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TRANSPORT VELOCITIES IN LINCOLN DIVISION STREAMS : I. REPORT

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1. INTRODUCTION

While river pollution from diffuse sources such as agricultural fertilizers is an increasing problem for water managers, a potentially more serious threat comes from the unforeseen pollution associated with occasional spillages into watercourses. Such spillages may arise, accidentally or deliberately, from industrial plants, agricultural operations, road traffic accidents or even sewage works. They can present serious problems to downstream water users and it is necessary to have an adequate means of predicting the downstream passage of a soluble pollutant, especially along rivers with public water supply intakes. That need is the basis for this report.

Prediction of travel times can also help to identify the source of a pollutant, which may result in subsequent legal proceedings against the offender. Indeed the 1985 pollution incident in Torrington Beck (Figure 1) provided a major incentive for this study. Results from there suggested that at-a-station mean velocity values are an unreliable basis for estimating travel times over long distances. Reach measurements are required.

The overall purpose of this project is to provide a numerical model which can be used to estimate transport velocities and travel times in Lincoln Division streams draining areas of up to 100 km^2. Previous attempts at modelling pollution travel times have used a variety of approaches, including the one-dimensional diffusion

equation (e.g. Brady and Johnson, 1981) and aggregated dead zone analysis (Young and Wallis, 1986). However, as Brewin and Martin (1988) have pointed out, theoretical modelling procedures are not yet sufficiently well-developed to cope with the vagaries of natural conditions and a reliance on empirical observations remains necessary. Consequently an empirical approach is adopted here. Most of the observations deal with relatively steady flow conditions but it was recognized initially that the occurrence of non-steady flow could introduce additional complications. This report also recounts the results of experiments into non-steady flow where the input is large relative to the discharge of the receiving stream. If the reader wishes to focus on the application of the model and omit those parts of the report which deal in detail with its derivation, then reference can be made immediately to section 6.

2. SAMPLE FRAMEWORK

Three streams were selected for intensive study (Figure 1) based on the recommendations of Anglian Water and various criteria:

(i) Size - the mean annual flood should be in the range of 0.5 - 5 $m^3 s^{-1}$, implying a maximum drainage area of about 100 km^2;

(ii) Availability of continuous discharge records - because of the need to correlate results with discharge measured at a gauging station, a study stream should have a permanent gauge somewhere along its length;

(iii) Accessibility - a study stream should have reasonable access along much of its length in order that test reaches can be established;

(iv) Absence of significant channel modifications.

The selected streams are:

River Lymn upstream of Partney gauge (TF 402676)

River Witham upstream of Saltersford gauge (SK 926335)

Long Eau upstream of Little Carlton Mill gauge (TF 402853)

In addition, Leasingham Beck was chosen for the non-steady flow experiments. Given the wide range of hydrologic and physiographic conditions in Lincoln Division catchments, the extent to which the study streams are representative of that range must be regarded as uncertain without an extensive survey.

The reach scale provided the basis for measurement and along each stream test reaches of two main kinds were established. Long reaches of 2-7 km were chosen to indicate travel times over a river length of operational significance such that each had a gauging station at its downstream end (Figures 2-4). Over this distance the smaller scale variations in streamflow velocity which are typical of natural rivers would tend to be averaged out. Short reaches of 100-250 m were chosen in order to assess those variations and provide data on the way in which velocity changes downstream at discharges of different frequency. 4 such reaches were established at various distances along both the Lymn and the Witham (Figures 2 and 3) since they are sufficiently long and have a more developed drainage network than has the Long Eau (Figure 4). Only one short reach was established along the Long Eau. An attempt was made to select the short reaches so that they were representative of the average channel over about 1 km.

Table 1 lists the channel and basin characteristics for each reach. Slope and cross-sectional properties within the short reaches were measured in the field, while the remaining data were obtained from 1:25,000 and 1:10,000 O.S. maps. The listed bankfull measurements are reach averages but the bankfull channel was not always easy to define, especially where the river is incised. The bed material is generally poorly sorted, with grain sizes ranging from medium sands (0.25 mm) to pebbles (64 mm). Aquatic vegetation which could influence velocity conditions was profuse during the summer months in several reaches, notably Sausthorpe, North Witham and Easton Park.

TABLE 1 REACH CHARACTERISTICS

Reach	Grid Reference	Bankfull Cross-Sectional Area (m^2)	Bankfull Width (m)	Bankfull Mean Depth (m)	Reach Slope ($m\ m^{-1}$)	Reach Sinuosity	Reach Length (m)	Drainage Area (km^2)	Stream Frequency (km^{-2})	Distance from Headwater (km)
R. LYMN:										
TETFORD	TF332744	1.08	2.73	0.40	0.00823	1.17	111.2	4.54	1.32	3.33
SOMERSBY	TF339727	1.67	2.94	0.57	0.00051	1.33	189.8	12.10	0.83	6.15
STOCKWITH	TF361703	4.60	5.77	0.80	0.00206	1.11	132.2	36.82	1.06	10.12
SAUSTHORPE (SHORT/LONG)	TF378685	5.71	6.09	0.97	0.00124	1.15/ 1.26	115/ 232.5	54.09	1.81	13.58
LONG REACH (STOCKWITH to PARTNEY)					0.0021	1.13	6824			
PARTNEY GAUGE	TF402676				0.0014			60.52	1.88	16.95
R. WITHAM:										
NORTH WITHAM	SK927216	1.87	4.18	0.44	0.00008	1.03	150	30.93	0.48	7.05
COLSTERWORTH	SK929239	3.49	5.00	0.70	0.00201	1.20	137	45.02	0.47	11.46
LONG REACH (928232 to COLSTERWORTH GAUGE)					0.0026	1.41	2368			
COLSTERWORTH GAUGE	SK928246				0.0025			51.3	0.45	12.19
EASTON PARK	SK926269	4.28	5.70	0.76	0.00110	1.13	202.7	54.81	0.49	14.93
GREAT PONTON	SK928312	10.40	10.47	0.97	0.00264	1.11	163.2	105.84	0.34	21.28
SALTERSFORD GAUGE	SK926335				0.0018			122.81	0.38	24.42
LONG EAU:										
PRIORY	TF383842	2.85	5.29	0.54	0.00287	1.03	168.1	14.37	0.28	6.06
LONG REACH (PRIORY to LITTLE CARLTON MILL)					0.0021	1.10	2907			
LITTLE CARLTON MILL GAUGE	TF402853				0.0020			20.20	0.30	8.97

The main distinction between the 3 basins lies in their degree of network development (Figures 2-4) and this is clearly reflected by stream frequency, a parameter which is defined as the number of channel junctions per unit area. The Witham and particularly the Long Eau have a notable absence of surface drainage as befits their largely limestone lithology.

3. METHODOLOGY

At the outset it was assumed that travel time or transport velocity is largely a function of streamflow velocity and that the two are controlled by the same set of factors. That set includes stream discharge (Q), channel roughness, the slope of the energy gradient, and the geometric characteristics of the channel. Since discharge is probably the most important factor and is certainly the only one which is continuously monitored, relationships between velocity and discharge provide the basis for the required model. Velocity is one of the most variable properties of natural streams, changing at a cross-section in response to short-term variations in discharge and downstream as discharge increases with drainage area (Knighton, 1984). It is therefore difficult to specify with certainty.

To mimic the behaviour of a soluble pollutant, tracer solutions are commonly used in the measurement of streamflow velocity. The tracer is injected as a gulp at the upstream end of a test reach, becomes rapidly dispersed in the stream, and can be monitored at a suitable downstream site. The resultant plot of tracer concentration against time enables the determination of 4 velocities corresponding to the leading edge (first arrival), peak, centroid (equivalent to the mean) and trailing edge of the tracer wave (Figure 5). All of these velocities figure in the subsequent analysis because each has an important part to play in predicting the downstream movement of a pollutant.

Different tracers were used for the short and long reaches. In the former common salt (NaCl) proved to be a reliable tracer, being cheap, non-toxic and easily detected by a conductivity meter. 3 kg of salt in 20 l of river water was the usual dosage. Tests were carried out on 3 separate occasions to check on the reliability of the method. Salt was not suitable over the long reaches where either Rhodamine WT or potassium iodide (KI) was used, the first on the Lymn and Long Eau, the second on the Witham. It had been hoped to use the Rhodamine dye on all 3 rivers but, after some delay, permission was not granted for the Witham. Delivery of the iodide electrode caused further delays so that measurements over the long reach of the Witham did not begin until August 1988. In the case of the long reaches water samples were taken at intervals of 3-8 minutes by means of an automatic sampler, the dye or iodide concentration being determined later in the laboratory.

Measurements were made over as wide a range of flows as possible, the largest discharge having a duration of 3% and the smallest one of 99%. Steady flow during a measurement period could not always be guaranteed, especially over the long reaches and when the discharge was high, but there were relatively few measurements at times of large discharge fluctuation. In all 184 separate observations were made over 13 test reaches at a time interval which ensured good representation of both intermediate and extreme discharges.

4. ANALYSIS OF RESULTS

4.1 Analytical approach

Leopold and Maddock (1953) argued that the relationship of velocity (v) to discharge (Q) has a log-linear or power-functional form:

$$v = a\ Q^{b} \qquad (1)$$

where a is the velocity at unit discharge and b is the rate of change. This is the main form of analysis adopted here, requiring a log transformation of the basic data. However, later work (Richards, 1973; Knighton, 1979) has suggested that the relationship is log-quadratic rather than log-linear:

$$\log v = m_1 + m_2 \log Q + m_3 (\log Q)^2 \qquad (2)$$

with $m_3 < 0$ to give a typically concave downward curve, indicating that velocity increases more slowly as the discharge becomes larger. Equation (2) reduces to equation (1) when $m_3 = 0$. Where appropriate, this alternative form is considered since it may give better estimates.

Velocity data in m s^{-1} are converted to travel times (TT) in min km^{-1} by:

$$TT = \frac{1000}{60.v} \qquad (3)$$

Travel time - discharge relationships can then be obtained using the same mode of analysis.

The discharge used in the relationships for each reach is not the local reach discharge but the simultaneous discharge at the appropriate gauging station - Partney for the Lymn reaches, Colsterworth for the

Witham reaches (although the Great Ponton results are correlated with the discharge at Saltersford as well), and Little Carlton Mill for the Long Eau reaches. The reasoning behind this is that, if velocity or travel time estimates are required at short notice, discharge information can be obtained quickly from telemetered gauges. Also, the frequency of a discharge can be determined from the flow duration curve which is usually available for a gauging station, and that is important when extrapolating beyond the study catchments. The use of gauge rather than reach discharge does mean, however, that the greater is the distance of the reach from the gauging station the poorer is likely to be the correlation between the reach and gauge discharges. That could affect the quality of the velocity estimates but, with gauge - reach distances being relatively short here, errors are likely to be small. Relationships between reach and gauge discharge are given in Table 2.

4.2 Long Reaches

Rhodamine WT in doses of 10-25 ml was the tracer used over the long reaches of the Lymn and Long Eau. Samples were taken at the downstream end of the test reaches every 3 (Long Eau) or 8 (Lymn) minutes over a period of up to 22 hours and dye concentrations were subsequently determined by fluorimetric methods in the laboratory. The tracer waves were usually well defined but the trailing edge was not always easy to identify, especially at low flows. The measurement length of the Long Eau reach was much shorter than that of the Lymn

TABLE 2 DISCHARGE RELATIONSHIPS

RIVER / REACH	a	b	ρ	Gauging Station
LYMN:				
Sausthorpe (Short)	0.93	1.01	0.991	Partney
Sausthorpe (Long)	1.08	1.13	0.992	Partney
Stockwith	0.62	1.03	0.997	Partney
Somersby	0.27	1.30	0.996	Partney
Tetford	0.093	0.88	0.987	Partney
WITHAM:				
Great Ponton (Saltersford)	0.82	1.24	0.987	Saltersford
Great Ponton (Colsterworth)	2.35	0.76	0.994	Colsterworth
Easton Park	1.08	0.79	0.988	Colsterworth
Colsterworth	0.93	1.00	0.988	Colsterworth
North Witham	0.69	1.40	0.986	Colsterworth
LONG EAU:				
Priory	0.67	0.76	0.966	Little Carlton Mill

Symbols: a, b are coefficients in $Q_{REACH} = aQ_{SIM}^{b}$ where Q_{REACH} is the discharge in the reach and Q_{SIM} is the simultaneous gauge discharge.

ρ is the correlation coefficient.

reach because of the interference introduced by a trout farm in Legbourne but it is regarded as sufficiently long to ensure representative results.

Measurements along the Witham were dogged by delay, in seeking permission to use Rhodamine WT (which was ultimately refused) and in obtaining alternative instrumentation. Only 2 measurements were subsequently made using potassium iodide as the tracer because from October onwards the discharge remained unseasonally low. These data were augmented by miscellaneous measurements made earlier - over a 600 m reach upstream of Colsterworth gauge using salt, and over a reach from Colsterworth gauge to Easton Park (2935 m) using phage (Figure 3). Thus the Witham relationships are calculated from a much more restricted set of measurements not made exactly over the same reach, although flow conditions in the different reaches were probably similar. Certainly the relationships are well defined (Figure 7).

The equations relating velocity and travel time to discharge are given in Tables 3-4 and Figures 6-8. The main points to note are:

(i) The linear relationships between velocity and discharge are all highly significant, the degree of correlation never falling below 0.95. Discharge should therefore be a good estimator of travel time.

(ii) The rates of change (b coefficients) are relatively high, indicating that velocity is very responsive to changing discharge. In the cases of the Lymn and Long Eau the rate of change increases

TABLE 3a LINEAR RELATIONSHIPS: VELOCITY - DISCHARGE

RIVER / REACH	LEADING EDGE				PEAK				CENTROID				TRAILING EDGE			
	a	b	ρ	SE_F	a	b	ρ	SE_F	a	b	ρ	SE_F	a	b	ρ	SE_F
LYMN:																
Long Reach	0.44	0.73	0.973	0.080	0.39	0.74	0.980	0.080	0.38	0.75	0.981	0.079	0.30	0.80	0.952	0.117
Sausthorpe (Short)	0.83	0.68	0.979	0.059	0.61	0.66	0.966	0.068	0.56	0.64	0.962	0.069	0.23	0.56	0.725	0.213
Sausthorpe (Long)	0.62	0.62	0.939	0.106	0.50	0.65	0.933	0.115	0.47	0.63	0.932	0.113	0.27	0.47	0.801	0.167
Stockwith	0.62	0.74	0.989	0.070	0.42	0.72	0.981	0.069	0.36	0.73	0.986	0.064	0.17	0.78	0.920	0.141
Somersby	0.33	0.60	0.981	0.057	0.25	0.60	0.977	0.061	0.24	0.61	0.971	0.067	0.15	0.72	0.941	0.108
Tetford	0.31	0.64	0.962	0.075	0.20	0.61	0.931	0.093	0.195	0.65	0.946	0.092	0.10	0.75	0.916	0.137
WITHAM:																
Long Reach	0.62	0.80	0.999	0.260	0.41	0.74	1.0	0.238	0.38	0.73	1.0	0.238	0.24	0.72	1.0	0.234
Great Ponton (Saltersford)	0.50	0.56	0.990	0.077	0.41	0.64	0.974	0.091	0.38	0.67	0.972	0.103	0.195	0.75	0.930	0.164
Great Ponton (Colsterworth)	0.79	0.34	0.926	0.108	0.70	0.39	0.913	0.126	0.66	0.41	0.906	0.136	0.37	0.46	0.909	0.163
Easton Park	0.57	0.58	0.994	0.094	0.44	0.61	0.996	0.093	0.40	0.62	0.995	0.108	0.25	0.63	0.967	0.161
Colsterworth	0.85	0.58	0.990	0.102	0.63	0.58	0.990	0.100	0.54	0.56	0.989	0.102	0.22	0.56	0.985	0.118
North Witham	0.74	0.91	0.943	0.189	0.53	0.98	0.945	0.201	0.43	0.95	0.949	0.189	0.20	0.97	0.945	0.199
LONG EAU:																
Long Reach	0.77	0.55	0.975	0.077	0.69	0.59	0.976	0.081	0.68	0.59	0.976	0.082	0.51	0.70	0.960	0.122
Priory	0.75	0.42	0.976	0.051	0.62	0.48	0.974	0.057	0.60	0.51	0.975	0.061	0.33	0.57	0.948	0.091

Symbols: a, b are coefficients in $v = aQ^b$ where v is velocity ($m\ s^{-1}$) and Q is discharge ($m^3\ s^{-1}$) at the gauge

ρ is the correlation co-efficient.

SE_F is the standard error of the forecast

Note: the relationships for the Sausthorpe reaches exclude discharges less than the 53% flow

TABLE 3b LINEAR RELATIONSHIPS: TRAVEL TIME - DISCHARGE

RIVER / REACH	LEADING EDGE				PEAK				CENTROID				TRAILING EDGE			
	a	b	ρ	SE_F	a	b	ρ	SE_F	a	b	ρ	SE_F	a	b	ρ	SE_F
YMN:																
Long Reach	37.7	-0.73	-0.973	0.080	43.3	-0.74	-0.980	0.080	43.6	-0.75	-0.981	0.079	56.0	-0.80	-0.952	0.117
Sausthorpe (Short)	20.1	-0.68	-0.979	0.059	27.3	-0.66	-0.966	0.068	29.8	-0.64	-0.962	0.069	72.5	-0.56	-0.725	0.213
Sausthorpe (Long)	26.9	-0.62	-0.939	0.106	33.3	-0.65	-0.933	0.115	35.5	-0.63	-0.932	0.113	61.7	-0.47	-0.801	0.167
Stockwith	26.9	-0.74	-0.989	0.070	39.7	-0.72	-0.981	0.069	45.9	-0.73	-0.986	0.064	96.6	-0.78	-0.920	0.141
Somersby	49.9	-0.60	-0.981	0.057	67.1	-0.60	-0.977	0.061	70.8	-0.61	-0.971	0.067	110.9	-0.72	-0.941	0.108
Tetford	53.8	-0.64	-0.962	0.075	81.3	-0.61	-0.931	0.093	85.1	-0.65	-0.946	0.092	162.9	-0.75	-0.916	0.137
ITHAM:																
Long Reach	26.8	-0.80	-0.999	0.260	40.6	-0.73	-1	0.238	44.2	-0.73	-1	0.238	70.2	-0.72	-1	0.234
Great Ponton (Saltersford)	33.1	-0.56	-0.990	0.077	40.6	-0.64	-0.974	0.091	43.8	-0.67	-0.972	0.103	85.5	-0.75	-0.930	0.164
Great Ponton (Colsterworth)	21.1	-0.34	-0.926	0.108	24.0	-0.39	-0.913	0.126	25.4	-0.41	-0.906	0.136	45.3	-0.46	-0.909	0.163
Easton Park	29.4	-0.58	-0.994	0.094	37.7	-0.61	-0.996	0.093	41.4	-0.62	-0.995	0.108	67.1	-0.63	-0.967	0.161
Colsterworth	19.7	-0.58	-0.990	0.102	26.4	-0.58	-0.990	0.100	31.0	-0.56	-0.989	0.102	75.0	-0.56	-0.985	0.118
North Witham	22.6	-0.91	-0.943	0.189	31.4	-0.98	-0.945	0.201	39.0	-0.95	-0.949	0.189	84.7	-0.97	-0.945	0.199
ONG EAU:																
Long Reach	21.6	-0.55	-0.975	0.077	24.0	-0.59	-0.976	0.081	24.4	-0.60	-0.976	0.082	32.8	-0.70	-0.960	0.122
Priory	22.2	-0.42	-0.976	0.051	27.0	-0.48	-0.974	0.057	27.8	-0.51	-0.975	0.061	49.7	-0.57	-0.948	0.091

Symbols: a, b are coefficients in $TT = aQ^b$ where TT is travel time (min km^{-1}) and Q is discharge ($m^3 s^{-1}$) at the gauge.

ρ is the correlation coefficient

SE_F is the standard error of the forecast

Note: the relationships for the Sausthorpe reaches exclude discharges less than the 53% flow

TABLE 4a QUADRATIC RELATIONSHIPS: VELOCITY - DISCHARGE

RIVER / REACH	LEADING EDGE				PEAK				CENTROID				TRAILING EDGE			
	a_1	a_2	a_3	ρ	a_1	a_2	a_3	ρ	a_1	a_2	a_3	ρ	a_1	a_2	a_3	ρ
LYMN:																
Long Reach	-0.36	0.40	-0.70	0.990	-0.42	0.42	-0.67	0.994	-0.42	0.42	-0.68	0.995	-0.54	0.32*	-1.00	0.978
Tetford	-0.51	0.40	-0.57	0.984	-0.69	0.42	-0.44*	0.945	-0.71	0.36	-0.66	0.972	-0.99	0.23*	-1.19	0.976
WITHAM:																
Great Ponton (Saltersford)	-0.27	0.48	-0.22	0.996	-0.36	0.55	-0.26	0.982	-0.38	0.52	-0.41	0.989	-0.66	0.58	-0.49*	0.948
North Witham	-0.16	0.50	-0.43	0.962	-0.31	0.52	-0.48	0.965								
LONG EAU:																
Priory	-0.16	0.29	-0.11*	0.982	-0.27	0.23	-0.20	0.988	-0.29	0.23	-0.22	0.991	-0.59	0.09*	-0.39	0.983

Symbols: a_1, a_2, a_3 are coefficients in $\log v = a_1 + a_2 \log Q + a_3 (\log Q)^2$ where v is velocity ($m\ s^{-1}$) and Q is discharge ($m^3\ s^{-1}$)

ρ is the correlation coefficient

* signifies that the coefficient is <u>not</u> significant at the 95% level

TABLE 4b QUADRATIC RELATIONSHIPS: TRAVEL TIME - DISCHARGE

RIVER / REACH	LEADING EDGE				PEAK				CENTROID				TRAILING EDGE			
	a_1	a_2	a_3	ρ	a_1	a_2	a_3	ρ	a_1	a_2	a_3	ρ	a_1	a_2	a_3	ρ
YMN:																
Long Reach	1.58	-0.40	0.69	0.990	1.64	-0.42	0.67	-0.994	1.645	-0.42	0.68	-0.995	1.76	-0.32*	1.00	-0.978
Tetford	1.73	-0.40	0.57	-0.984	1.91	-0.42	0.44*	-0.945	1.93	-0.36	0.66	-0.972	2.21	-0.23*	1.19	-0.976
ITHAM:																
Great Ponton (Saltersford)	1.49	-0.48	0.22	-0.996	1.58	-0.55	0.26	-0.982	1.60	-0.52	0.41	-0.989	1.88	-0.58	0.49*	-0.948
North Witham	1.38	-0.50	0.43	-0.962	1.53	-0.52	0.48	-0.965								
ONG EAU:																
Priory	1.38	-0.29	0.11*	-0.982	1.49	-0.23	0.20	-0.988	1.51	-0.23	0.22	-0.991	1.81	-0.09*	0.39	-0.983

Symbols: a_1, a_2, a_3 are coefficients in $\log TT = a_1 + a_2 \log Q + a_3 (\log Q)^2$ where TT is travel time ($min\ km^{-1}$) and Q is discharge ($m^3\ s^{-1}$).

ρ is the correlation coefficient.

* signifies that the coefficient is not significant at the 95% level.

TABLE 5a SPLIT LINEAR REGRESSION RELATIONSHIPS: VELOCITY - DISCHARGE

IVER / REACH	LEADING EDGE				PEAK				CENTROID				TRAILING EDGE				APPLICABLE DISCHARGE RANGE, $m^3 s^{-1}$
	a	b	ρ	SE_F	a	b	ρ	SE_F	a	b	ρ	SE_F	a	b	ρ	SE_F	
YMN:																	
Sausthorpe (Short)	0.82	0.64	0.983	0.053	0.60	0.60	0.980	0.052	0.55	0.58	0.983	0.046	0.22	0.38	0.693	0.159	≥ 0.40
	3.08	2.09	0.970	0.316	2.58	2.28	0.966	0.326	2.24	2.22	0.968	0.302	0.56	1.60	0.902	0.360	≤ 0.42
Sausthorpe (Long)	0.59	0.51	0.993	0.040	0.48	0.52	0.998	0.028	0.45	0.51	0.998	0.034	0.25	0.31	0.863	0.088	≥ 0.36
	4.66	2.66	0.977	0.349	4.44	2.84	0.975	0.386	4.36	2.87	0.980	0.349	3.50	3.07	0.978	0.390	≤ 0.38
ITHAM:																	
Great Ponton (Colsterworth)	0.70	0.14	0.815	0.065	0.59	0.13	0.883	0.045	0.55	0.14	0.920	0.039	0.32	0.25	0.770	0.127	≥ 0.18
	1.45	0.56	0.963	0.091	1.36	0.63	0.960	0.108	1.39	0.68	0.955	0.122	0.74	0.72	0.928	0.188	≤ 0.18

ymbols: a, b are coefficients in $v = aQ^b$ where v is velocity ($m\ s^{-1}$) and Q is gauge discharge ($m^3\ s^{-1}$).

ρ is the correlation coefficient.

SE_F is the standard error of the forecast.

TABLE 5b SPLIT LINEAR REGRESSION RELATIONSHIPS: TRAVEL TIME - DISCHARGE

IVER / REACH	LEADING EDGE				PEAK				CENTROID				TRAILING EDGE				APPLICABLE DISCHARGE RANGE, $m^3 s^{-1}$
	a	b	ρ	SE_F	a	b	ρ	SE_F	a	b	ρ	SE_F	a	b	ρ	SE_F	
YMN:																	
Sausthorpe (Short)	20.3	-0.64	-0.983	0.053	27.7	-0.60	-0.980	0.052	30.3	-0.58	-0.983	0.046	74.8	-0.38	-0.693	0.159	≥ 0.40
	5.40	-2.09	-0.970	0.316	6.47	-2.28	-0.966	0.326	7.43	-2.22	-0.968	0.302	29.6	-1.60	-0.902	0.360	≤ 0.42
Sausthorpe (Long)	28.2	-0.51	-0.993	0.040	35.1	-0.52	-0.998	0.028	37.3	-0.51	-0.998	0.034	66.5	-0.31	-0.863	0.088	≥ 0.36
	3.58	-2.66	-0.977	0.349	3.76	-2.84	-0.975	0.386	3.83	-2.87	-0.980	0.349	4.76	-3.07	-0.978	0.390	≤ 0.38
ITHAM:																	
Great Ponton (Colsterworth)	23.7	-0.14	-0.815	0.065	28.2	-0.13	-0.883	0.045	30.3	-0.14	-0.920	0.039	52.5	-0.25	-0.770	0.127	≥ 0.18
	11.5	-0.56	-0.963	0.091	12.3	-0.63	-0.960	0.108	12.0	-0.68	-0.955	0.122	22.4	-0.72	-0.928	0.188	≤ 0.18

mbols: a, b are coefficients in $TT = aQ^b$ where TT is travel time (min km^{-1}) and Q is gauge discharge ($m^3 s^{-1}$).

ρ is the correlation coefficient.

SE_F is the standard error of the forecast.

progressively from the leading edge through the peak and centroid to the trailing edge velocities so that the difference in time between the arrival and end of a solute wave will become progressively less as discharge increases.

(iii) The peak and centroid relationships are almost identical. Consequently, if the source and average speed of travel of a pollutant are known, the passage of the peak concentration can be reasonably estimated for any downstream point.

(iv) The difference between the leading edge and centroid lines is less than that between the centroid and trailing edge lines, which is indicative of asymmetry in the solute wave. This is especially the case for the Long Eau (Figure 8) where the passage of a solute can be expected to have a longer tail.

(v) There is much greater similarity between the Lymn and Witham results (the peak and centroid relationships are almost identical) than between the Lymn and Long Eau ones. Indeed velocities in the Long Eau seem to be surprisingly high considering the low channel gradient (Table 1) and limited surface drainage (Figure 4). In contrast to the Lymn there is little contribution from tributary inflow along the test reach.

(vi) A log-quadratic function (equation (2)) was fitted to the Lymn and Long Eau data to see if the relationships could be improved. The additional term was not significant in the case of the Long Eau but the last (lowest discharge) data point does seem to play a major role in linearizing the plot (Figure 8). The log-quadratic form was statistically significant for the Lymn as the distribution of points would lead one to expect (Figure 6) but the vertex (or turning point) of the curves lies approximately at a discharge of 2 $m^3 s^{-1}$ (duration of 2%). Above this discharge declining velocities would therefore be predicted, which seems unreasonable. The recommendation is as follows - for simplicity use the linear relationships, although they will tend to overpredict velocity at low or high discharges outside the measurement range; for greater accuracy in that range use an average of the linear and quadratic estimates.

Overall the relationships are consistent and well-defined so that they can be used with confidence. More data are obviously required for the Witham to see if its almost perfect plots (Figure 7) are maintained, while measurements need to be made on the other rivers at lower and higher discharges than was possible during the study period. Steadiness of the flow is difficult to ensure at high discharges over long reaches but can be virtually guaranteed over short ones.

4.3 Short reaches

Common salt was the tracer universally used over the short reaches and generally gave good results. The velocity/travel time relationships with discharge are listed in Tables 3-5 and plotted in Figures 9-19 where the appropriate gauge at which the discharge was measured is indicated. Because of its proximity to the Saltersford gauge (Figure 3) two sets of results were calculated for the Great Ponton reach (Figures 14 and 15), using respectively the Saltersford and Colsterworth discharges. At Sausthorpe measurements were made over two test reaches of different length for comparative purposes.

The main points can be summarized as follows:

(i) The degree of correlation between velocity/travel time and discharge is generally very good, rarely falling below 0.9. The Easton Park and Colsterworth reaches have the most consistent sets of relationships, both covering two cycles of logarithms (Figures 16 and 17), while the Sausthorpe reaches have the least (Figures 9 and 10). Of the remainder the Stockwith, Somersby and Great Ponton (Saltersford) reaches have the best correlations (Figures 11, 12 and 14). On the whole the short reach results should provide reasonably accurate estimates of travel time from discharge.

(ii) Comparing the 4 velocities, the trailing edge usually has the lowest degree of correlation. This reflects its greater natural variability and the occasional difficulty in defining the tail of the tracer wave. The implication is that the travel time of the trailing edge cannot be predicted as accurately as that of the other wave components and standard errors of forecast are commensurately higher.

(iii) Based on data from more than 300 cross-sections worldwide, the average rate of change of velocity with discharge is 0.45. Here, only at Great Ponton (Colsterworth) does the b coefficient fall below this value (Table 3a). Thus the study reaches are characterised by a relatively rapid response of velocity to discharge. The largest rate of change is at North Witham (Figure 18) where low-flow velocities were very small but high-flow ones were similar to those in other Witham reaches.

(iv) It might be expected that, as discharge increases, the difference between the start and end of a solute wave will decrease. Consequently the rate of change of velocity with discharge will become progressively greater from leading edge to trailing edge. Such a well-defined progression is only present in 3 reaches (Great Ponton, Easton Park, Priory), although in most the trailing edge rate of change is higher than the others, sometimes appreciably so (Somersby, Tetford, Great Ponton).

(v) Using the velocity-discharge relationships, the approximate ratio of each reference velocity to the corresponding centroid (or mean) velocity can be calculated. The summary statistics are given in Table 6 and rather surprisingly the leading edge ratio shows the greatest variability, with values ranging from 1.20 (Great Ponton (Colsterworth)) to 1.72 (Stockwith). Such ratios can be used to estimate the velocity of other components of a solute wave when only the mean flow velocity is known.

TABLE 6. RATIOS OF LEADING EDGE, PEAK AND TRAILING EDGE VELOCITIES TO CENTROID VELOCITY

	V_L/V_C	V_P/V_C	V_T/V_C
Mean	1.45	1.10	0.52
Standard deviation	0.18	0.07	0.07

(vi) Log-quadratic functions (equation (2)) were fitted to the data of the Tetford, Great Ponton (Saltersford), North Witham and Priory reaches (Table 4). Not all of the relationships are statistically significant, however. The following recommendations are made:

Tetford - because of the position of the vertex (at a discharge of only 2 m^3 s^{-1}), estimates should be based on the average of the velocities/travel times calculated from the linear and quadratic relationships. This applies particularly at very high and very low flows when use of the linear relationships alone would tend to overestimate velocities or underestimate travel times.

Great Ponton (Saltersford) - quadratic relationships produce significantly better estimates of leading edge, peak and centroid velocities but not trailing edge velocity.

North Witham - leading edge and peak velocities should be estimated from the quadratic relationships. It should be noted, however, that their graphs contain an extra point (at the lowest discharge of 0.076 m^3 s^{-1}) which seems to have a marked effect on the form of the relationship (Figure 18). Because of the excessive slowness of the flow, the centroid and trailing edge of the tracer wave could not be defined at that discharge. This case illustrates how a single observation made at an extreme flow can significantly influence results.

Priory - the same remarks as for Tetford apply. Relative to the linear relationships, estimates at very high or very low flows can be improved by using the average of the values calculated from the linear and quadratic relationships.

(vii) In two reaches, Sausthorpe and Great Ponton (Colsterworth), neither a linear nor a quadratic function seems to fit the distribution of points particularly well (Figures 9, 10 and 15). In both cases a split linear regression is used but this requires a somewhat arbitrary decision as to which points apply to which line. Some points are included in both regressions and these are marked by an asterisk on the graphs.

Sausthorpe - both test reaches have data plots with the same basic form, the two observations at the lowest discharges having particularly low velocities (Figures 9 and 10). That effect is thought to be caused by within-channel vegetation which significantly slowed the velocity at small discharges in the late summer. Unfortunately the low-flow regression line tends to give questionable results at very low flows and it is recommended that a regression which excludes the last two data points be used for predictive purposes (shown as solid lines on the graphs). The equations will tend to overestimate velocity at low flows but they are probably more representative of average conditions.

Great Ponton (Colsterworth) - the difference in slope between the high-flow and low-flow lines is less acute than in the Sausthorpe case and the twofold approach is better supported by the data in not being dependent on the position of only 2 or 3 points (Figure 15). Consequently the split regression model is recommended in this instance (Table 5). It shows that velocities respond much more slowly to increasing discharge in the higher flow than in the lower flow range.

(viii) Two sets of results are given for the Great Ponton reach and, although either can be used, the Saltersford relationships appear to be more consistent, possibly because the reach lies downstream of the discharge addition from Cringle Brook and is closer to that gauge (Figure 3).

(ix) Although all the relationships for the short reaches are statistically significant, they are not always as good as the long reach relationships. Three reasons can be put forward for this. Firstly, it is very difficult to ensure that a short reach is representative of a longer stretch of river. Secondly, there is the problem of correlating reach velocity with discharge at a gauge which may be some distance away, although in the case of the Lymn relationships for distant reaches (Tetford, Somersby) are better than those for a proximal one (Sausthorpe). Thirdly, short reach measurements are more responsive to local influences, especially at low flows. Within-channel vegetation significantly affected low-flow conditions at Sausthorpe and North Witham, to such an extent at the latter that the flow velocity was close to zero when the discharge at Colsterworth gauge still had a duration of 76%. The disparity in velocity between the last two data points in the Tetford plots (Figure 13), especially as regards the trailing edge, reflects the influence of a debris dam which built up during the summer. Set against these problems, short reach measurements are less expensive in time and equipment, and can be carried out more easily during a pollution incident. Apart from the disappointing Sausthorpe results, the short reach relationships should give reasonable travel time estimates.

4.4. At-a-station hydraulic geometry

To provide a basis for comparison with the preceding reach results, cross-sectional data supplied by Anglian Water were analysed using the hydraulic geometry approach in which relationships having the same form as equation (1) (or equation (2)) were calculated. With the exception of Sausthorpe, the measurements were made close to existing gauging stations. Mean velocity refers to the mean in the cross-section and is comparable with the centroid velocity. Maximum velocity is defined as the largest average velocity measured at a vertical and can be regarded as similar to the leading edge velocity. It is approximately 1.3 times the mean.

The relationships are shown in Figures 20-24. The subdivided nature of the Saltersford section makes a comparison with the others difficult but that section does have by far the highest rates of change of velocity (Figure 22). Elsewhere the response of velocity to changing discharge is more modest, in the range of 0.4-0.55 except at Partney where velocity increases relatively slowly (Figure 20). Depth is the most adjustable variable at that section and, somewhat unusually, width adjusts almost as rapidly as velocity to accommodate an increase in discharge.

The relationships indicate a wide range of cross-sectional forms, from narrow and deep (Little Carlton Mill) to wide but not necessarily shallow (Colsterworth). Not surprisingly, therefore, they show a lack of consistency in both coefficient and exponent values. The narrow, deep form of the Long Eau section may explain the relatively high velocities in this low-gradient Chalk-bedrock stream, although the rate of change of velocity seems to decline at higher discharges (Figure 24). In that regard the section at Little Carlton Mill has much in common with the Priory Reach (Figure 19).

4.5 Comparison of results

The velocity-discharge relationships for each reach and hydraulic geometry section are plotted on Figures 25-27 over the relevant discharge ranges. Taking each river in turn, the following comments are appropriate:

Lymn - The results for the Long Reach, which includes the Stockwith and Sausthorpe short reaches, indicate an appreciably lower leading edge but higher trailing edge velocity than the comparable velocities in those two reaches (Figure 25). This disparity may reflect the difficulty of accurately defining the margins of the dye trace at Partney, especially at its trailing edge, although the lower leading edge velocity could represent a distance effect associated with greater diffusion over increasing reach length. The centroid line occupies a more reasonable position, part way between the Stockwith and Sausthorpe lines but nearer the former. Unexpectedly the overall trend is for a progressive increase in Long Reach velocities (from leading edge to trailing edge) relative to the velocities in the included reaches.

The short reach lines have similar slopes and occupy their correct position as regards downstream sequence if it is assumed that velocity increases in that direction (see section 4.6). However, their relative position changes from leading edge to trailing edge - Stockwith and Somersby velocities become more nearly alike as Sausthorpe-Stockwith and Somersby-Tetford differences increase. The intermediate reaches thus become more distinct from their downstream and upstream counterparts.

At Sausthorpe the shorter reach has higher velocities except at the trailing edge. The greatest contrast lies in the leading edge velocity, which may indicate different levels of mixing of the tracer over the two reach lengths. These different results over the short and long reaches underline the problem of providing accurate velocity-discharge relationships when local velocity conditions can be so variable. However, the Sausthorpe lines are in their expected relative position and the average of the two sets of results is used in subsequent calculations.

The hydraulic geometry relationships for the Sausthorpe and Partney sections are approximately in their correct positions but their rates of change of velocity are significantly lower than are those of the short reach relationships. Consequently they could be used to give reasonable estimates of velocity up to a discharge of 1 m^3 s^{-1} but would tend to underpredict at higher flows.

Overall there is a reassuring degree of consistency in the reach relationships. The main concern lies in the behaviour of the Long Reach velocities relative to that of the Sausthorpe and Stockwith ones, especially at the leading and trailing edges. A decision needs to be made as to how velocities and travel times are to be estimated over this stretch of river (see section 6).

Witham - The Long Reach lies downstream of North Witham and includes the short test reach at Colsterworth. Although its relationships are based on a limited number of measurements over slightly different lengths, they are appropriately placed on the plots (Figure 26), intermediate between the North Witham and Colsterworth regressions with a tendency to become closer to the latter in the progression from leading edge to trailing edge. This relative upward shift of the Long Reach results has already been noted in the Lymn plots.

The positioning of the short reach lines broadly corresponds to the expected downstream pattern but

Colsterworth plots too high relative to Easton Park. One or both of these reaches may not have been truly representative but without extensive surveys it is very difficult to ensure that a short reach is typical of more general conditions. Unlike the Lymn, the lines become steeper with greater distance upstream so that they tend to converge. There is thus greater uniformity in velocity at higher discharges along the Witham.

Velocity at the Colsterworth gauge is intermediate between that in the Colsterworth and Easton Park reaches but only at low and medium discharges. Because the rate of change of velocity is lower at the gauge section than in the test reaches, as in the case of the Lymn, the at-a-station relationships would tend to underpredict velocity at higher flows.

A further comparison can be effected using information supplied by Anglian Water. The Authority categorized the Upper Witham into 5 types and obtained a mean velocity ($\bar{V}$) - discharge relationship for each category. With respect to the test reaches used in this study, the relevant relationships are:

Category 5 (Great Ponton) $\bar{V}=0.54Q^{0.42}$ (4)

Category 4 (Easton Park, Colsterworth)

$\bar{V}=0.50Q^{0.70}$ (5)

Category 3 (North Witham) $\bar{V}=0.40Q^{0.90}$ (6)

The progressive upstream increase in the rate of change of velocity noted earlier is again present and, when the equations are compared with their short reach equivalents (Figure 26, Table 3a), there is a high degree of correspondence, especially for North Witham. This agreement not only engenders confidence in the short reach results but also suggests that the procedure whereby the above relationships were derived could be effectively used on other rivers within the Lincoln Division.

Long Eau - The overriding characteristic in Figure 27 is the proximity of the various lines, especially on the centroid/mean velocity graph. As in the cases of the Lymn and Witham, there is a progressive upward shift in the relative position of the Long Reach line from leading edge to trailing edge but the difference between the reach relationships is comparatively small. An interesting point of similarity is the need to apply log-quadratic equations to both the Priory Reach and Little Carlton Mill data. The Long Reach data also show a similar tendency (Figure 8, especially trailing edge) but unfortunately only one measurement was made in the higher flow range and even then only the trailing edge of the tracer wave could be adequately defined because of sampler failure. Considering that the various relationships are based on measurements made at different scales and locations (long reach, short reach, cross-section), their similarity is quite remarkable and suggests strongly that, with the possible exception of the trailing edge, velocity conditions are relatively uniform along this river. The relative constancy in the cross-sectional form of this embanked channel is probably the main reason for the uniformity observed.

4.6 Inter-basin relationships

A subsidiary element of the initial brief was to examine the possibility of deriving equations which relate velocity conditions to catchment characteristics. Centroid velocities were calculated for this purpose from the short reach relationships for the Lymn and Witham catchments at discharges having durations of 5%, 20%, 50%, 80% and 95%, durations which were believed to represent moderate high, high intermediate, intermediate, low intermediate and low flow conditions respectively. Two forms of analysis were carried out:

$$V_C=f(A_d, s, S, SF) \qquad (7)$$

$$V_C=f(L, s, S, SF) \qquad (8)$$

where A_d is drainage area (km^2), s is reach slope ($m\ m^{-1}$), S is reach sinuosity, SF is stream frequency (km^{-2}) and L is distance from headwaters (km). The results are plotted in Figure 28 and tabulated in Table 7.

Neither reach sinuosity nor stream frequency has a significant effect on centroid velocity. Regarding the remaining variables, the following comments can be made:

(i) Centroid velocity at the 5% flow is significantly correlated with both drainage area and distance downstream. The relationships indicate a progressive increase in velocity downstream as has been found elsewhere (Knighton, 1984) and, although the scatter of points is quite wide on the two graphs, the equations could be used to provide reasonable estimates at higher flows.

TABLE 7 INTER-BASIN RELATIONSHIPS

FLOW URATION	DRAINAGE AREA RELATIONSHIPS									DISTANCE DOWNSTREAM RELATIONSHIPS								
	a	b	ρ	SE_E	a	b	c	ρ	SE_E	a	b	ρ	SE_E	a	b	c	ρ	SE_E
5%	0.125	0.35	0.938	0.060						0.12	0.56	0.894	0.078					
20%	0.089	0.30	0.785	0.111	0.18	0.33	0.12	0.896	0.088	0.073	0.55	0.835	0.099					
50%	0.052	0.32	0.679	0.163	0.16	0.37	0.19	0.865	0.122	0.038	0.62	0.770	0.142					
80%	0.038	0.29*	0.472*	0.249	0.21	0.36	0.29	0.798	0.187	0.025	0.62*	0.605*	0.225	0.13	0.63	0.25	0.825	0.175
95%	0.027	0.30*	0.434*	0.290	0.19	0.38*	0.33	0.778	0.222	0.017	0.67*	0.574*	0.264	0.11	0.69	0.29	0.809	0.207

ymbols: a, b, c are coefficients in $v_c = aA_d^b$, $v_c = aA_d^b s^c$, $v_c = aL^b$ or $v_c = aL^b . s^c$ where v_c is centroid velocity ($m\ s^{-1}$), A_d is drainage area (km^2), L is distance downstream (km) and s is channel slope ($m\ m^{-1}$).

ρ is the correlation coefficient.

SE_E is the standard error of estimate.

* signifies that the coefficient is <u>not</u> statistically significant at the 95% level.

(ii) The level of correlation progressively deteriorates from the 5% to the 95% flow so that estimates will become commensurately less reliable. Neither drainage area nor distance downstream has a significant individual influence on velocity at the 80% or 95% flow.

(iii) As the individual influence of drainage area or distance downstream declines, so reach slope becomes more important. It is never significant on its own but, in combination with either drainage area or distance downstream, its significance gradually improves as the discharge becomes less (i.e. as the flow duration increases). Indeed in the 95% combined relationship, slope is a significant variable while drainage area is not (Table 7). The increasing importance of slope is regarded as symptomatic of the increasing influence of local factors on velocity conditions at lower discharges. It is caused principally by the North Witham and Easton Park reaches which have particularly low slopes (Table 1). Velocities in those reaches plot further and further below the other points as flow duration increases from 5% to 95% (Figure 28).

(iv) Distance downstream is a more significant correlate, either singly or in combination with slope, than drainage area at all flows apart from the 5%. Also, it retains its individual influence longer and velocity responds more rapidly to it. Consequently distance downstream may be preferred to drainage area for estimation purposes.

Measurements of drainage area or distance downstream can be made quickly and accurately from maps at a large enough scale (1:25,000 or larger). The reach slope values used in the analysis were measured in the field using a surveyor's level but slope can be estimated from maps by measuring channel length between 2, or preferably more, contour lines over a representative stretch of river. Slope was measured in this way over the Long Reach of the Lymn and for the Colsterworth gauge, and the values obtained are similar respectively to the surveyed slopes in the Stockwith and Colsterworth reaches (Table 1). Armed with the requisite map measurements, the equations can be used to estimate centroid velocity and, by means of the multipliers in Table 6 (1.45 for the leading edge, 1.10 for the peak, 0.52 for the trailing edge), the other velocities as well. However, a note of caution needs to be issued - while the estimates may be reasonable at higher flows, they will probably be less reliable at lower ones. More data are needed to improve the reliability of the basin-scale relationships.

4.7. Solute concentration

For information purposes rather than as part of the main study, selected concentration-time graphs are given in Figures 29-31 for the various study reaches. The graphs show how dye concentration (long reaches) or relative salt concentration (short reaches) varied over time at discharges of different duration.

As expected, the tracer wave is displaced laterally along the time axis and its time base lengthened as discharge decreases. More surprisingly, two patterns of change are apparent in the form of the concentration graphs - in some reaches (e.g. Sausthorpe, Figure 29) peak concentration rises and then falls as the discharge becomes less, reaching a maximum at intermediate flows, while in other (e.g. Colsterworth, Figure 30) peak concentration continues to rise throughout the flow range. Although there are variations on these two themes, their manifestation does have implications for the prediction of pollutant transport. For example, there may be a need to know the likely value of peak concentration at a given discharge when monitoring the downstream movement of a pollutant, especially along a river with public water intakes. More work needs to be carried out on possible variations in the level of solute concentration and these results could provide a useful starting point.

5. NON-STEADY FLOW EXPERIMENTS

The preceding section was concerned with relatively steady flow conditions in that individual measurements were made at approximately constant discharge and the volume of the input (injected solute) was small compared with that of the stream. However, situations may arise, particularly is small streams, where the rate of inflow of a pollutant is similar to or even larger than the rate of flow of the receiving stream. Preliminary experiments were carried out in order to investigate such a situation.

The experiments were carried out on 4 days in June/July 1988 along an 850 m length of Leasingham Beck (Figures 1 and 32). That stream was chosen because groundwater could be pumped into the stream from an adjacent well, thereby replicating the desired condition. The groundwater was input via a weir tank at a rate of 12.6 l s^{-1}, approximately 8 times greater than the natural stream discharge at that time. 3 measurement sites were established (Figure 32), at distances of 55 m (Bridge site), 378 m (Church site) and 850 m (Estate site) downstream from the input point. The following measurements were made:

Conductivity - Input point, Bridge site, Church site, Estate site

Discharge (using a V-notch weir) : Estate site

Water level (using a staff gauge): Church site

Water temperature: Estate site

After the first experiment it was decided to label the groundwater input with either a gulp injection of

Rhodamine WT or a constant rate injection of a salt/dye mixture. Bottle samples were taken at regular intervals at the Church and Estate sites for later laboratory measurement of dye concentration.

The input characteristics of the 4 days are shown on the accompanying graphs (Figures 33-36). Early on it was realized that some of the input flowed upstream initially and moved downstream only after the pumping had stopped. In most of the subsequent experiments (29/6, 5/7 a.m., 6/7) upstream flow was prevented by placing a board across the culvert immediately above the input point.

The main results of the experiments can be summarized as follows:

(i) Consistently at all sites there is an initial rise in conductivity which precedes the arrival of the less conductive groundwater. This rise is thought to represent a flushing effect as soluble material is mobilized and transported downstream by the increased input. When there are 2 inputs on a single day the conductivity peak has a much lower value in the afternoon when the availability of material would be less. One implication of this result is that, if a large input occurs after a period of low flow and soluble pollutants are already stored in the reach, they could be mobilized and become concentrated on the leading edge of the increased flow.

(ii) A comparison of the dye traces at the Church and Estate sites indicates several distance effects. The peak concentration at the latter is about half that at the former, presumably because of increased dispersion. Peaks are broader, flatter and less distinct at the Estate site. This is particularly noticeable on the plots of 29/6 and 6/7 (Figures 34 and 36) when the twin dye and conductivity peaks at the Church site are no longer discernible further downstream. This fusion is attributed to greater mixing and a decrease of solute velocity relative to that of the flow. Whereas the dye peaks correspond reasonably well with the flow peaks at the Church site, they lag the flow peaks at the Estate site by an hour or more. The longest lag of 165 min occurs on 6/7 (Figure 36) when, significantly, the background flow in the stream had been raised prior to the main input. If, as expected, this lag effect increases with distance downstream, then the time base of the solute (or pollutant) wave will become progressively longer and its trailing edge more difficult to define. In addition, the potential for temporary storage will increase as the solute lags further behind the main flow and comes under the influence of lower velocity conditions.

(iii) The plots themselves contain evidence of short-term storage during the experimental period. The higher dye concentration values in the early part of the runs on 29/6 and 6/7 (Figures 34 and 36) are believed to represent the flushing-out of dye residual from the previous day. Also, the secondary peak at the Church site on 28/6 (Figure 33) probably results from part of the input moving upstream initially, to be released only after the end of pumping. The smaller dye peak of the second run on 5/7

(Figure 35) indicates that less dye was recovered on the second run than on the first, suggesting a greater likelihood of storage when, as in natural conditions, upstream flow is not prevented at the input point. Such upstream flow is more probable where, as in many Lincolnshire rivers, channel slopes are low. These several characteristics highlight the difficulty of predicting pollution levels along a stream when the rate of input is relatively large, since some of the pollutant may be temporarily stored and mobilized only when higher flows return.

(iv) Average solute velocities for the leading edge and peak of the dye waves are given in Table 8. The low standard errors indicate a high level of consistency for

Table 8. Average solute velocities (m s^{-1})

	Input point to Church site (378 m)		Church site to Estate site (472 m)	
	Mean	Standard error	Mean	Standard error
Leading Edge	0.082	0.003	0.063	0.006
Peak	0.069	0.001	0.050	0.004

the 4 days. In particular the different initial flow conditions of 29/6 and 6/7 seem to have no appreciable effect on solute velocity. The significant decrease in velocity below the Church site explains the downstream effects noted earlier, especially the increased lag. Compared with values calculated from the Easton Park and Colsterworth relationships at a discharge of 0.0126 m^3

s^{-1}, these velocities are about 50 per cent higher, suggesting that steady-flow equations could give unreliable estimates under non-steady conditions. However, the comparison may not be entirely valid and, in any case, the number of velocity measurements in Leasingham Beck was unavoidably small.

Although preliminary, these experiments indicate several complex features of solute transport when the rate of input is relatively large. Because of distance and storage effects in particular, prediction of travel times and identification of pollutant source would become increasingly difficult with distance downstream. These experiments need to be extended to cover a wider range of input discharges (both relative and absolute) with more intensive monitoring.

6. APPLICATION OF THE MODEL

6.1 Practical recommendations

During a pollution incident the following steps are to be followed:

(1) Telephone the nearest gauging station and obtain a stage reading.

(2) Convert the stage reading into an equivalent discharge (in $m^3 s^{-1}$) using the rating tables.

(3) Based on the location of the pollutant in the river system, choose an appropriate river length for estimation purposes (see section 6.2).

(4) Estimate the travel times for that length using either the travel time tables (Appendices A-K) or the corresponding equations (Tables 3, 4, 5, 7). The peak is usually the most recognizable part of a pollutant wave but the key questions are:

When will the pollutant reach here? (leading edge)

When will it have passed? (trailing edge)

These questions can be answered by either:

(i) Using the leading edge and trailing edge travel time estimates for the appropriate river length directly; or

(ii) Using average leading edge/peak and trailing edge/peak travel time ratios of 0.76 and 2.12 respectively - thus, if the time of arrival of the peak is estimated at 65 minutes, that of the leading edge will be 0.76 x 65 = 49 minutes, and that of the trailing edge will be 2.12 x 65 = 138 minutes.

(5) Add a safety margin to the leading edge and trailing edge travel time estimates. The standard errors given in Tables 3-5 and 7 can help in this regard. Approximate 95% error bounds can be calculated using 2 x Standard Error:

E.g. At Stockwith $TT_L = 26.9Q^{-0.74}$ $SE_F = 0.07$

For a discharge at Partney of 0.5 $m^3 s^{-1}$,

$TT_L = 45 \text{ min km}^{-1}$

The approximate 95% limits are:

$\log^{-1} (\log TT_L \pm 2.SE_F) =$

$\log^{-1} (1.65 \pm 0.14) =$

$\log^{-1} (1.51, 1.79) =$

(32 min km^{-1}, 62 min km^{-1}).

A larger safety margin needs to be added where travel times are estimated at discharges further from the mean. This raises a general point - the most reliable estimates will be made nearest the middle of the measured discharge range.

The travel time equations can provide a basis for computerization of the estimation procedure which should speed up forecasting. In the first instance a desk-top micro-computer would probably suffice but, as more data become available, the Authority should consider the development of a more sophisticated system.

6.2 Choice of reach equations

Two basic approaches are advocated, the choice of which depends on whether or not the pollution incident occurs on one of the study streams.

(1) Pollution in one of the study streams

The following recommendations are made regarding the choice of reach equations:

LYMN -

UPPER REACHES (upstream of Double Dike) - use the averages of the linear and quadratic relationships for Tetford (Appendix A)

UPPER MIDDLE REACHES (from Double Dike to the right bank tributary at 355708)- use the Somersby relationships (Appendix B)

LOWER MIDDLE REACHES (from 355708 to the right bank tributary at 378687)- use the Stockwith Mill relationships (Appendix C)

LOWER REACHES (378687 to Partney gauge)- use the averages of the Sausthorpe (short) and Sausthorpe (long) relationships (Appendix D)

STOCKWITH to PARTNEY - if estimates are required which are more general than those provided by the 2 reaches above, then the averages of the linear and quadratic relationships for the Long Reach give a viable alternative (Appendix E)

WITHAM -

UPPER REACHES (upstream of the left bank tributary at 927231; category 3 of the AW classification) - use the North Witham relationships (Appendix F)

UPPER/MIDDLE REACHES (930223 to Easton; category 3/4 of the AW classification)- the Long Reach relationships provide an alternative to those immediately above and below (Appendix G)

MIDDLE REACHES (927231 to Cringle Brook; category 4 of the AW classification) - use the averages of the Colsterworth and Easton Park relationships (Appendix H)

LOWER REACHES (Cringle Brook to Saltersford gauge; category 5 of the AW classification) - use the Great Ponton relationships based on either the Colsterworth or Saltersford gauge discharge (Appendices I and J)

LONG EAU (Legbourne to Little Carlton Mill) - because the Priory Reach measurements cover a larger discharge range than do the Long Reach ones and because the two sets of relationships are similar (Figure 27), it is recommended that the averages of the Priory Reach and Long Reach relationships be used (Appendix K)

(2) Pollution in a non-study stream

Two strategies are suggested, either or both of which can be used:

(i) Compare the affected stream with the study streams and use the equations for that study stream/reach which most closely corresponds to it in terms of reach and basin characteristics (see Table 1); a comparison could also be based on the shape of the flow-duration curves, taking account of their relative steepness and the relative magnitude of the discharge at various percentage flows.

(ii) Measure the drainage area (km^2), distance from source (km) and slope ($m\ m^{-1}$) of the affected reach from 1:25,000 or 1:10,000 O.S. maps and use the appropriate relationships from Table 7. The relationships there refer to centroid velocity at 5 different flows - to obtain the leading edge, peak and trailing edge velocities, use the multipliers in Table 6; to convert velocities (in m s^{-1}) to travel times (min km^{-1}), use equation (3); with the flow duration of the discharge in the affected stream known or estimated, use the relationships at an immediately higher and lower duration to provide upper and lower bounds.

Travel time estimates on non-study streams will probably be much less reliable and the greater is the difference between the affected and study streams the greater is the uncertainty likely to be. The estimation procedure should be used with extreme caution, if at all, over river lengths with a drainage area which is much in excess of 100 km^2. However, the results in this report do provide a basis for calibrating non-study streams. If, for example, there is a need to predict the source of a pollutant after the event, then the following steps could be followed:

(1) Use either of the above strategies to estimate travel times at the existing discharge;

(2) Make a test run on the affected stream at that discharge and compare the measured travel times with the estimated ones;

(3) Use the ratios of the two sets of results to modify the given equations so that they can be used to estimate travel times at the discharge when the pollution incident occurred.

One final point needs to be made. The hydraulic geometry relationships derived from cross-sectional measurements made at gauging stations provide reasonably consistent estimates of velocity conditions (Figures 25-27), especially in the Long Eau. Assuming that the Authority has such records for most, if not all, of its gauging stations, the analysis of those records could provide an additional basis for estimating travel times in non-study streams.

6.3 Testing the model

The estimation procedure was tested in non-study streams over reaches which varied in length from 461 m to 805 m (Table 9). Each was situated close to a gauging station. Unfortunately the test runs using salt and potassium iodide as tracers had to be made at low discharges, although the 57% flow of Stainfield Beck was rather unexpected in view of the prevailing regional flow conditions.

Table 10 contains the data on observed and estimated velocities, the latter being obtained by both of the methods suggested in the previous section for non-study streams. Method (i) based on direct use of the equations for a comparable reach varies considerably in the level of agreement between observed and estimated velocities - excellent for Cringle Brook, good for the West Glen, poor for Stainfield Beck (except the trailing edge), very poor for Heighington Beck. These results are not altogether surprising since, on the one hand, Cringle Brook is a tributary of the Witham (Figure 3) and the West Glen is

TABLE 9. TEST REACH DATA

	GRID REFERENCE	DATE OF MEASUREMENT	TEST REACH LENGTH, m	DISCHARGE, $m^3 s^{-1}$	DRAINAGE AREA, km^2	DISTANCE FROM SOURCE, km	CARTOGRAPHIC SLOPE, $m m^{-1}$
CRINGLE BROOK	SK 927303	9.2.89	461	0.122 (83%)	42.3	11.27	0.0031
HEIGHINGTON BECK	TF 042697	16.2.89	493	0.035 (87%)	24.0	7.88	0.0041
STAINFIELD BECK	TF 127739	16.2.89	638	0.085 (57%)	37.2	15.39	0.0020
R. WEST GLEN	SK 987262	9.2.89	805	0.041 (84%)	33.2	9.21	0.0021

Note: numbers in brackets refer to flow duration.

TABLE 10. TEST REACH RESULTS

RIVER	COMPARABLE STUDY STREAM/FLOW DURATION	LEADING EDGE VELOCITY, $m\ s^{-1}$	PEAK VELOCITY, $m\ s^{-1}$	CENTROID VELOCITY, $m\ s^{-1}$	TRAILING EDGE VELOCITY, $m\ s^{-1}$
CRINGLE BROOK					
Observed		0.210	0.146	0.128	0.070
Method (i)	WITHAM/MIDDLE REACHES	0.210	0.154	0.138	0.067
Method (ii)	80%			0.151/0.141	
	95%			0.117/0.110	
HEIGHINGTON BECK					
Observed		0.316	0.249	0.245	0.087
Method (i)	LONG EAU	0.168	0.109	0.095	0.039
Method (ii)	80%			0.134/0.121	
	95%			0.104/0.093	
STAINFIELD BECK					
Observed		0.273	0.201	0.183	0.062
Method (i)	LYMN/SAUSTHORPE	0.144	0.111	0.108	0.072
Method (ii)	50%			0.187/0.207	
	80%			0.127/0.154	
WEST GLEN					
Observed		0.093	0.067	0.061	0.034
Method (i)	WITHAM/MIDDLE REACHES	0.111	0.081	0.072	0.035
Method (ii)	80%			0.124/0.113	
	95%			0.094/0.085	

Note: In each pair of estimates of centroid velocity at a given flow duration, the first number refers to the relevant drainage area relationship and the second to the relevant distance downstream relationship in Table 7.

close to the Witham in location, basement geology and basin physiography, while on the other Stainfield Beck and Heighington Beck are far from the study catchments in many respects. Method (ii) based on the drainage area or distance downstream relationships (with slope included) also gives a wide range of agreement - from good for Cringle Brook and Stainfield Beck, to very poor for Heighington Beck. The velocities in Heighington Beck which drains the dip slope of the limestone escarpment south of Lincoln were surprisingly high in view of the low discharge and small cross-sectional area of flow (at a discharge of 0.035 m^3 s^{-1} and an average velocity of 0.245 m s^{-1}, the stream only had a capacity of 0.14 m^2 - with an approximate width of 1.5 m, this gives a mean depth of only 0.09 m when resistance should have been high and velocity correspondingly low). Even though the stream has quite a steep slope (Table 9), the level of disparity between observed and estimated velocities cannot easily be explained. This case, together with Stainfield Beck to a lesser extent, highlights the difficulty of accurately predicting travel times in non-study streams which have not been calibrated in some way. However, as pointed out earlier, predictions at low flows are likely to be the least reliable.

7. CONCLUSION

The measurements of streamflow velocity cover a reasonably wide range of discharges - from a duration of 4% to 73% on the Lymn, from 3% to 99% on the Witham, from 2% to 98% on the Long Eau. As a result the velocity - discharge relationships are generally well-defined and should provide a sound basis for estimating the travel times of soluble pollutants. They will perform best at intermediate discharges (10% - 75%) in the study basins and worst at low discharges in non-study streams which differ appreciably from the study streams in reach and basin characteristics. More measurements need to be made of velocity during extreme flows (durations of <5%, >85%) and especially at the low end of the discharge range when local factors can have a major influence on velocity conditions. At low flows also the available dilution is less and the potential impact of a pollutant likely to be greater. Application of the calculated relationships to non-study streams will produce less reliable estimates but the results presented here do provide a framework for extrapolation, particularly if individual test runs can be carried out. Data from such a run could be used to adjust the values of 'a' (see equation (1)) in the equations for a comparable study reach, the adjusted equations then being applicable at other discharges.

Calibration of non-study streams can be carried out quickly and cheaply by using salt as a tracer over reaches of about 200 m. However, short reach measurements are more susceptible to local influences, especially at low flows, and their representativeness of longer reaches is difficult to ensure. Long reach measurements over more than 3 km are therefore preferable but they are expensive of time and equipment, particularly when samples have to be returned to the laboratory for analysis. The Authority should consider the setting-up of a rapid and efficient measurement procedure which uses a tracer whose concentration can be continuously monitored in the field. Potassium iodide may be a suitable tracer for this task.

This study has demonstrated the variability of streamflow velocity both within and between drainage basins. Consequently it should be regarded as a starting point and not an end point for the prediction of pollution travel times in Lincoln Division streams. There is plenty of scope for further work:

1. In view of the reasonable comparisons between at-a-station hydraulic geometry and reach results (Figures 25-27), velocity - discharge relationships can be calculated from existing gauging station data to provide an additional basis for estimating travel times in non-study streams. Regarded as an interim measure, such work can be carried out quickly with little or no extra field measurement.
2. The approach adopted here can be extended to other streams of the same size or larger, which would augment the data base and result in improved basin-scale relationships. Initially individual test runs could be carried out to extend the application of the model in the way suggested above, focusing on those

non-study streams which are particularly susceptible to pollution.

3. The requisite computer software should be developed so that the results contained in this report can be used quickly to provide travel time estimates during a pollution incident.

4. The use of in-channel storage as a means of attenuating and delaying pollutant transport could be investigated. This suggestion stems directly from observations at Great Ponton where flow backs up behind a sluice and is consequently slowed. An inventory of possible short-term storage sites in Lincoln Division streams could be useful when dealing with a pollution incident.

5. An extension of (4) would involve a more general study of the effects of backed-up flow on travel times.

6. In certain reaches, notably North Witham, the growth of within-channel vegetation slowed the velocity considerably during the summer months. There is a need to investigate the seasonal aspects of the travel time - discharge relationship associated with vegetation growth and dieback, especially if channel maintenance operations along small streams are being reduced.

7. The non-steady flow experiments reported in section 5 represent only a preliminary investigation of a more general problem. A wider range of input and background discharges needs to be considered, with

more intensive monitoring over longer river distances. Such monitoring would require intensive use of personnel and equipment.

8. The Authority should consider the development of a theoretical approach based on the diffusion equation and/or "dead zone analysis", which would operate in tandem with the kind of empirical approach adopted here. Variations in the level of solute concentration (see Figures 29-31) and aspects of the non-steady flow problem could be investigated through such an approach.

This list of suggestions is not exhaustive but it provides an indication of the lines of enquiry which the Authority could pursue. Some of the suggestions can be implemented almost immediately, while others will need more careful consideration. The empirical model contained in this report provides a springboard for more extensive investigations of transport velocities in Lincoln Division streams.

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ADK/RC/JW/TRANSVEL

APPENDIX A: RIVER LYMN, UPPER REACHES (UPSTREAM OF TF 338743)

TRAVEL TIMES (Entries are MINUTES over 1 KM)

DISCHARGE AT PARTNEY GAUGE, $m^3\ s^{-1}$	2	1.75	1.5	1.25	1	0.9	0.8	0.7	0.6	0.5	0.4	0.35	0.3	0.25	0.2
EQUIVALENT FLOW DURATION	2%	3%	4%	6%	9%	11%	13%	17%	23%	32%	43%	49%	60%	73%	89%
LEADING EDGE	40	42	44	48	53	56	60	65	72	81	96	106	120	141	172
PEAK	59	63	67	72	81	85	91	98	108	121	141	155	173	200	239
CENTROID	65	68	71	76	85	89	95	103	114	129	152	169	192	226	280
TRAILING EDGE	137	138	140	147	162	171	183	200	223	258	316	361	427	532	720

Measured discharge range: $0.26 - 1.46\ m^3\ s^{-1}$

Entries are the averages of the Tetford linear and quadratic relationships for travel time (TT) against discharge (Q):

Leading Edge: $TT_L = 53.8Q^{-0.64}$ $\log TT_L = 1.73 - 0.40 \log Q + 0.57 (\log Q)^2$

Peak: $TT_P = 81.3Q^{-0.61}$ $\log TT_P = 1.91 - 0.42 \log Q + 0.44 (\log Q)^2$

Centroid: $TT_C = 85.1Q^{-0.65}$ $\log TT_C = 1.93 - 0.36 \log Q + 0.66 (\log Q)^2$

Trailing Edge: $TT_T = 162.9Q^{-0.75}$ $\log TT_T = 2.21 - 0.23 \log Q + 1.19 (\log Q)^2$

APPENDIX B: RIVER LYMN, UPPER MIDDLE REACHES (TF338743 to TF355708)

TRAVEL TIMES (Entries are MINUTES over 1 KM)

DISCHARGE AT PARTNEY GAUGE, $m^3\ s^{-1}$	2	1.75	1.5	1.25	1	0.9	0.8	0.7	0.6	0.5	0.4	0.35	0.3	0.25	0.2
EQUIVALENT FLOW DURATION	2%	3%	4%	6%	9%	11%	13%	17%	23%	32%	43%	49%	60%	73%	89%
LEADING EDGE	32	36	39	43	50	53	57	61	67	75	86	94	102	115	131
PEAK	44	48	52	58	67	71	76	83	91	101	116	126	138	154	176
CENTROID	46	50	55	61	71	75	81	88	96	108	123	134	147	165	188
TRAILING EDGE	67	74	82	94	111	119	130	143	160	182	214	236	263	301	353

Measured discharge range: 0.28 - 1.32 $m^3\ s^{-1}$

Entries are calculated from the Somersby travel time (TT) - discharge (Q) relationships:

Leading Edge: $TT_L = 49.9Q^{-0.60}$

Peak: $TT_P = 67.1Q^{-0.60}$

Centroid: $TT_C = 70.8Q^{-0.61}$

Trailing Edge: $TT_T = 110.9Q^{-0.72}$

APPENDIX C: RIVER LYMN, LOWER MIDDLE REACHES (TF 355708 to TF 378687)

TRAVEL TIMES (Entries are MINUTES over 1 KM)

DISCHARGE AT PARTNEY GAUGE, m^3s^{-1}	2	1.75	1.5	1.25	1	0.9	0.8	0.7	0.6	0.5	0.4	0.35	0.3	0.25	0.2
EQUIVALENT FLOW DURATION	2%	3%	4%	6%	9%	11%	13%	17%	23%	32%	43%	49%	60%	73%	89%
LEADING EDGE	16	18	19	22	27	29	31	35	39	44	52	58	65	75	88
PEAK	24	27	29	33	40	42	46	51	57	65	76	85	94	108	126
CENTROID	27	31	34	39	46	49	54	59	66	76	89	99	110	126	148
TRAILING EDGE	56	62	70	81	97	104	114	127	143	165	197	219	247	284	338

Measured discharge range: 0.26 - 1.34 $m^3 s^{-1}$

Entries are calculated from the Stockwith travel time (TT) - discharge (Q) relationships:

Leading Edge: $TT_L = 26.9Q^{-0.74}$

Peak: $TT_P = 39.7Q^{-0.72}$

Centroid: $TT_C = 45.9Q^{-0.73}$

Trailing Edge: $TT_T = 96.6Q^{-0.78}$

APPENDIX D: RIVER LYMN, LOWER REACHES (TF 378687 to TF 402676)

TRAVEL TIMES (Entries are MINUTES over 1 KM)

ISCHARGE AT ARTNEY GAUGE, $m^3\ s^{-1}$	2	1.75	1.5	1.25	1	0.9	0.8	0.7	0.6	0.5	0.4	0.35	0.3	0.25
QUIVALENT LOW DURATION	2%	3%	4%	6%	9%	11%	13%	17%	23%	32%	43%	49%	60%	73%
EADING EDGE	15	16	18	20	23	25	27	29	32	36	42	46	51	57
EAK	19	21	23	26	30	32	35	38	42	47	55	60	66	75
ENTROID	21	22	25	28	32	34	37	40	45	50	58	63	70	78
RAILING EDGE	46	50	54	59	67	70	75	80	87	96	108	115	125	137

Discharge range: 0.35 - 1.4 $m^3\ s^{-1}$

ntries are the averages of the Sausthorpe (short) and Sausthorpe (long) linear travel time (TT) - discharge (Q) relationships:

	Sausthorpe (short)	Sausthorpe (long)
Leading Edge:	$TT_L = 20.1Q^{-0.68}$	$TT_L = 26.9Q^{-0.62}$
Peak:	$TT_P = 27.3Q^{-0.66}$	$TT_P = 33.3Q^{-0.65}$
Centroid:	$TT_C = 29.8Q^{-0.64}$	$TT_C = 35.5Q^{-0.63}$
Trailing Edge:	$TT_T = 72.5Q^{-0.56}$	$TT_T = 61.7Q^{-0.47}$

APPENDIX E: RIVER LYMN, STOCKWITH MILL to PARTNEY GAUGE

TRAVEL TIMES (Entries are MINUTES over 1 KM)

DISCHARGE AT PARTNEY GAUGE, $m^3 s^{-1}$	2	1.75	1.5	1.25	1	0.9	0.8	0.7	0.6	0.5	0.4	0.35	0.3	0.25	0.2
EQUIVALENT FLOW DURATION	2%	3%	4%	6%	9%	11%	13%	17%	23%	32%	43%	49%	60%	73%	89%
.EADING EDGE	28	29	32	36	38	40	43	46	52	60	72	81	92	111	140
'EAK	31	33	35	38	43	46	50	54	60	70	83	94	108	129	162
:ENTROID	32	34	36	38	44	46	50	54	61	70	84	96	110	131	166
'RAILING EDGE	44	46	47	50	56	60	64	71	80	92	114	130	152	188	249

Measured discharge range: 0.27 - 1.21 $m^3 s^{-1}$

ntries are the averages of the Long Reach linear and quadratic relationships for travel time (TT) against discharge (Q):

Leading Edge:	$TT_L = 37.7Q^{-0.73}$	$\log TT_L = 1.58 - 0.40 \log Q + 0.69 (\log Q)^2$
Peak:	$TT_P = 43.3Q^{-0.74}$	$\log TT_P = 1.64 - 0.42 \log Q + 0.67 (\log Q)^2$
Centroid:	$TT_C = 43.6Q^{-0.75}$	$\log TT_C = 1.645 - 0.42 \log Q + 0.68 (\log Q)^2$
Trailing Edge:	$TT_T = 56.0Q^{-0.80}$	$\log TT_T = 1.76 - 0.32 \log Q + 1.0 (\log Q)^2$

APPENDIX F: RIVER WITHAM, UPPER REACHES (SOUTH WITHAM to SK 927231; CATEGORY 3 OF AW CLASSIFICATION)

TRAVEL TIMES (Entries are MINUTES over 1 KM)

DISCHARGE AT COLSTERWORTH GAUGE, m^3s^{-1}	2	1.5	1	0.8	0.6	0.5	0.4	0.3	0.25	0.2	0.175	0.15	0.125	0.1	0.08
EQUIVALENT FLOW DURATION	1.2%	2%	4.5%	7%	10%	13%	18%	27%	32%	44%	48%	55%	61%	68%	76%
EADING EDGE	18	20	23	27	32	37	44	57	68	87	101	121	152	204	279
EAK	26	28	33	38	46	53	65	85	104	134	157	192	246	338	424
ENTROID	27	29	39	48	63	75	93	122	145	179	204	236	281	347	429
RAILING EDGE	43	57	84	105	139	165	206	272	324	403	459	533	636	790	981

Measured discharge range: 0.06 - 1.63 $m^3\ s^{-1}$ Note: flow velocity was virtually 0 at discharges below 0.08 $m^3\ s^{-1}$

ntries are calculated from the North Witham travel time (TT) - discharge (Q) relationships:

Leading Edge: $\log TT_L = 1.38 - 0.50 \log Q + 0.43 (\log Q)^2$

Peak: $\log TT_P = 1.53 - 0.52 \log Q + 0.48 (\log Q)^2$

Centroid: $TT_C = 39.0\ Q^{-0.95}$

Trailing Edge: $TT_T = 84.7\ Q^{-0.97}$

APPENDIX G : RIVER WITHAM, UPPER/MIDDLE REACHES
(SK 930223 to EASTON; CATEGORY 3/4 OF AW CLASSIFICATION)

TRAVEL TIMES (Entries are MINUTES over 1 KM)

DISCHARGE AT COLSTERWORTH GAUGE, $m^3\ s^{-1}$	1	0.8	0.6	0.5	0.4	0.3	0.25	0.2	0.175	0.15	0.125	0.1	0.08	0.06	0.04
EQUIVALENT FLOW DURATION	4.5%	7%	10%	13%	18%	27%	32%	44%	48%	55%	61%	68%	76%	84%	96%
LEADING EDGE	27	32	40	46	55	70	81	97	108	122	141	169	202	254	351
PEAK	41	47	58	67	79	97	111	131	144	162	185	218	256	316	425
CENTROID	44	52	64	73	86	106	121	143	157	176	201	237	279	344	463
TRAILING EDGE	70	82	101	115	135	167	190	223	246	275	313	368	432	532	712

Measured discharge range : 0.024 - 0.67 $m^3\ s^{-1}$

Entries are calculated from the Long Reach travel time (TT) - discharge (Q) relationships:

Leading Edge: $TT_L = 26.8Q^{-0.80}$

Peak: $TT_P = 40.6Q^{-0.73}$

Centroid: $TT_C = 44.2Q^{-0.73}$

Trailing Edge: $TT_T = 70.2Q^{-0.72}$

APPENDIX H: RIVER WITHAM, MIDDLE REACHES (SK 927231 to CRINGLE BROOK; CATEGORY 4 OF AW CLASSIFICATION)

TRAVEL TIMES (Entries are MINUTES over 1 KM)

DISCHARGE AT COLSTERWORTH GAUGE, m^3s^{-1}	2	1	0.8	0.6	0.5	0.4	0.3	0.25	0.2	0.175	0.15	0.125	0.1	0.08	0.06	0.04
EQUIVALENT FLOW DURATION	1.2%	4.5%	7%	10%	13%	18%	27%	32%	44%	48%	55%	61%	68%	76%	84%	96%
LEADING EDGE	16	24	27	33	36	41	49	54	62	67	73	82	93	106	125	158
PEAK	21	32	36	43	48	55	65	73	83	90	99	111	126	145	172	219
CENTROID	23	36	41	49	54	62	74	82	94	102	111	124	142	162	193	246
TRAILING EDGE	47	71	81	96	107	122	145	161	184	200	219	244	279	318	378	482

Measured discharge range: 0.024 - 2.67 $m^3 s^{-1}$

Entries are the averages of the Colsterworth and Easton Park travel time (TT) - discharge (Q) relationships:

	Colsterworth	Easton Park
Leading Edge:	$TT_L = 19.7Q^{-0.58}$	$TT_L = 29.4Q^{-0.58}$
Peak:	$TT_P = 26.4Q^{-0.58}$	$TT_P = 37.7Q^{-0.61}$
Centroid:	$TT_C = 31.0Q^{-0.56}$	$TT_C = 41.4Q^{-0.62}$
Trailing Edge:	$TT_T = 75.0Q^{-0.56}$	$TT_T = 67.1Q^{-0.63}$

APPENDIX I : RIVER WITHAM, LOWER REACHES
(CRINGLE BROOK to SALTERSFORD GAUGE; CATEGORY 5 OF AW CLASSIFICATION)

TRAVEL TIMES (Entries are MINUTES over 1 KM)

DISCHARGE AT COLSTERWORTH GAUGE, $m^3\ s^{-1}$	2	1	0.8	0.6	0.5	0.4	0.3	0.25	0.2	0.175	0.15	0.125	0.1	0.08	0.06	0.04
EQUIVALENT FLOW DURATION	1.2%	4.5%	7%	10%	13%	18%	27%	32%	44%	48%	55%	61%	68%	76%	84%	96%
LEADING EDGE	21	24	24	25	26	26	28	28	29	38	40	42	46	49	54	63
PEAK	25	28	29	30	30	31	32	33	34	47	50	54	58	64	71	84
CENTROID	27	30	31	32	33	34	35	36	37	51	55	59	65	71	80	95
TRAILING EDGE	44	52	55	59	62	66	70	74	78	100	108	117	130	144	165	199

Measured discharge range : 0.025 - 1.77 $m^3\ s^{-1}$

Entries are calculated from the Great Ponton (Colsterworth) travel time (TT) - discharge (Q) relationships:

	$Q < 0.18\ m^3\ s^{-1}$	$Q \geqslant 0.18\ m^3\ s^{-1}$
Leading Edge:	$TT_L = 11.5Q^{-0.56}$	$TT_L = 23.7Q^{-0.14}$
Peak:	$TT_P = 12.3Q^{-0.63}$	$TT_P = 28.2Q^{-0.13}$
Centroid:	$TT_C = 12.0Q^{-0.68}$	$TT_C = 30.3Q^{-0.14}$
Trailing Edge:	$TT_T = 22.4Q^{-0.72}$	$TT_T = 52.5Q^{-0.25}$

APPENDIX J : RIVER WITHAM, LOWER REACHES
(CRINGLE BROOK to SALTERSFORD GAUGE; CATEGORY 5 OF AW CLASSIFICATION)

TRAVEL TIMES (Entries are MINUTES over 1 KM)

DISCHARGE AT SALTERSFORD GAUGE, $m^3\ s^{-1}$	3	2.5	2	1.5	1.25	1	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.25	0.2	0.15
EQUIVALENT FLOW DURATION	1%	1.6%	4%	7.5%	14%	25%	30%	36%	43%	51%	55%	62%	68%	73%	86%	95%
LEADING EDGE	20	21	23	25	27	30	32	34	37	40	45	51	62	71	84	106
PEAK	23	25	27	30	33	38	40	43	46	51	58	69	86	101	123	162
CENTROID	27	28	30	33	35	39	42	45	49	54	62	74	96	115	145	202
TRAILING EDGE	37	43	50	63	72	86	92	101	111	125	143	169	210	241	285	354

Measured discharge range : 0.21 - 2.49 $m^3\ s^{-1}$

Entries are calculated from the Great Ponton (Saltersford) travel time (TT) - discharge (Q) relationships:

Leading Edge: $\log TT_L = 1.49 - 0.48 \log Q + 0.21 (\log Q)^2$

Peak: $\log TT_P = 1.58 - 0.55 \log Q + 0.26 (\log Q)^2$

Centroid: $\log TT_C = 1.60 - 0.52 \log Q + 0.41 (\log Q)^2$

Trailing Edge: $TT_T = 85.5\ Q^{-0.75}$

APPENDIX K: LONG EAU (LEGBOURNE to LITTLE CARLTON MILL)

TRAVEL TIMES (Entries are MINUTES over 1KM)

DISCHARGE AT LITTLE CARLTON MILL GAUGE, $m^3\ s^{-1}$	1	0.8	0.6	0.5	0.4	0.35	0.3	0.25	0.2	0.18	0.16	0.14	0.12	0.1	0.08	0.06
EQUIVALENT FLOW DURATION	1.5%	2.5%	4.5%	6.5%	8%	10%	15%	21%	37%	44%	52%	62%	71%	81%	89%	98%
LEADING EDGE	22	24	28	30	34	36	38	42	48	50	53	56	62	67	75	86
PEAK	26	29	34	36	41	44	48	52	60	63	67	72	78	88	100	118
CENTROID	27	30	34	38	42	46	50	55	62	66	71	76	84	94	107	128
TRAILING EDGE	45	50	57	64	72	78	86	96	110	118	128	140	155	176	208	258

Measured discharge range: $0.06 - 1.0\ m^3\ s^{-1}$

Entries are the averages of the Priory Reach and Long Reach relationships for travel time (TT) against discharge (Q):

	Priory Reach – average of linear and quadratic relationships		Long Reach
Leading Edge:	$TT_L = 22.2Q^{-0.42}$		$TT_L = 21.6Q^{-0.55}$
Peak:	$TT_P = 27.0Q^{-0.48}$	$\log TT_P = 1.49 - 0.23 \log Q + 0.20 (\log Q)^2$	$TT_P = 24.0Q^{-0.59}$
Centroid:	$TT_C = 27.8Q^{-0.51}$	$\log TT_C = 1.51 - 0.23 \log Q + 0.22 (\log Q)^2$	$TT_C = 24.4Q^{-0.60}$
Trailing Edge:	$TT_T = 49.7Q^{-0.57}$	$\log TT_T = 1.81 - 0.09 \log Q + 0.39 (\log Q)^2$	$TT_T = 32.8Q^{-0.70}$