Applications of the concept of river tracer data similarity

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Abstract

The response of a river to a pollution incident is heavily influenced by the river's flow rate. To capture the full range of this response tracer experiments are often used. The paper discusses how the concept of similarity of temporal concentration profiles can be used to better exploit the information content of such experiments. Examples are given showing that poor quality tracer data, that might be thought to be of little use, may yet contain valuable information. Extracting this information has the potential of improving predictions of pollutant travel times, in particular, as well as offering the prospect of improving estimates of flow rates (via dilution gauging) and dispersion coefficients (via several methods).

Key words

Solute transport, travel times, rivers, tracer data, similarity

Introduction

When there is a pollution incident in a river users of the water further downstream need to be warned about the potential impact on their activities. The nature of their response depends on the sensitivity of the water use to the particular pollutant. For example, public water supply abstractions may need to be temporarily stopped, or extra treatment measures may need to be implemented, before the abstracted water is used. The key issues are the arrival time of the polluted water, the duration of elevated pollution levels and the range of concentration of the pollutant at the abstraction location.

To aid the prediction of these issues, much effort has been expended on developing tools that simulate pollutant transport along river systems, ranging from sophisticated mathematical models of the transport processes such as the Advection-Dispersion Equation (Fischer 1967; Fischer 1968), the Transient Storage Model (Bencala and Walters 1983; Runkel 1998) and the Aggregated Dead Zone Model (Beer and Young 1983; Wallis et al 1989) to simple rules of thumb (e.g. Rutherford 1994). This work has included the execution of tracer experiments in which the responses of rivers to tracer releases are observed by measuring the temporal variation of tracer concentration at several locations downstream of the release location. Not only does such data enable simulation tools to be checked, but also, and very importantly, the data in their own right encapsulate the responses of rivers. Thus it is possible to build warning systems for sensitive locations based only on tracer data without recourse to modelling the transport processes.

An important limitation of this approach, however, is that solute transport is controlled by river flow rate. So that at high flow rates travel times are short and dilution rates are high, but at low flow rates travel times are long and dilution rates are low. Clearly, therefore, since pollution incidents may occur at any flow condition, tracer data is needed across a wide range of river flow rates. An important question is: how many tracer experiments are needed to capture the dependence of a river's response on flow rate? From that two important follow-up questions are: which features of the solute transport should these experiments quantify, and how precisely? Since all the important features vary non-linearly with flow rate a minimum of three experiments would be required, but as the flow rate range were expanded increasingly more would be needed. Green et al (1994) discuss some of the issues that ensue when only a few experiments are available for constructing a predictive model. They also argue that incorporating uncertainty into all stages of the modelling process is worthwhile.

Clearly, in any campaign designed to measure the response of a river system to pollution events collecting high quality data in which complete and well-resolved temporal concentration profiles are captured would be the aim for all the experiments undertaken, but this is not always achieved – humans and machines sometimes fail. For example, Figure 1 shows data from a tracer experiment on the river Swale in which the aim was to collect good quality data at six sites (the identifier NE18 refers to the record label for this tracer experiment in the database described in the following section). Whereas the data at the first two sites appears to be quite good, the data at the other four sites is much poorer and may be of little use. In contrast, Figure 2 shows another data set from the same river in which good quality data was

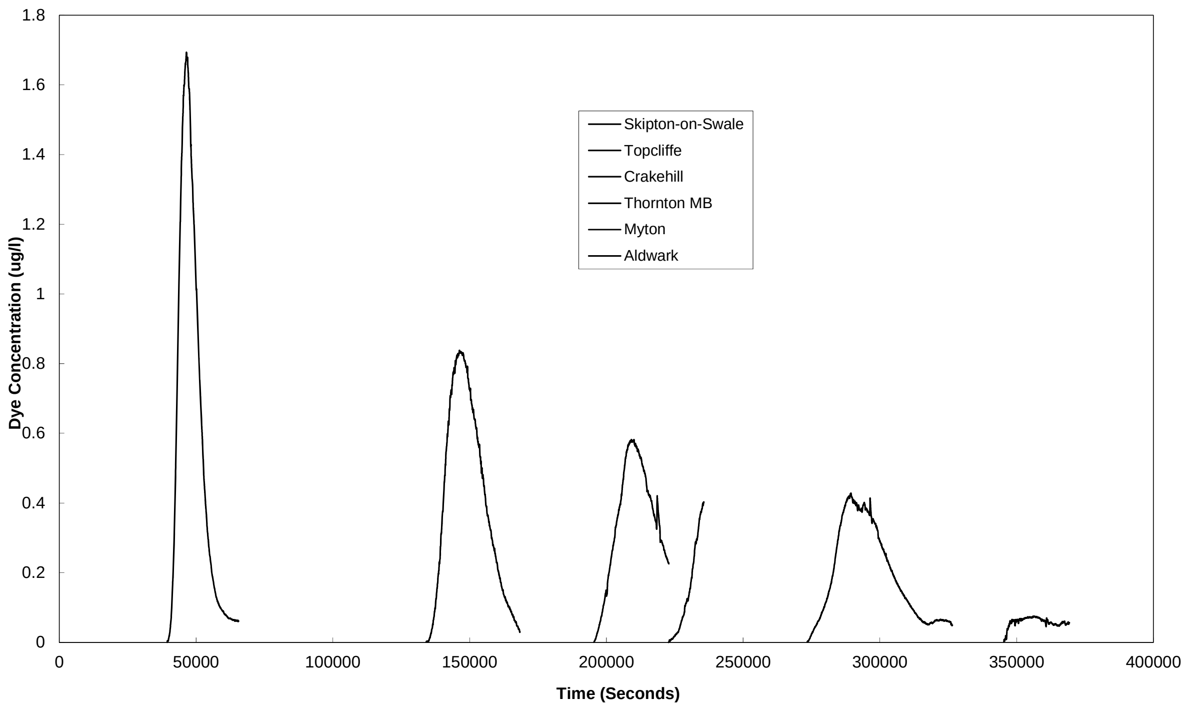

Figure 1 Observed temporal tracer concentration profiles, River Swale (NE18).

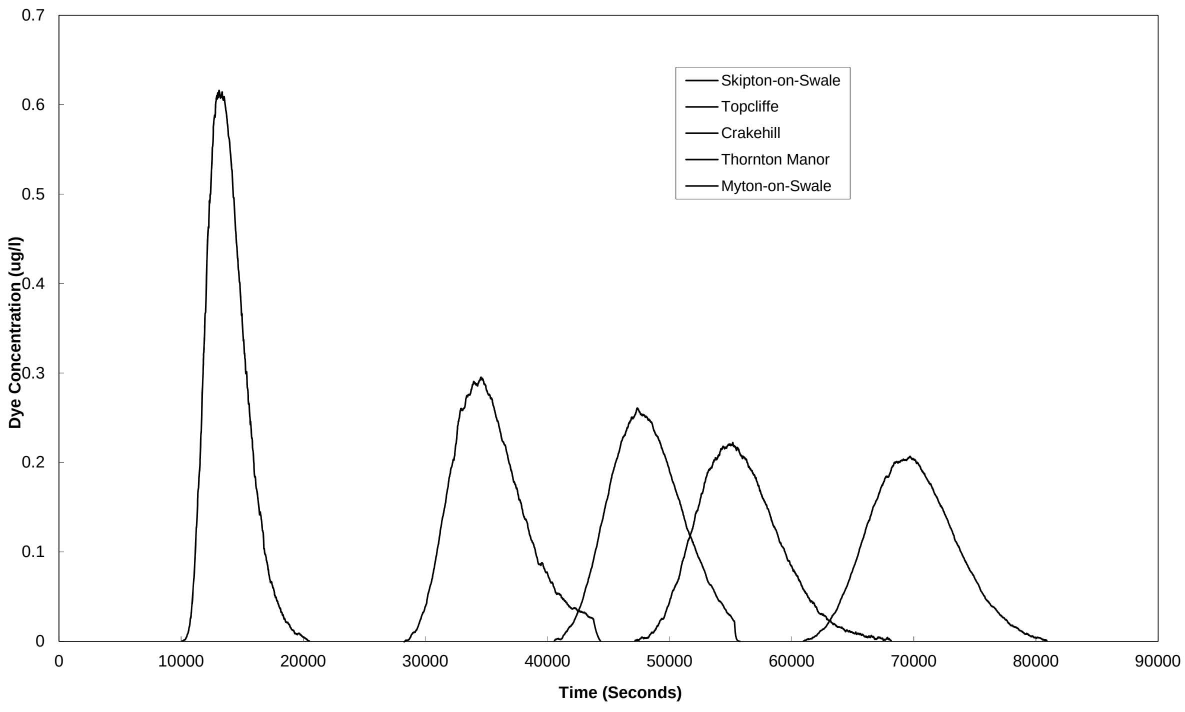

Figure 2 Observed temporal tracer concentration profiles, River Swale (NE20).

collected at the first five sites. Note, however, that the quite good data, and even the good data, in these examples are not perfect – some of the tails of the profiles are missing or appear unusual.

Recently, an idea from the 1970s (Day and Wood 1976) has been revived that offers the possibility of increasing the useful information that can be extracted from poor quality tracer data. In this, the temporal concentration profiles observed at a given site following tracer released under different flow rates appear to have a common shape when plotted in a non-dimensional form (Rutherford et al 1980; Sukhodolov et al 1997; Wallis 2005; Wallis and Manson 2011). This similarity implies that features of the solute transport not captured during one tracer experiment could be predicted from another tracer experiment. Clearly, the use of this idea could have significant economic benefits to water industry companies and regulators because whereas it might currently be thought that resources are wasted if tracer data is of poor quality, in many cases useful information can still be extracted. Indeed, the planning of future tracer experiments could be enhanced significantly by re-appraising the objectives of the experiments.

Some comparable ideas to the similarity concept explored herein have been reported by Kilpatrick and Taylor (1986) and Jobson (1997). In particular, they combine a unit-response curve and a unit-peak attenuation concept to aid the simulation of the response of a river system to a range of pollutant spills under a range of river flow rates. Interestingly, also, some similar concepts are used in chemical engineering (with some applications to the waste water industry), see, e.g. Danckwerts (1953) and Levenspiel (1972).

The aims of the paper are to illustrate the idea of similarity and to show how it may be applied to increase the amount of useful information that can be extracted from a set of tracer data. The paper uses tracer data collected by the Environment Agency of England and Wales (EA) (Guymer 2002). Some aspects of this data set are described in the next section.

Environmental Agency travel time database

Some of the tracer data collected in rivers by the different regions of the EA were collated and then analysed to give travel time and dispersion parameters by Guymer (2002). Rhodamine WT dye was used in the fieldwork, which is probably the water industry's preferred tracer because it generally behaves conservatively, has no known environmental consequences and is relatively easy to measure in-situ or by laboratory analysis of water samples. The philosophy underlying the EA's approach is that most pollutants released to rivers are transported downstream in similar ways. It can be assumed with some confidence that the transport of any soluble material is well represented by the observed behaviour of Rhodamine WT. The fate of fine suspended material would also be well represented provided high levels of turbulent mixing were maintained in the flow. Coarser material would tend to settle out, but the bulk movement of such material, characterised by e.g. the travel time of the peak concentration, would be closely related to the behaviour of a solute. However, immiscible substances such as oil, paint and highly buoyant liquids such as power station cooling water may not be because they would only interact with the flow conditions at or near the surface. In such cases, travel times would be shorter than those observed using a soluble tracer such as Rhodamine WT.

The EA tracer information together with data on the physical characteristics of the traced reaches and the corresponding river discharge statistics were entered into a database. Subsequently a meta-analysis was undertaken (Guymer 2004) aimed at relating transport characteristics of rivers to relevant hydrological variables.

Following a similar analysis by Jobson (1997) the relationship given below was found to give the best description of observed reach mean velocity:

$$u = 0.268(Da)^{0.300}(Q')^{0.616}(S_0)^{0.267} \qquad (1)$$

where u is the observed reach mean velocity, Da is the drainage area corresponding to the downstream end of the reach, Q' is the relative flow rate (defined as the ratio of the observed flow rate to the mean annual flow rate) and S_0 is the longitudinal slope of the reach. The R^2 value (coefficient of determination) for this relationship was 0.59, suggesting that although observed and predicted velocities were well correlated there was considerable uncertainty in the predicted values. The uncertainty has several sources: for example, it is very unlikely that relatively simple expressions of this type would be able to capture the highly variable nature of natural water courses across a wide range of catchment scales, and there are errors of varying magnitudes both in the observed velocities and in the explanatory variables. So, although equation (1), combined with reach length data, could be used to predict travel times at specific locations on un-traced rivers to aid the response of a water authority to a pollution incident, it is unlikely that there would be much confidence in the predictions.

Nevertheless, in river reaches for which no tracer experiments had been successfully undertaken, this would be a good initial course of action. In contrast, for rivers in which tracer experiments had been undertaken the availability of the tracer data (and any relevant derived parameters) would be invaluable. Clearly, any technique that has the potential to increase the amount of useful information that can be gleaned from such data, particularly if its poor quality might deter it from even being considered for use, should be of interest to the UK water industry.

Similarity of temporal concentration profiles

Figure 3 shows temporal concentration profiles observed at one location (Burnsall) on the river Wharfe during five tracer experiments which were undertaken at different river flow rates. The tracer was released at the same location (Hebden Stepping Stones) in all the experiments. Relevant details of the experiments are shown in Table 1. The flow rates are those recorded at the Addingham gauging station (located about 20km downstream of the tracer release site) at the time of tracer release and the masses of tracer are nominal amounts estimated from the flow rate and the area under the concentration profile observed at Burnsall (located about 4km downstream of the tracer release site). As would be expected, the concentration profile from the highest flow rate experiment arrives quickest and the concentration profile from the lowest flow rate experiment arrives slowest. The peak concentrations vary because they are influenced by the mass of tracer released, the dilution available and the longitudinal dispersion taking place in the flow. The latter is determined by the mixing characteristics of the flow and the time of travel between the tracer release location and the observation location.

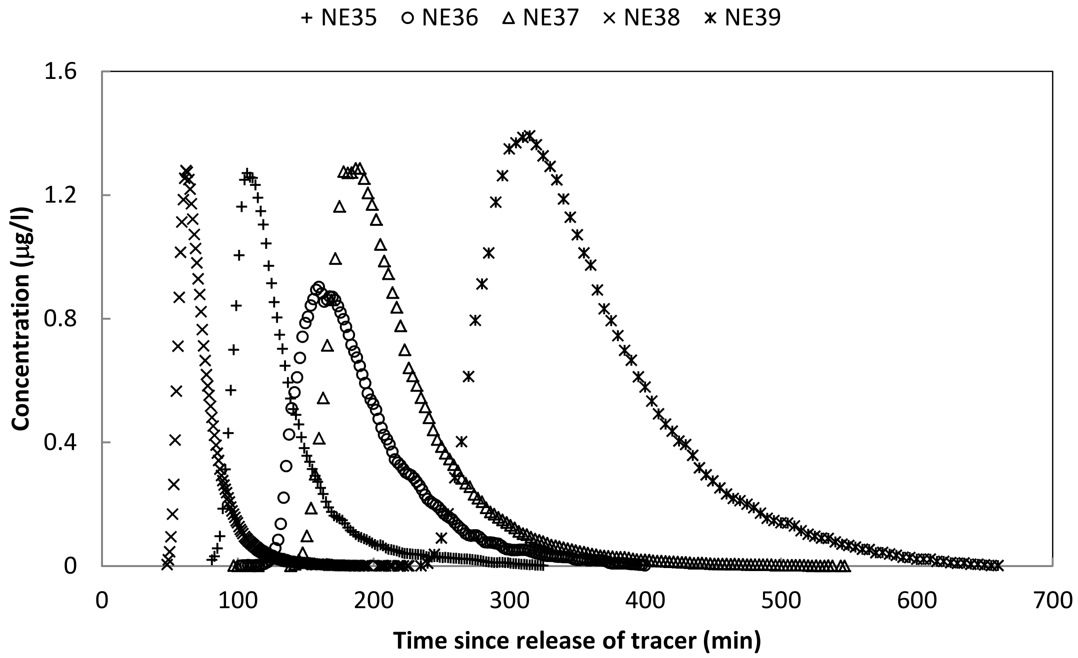

Figure 3 Observed temporal tracer concentration profiles at Burnsall, River Wharfe, for five tracer experiments.

The data can be converted into a non-dimensional form by applying the following two transformations:

$$C = \frac{c}{c_P} \tag{2}$$

$$\tau = \frac{t - t_L}{t_T - t_L} \tag{3}$$

in which C is the non-dimensional concentration at time, t, c is the corresponding dimensional concentration, c_P is the peak dimensional concentration in the profile, τ is the non-dimensional time and t_L and t_T define the times of the leading and trailing edges, respectively, of a dimensional concentration profile. These edges are defined as the times when the concentrations on the rising and falling limbs, respectively, are 10% of the peak concentration. Using a concentration of 10% of the peak concentration to identify the edges is an arbitrary, but realistic, choice. Figure 4 shows the non-dimensional profiles at Burnsall for the tracer experiments shown in Figure 3.

It is clear that all five non-dimensional profiles are similar, which implies that they have similar characteristics. This is confirmed by Table 2 in which measures of the size and shape of the profiles are given (columns 2 and 3, respectively). The centroid of a profile occurs a little later than its peak and the difference in their timings reflects the asymmetry of the profile. The degree of similarity between the non-dimensional profiles is quantified in column 4, which shows the root-mean-square (RMS) error between each non-dimensional profile and the mean non-dimensional profile. Four steps were required in this analysis. Firstly, each non-dimensional profile was converted into a standard form by sorting the data into a series of bins of width 0.1 non-dimensional time units. Secondly, the average non-dimensional concentration in each bin of each non-dimensional profile was determined and associated with the time at the centre of the bin. Thirdly, the mean non-dimensional profile was obtained by calculating, for each bin, the mean of the five individual bin-average non-dimensional concentrations. Fourthly, the RMS error was calculated between each bin-average profile and the mean profile. Clearly the RMS errors are consistent with the visual agreement shown in Figure 4, being of the order of 1% of the peak non-dimensional concentration.

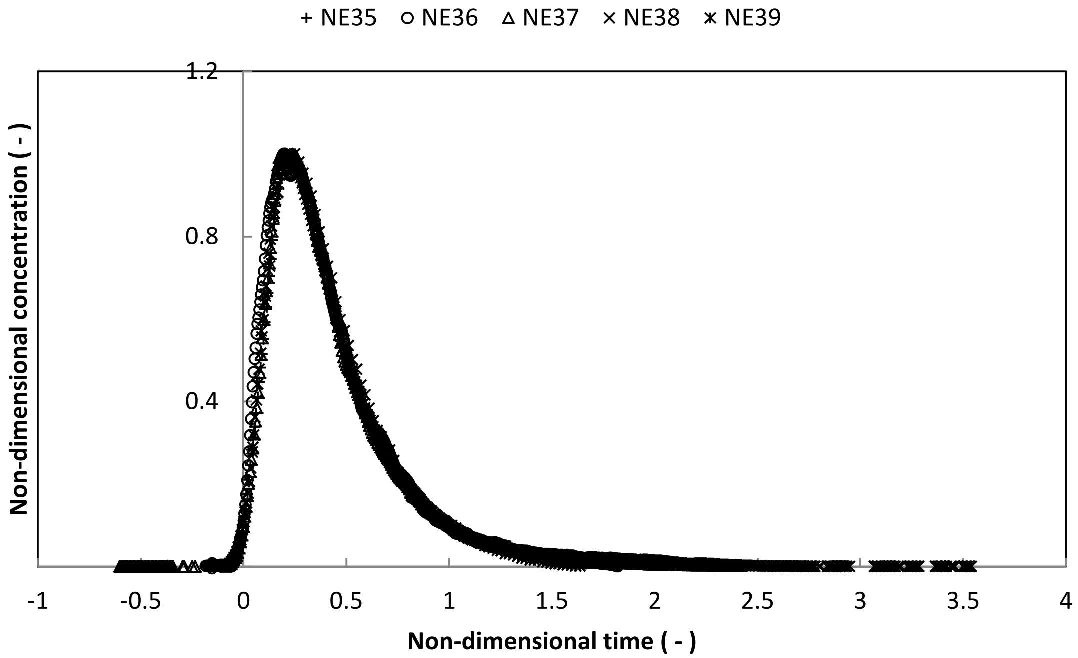

Figure 4 Non-dimensional temporal tracer concentration profiles at Burnsall, River Wharfe, for five tracer experiments.

It is worth noting that had t_L and t_T been defined differently, for example as 15% or 5% of the peak concentration, the non-dimensional profiles would have had a different shape to those shown in Figure 4, but the similarity between experiments would have remained. It is also worthy of note that this type of similarity of non-dimensional temporal concentration profiles is not unique to this stretch of the River Wharfe: it was also found in supplementary analysis undertaken for this paper on other rivers in the EA travel time database and it has been found elsewhere. For example such findings were reported by: Day and Wood 1976 on mountain streams in New Zealand and Canada; Rutherford et al 1980 on the Waikato River in New Zealand; Sukhodolov et al 1997 on small lowland rivers in Moldova; and Wallis 2005 and Wallis and Manson 2011 on a suburban stream in Scotland. Interestingly, the study of similarities and differences between non-dimensional tracer residence time distributions has been mooted as a way of identifying flow regimes in urban drainage structures (Stovin et al 2010a; 2010b). It is not clear if there is any link between these non-dimensional residence time distributions and the non-dimensional profiles under study in the current paper. However, they can both be interpreted as a form of response function that characterises solute transport in water courses.

Application to travel times

Previous tracer studies in rivers have shown that travel time (or the corresponding velocity and advective time delay) is strongly correlated with river flow rate (see e.g. Rutherford 1994; Jobson 1997), and that power-law or inverse equations can describe the relationship (see e.g. Wallis et al 1989; Smith et al 2006; Camacho and Gonzalez 2008). Figure 5 shows the travel times of the leading edge (t_L), peak (t_P) and trailing edge (t_T) of the temporal concentration profiles at Burnsall plotted against river flow rate. As before the leading and trailing edges are defined as the time for which the concentration is 10% of the peak concentration. Power-law equations are fitted to the data, from which the travel time at any flow rate could be estimated.

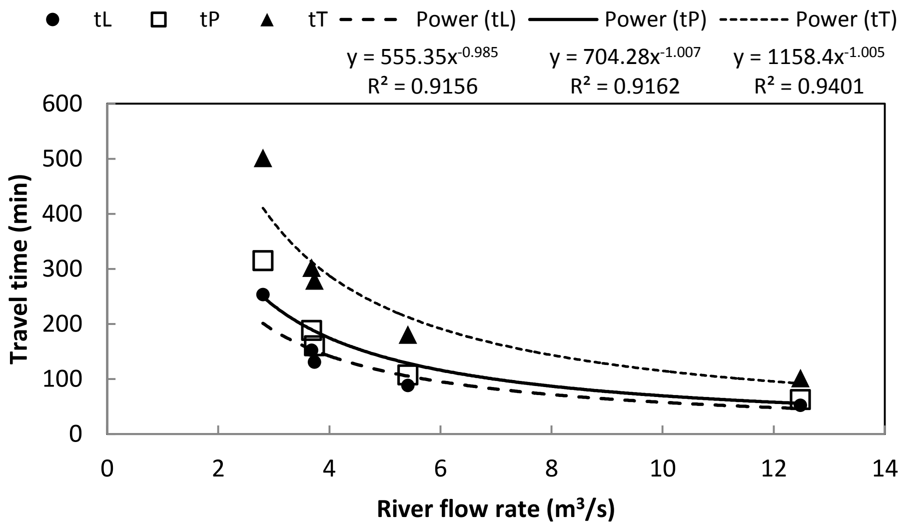

Figure 5 Variation of travel times of leading edge, peak and trailing edge of observed concentration profiles with flow rate for Burnsall.

Consider now the scenario in which only two of the tracer experiments at Burnsall had captured the complete concentration profile and the other three experiments had only captured data around the peak. Clearly, the relationship between the travel time of the peak and the flow rate is known to the same degree of detail as before, but the same cannot be said for the travel times of the leading and trailing edges. However, if the two complete profiles were plotted in non-dimensional form, they would be found to be of similar shape and it would be reasonable to assume that the other three (incomplete) profiles have the same non-dimensional shape as the two complete ones. A particularly useful consequence of the similarity of the non-dimensional profile shapes is that the ratios of any two travel times are also similar. Hence, in the scenario under consideration, it is possible to estimate the travel times of the three leading and trailing edges that were not observed from the peak travel times that were observed and information gleaned from the two experiments that captured the full concentration profiles.

This idea is summarised in Tables 3 and 4 for the Burnsall data. Table 3 shows travel times and travel time ratios for all five experiments: it confirms the approximate constancy of the ratios of leading edge travel time to peak travel time and trailing edge travel time to peal travel time (columns 6 & 7). Table 4 shows data for the scenario introduced above: complete observed data for two experiments (NE38 and NE39), observed peak travel times for three other experiments (NE35, NE36 and NE37) and estimated travel times of the leading and trailing edges for those three experiments (light shading). The latter were calculated using the mean travel time ratios from experiments NE38 and NE39 (dark shading). The percentage errors between estimated and observed travel times range from -0.3 to 7.5 (values shown in brackets in columns 4 & 5).

The benefits of being able to estimate the missing observations of the leading and trailing edges of concentration profiles can be extended to the situation of predicting conditions under river flow rates not covered by any tracer experiments. Table 5 shows predicted travel times of the leading and trailing edges of concentration profiles at Burnsall at representative low, medium and high flows. Predictions are shown for two cases both of which use a prediction of the peak travel time and exploit the constancy of the ratios of the travel times. In Case 1, the relationship between peak travel time and flow rate shown in Figure 5 is used to predict the peak travel time and the travel time ratios (column 3) are derived using data from all five experiments, i.e. the averages of the values in columns 6 and 7 of Table 3. Case 2 considers the same scenario introduced earlier and uses the same predictions of peak travel time as Case 1 (since under the scenario all five peaks were observed), but the travel time ratios (column 5) are estimated from the only two experiments in which complete profiles are available under this scenario (NE38 and NE39). The errors for all three flow rates between the Case1 and Case 2 values are -0.2% and 2.5%, respectively, for the leading and trailing edge travel times.

Note that in the absence of similarity, the leading edge and trailing edge travel times could only be predicted from relationships such as those shown in Figure 5. However, the non-linear nature of these relationships would preclude an accurate prediction from only two data points. Clearly, therefore, the application of similarity can lead to improved predictions of travel times in rivers.

Other applications

There are several uses of temporal concentration profile data that are compromised if the profile is incomplete, for example, (gulp injection) dilution gauging and estimating dispersion coefficients. In the former, river flow rate is calculated using the area under the profile. Clearly, if part of the profile is missing the accurate determination of the profile area is hindered. In the latter, properties of the profile (centroid location and variance) are used in the method of moments (see, e.g. French 1986; Rutherford 1994; Wallis and Manson 2004) or the fit of a predicted profile (typically obtained using one of several routing procedures) is optimised to an observed profile (see, e.g. French 1986; Rutherford 1994; Singh and Beck 2003; Wallis and Manson 2004; Wallis et al 2014) in order to estimate dispersion coefficients (and, in some cases, velocities of flow). Again, the results of such exercises would be thrown into doubt if large portions of concentration profiles were missing. Therefore methods for filling in missing data or even for reconstructing whole profiles have a potential for increasing the value of what might otherwise be considered to be poor value data. To this end, the first author has undertaken several previous studies in which the existence of similarity between tracer concentration profiles has led to improved estimates of dispersion coefficients from relatively poor quality tracer data (Wallis 2008; Wallis and Manson 2010; Wallis and Manson 2011). Below are some examples of how profiles may be completed or reconstructed, again using data from the EA travel time database.

Figure 6 shows temporal tracer profiles observed during three tracer experiments at Crakehill on the river Swale. Profile NE17 is a good quality profile; profile NE18 has a missing tail and part of the observed trailing limb is clearly wrong; profile NE20 is a

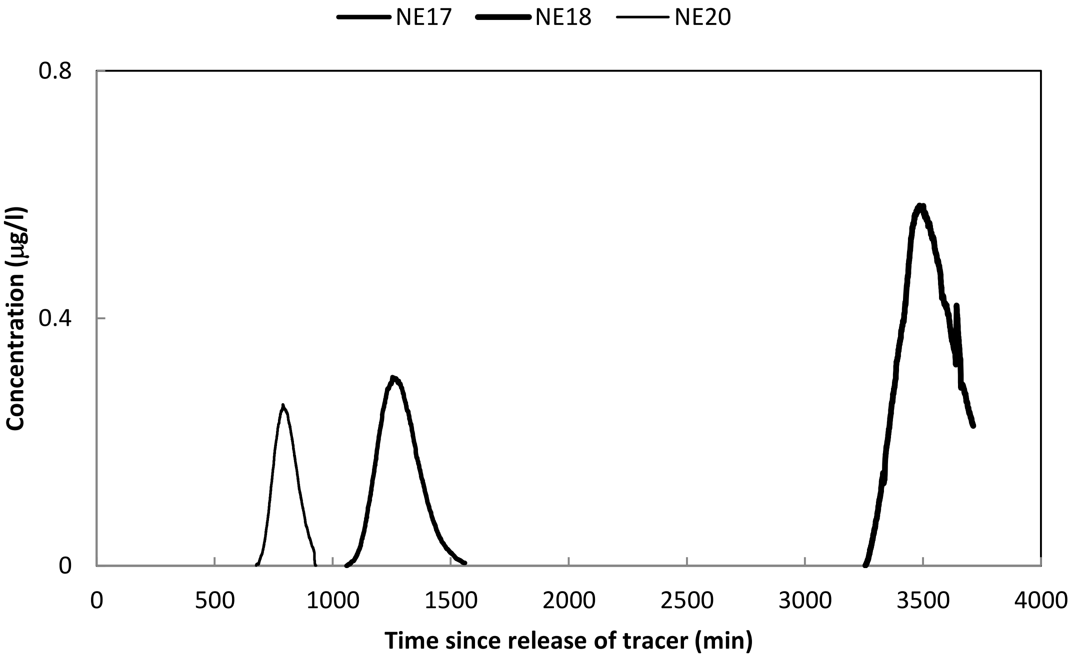

Figure 6 Observed temporal tracer concentration profiles at Crakehill, River Swale, for three tracer experiments.

good quality profile except that the end of tail is unusually steep. The NE18 and NE20 profiles are also shown in Figures 1 and 2, respectively. The problem with the end of profile NE20 is probably caused by incorrectly recorded times of the concentrations. Figure 7 shows the non-dimensional profiles for NE17 and NE20: clearly they are very similar and the problem with the tail of the NE20 profile is exposed. Since the times when the concentration of profile NE20 was 10% of its peak concentration (t_L and t_T) were observed, it is easy to reconstruct the whole profile using the shape of the non-dimensional NE17 profile (by re-arranging equations 2 and 3). The result is shown in Figure 8, where the constructed tail is clearly a significant improvement on the observed one.

Reconstructing profile NE18 is not as easy because the falling limb stops before the time when the concentration was 10% of the peak concentration. However, if it is assumed that the non-dimensional profile of NE18 is similar to the non-dimensional profile of NE17, then the travel time ratio t_T/t_P from NE17 can be used to predict t_T for NE18, and then the whole profile can be reconstructed using the non-dimensional profile of NE17 (with the observed leading edge and peak for NE18). The result (Reconstructed (1)) is shown in Figure 9. Clearly, the agreement between the observed and reconstructed profiles is not as good as in the previous case (Figure

8). The reason for this is that the predicted t_T is too large, for which there are at least two possible causes. Firstly, perhaps the whole of the observed profile is dubious: we know that it is incomplete and it contains errors on the trailing limb. If we accept the profile as being generally reliable, however, the flow rate during that experiment may be significant: it was 3.2 m^3/s, which is much smaller than the flow rates of the other two experiments (NE17 – 10.3 m^3/s; NE20 – 18.6 m^3/s). Perhaps the flow regime in the reach at this very low flow (Q95 is about 3 m^3/s) is different enough from that at higher flows that the similarity concept no longer applies. For example, it is not unusual that at very low flows water is confined to one or more channels incised in a river's bed whilst at medium and high flows water occupies the full cross-section available. As a consequence the active river channel may have very different hydraulic characteristics (e.g. roughness and channel shape) at very low flows compared to medium and high flows, which may affect the travel time and/or mixing characteristics of the flow, thus affecting the shape of the non-dimensional concentration profile. A brief sensitivity analysis revealed that increasing the travel time ratio t_T/t_P from NE17 worsened the agreement between reconstructed and observed profiles whilst decreasing it improved the agreement. Using 93% of the original value gave a very good fit, as shown in Figure 9 (Reconstructed (2)). This result suggests that the non-dimensional concentration profile may indeed have a different shape under very low flow conditions.

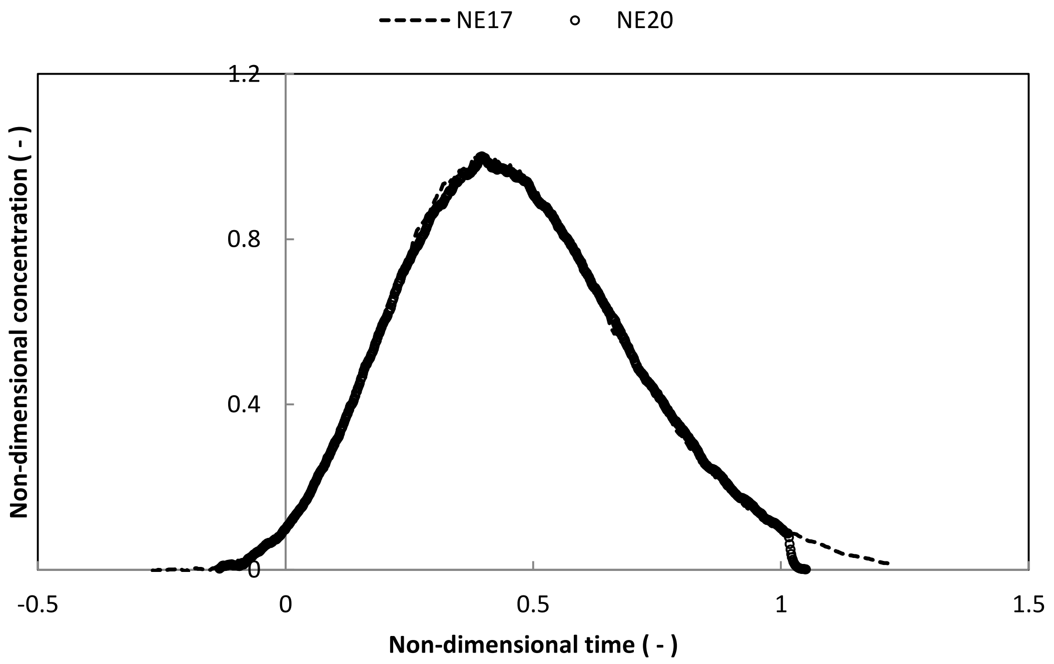

Figure 7 Non-dimensional temporal tracer concentration profiles at Crakehill, River Swale, for two tracer experiments.

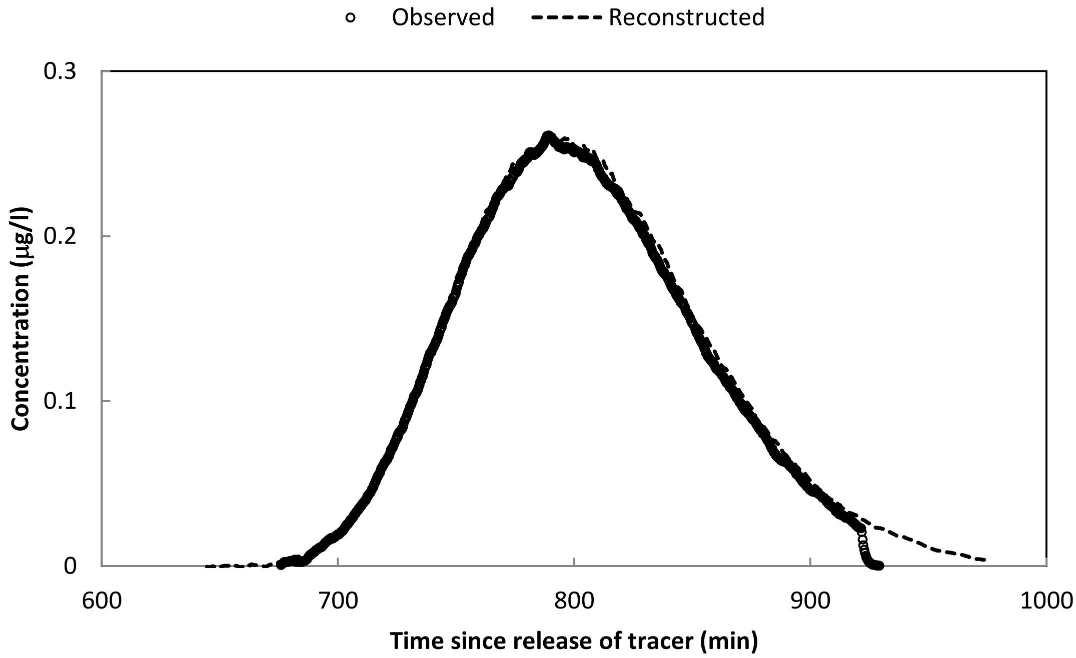

Figure 8 Comparison of observed and reconstructed temporal tracer concentration profiles at Crakehill (NE20).

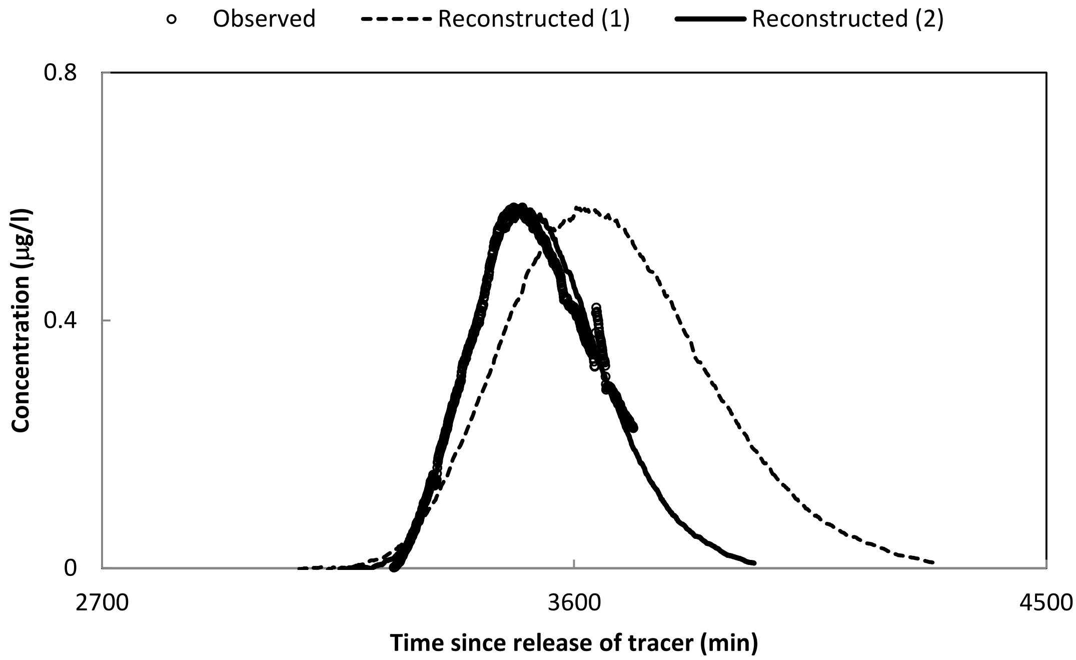

Figure 9 Comparison of observed and reconstructed temporal tracer concentration profiles at Crakehill (NE18): Reconstructed (1) refers to use of unaltered t_T/t_P from NE17 and Reconstructed (2) refers to use of modified t_T/t_P from NE17

In order to investigate further the ability of the similarity approach to reproduce concentration profiles a broader and more demanding set of reconstructions was undertaken. In this, whole profiles at five locations on the river Swale at three river flow rates (15 cases in all) were reconstructed. For each location the observed non-dimensional profile together with the corresponding leading and trailing edge travel time ratios at a flow rate of 10.3 m^3/s (NE17) were used together with just the observed peak concentrations for each of the other flow rates - 3.2 m^3/s (NE18), 5.5 m^3/s (NE19), 18.6 m^3/s (NE20). Comparisons were then made between the reconstructed profiles and the observed profiles for those cases where the latter

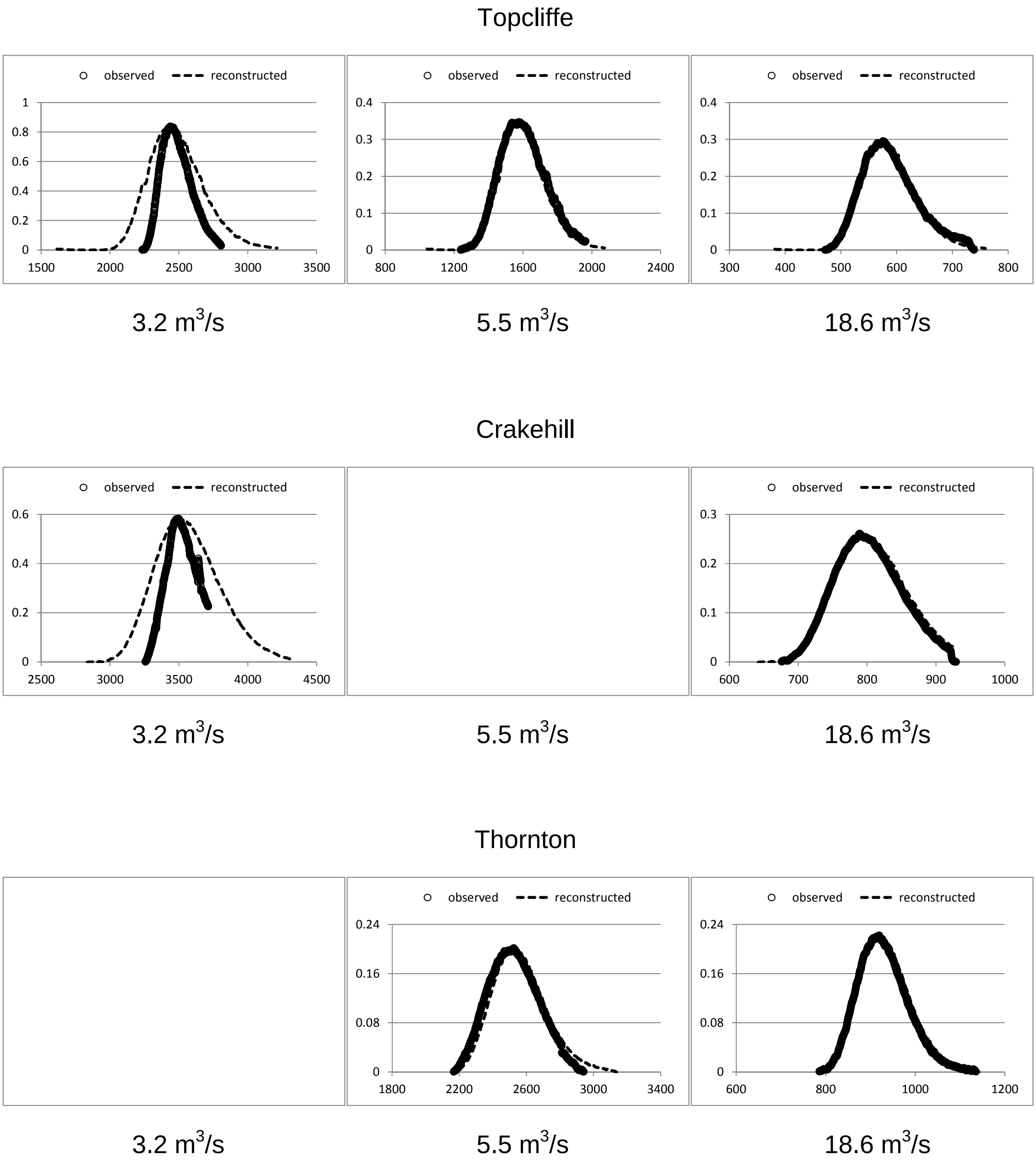

Figure 10 Comparison of observed and reconstructed concentration profiles at three locations for three flow rates (blank panel indicates no observations available)

existed (twelve out of fifteen). Table 6 summarises the quality of the agreement by presenting coefficients of determination for all the cases and Figure 10 shows concentration profiles from three of the locations to illustrate the quality of the agreement.

These results suggest that good or excellent profiles can be constructed at all locations at flow rates smaller and greater than the one used to provide the non-dimensional concentration profile, see results in centre and right-hand panels of Figure 10 for flow rates of 18.6 m^3/s and 5.5 m^3/s, respectively. However, the results also show that at the very low flow rate case (left-hand panel of Figure 10) relatively poor profiles are found at all locations, suggesting that the very low flow rate issue introduced earlier is not location specific, but is perhaps a generic issue. Clearly, further work is needed to examine this.

It is worth emphasising the importance of capturing the peaks of concentration profiles during tracer experiments. All of the applications described in this and the previous section rely on having this information. If the peak is not observed then neither the required non-dimensional concentration nor the required leading and trailing edge travel time ratios can be calculated. Even if much of the leading and trailing edges were to be observed, without information on the peak it is not clear how, or even if, the similarity concept could be used. Clearly, without the peak concentration it is not possible to know what 10% of the peak concentration might be. However, depending on what other information were available, it could be possible to predict the time and concentration of the peak using another method. For example, travel time-flow rate relationships derived from other experiments (e.g. Figure 5) would offer a way of predicting the time of the peak (and the leading and trailing edges) and the unit-peak attenuation approach (Kilpatrick and Taylor 1986; Jobson 1997) could be used to predict the peak concentration.

Finally (following a Reviewer’s comment) we investigated if the existence of similar non-dimensional concentration profiles at a location over a range of flow rates might be connected with observations in some rivers that suggest the dispersive fraction for a reach is approximately invariant with flow rate (see, e.g. Wallis et al 1989). The dispersive fraction is the ratio of the time delay of the leading edge to the time delay of the centroid, with the two time delays being evaluated between two observed concentration profiles, one at either end of a river reach. We used the river Swale data already described, and the results are shown in Table 7 for four reaches and four flow rates, where data is available.

Overall the values are towards the low end of the range found in other rivers. There is some (expected) variation between reaches, reflecting spatial variations in hydraulic and mixing characteristics. For example, the two largest values are both in the Crakehill-Thornton reach and two of the three lowest values are in the Topcliffe-Crakehill reach. There is no consistent pattern with flow rate. For example the dispersive fraction tends to decrease with increasing flow rate in the Skipton-Topcliffe reach, but the opposite occurs in the Thornton-Myton reach. It is, however, interesting to observe that both the available values at the lowest flow rate are quite small, which might be resonant with the idea aired above that different non-dimensional concentration profiles apply at very low flow rates to those at medium and high flow rates. With such a small number of data, however, it is difficult to place much confidence in these findings, but further work on this appears to be warranted.

Conclusions

The paper has discussed and illustrated several ways in which data from tracer experiments in rivers may be more greatly exploited, particularly when it is of poor quality. The following specific conclusions may be drawn.

1. When plotted in non-dimensional form river tracer data from an EA database follows the concept of similarity, i.e. non-dimensional temporal concentration profiles from a specific location observed under different flow conditions have a common shape.
2. This allows unobserved characteristic features of individual profiles to be estimated from other, more completely observed, profiles.
3. As a result, predictions of characteristic travel times of pollutants in rivers over a range of flow rates can be improved.
4. In addition, the similarity concept allows missing segments of partially observed profiles to be reconstructed.
5. Furthermore, the similarity concept enables good quality location-specific whole concentration profiles to be reconstructed over a wide range of flow rates using only one observed profile and just the observed peaks at other flow rates.
6. The completion of partially observed and the reconstruction of unobserved concentration profiles have the potential to improve the estimation of flow rates and solute transport characteristics (e.g. dispersion coefficients and dispersive fractions) from river tracer data.
7. A possible limitation of the application of similarity (specifically at very low flows) has been suggested, but further work is needed to substantiate this.
8. No clear link was found between the common shape of non-dimensional temporal concentration profiles at a location over a range of flow rates and the approximate invariance of the reach dispersive fraction with flow rate. However, the small values of dispersive fraction found at the lowest flow rate may be connected with the difficulties encountered in applying similarity concepts at very low flow rates.
9. The full value of existing poor quality tracer data has probably not been exploited. Using the ideas introduced in this paper, a re-analysis of archived tracer data could yield valuable information on pollutant transport in the UK's rivers at relatively little cost.

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Figure captions

Figure 1 Observed temporal tracer concentration profiles, River Swale (NE18).

Figure 2 Observed temporal tracer concentration profiles, River Swale (NE20).

Figure 3 Observed temporal tracer concentration profiles at Burnsall, River Wharfe, for five tracer experiments.

Figure 4 Non-dimensional temporal tracer concentration profiles at Burnsall, River Wharfe, for five tracer experiments.

Figure 5 Variation of travel times of leading edge, peak and trailing edge of observed concentration profiles with flow rate for Burnsall.

Figure 6 Observed temporal tracer concentration profiles at Crakehill, River Swale, for three tracer experiments.

Figure 7 Non-dimensional temporal tracer concentration profiles at Crakehill, River Swale, for two tracer experiments.

Figure 8 Comparison of observed and reconstructed temporal tracer concentration profiles at Crakehill (NE20).

Figure 9 Comparison of observed and reconstructed temporal tracer concentration profiles at Crakehill (NE18): Reconstructed (1) refers to use of unaltered t_T/t_P from NE17 and Reconstructed (2) refers to use of modified t_T/t_P from NE17.

Figure 10 Comparison of observed and reconstructed concentration profiles at three locations for three flow rates (blank panel indicates no observations available).

Tables

Table 1 Summary information on tracer experiments: River Wharfe.

Reference number	Date	Flow rate (m^3/s)	Mass of tracer (g)
NE35	30/08/1994	5.418	20
NE36	23/05/1994	3.736	16
NE37	22/11/1993	3.681	22
NE38	17/09/1993	12.485	25
NE39	06/09/1993	2.807	30

Table 2 Summary of characteristics of non-dimensional tracer profiles: Burnsall.

Reference number	Area under profile (-)	Centroid location (-)	RMS error (-)
NE35	0.529	0.460	0.0070
NE36	0.532	0.415	0.0134
NE37	0.517	0.433	0.0056
NE38	0.519	0.436	0.0044
NE39	0.521	0.410	0.0107

Table 3 Observed travel times for Burnsall.

Reference	Flow rate (m^3/s)	t_P (min)	t_L (min)	t_T (min)	t_L/t_P (-)	t_T/t_P (-)
NE35	5.418	107	87.82	180.56	0.821	1.687
NE36	3.736	160	130.26	278.66	0.814	1.742
NE37	3.681	188	152.12	301.90	0.809	1.606
NE38	12.485	62	51.52	100.98	0.831	1.629
NE39	2.807	315	253.15	501.73	0.804	1.593

Table 4 Observed and estimated travel times for Burnsall: percentage errors shown in brackets. In columns 3-7, all unshaded values are observed data, dark shading represents values calculated from observations in NE38 & NE39 and light shading represents values for NE35, NE36 & NE37 estimated from corresponding observed t_P (column 3) and calculated t_L/t_P & t_T/t_P (columns 6 and 7).

Reference	Flow rate (m^3/s)	t_P (min)	t_L (min)	t_T (min)	t_L/t_P (-)	t_T/t_P (-)
NE38	12.485	62	51.52	100.98	0.831	1.629
NE39	2.807	315	253.15	501.73	0.804	1.593
NE35	5.418	107	87.45 (0.4)	172.35 (4.5)	0.817	1.611
NE36	3.736	160	130.76 (-0.4)	257.72 (7.5)	0.817	1.611
NE37	3.681	188	153.65 (-1.0)	302.82 (-0.3)	0.817	1.611

Table 5 Predicted travel times for Burnsall at representative low, medium and high flow rates.

Flow rate (m^3/s)	Profile feature	Case 1		Case 2	
		Travel time ratio	Travel time (min)	Travel time ratio	Travel time (min)
1.5	Leading edge	0.816	381.9	0.817	382.6
1.5	Trailing edge	1.651	773.1	1.611	754.1
5.0	Leading edge	0.816	113.6	0.817	113.8
5.0	Trailing edge	1.651	230.0	1.611	224.3
20.0	Leading edge	0.816	28.1	0.817	28.2
20.0	Trailing edge	1.651	56.9	1.611	55.5

Table 6 Coefficients of determination between reconstructed and observed whole concentration profiles: River Swale

Flow rate (m^3/s)	Location				
	Skipton	Topcliffe	Crakehill	Thornton	Myton
3.2	0.7912	0.7502	0.8067	n/a	n/a
5.5	0.9659	0.9927	n/a	0.9818	0.9883
18.6	0.9964	0.9958	0.9949	0.9953	0.9930

Table 7 Dispersive fractions: River Swale

Flow rate (m^3/s)	Reach			
	Skipton - Topcliffe	Topcliffe - Crakehill	Crakehill - Thornton	Thornton - Myton
3.2	0.069	0.043	n/a	n/a
5.5	0.126	n/a	n/a	0.139
10.3	0.132	0.132	0.177	0.114
18.6	0.152	0.068	0.204	0.084