51	250.82	164.79	83.54
	52.00	492.57	355.03	255.67	167.97	85.06

Figure 6.18 River Waveney : Predicted Time to Peak Concentration (Tp) for a spillage at Diss

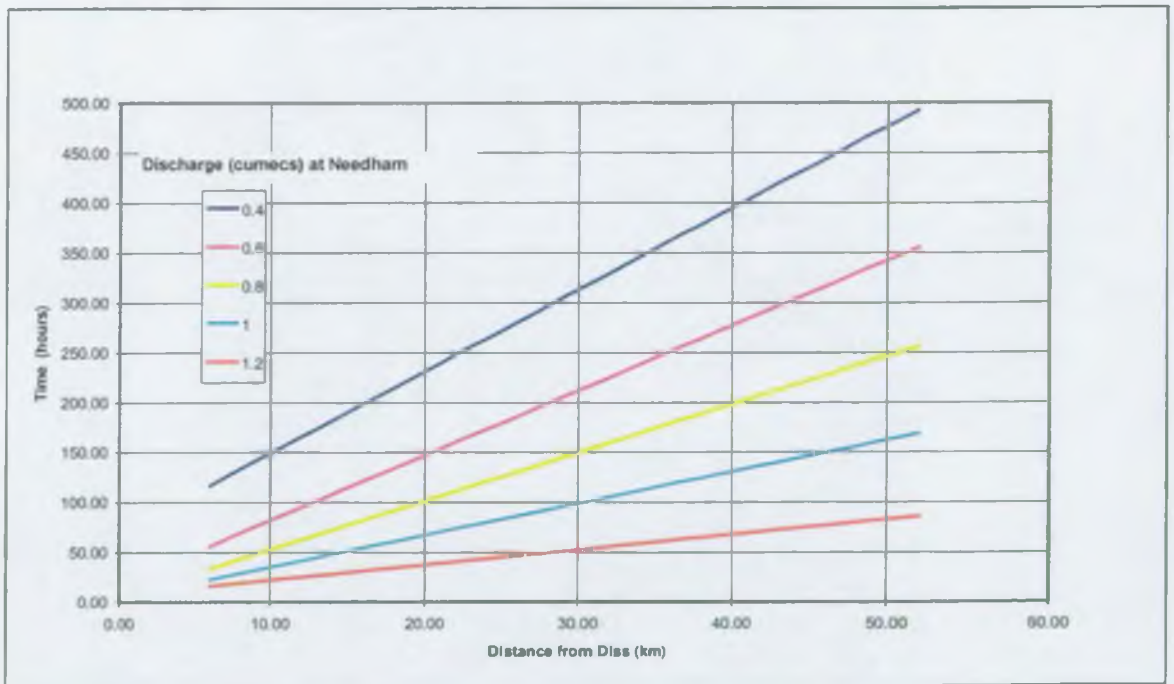


Table 6.15 River Waveney: Predicted time to arrival from spillage at Diss (hours from injection)

		Discharge (cumecs)				
		0.4	0.6	0.8	1	1.2
Distance from Diss (km)						
(Billingford)	**6.00**	106.23	50.54	29.83	19.82	14.19
	7.00	113.73	56.51	34.28	22.74	15.58
	8.00	121.23	62.49	38.72	25.65	16.97
	9.00	128.74	68.46	43.17	28.57	18.35
	10.00	136.24	74.43	47.61	31.48	19.74
	11.00	143.74	80.41	52.06	34.40	21.12
	12.00	151.25	86.38	56.50	37.31	22.51
	13.00	158.75	92.36	60.95	40.23	23.90
	14.00	166.25	98.33	65.39	43.15	25.28
(Needham Mill)	**15.00**	173.76	104.30	69.84	46.06	26.67
	16.00	181.26	110.28	74.28	48.98	28.05
	17.00	188.76	116.25	78.73	51.89	29.44
	18.00	196.27	122.23	83.17	54.81	30.82
	19.00	203.77	128.20	87.62	57.72	32.21
	20.00	211.28	134.18	92.06	60.64	33.60
	21.00	218.78	140.15	96.51	63.55	34.98
	22.00	226.28	146.12	100.95	66.47	36.37
(Homersfield Sluices)	**23.00**	233.79	152.10	105.39	69.38	37.75
	24.00	241.29	158.07	109.84	72.30	39.14
	25.00	248.79	164.05	114.28	75.21	40.53
	26.00	256.30	170.02	118.73	78.13	41.91
	27.00	263.80	175.99	123.17	81.04	43.30
	28.00	271.30	181.97	127.62	83.96	44.68
	29.00	278.81	187.94	132.06	86.88	46.07
	30.00	286.31	193.92	136.51	89.79	47.46
	31.00	293.82	199.89	140.95	92.71	48.84
	32.00	301.32	205.87	145.40	95.62	50.23
	33.00	308.82	211.84	149.84	98.54	51.61
	34.00	316.33	217.81	154.29	101.45	53.00
	35.00	323.83	223.79	158.73	104.37	54.39
	36.00	331.33	229.76	163.18	107.28	55.77
	37.00	338.84	235.74	167.62	110.20	57.16
	38.00	346.34	241.71	172.07	113.11	58.54
	39.00	353.84	247.68	176.51	116.03	59.93
	40.00	361.35	253.66	180.96	118.94	61.32

	Discharge (cumecs)				
	0.4	**0.6**	**0.8**	**1**	**1.2**
Distance from Diss (km)					
41.00	368.85	259.63	185.40	121.86	62.70
42.00	376.35	265.61	189.85	124.78	64.09
43.00	383.86	271.58	194.29	127.69	65.47
44.00	391.36	277.56	198.73	130.61	66.86
45.00	398.87	283.53	203.18	133.52	68.24
46.00	406.37	289.50	207.62	136.44	69.63
(Ellingham) **47.00**	413.87	295.48	212.07	139.35	71.02
48.00	421.38	301.45	216.51	142.27	72.40
49.00	428.88	307.43	220.96	145.18	73.79
(Shipmeadow) **50.00**	436.38	313.40	225.40	148.10	75.17
51.00	443.89	319.38	229.85	151.01	76.56
52.00	451.39	325.35	234.29	153.93	77.95

Figure 6.19 River Waveney: Predicted Time of Arrival (Te) for a spillage at Diss

Table 6.16 River Waveney: Predicted Through Time from spillage at Diss (hours from arrival)

Distance from Diss (km)		Discharge (cumecs) 0.4	0.6	0.8	1	1.2
(Billingford)	**6.00**	69.00	42.80	33.06	28.35	25.70
	7.00	72.53	45.61	35.15	29.72	26.36
	8.00	76.06	48.42	37.24	31.09	27.01
	9.00	79.59	51.23	39.33	32.47	27.66
	10.00	83.12	54.04	41.42	33.84	28.31
	11.00	86.65	56.85	43.52	35.21	28.96
	12.00	90.18	59.66	45.61	36.58	29.61
	13.00	93.71	62.47	47.70	37.95	30.27
	14.00	97.24	65.28	49.79	39.32	30.92
(Needham Mill)	**15.00**	100.77	68.09	51.88	40.69	31.57
	16.00	104.30	70.90	53.97	42.07	32.22
	17.00	107.83	73.71	56.06	43.44	32.87
	18.00	111.36	76.53	58.15	44.81	33.53
	19.00	114.89	79.34	60.24	46.18	34.18
	20.00	118.42	82.15	62.33	47.55	34.83
	21.00	121.95	84.96	64.42	48.92	35.48
	22.00	125.48	87.77	66.52	50.29	36.13
(Homersfield Sluices)	**23.00**	129.01	90.58	68.61	51.67	36.79
	24.00	132.54	93.39	70.70	53.04	37.44
	25.00	136.07	96.20	72.79	54.41	38.09
	26.00	139.60	99.01	74.88	55.78	38.74
	27.00	143.13	101.82	76.97	57.15	39.39
	28.00	146.66	104.63	79.06	58.52	40.05
	29.00	150.18	107.44	81.15	59.89	40.70
	30.00	153.71	110.25	83.24	61.27	41.35
	31.00	157.24	113.06	85.33	62.64	42.00
	32.00	160.77	115.87	87.43	64.01	42.65
	33.00	164.30	118.68	89.52	65.38	43.31
	34.00	167.83	121.49	91.61	66.75	43.96
	35.00	171.36	124.30	93.70	68.12	44.61
	36.00	174.89	127.11	95.79	69.49	45.26
	37.00	178.42	129.92	97.88	70.87	45.91
	38.00	181.95	132.73	99.97	72.24	46.57
	39.00	185.48	135.54	102.06	73.61	47.22
	40.00	189.01	138.35	104.15	74.98	47.87

		Discharge (cumecs)				
	Distance from Diss (km)	0.4	0.6	0.8	1	1.2
	41.00	192.54	141.16	106.24	76.35	48.52
	42.00	196.07	143.98	108.33	77.72	49.17
	43.00	199.60	146.79	110.43	79.10	49.83
	44.00	203.13	149.60	112.52	80.47	50.48
	45.00	206.66	152.41	114.61	81.84	51.13
	46.00	210.19	155.22	116.70	83.21	51.78
(Ellingham)	**47.00**	213.72	158.03	118.79	84.58	52.43
	48.00	217.25	160.84	120.88	85.95	53.09
	49.00	220.78	163.65	122.97	87.32	53.74
(Shipmeadow)	**50.00**	224.31	166.46	125.06	88.70	54.39
	51.00	227.84	169.27	127.15	90.07	55.04
	52.00	231.37	172.08	129.24	91.44	55.69

Figure 6.20 River Waveney : Predicted Through Time (td) for a spillage at Diss

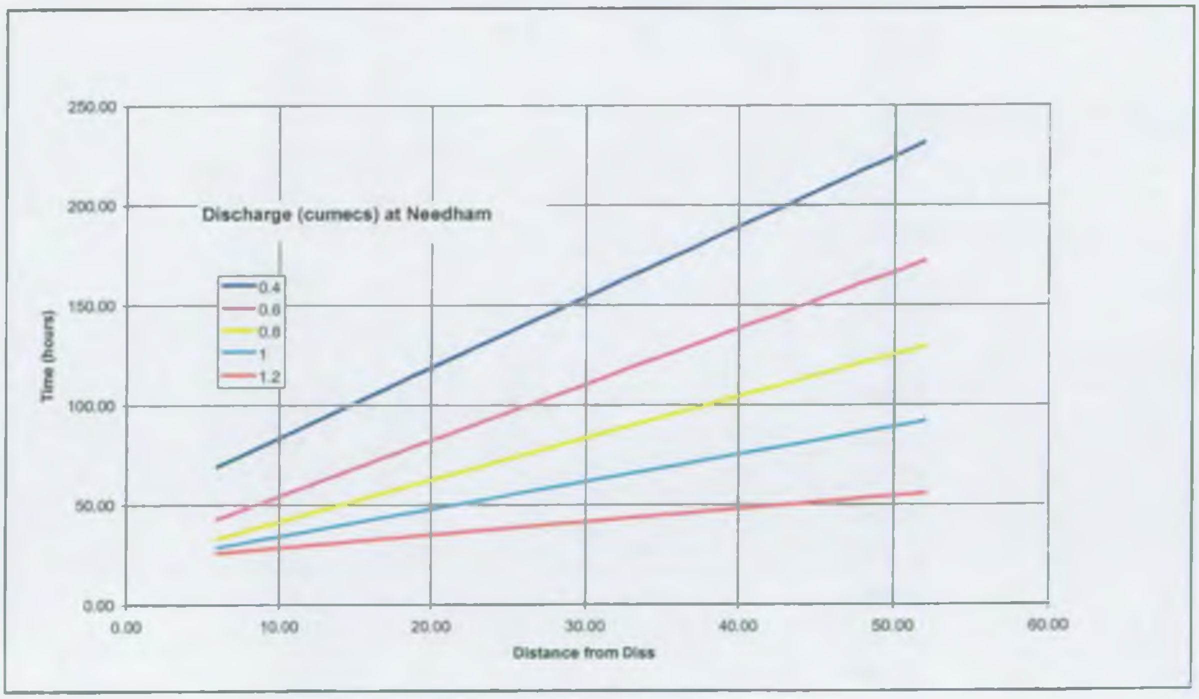
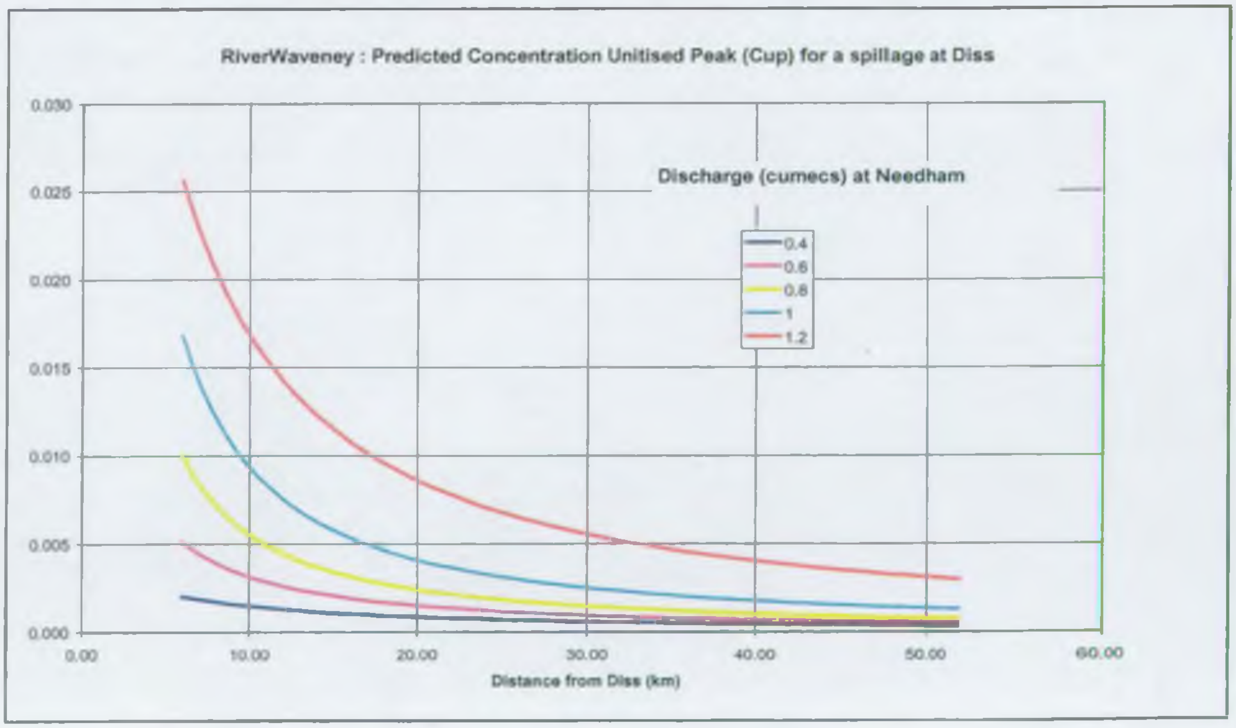


Table 6.17 River Waveney: Predicted Cup from spillage at Diss ($\mu g\ l^{-1}$ per g of dye injected)

Distance from Diss (km)		Discharge (cumecs) 0.4	0.6	0.8	1	1.2
(Billingford)	6.00	0.002	0.005	0.010	0.017	0.026
	7.00	0.002	0.004	0.008	0.014	0.023
	8.00	0.002	0.004	0.007	0.012	0.020
	9.00	0.002	0.003	0.006	0.011	0.018
	10.00	0.001	0.003	0.006	0.009	0.017
	11.00	0.001	0.003	0.005	0.008	0.015
	12.00	0.001	0.003	0.004	0.008	0.014
	13.00	0.001	0.002	0.004	0.007	0.013
	14.00	0.001	0.002	0.004	0.006	0.012
(Needham Mill)	15.00	0.001	0.002	0.003	0.006	0.012
	16.00	0.001	0.002	0.003	0.005	0.011
	17.00	0.001	0.002	0.003	0.005	0.010
	18.00	0.001	0.002	0.003	0.005	0.010
	19.00	0.001	0.002	0.003	0.004	0.009
	20.00	0.001	0.001	0.002	0.004	0.009
	21.00	0.001	0.001	0.002	0.004	0.008
	22.00	0.001	0.001	0.002	0.004	0.008
(Homersfield Sluices)	23.00	0.001	0.001	0.002	0.003	0.007
	24.00	0.001	0.001	0.002	0.003	0.007
	25.00	0.001	0.001	0.002	0.003	0.007
	26.00	0.001	0.001	0.002	0.003	0.006
	27.00	0.001	0.001	0.002	0.003	0.006
	28.00	0.001	0.001	0.002	0.003	0.006
	29.00	0.001	0.001	0.002	0.003	0.006
	30.00	0.001	0.001	0.001	0.002	0.006
	31.00	0.001	0.001	0.001	0.002	0.005
	32.00	0.001	0.001	0.001	0.002	0.005
	33.00	0.001	0.001	0.001	0.002	0.005
	34.00	0.000	0.001	0.001	0.002	0.005
	35.00	0.000	0.001	0.001	0.002	0.005
	36.00	0.000	0.001	0.001	0.002	0.005
	37.00	0.000	0.001	0.001	0.002	0.004
	38.00	0.000	0.001	0.001	0.002	0.004
	39.00	0.000	0.001	0.001	0.002	0.004
	40.00	0.000	0.001	0.001	0.002	0.004

		Discharge				
		0.4	0.6	0.8	1	1.2
Distance from Diss (km)						
	41.00	0.000	0.001	0.001	0.002	0.004
	42.00	0.000	0.001	0.001	0.002	0.004
	43.00	0.000	0.001	0.001	0.002	0.004
	44.00	0.000	0.001	0.001	0.002	0.004
	45.00	0.000	0.001	0.001	0.001	0.003
	46.00	0.000	0.001	0.001	0.001	0.003
(Ellingham)	47.00	0.000	0.001	0.001	0.001	0.003
	48.00	0.000	0.001	0.001	0.001	0.003
	49.00	0.000	0.001	0.001	0.001	0.003
(Shipmeadow)	50.00	0.000	0.001	0.001	0.001	0.003
	51.00	0.000	0.000	0.001	0.001	0.003
	52.00	0.000	0.000	0.001	0.001	0.003

Figure 6.21 : Predicted Cup for a spillage at Diss (μg l^{-1} per g of dye injected)



6.6.3 River Wensum

Table 6.19 River Wensum Predictive Equations

Variable	Equation	R^2	Equation No
Great Ryburgh Tp	$= 45.693Q^{-0.8703}$	0.9611	6.17
Slope Tp-dist	= -1.371(Log Q) + 3.5049	0.7536	6.18
Tp	= Great Ryburgh Tp + [x (slope Tp-dist)]		6.19
Te	= 0.7695 Tp + 2.3203*	0.9587	6.20
Td	= 0.5206 Tp	0.8886	6.21
Cup	$= 0.1282\ Tp^{-0.5759}$	0.3105	6.22

where Q = Discharge at Swanton Morley (combined) (cumecs)
x = Distance from Great Ryburgh (km)
Tp = Time to peak concentration (hours from injection)
Te = Time to arrival (hours from injection)
Td = Through time (hours from arrival)
Cup = Concentration Unitised Peak ($\mu g\ l^{-1}$ per g of dye injected)

* at very high discharges over short distances this equation overestimates the time to arrival. The following tables have been adjusted to avoid this problem.

Table 6.19 River Wensum: Predicted time to peak concentration from spillage at Sculthorpe (hours from injection)

Distance from Sculthorpe (km)	Discharge (cumecs) 1	2	3	4	5	6	7	8	9	10
(Great Ryburgh) **9.35**	45.69	25.00	17.56	13.67	11.26	9.61	8.40	7.48	6.75	6.16
10.00	47.97	26.66	18.86	14.72	12.10	10.29	8.95	7.90	7.07	6.39
11.00	51.48	29.21	20.86	16.32	13.40	11.34	9.78	8.56	7.56	6.73
12.00	54.98	31.77	22.86	17.92	14.70	12.39	10.62	9.21	8.06	7.08
13.00	58.49	34.32	24.86	19.53	16.00	13.43	11.46	9.87	8.55	7.43
14.00	61.99	36.87	26.86	21.13	17.30	14.48	12.29	10.52	9.04	7.78
15.00	65.50	39.43	28.86	22.74	18.60	15.53	13.13	11.17	9.53	8.13
16.00	69.00	41.98	30.85	24.34	19.89	16.58	13.97	11.83	10.03	8.47
17.00	72.51	44.54	32.85	25.95	21.19	17.63	14.81	12.48	10.52	8.82
18.00	76.01	47.09	34.85	27.55	22.49	18.68	15.64	13.14	11.01	9.17
19.00	79.52	49.65	36.85	29.15	23.79	19.72	16.48	13.79	11.50	9.52
20.00	83.02	52.20	38.85	30.76	25.09	20.77	17.32	14.44	12.00	9.87
21.00	86.53	54.76	40.85	32.36	26.39	21.82	18.15	15.10	12.49	10.21
22.00	90.03	57.31	42.85	33.97	27.68	22.87	18.99	15.75	12.98	10.56
(Swanton Morley) **23.00**	93.53	59.87	44.85	35.57	28.98	23.92	19.83	16.41	13.47	10.91
24.00	97.04	62.42	46.84	37.18	30.28	24.97	20.66	17.06	13.97	11.26
25.00	100.54	64.97	48.84	38.78	31.58	26.02	21.50	17.71	14.46	11.61
26.00	104.05	67.53	50.84	40.38	32.88	27.06	22.34	18.37	14.95	11.95
27.00	107.55	70.08	52.84	41.99	34.18	28.11	23.18	19.02	15.44	12.30
28.00	111.06	72.64	54.84	43.59	35.47	29.16	24.01	19.68	15.94	12.65
29.00	114.56	75.19	56.84	45.20	36.77	30.21	24.85	20.33	16.43	13.00
30.00	118.07	77.75	58.84	46.80	38.07	31.26	25.69	20.98	16.92	13.35
31.00	121.57	80.30	60.84	48.41	39.37	32.31	26.52	21.64	17.41	13.69
32.00	125.08	82.86	62.83	50.01	40.67	33.35	27.36	22.29	17.91	14.04
33.00	128.58	85.41	64.83	51.61	41.97	34.40	28.20	22.95	18.40	14.39
34.00	132.09	87.97	66.83	53.22	43.26	35.45	29.04	23.60	18.89	14.74
35.00	135.59	90.52	68.83	54.82	44.56	36.50	29.87	24.25	19.38	15.09
36.00	139.10	93.08	70.83	56.43	45.86	37.55	30.71	24.91	19.88	15.44
37.00	142.60	95.63	72.83	58.03	47.16	38.60	31.55	25.56	20.37	15.78
38.00	146.11	98.18	74.83	59.64	48.46	39.64	32.38	26.22	20.86	16.13
(Lenwade) **39.00**	149.61	100.74	76.83	61.24	49.76	40.69	33.22	26.87	21.35	16.48
40.00	153.12	103.29	78.82	62.84	51.05	41.74	34.06	27.52	21.85	16.83

Distance from Sculthorpe (km)	Discharge (cumecs) 1	2	3	4	5	6	7	8	9	10
41.00	156.62	105.85	80.82	64.45	52.35	42.79	34.89	28.18	22.34	17.18
42.00	160.13	108.40	82.82	66.05	53.65	43.84	35.73	28.83	22.83	17.52
43.00	163.63	110.96	84.82	67.66	54.95	44.89	36.57	29.49	23.32	17.87
44.00	167.14	113.51	86.82	69.26	56.25	45.93	37.41	30.14	23.82	18.22
45.00	170.64	116.07	88.82	70.87	57.55	46.98	38.24	30.79	24.31	18.57
46.00	174.15	118.62	90.82	72.47	58.84	48.03	39.08	31.45	24.80	18.92
47.00	177.65	121.18	92.81	74.07	60.14	49.08	39.92	32.10	25.29	19.26
48.00	181.16	123.73	94.81	75.68	61.44	50.13	40.75	32.76	25.79	19.61
49.00	184.66	126.29	96.81	77.28	62.74	51.18	41.59	33.41	26.28	19.96
50.00	188.17	128.84	98.81	78.89	64.04	52.23	42.43	34.06	26.77	20.31
51.00	191.67	131.39	100.81	80.49	65.34	53.27	43.27	34.72	27.26	20.66
(Costessey Pits) **52.00**	195.18	133.95	102.81	82.10	66.64	54.32	44.10	35.37	27.76	21.00
53.00	198.68	136.50	104.81	83.70	67.93	55.37	44.94	36.03	28.25	21.35
54.00	202.19	139.06	106.81	85.30	69.23	56.42	45.78	36.68	28.74	21.70
55.00	205.69	141.61	108.80	86.91	70.53	57.47	46.61	37.33	29.23	22.05
56.00	209.20	144.17	110.80	88.51	71.83	58.52	47.45	37.99	29.73	22.40
57.00	212.70	146.72	112.80	90.12	73.13	59.56	48.29	38.64	30.22	22.74
58.00	216.21	149.28	114.80	91.72	74.43	60.61	49.12	39.30	30.71	23.09
(Heigham) **59.00**	219.71	151.83	116.80	93.33	75.72	61.66	49.96	39.95	31.20	23.44
60.00	223.22	154.39	118.80	94.93	77.02	62.71	50.80	40.60	31.70	23.79

Figure 6.22 River Wensum : Predicted Time to Peak Concentration for a spillage at Sculthorpe

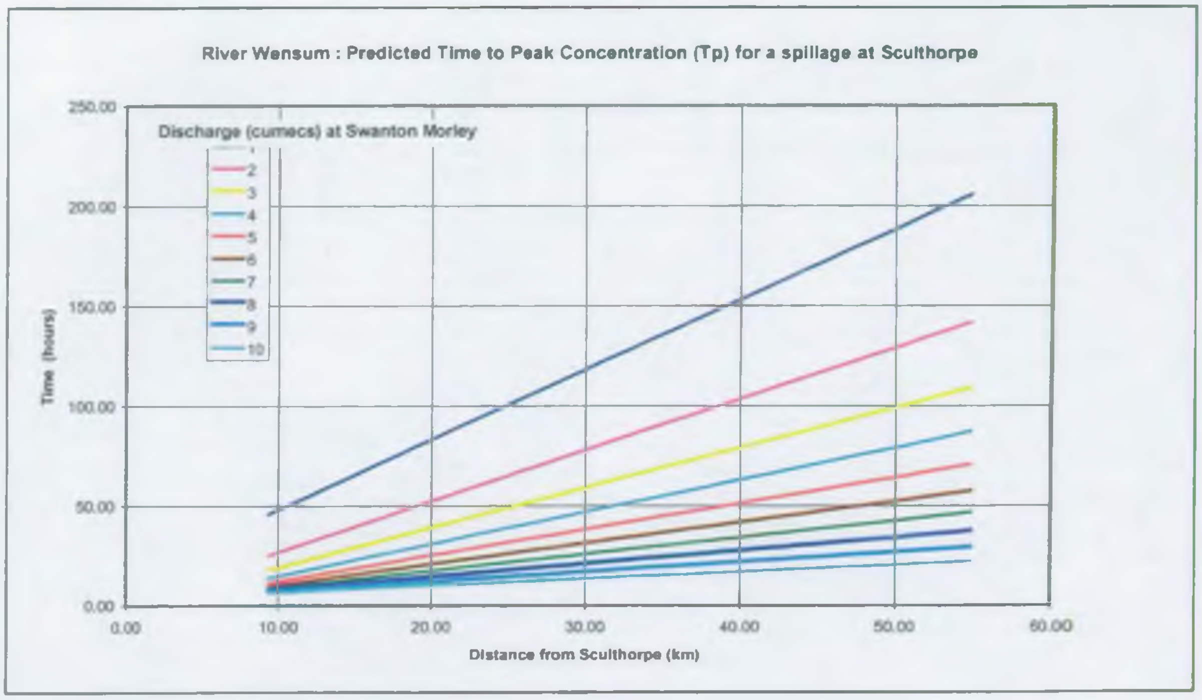


Figure 6.23 River Wensum : Predicted Time of arrival (Te) for a spillage at Sculthorpe

Figure 6.24 River Wensum : Predicted Through Time (td) for a spillage at Sculthorpe

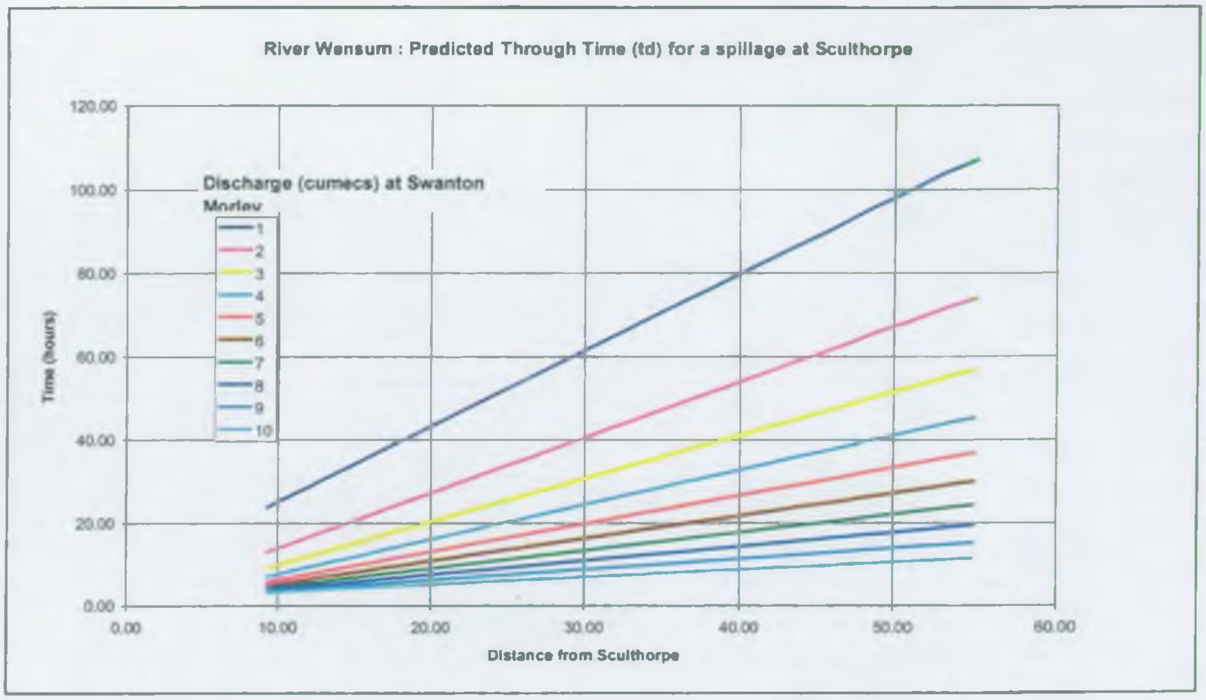
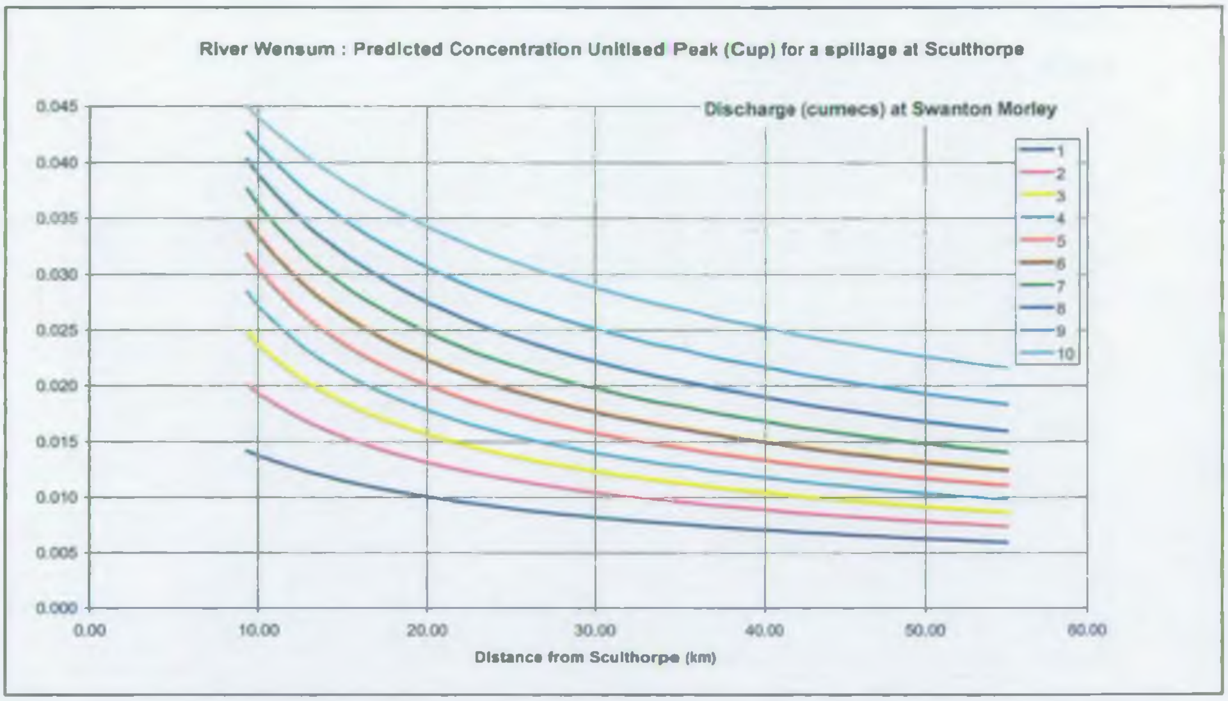


Table 6.22 River Wensum : Predicted Cup from spillage at Sculthorpe ($\mu g\ l^{-1}$ per g of dye injected)

Distance (km) from Sculthorpe	Discharge (cumecs) 1	2	3	4	5	6	7	8	9	10
(Great Ryburgh) 9.35	0.014	0.020	0.025	0.028	0.032	0.035	0.038	0.040	0.043	0.045
10.00	0.014	0.019	0.024	0.027	0.030	0.033	0.036	0.039	0.042	0.044
11.00	0.013	0.018	0.022	0.026	0.029	0.032	0.034	0.037	0.040	0.043
12.00	0.013	0.017	0.021	0.024	0.027	0.030	0.033	0.036	0.039	0.042
13.00	0.012	0.017	0.020	0.023	0.026	0.029	0.031	0.034	0.037	0.040
14.00	0.012	0.016	0.019	0.022	0.025	0.028	0.030	0.033	0.036	0.039
15.00	0.012	0.015	0.018	0.021	0.024	0.026	0.029	0.032	0.035	0.038
16.00	0.011	0.015	0.018	0.020	0.023	0.025	0.028	0.031	0.034	0.037
17.00	0.011	0.014	0.017	0.020	0.022	0.025	0.027	0.030	0.033	0.037
18.00	0.011	0.014	0.017	0.019	0.021	0.024	0.026	0.029	0.032	0.036
19.00	0.010	0.014	0.016	0.018	0.021	0.023	0.026	0.028	0.031	0.035
20.00	0.010	0.013	0.016	0.018	0.020	0.022	0.025	0.028	0.031	0.034
21.00	0.010	0.013	0.015	0.017	0.019	0.022	0.024	0.027	0.030	0.034
22.00	0.010	0.012	0.015	0.017	0.019	0.021	0.024	0.026	0.029	0.033
(Swanton Morley) 23.00	0.009	0.012	0.014	0.016	0.018	0.021	0.023	0.026	0.029	0.032
24.00	0.009	0.012	0.014	0.016	0.018	0.020	0.022	0.025	0.028	0.032
25.00	0.009	0.012	0.014	0.016	0.018	0.020	0.022	0.024	0.028	0.031
26.00	0.009	0.011	0.013	0.015	0.017	0.019	0.021	0.024	0.027	0.031
27.00	0.009	0.011	0.013	0.015	0.017	0.019	0.021	0.024	0.027	0.030
28.00	0.009	0.011	0.013	0.015	0.016	0.018	0.021	0.023	0.026	0.030
29.00	0.008	0.011	0.013	0.014	0.016	0.018	0.020	0.023	0.026	0.029
30.00	0.008	0.010	0.012	0.014	0.016	0.018	0.020	0.022	0.025	0.029
31.00	0.008	0.010	0.012	0.014	0.015	0.017	0.019	0.022	0.025	0.028
32.00	0.008	0.010	0.012	0.013	0.015	0.017	0.019	0.021	0.024	0.028
33.00	0.008	0.010	0.012	0.013	0.015	0.017	0.019	0.021	0.024	0.028
34.00	0.008	0.010	0.011	0.013	0.015	0.016	0.018	0.021	0.024	0.027
35.00	0.008	0.010	0.011	0.013	0.014	0.016	0.018	0.020	0.023	0.027
36.00	0.007	0.009	0.011	0.013	0.014	0.016	0.018	0.020	0.023	0.027
37.00	0.007	0.009	0.011	0.012	0.014	0.016	0.018	0.020	0.023	0.026
38.00	0.007	0.009	0.011	0.012	0.014	0.015	0.017	0.020	0.022	0.026
(Lenwade) 39.00	0.007	0.009	0.011	0.012	0.014	0.015	0.017	0.019	0.022	0.026
40.00	0.007	0.009	0.010	0.012	0.013	0.015	0.017	0.019	0.022	0.025

Distance (km) from Sculthorpe	Discharge (cumecs) 1	2	3	4	5	6	7	8	9	10
41.00	0.007	0.009	0.010	0.012	0.013	0.015	0.017	0.019	0.021	0.025
42.00	0.007	0.009	0.010	0.011	0.013	0.015	0.016	0.018	0.021	0.025
43.00	0.007	0.009	0.010	0.011	0.013	0.014	0.016	0.018	0.021	0.024
44.00	0.007	0.008	0.010	0.011	0.013	0.014	0.016	0.018	0.021	0.024
45.00	0.007	0.008	0.010	0.011	0.012	0.014	0.016	0.018	0.020	0.024
46.00	0.007	0.008	0.010	0.011	0.012	0.014	0.016	0.018	0.020	0.024
47.00	0.006	0.008	0.009	0.011	0.012	0.014	0.015	0.017	0.020	0.023
48.00	0.006	0.008	0.009	0.011	0.012	0.013	0.015	0.017	0.020	0.023
49.00	0.006	0.008	0.009	0.010	0.012	0.013	0.015	0.017	0.020	0.023
50.00	0.006	0.008	0.009	0.010	0.012	0.013	0.015	0.017	0.019	0.023
51.00	0.006	0.008	0.009	0.010	0.012	0.013	0.015	0.017	0.019	0.022
(Costessey Pits) **52.00**	0.006	0.008	0.009	0.010	0.011	0.013	0.014	0.016	0.019	0.022
53.00	0.006	0.008	0.009	0.010	0.011	0.013	0.014	0.016	0.019	0.022
54.00	0.006	0.007	0.009	0.010	0.011	0.013	0.014	0.016	0.019	0.022
55.00	0.006	0.007	0.009	0.010	0.011	0.012	0.014	0.016	0.018	0.022
56.00	0.006	0.007	0.009	0.010	0.011	0.012	0.014	0.016	0.018	0.021
57.00	0.006	0.007	0.008	0.010	0.011	0.012	0.014	0.016	0.018	0.021
58.00	0.006	0.007	0.008	0.009	0.011	0.012	0.014	0.015	0.018	0.021
(Heigham) **59.00**	0.006	0.007	0.008	0.009	0.011	0.012	0.013	0.015	0.018	0.021
60.00	0.006	0.007	0.008	0.009	0.011	0.012	0.013	0.015	0.018	0.021

Figure 6.25 River Wensum : Predicted Cup for a spillage at Sculthorpe ($\mu g\ l^{-1}$ per g of dye injected)



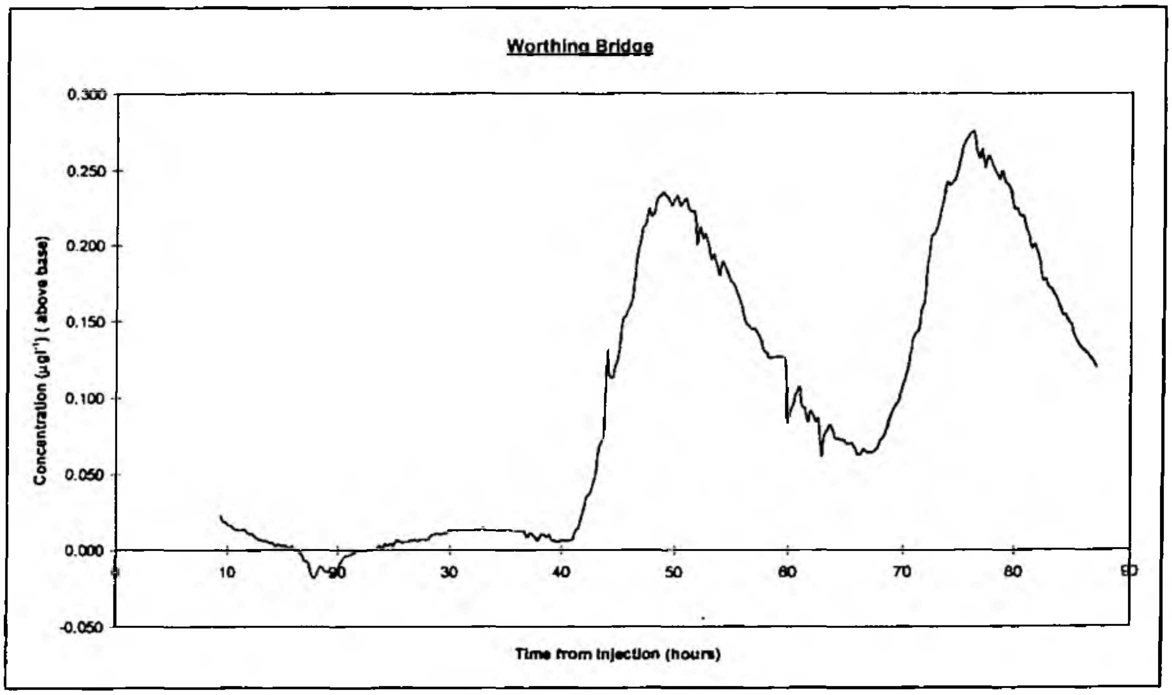
7. EVALUATION

7.1 Replicability of the results

In order to test the replicability of the dye tracing field methodology, one dye trace was repeated using a second injection 24 hours after the first. The same volume of dye was used and the dye was injected in the same location. The river used was the Wendling Beck because only a small amount of dye was necessary for this shorter reach and there was, therefore, no problem with an unnecessary amount of dye in the river. A period of 24 hours was chosen because this was envisaged as the minimum amount of time between injections that would allow the wave of the first dye injection to pass the downstream monitoring site before the arrival of the second. Any longer period between injections would almost certainly involve a change in the river discharge.

The concentration-time distribution can be seen in Figure 7.1. As can be seen, the two peaks of dye are remarkably consistent in timing, magnitude and dispersion, confirming that the technique provides replicable results for similar conditions.

Figure 7.1 Concentration - Time Distribution for Wendling Beck with 2 injections



7.2 Accuracy of predictions.

Traditional experimental design demands that part of the data set be used for model building and another part reserved for validation and evaluation of predictive powers. Given the high cost of time of travel experiments and the limits of the current contract, this has not been possible here. A first attempt at evaluation of accuracy can be made, however, by comparing actual and predicted results for the monitored points at the discharges occurring during each trace. This would indicate a range of error up to a maximum of 20-25% with most errors below 10%. Table 7.2 shows the range of error for time of arrival and time to peak on the River Bure.

Table 7.1 Percentage errors in prediction - River Bure

	Time of Arrival	Time to Peak
Ingworth	+19.5	-0.13
Oxnead	+7.4	+9.7
Horstead	+18.9	+16.9
Belaugh	-18.4	-6.4
Ingworth	-13.9	+1.7
Oxnead	+1.4	+8.4
Horstead	+9.3	+16.5
Belaugh	-3.4	-3.8
Ingworth	-25.2	-0.5
Oxnead	-9.3	+0.8
Horstead	+1	+7.7
Belaugh	-11.5	-6.3

Overall the predictive aspects of the work proved to be successful with excellent coefficients of determination for Time to Arrival and Time to Peak and good coefficients for throughtime. The predictions for through time and Cup are necessarily less effective since through time is harder to measure and both parameters are affected by factors other than discharge. These include the amount of weed in the channel and the state of the sluices and weirs at the time of the experiment.

In a previous study for the Environment Agency NE region, Wilson (1997) was able to do a more rigorous examination of the accuracy of results obtained by the three different methods outlined in section 6.1. It was found that the empirical approach was more effective than the ADZ model at predicting the time of arrival, the time to peak concentration and the through time but less effective at predicting the peak concentration. Wilson concludes that the empirical approach is of more value to water companies and the Environment Agency since the timings of arrival and peak are of more value in the immediate aftermath of a spillage when very little time is available for complex modelling strategies.

7.3 Transferability of the predictive models to other river systems

The ability to apply a model to an area other than that for which it was initially constructed is essential if the model is to be of value to a wider audience. There is scope for the predictive strategy considered here to be transferred to other river systems, but the large data requirements for each of the models necessitate that some data collection be completed before they could be used. This arises because the models do not utilise parameters directly related to the nature of the catchment. The absence of the use of catchment characteristics to produce the models means that field data must be used to provide the base information for construction.

As detailed in section 6, data from three tracer experiments are required to successfully develop a modelling strategy. Having obtained this information any of the three modelling techniques can be used to make predictions about the behaviour of pollutants from spillages. Therefore, the approaches are transferable because they can be used on other river catchments.

A more ideal situation would be to reduce the amount of data which must be collected in the field using tracer experiments. These are expensive both financially and in the amount of time required to complete them successfully. The potential for using information about other catchment characteristics to reduce the number of traces required is currently the focus of further research by the authors. This would allow the model to be more readily transferable, although it is still likely that some experimentation would be required on which to base the predictive system.

8. ACKNOWLEDGEMENTS

This project was funded by the Environment Agency; thanks to Chris McArthur, Claire Bennett and Andy Baker for their help and support. The authors would also like to thank the large number of people who helped with the long periods of fieldwork. These included Julia Meaton, Alan Dixon, Rachel Harding, Julie McNish, Sally Barker, Rob Johnson, Jonathan Barrett, Jonathan Vann, Diana de Nooijer, Liz O'Brien, Richard Coulton, Dennis Sinnott and David Turnbull. Thanks are also due to Judy Soothill and Sally Ward for help in preparing the report. Special thanks go to Doug Wilson whose efforts and advice were essential to this study. A great many riparian land owners gave us access, allowed us to camp and even made us coffee; thanks to Mrs Crampton, Dennis and Jenny and many others. Finally the other authors would like to thank John Shacklock - his hard work at the outset of the project necessarily came to an abrupt end with his accident in Vienna; we wish him well.

9. REFERENCES

Brady, J A, Johnson, P (1981) Predicting times of travel, dispersion and peak concentrations of pollution incidents in streams, *Journal of Hydrology*, No. 53, pp. 135-150.

Church, M (1974) Electrochemical and fluorimetric tracer techniques for streamflow measurements, *BGRG Technical Bulletin*, No. 12.

Fischer, H B (1969) The effect of bends on dispersion in streams, *Water Resources Research*, Vol. 5, No. 2, pp. 496-506.

Fischer, H B (1967) The mechanics of dispersion in natural streams, *Journal of the Hydraulics Division, ASCE*, HY6, November, pp. 187-216.

Fischer, H B (1968) Dispersion predictions in natural streams, *Journal of the Sanitary Engineering Division, ASCE*, SA 5, October, pp. 927-943.

Fischer, H B et al (1979) *Mixing in Inland and Coastal Waters*, New York Academic Press

François, O, Calmels, P (1997) Field tracer tests for the simulation of pollutant dispersion in the Doller river (France), *Tracer Hydrology*, No 97, pp. 121-125.

HMSO (1991) *Water Industry Act 1991*, HMSO, London.

Kilpatrick, F A, Taylor, K R (1986) Generalisation and applications of tracer dispersion data, *Water Resources Bulletin*, Vol. 22, No. 4, pp. 537-548.

Leibundgut, Ch, Hadi, S (1997) A contribution to toxicity of fluorescent tracers, *Tracer Hydrology*, No 97, pp. 69-75.

National Rivers Authority (1992) *Water Resources Development Strategy - a discussion document,* National Rivers Authority.

National Rivers Authority (1993) *Gipping / Stour Catchment Management Plan, January 1993,* National Rivers Authority.

National Rivers Authority (1994) *Water Pollution Incidents in England and Wales - 1993,* Water Quality Series No. 21, National Rivers Authority.

National Rivers Authority (1995) *Yare Catchment Management Plan, Action Plan,* National Rivers Authority.

Nordin, C F, Troutman, B M (1980) Longitudinal dispersion in rivers: the persistence of skewness in observed data, *Water Resources Research,* Vol. 16, No. 1, pp. 123-128.

Rutherford, J C (1994) *River Mixing*, Wiley.

Sabol, G V, Nordin, C F Jr (1978) Dispersion in rivers as related to storage zones, *Journal of the Hydraulics Division, ASCE,* HY 5, May, pp. 695-708.

Smart, P L and Laidlaw, I M S (1977) An evaluation of some fluorescent dyes for water tracing, *Water Resources Research,* **13**, (1), pp. 41 - 59.

Smart, P L (1984) A Review of the toxicity of twelve fluorescent dyes used for water tracing, *NSS Bulletin,* **46**, pp. 21 -33.

Thackston, E L, Schnelle, K B (1970) Predicting effects of dead zones on stream mixing, *Journal of the Sanitary Engineering Division, ASCE,* SA 2, April, pp. 319-331.

Wallis, S G, Young, P C, Bevan, K J (1989) Experimental investigation of the aggregated dead zone model for longitudinal solute transport in stream channels, *Proceedings of the Institution of Civil Engineers*, Part 2, No. 87, pp. 1-22.

Wilson, D A (1997) *An investigation into travel times and dispersion of pollution incidents into non-tidal river systems and the development of predictive network models*, Unpublished Ph.D. thesis, School of Applied Sciences, The University of Huddersfield.

Wilson, D A, Butcher, D P, Labadz, J C (1997) Prediction of travel times and dispersion of pollutant spillages in non-tidal rivers, *BHS 6th National Hydrology Symposium*, Salford.

Wilson, D A, Butcher, D P, Labadz, J C (2000) Varaitions in time of travel in UK river systems. in Foster I D L (ed) *Tracers in Geomorphology.* Wiley and Sons. Chichester

Young, P C, Wallis, S G (1993) Solute Transport and Dispersion in Channels, *Channel Network Hydrology*, Chapter 6, pp. 128-173.

APPENDIX A WILSON *ET AL.* (1997)

APPENDIX B RECEIPT FOR DYE

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and

Department of Land-based Studies
Nottingham Trent University

FINAL REPORT
to The Environment Agency

RIVER TIMES OF TRAVEL PROJECT
CM97/1A

Appendix C - Time of Travel Data

FEBRUARY 2000

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