PREDICTING THE DEPOSITION OF HIGHWAY-DERIVED SEDIMENTS IN A RECEIVING RIVER REACH

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Abstract

Previous research has shown that highway runoff contains contaminated particles which, if deposited within the receiving water, may negatively impact on the ecology. A preliminary investigation into the potential benefit of field sediment tracing studies has been performed as a component of an integrated research programme, commissioned by the UK Highways Agency and the Environment Agency, on the impact of contaminated sediment. The sediment tracing study utilised two sediment sizes, with both magnetic and fluorescent properties, which were introduced into a simulated runoff event. Visual evidence showed deposition of the coarse sediment adjacent to the outfall bank within the first 5 m downstream from the outfall. Photographs taken during the introduction of the sediment show a plume of predominantly fine particles emerging from the outfall pipe and being conveyed through the reach. This provided an envelope of extremes of expected sediment behaviours. Limited success of the experimental work, including several practical difficulties of sediment recovery, prompted the consideration of alternative methods for predicting sediment behaviour based on locally-derived characteristics of the highway runoff sediment load combined with measured receiving water hydraulic characteristics. Importantly the method proposed recognizes the need to consider spatial variations in the cross-sectional velocity distribution in open channel flows and a reach travel time distribution is employed in preference to a single reach mean velocity. The results are coupled with knowledge of sediment characteristics to provide a method for estimating likely sediment deposition, and predictions are consistent with the field observations.

Keywords: Sediment, Pollutant, Highway, Runoff, Tracers, Receiving water, River, Travel time, Deposition.

1. INTRODUCTION

An integrated research programme was jointly funded by the UK Highways Agency (HA) and the Environment Agency to provide authoritative advice on the circumstances in which highway runoff is likely to have a significant ecological effect. As part of this study a series of key research questions focused on the ecological impact of <63 μm particulate material discharged in highway runoff. Two of these key questions were:

- Are stream organisms exposed to accumulated highway-derived particulate matter?
- What processes produce and control the observed impacts and how are they mediated?

To address these questions, detailed studies were performed in six rivers in the UK which receive highway drainage. A minimum of 10 storm events were sampled at each site and the amount of particulate material discharged during each event and its associated metal and PAH contaminants measured. More than 97% of particulate material discharged during storm events was found to be less than 63 μm in size and particle-associated contaminants were detected in all storm samples at all sites. In situ deployments of invertebrates were performed on four occasions to assess the potential bioaccumulation of particle-associated contaminants in highway drainage. The results (Gaskell *et. al.*, 2004 & 2007) showed that stream organisms can be exposed to accumulated highway-derived particulate material. This was especially evident where very low receiving water velocities favour accumulation of fine particulate material and contaminants appear to be taken up by stream organisms from highway-derived particulate material.

This paper describes results from an additional preliminary field study to investigate techniques to directly monitor the fate of particulate matter in a receiving watercourse. However, the sediment tracing study achieved limited success and so an alternative solute tracing method has been suggested that can provide information on the spatial velocity distributions. This has been coupled with a simple particle settling calculation to estimate the likelihood of sediment deposition. The basis for this theoretical approach will be outlined prior to the field monitoring work being described.

2. BACKGROUND

Highway runoff is episodic and its composition varies over short temporal scales. Most contaminants are washed off highways at the start of storm events, with many of the contaminants in highway runoff being associated with particulate material (Legret & Pagotto, 1999). The loads and particle sizes of sediments in highway runoff are dependent upon storm characteristics – such as antecedent period, storm intensity and duration – combined with the hydraulics of the highway drainage system (pavement area, carriageway slope and the presence and maintenance of sediment traps) (Irish *et al.*, 1998). The main factors affecting the dispersion, sedimentation and re-distribution of such material are the receiving water flow characteristics – discharge, velocity, bathymetry, bed material and vegetation – in association with particle and outfall characteristics (particle size, material density, load and outfall design).

The original HA brief stated that 3 study sites should be ‘accumulating’ and 3 should be ‘dispersing’, without defining the criteria. In the original site survey this was quantified as sites with reach mean velocities either above or below a reach mean velocity of 0.1 m/s. However, in reality, all reaches will exhibit a proportion of both processes and it is useful to examine approaches that could suggest the probability of material being deposited. This may be achieved by adopting a ‘settling tank approach’ to the reach and considering parameters such as longitudinal velocity, flow depth and particle characteristics. It is important to note that this approach assumes a uniform cross-sectional velocity distribution.

Many models of particle settling have been developed and these include theoretically based formulae, regression based methods, and, more recently, mathematical simulation of the dynamic processes. The original theory into settling tanks, developed by Hazen (1904) was expanded by Camp (1946) who considered an ideal rectangular continuous flow settling basin. To determine the efficiency of removal it is necessary to consider the entire range of settling velocities present in the system. This may be achieved by means of the settling velocity curve, which is a function of particle density, shape and size.

Disadvantages of adapting this approach to receiving river reaches are that it does not allow for any spatial variations that might arise from channel geometry, nor does it account for turbulence, or for any cross-sectional variations of suspended sediment concentration throughout the inflow. A further disadvantage of this approach is its dependence upon accurate settling velocity data and it is only valid under uniform, steady flow conditions. The US EPA (1975) proposed an alternative methodology to estimate sediment removal under dynamic conditions which includes a turbulence or short circuiting constant. However, it is clear from this brief review, that the main parameters controlling the proportion of material likely to deposit within a receiving water reach are the particle characteristics and the receiving water velocity field.

The main challenge in attempting to employ a particle settling approach to predict the fate of highway-derived sediment is how to include the effects of temporal variations in receiving water discharge and spatial variations in velocity within the receiving water reach. Temporal variations in discharge may be considered using either estimates from time series river discharge records or employing run-off prediction models and are not considered in this paper.

The spatial variations in velocity within the receiving water reach may be quantified using solute tracing techniques. Solute fluorescent tracers have been used extensively to elucidate flow paths in free flowing water bodies. Introduction of a tracer cloud at an upstream location, and the subsequent measurement of the temporal concentration distribution at downstream locations, may be used to indicate both the reach mean velocity, via determination of the travel time, and the variation in velocities experienced by individual particles. This variation in velocities, or differential advection, leads to the concept of longitudinal dispersion and is shown by the increase in spread of the tracer cloud over time.

The aims of the research presented here were: to undertake a feasibility study on the practicality of monitoring the fate of sediments discharged from a highway outfall; and to explore the potential of modelling the probability of deposition using a modified form of settling tank theory, in which a travel time distribution is employed to account for spatial variations in longitudinal velocity.

3. FIELD STUDY

The objective of the field investigation was to utilise uniquely-labelled tracer particles to determine whether sediments would deposit close to the outfall or be transported away from the study reach. For any deposited particles, the spatial distribution on the bed would be of interest. The approach adopted was novel, involving the use of two particle types, both of which were magnetic, uniquely and brightly coloured and fluorescent. A single sediment input and monitoring experiment was undertaken from an artificially generated discharge event.

The site selected for this sediment tracing work was HA08, Fig. 1 and Fig. 2, which is located where the M5 crosses the River Salwarpe near junction 5, south west of Birmingham, near Wychbold, UK. Field sediment tracing studies were performed on 2nd, 3rd and 4th August 2006. This site was originally deemed ‘dispersing’ but throughout the year had significant vegetation growth which influenced the flow characteristics. For this study it benefitted from having good vehicle access.


Fig. 1 Receiving Water Reach - looking upstream from mid-reach


Fig. 2 Receiving Water Reach - looking upstream from downstream boundary

A detailed survey was undertaken, comprising cross-sectional surveys at 10 m intervals from the outfall pipe. This extended 80 m downstream to the end of the reach. The bed, water surface and velocity profiles were determined at 0.5 m intervals across the cross-sections. Examples of the data collected at 0 m, 40 m and 80 m downstream of the outfall pipe are presented in Fig. 3. These show significant variations in velocity (approx. 0.0-0.5 m/s) and water depth (up to 350 mm) both within and between the cross-sections. This highlights the potential difficulties associated with using ideal settling velocity tank assumptions to predict sediment deposition within a natural channel reach. The water surface slope was found to be 1 in 275.

4. SEDIMENT TRACING STUDY

Earlier investigations (Gaskell *et al*, 2007) showed that the majority of highway-derived particulates have a particle size of less than 63 µm, although exceptional conditions may see this increase to the order of 150 µm. As a consequence, it was intended to investigate two particle size fractions, <63 µm and 63-150 µm. To distinguish between particulates introduced to the flow from the simulated highway discharge and existing river bed material, uniquely labelled tracer particles were used. These were manufactured in two size fractions, each having magnetic and fluorescent properties and supplied by Partrac (www.partrac.com). The excitation wavelength was unique to each individual fraction and the density of the material was manufacturing process-dependent. The finer 'green' particles had a density of 1936 kg/m^3, whilst the coarser 'red' ones had a density of 2600 kg/m^3. The particle size distribution of each fraction is shown in Fig. 4. This shows that whilst there is some slight overlap between the two fractions, the maximum particle size of the smaller is <58 µm, and the d_{10} and d_{95} of the larger are 63 µm and 218 µm respectively.

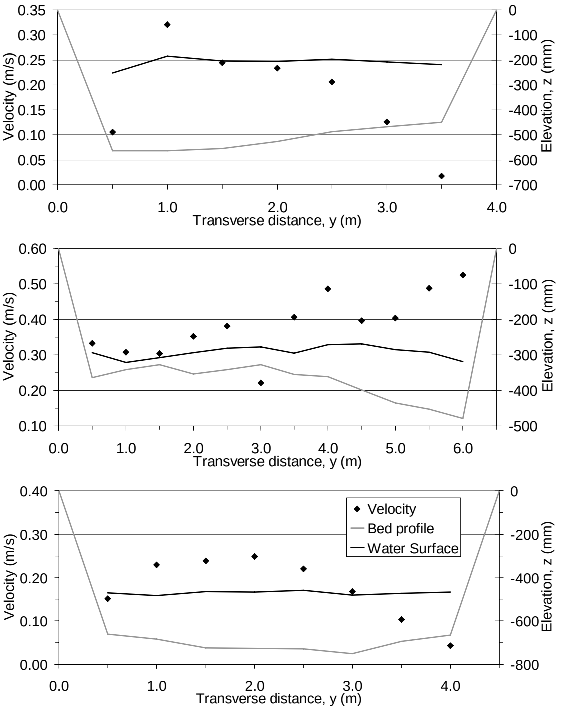


Fig. 3 Cross-sectional shape and velocity variation at 0 m, 40 m and 80 m downstream from outfall.

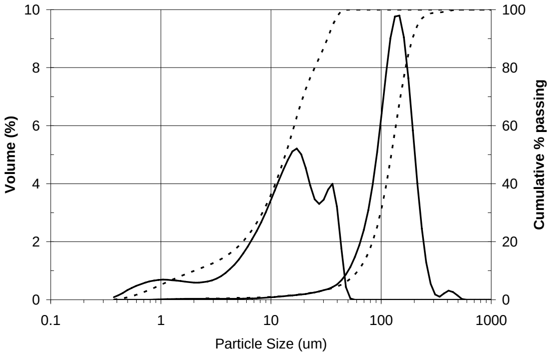


Fig. 4 Particle Size Distribution for the sediment tracers

Fig. 5 Discharge to river

The aim of the study was to determine the amount of material deposited within or transported out of the reach during the simulated discharge event. Ideally, the amount and location would be determined for the material deposited and a spatial and temporal concentration profile would be determined for the material exiting the reach in suspension.

A steady discharge was required from the outfall pipe to introduce the two sediment tracers to the river, Fig. 5. With the aim of replicating a discharge event from the outfall, water was extracted from the main body of the river flow approx. 25 m upstream of the outfall and pumped to the final manhole chamber of the drainage system. As the resolution of the data obtained would be dependant upon the measuring technique employed, it was necessary to increase the total mass loading of the input from that normally experienced in event conditions. Consequently 15 kg of each sediment fraction was introduced to the system. The injection regime involved combining 1 kg of each of the tracer fractions and premixing with 6 l of water (5 ml of soap included to remove surface tension effects). The mixture was then introduced to the simulated highway drainage flow in the manhole chamber over a 2 minute period. Consequently 15 'pulses' were seen emerging from the discharge pipe over a half hour period (10:00-10:30hrs), Fig. 6. To assess the receiving water's hydraulic characteristics during the sediment tracing study, longitudinal solute traces were undertaken immediately prior to, and post sediment injection.

4.1 Determination of the suspended load

It was initially envisaged that the fluorescent properties of the two size fractions would be utilised to determine temporal concentration profiles at predetermined locations within the cross section. However, preliminary trials revealed difficulties in accurately converting the available Series 10 Turner Designs field fluorometers for use with sediment. It was not possible to obtain a calibration which also accounted for the influence of sediment concentration. However, whilst direct quantifiable measurements of the fluorescent tracer were not obtained, the in-situ Turner Designs SCUFA (www.turnerdesigns.com) instruments detected small increases in fluorescence between the solute traces and a significant signal on the turbidity channel 80 m downstream of the outfall, Fig. 6.

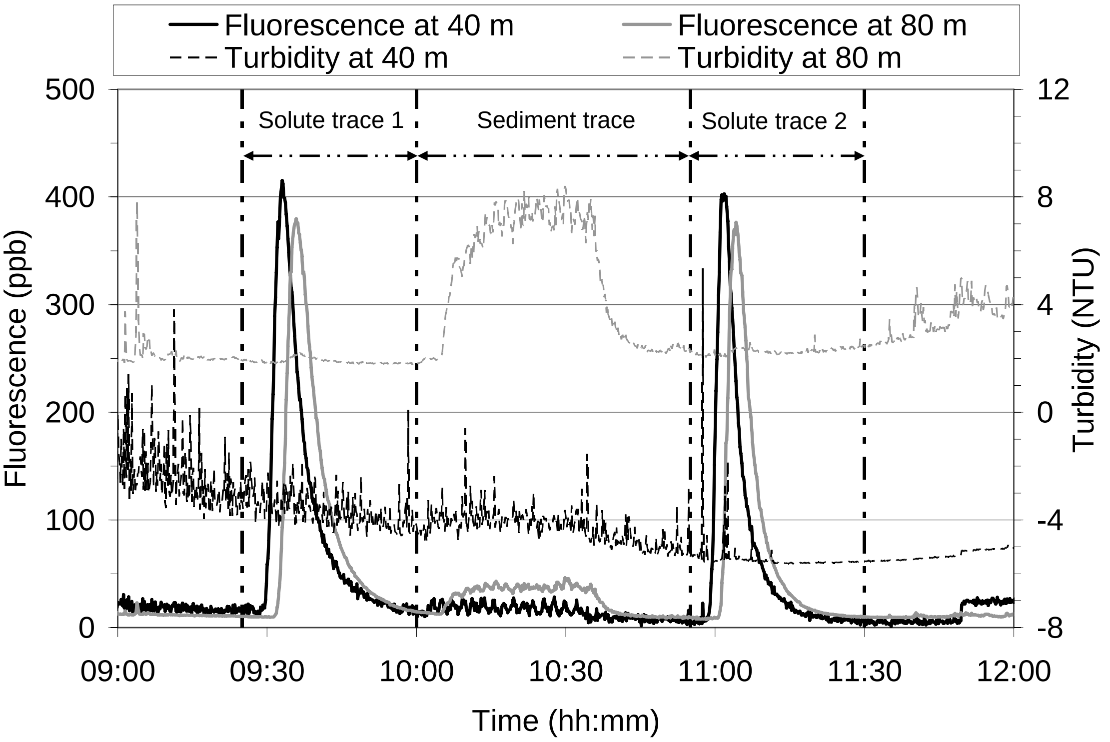


Fig. 6 Fluorescence and turbidity recorded 40 m and 80 m downstream of outfall

To determine a measure of the total load exiting the reach, approaches based on direct physical recovery were utilised. The intention was that the mass and magnetism of the tracer particles would be used to remove them from sampled water, and their size characteristics would then be used to distinguish between the two fractions. The principle was to sample a certain portion of the flow (spread across four positions in the river cross-section at the downstream end of the reach), and to attempt to extract all of the labelled tracer particles contained within that fraction of the flow (using settling tubes and magnets). Knowing the proportion of discharge sampled, the collected load would then be multiplied by an appropriate factor to estimate the total load transported out of the reach. By implication, the load deposited on the bed would be inferred to equate to the difference between this load and the initial quantity injected.

At four equidistant locations, Fig. 7, across the channel width, water was continuously extracted from the mid depth of the flow through 25 mm internal diameter pipes. This was then passed through a 3m long, 150 mm diameter settling tube, Fig. 8, where the majority of material was anticipated to settle out of suspension, before being passed over a 12000 gauss magnet, Fig. 9, to remove any remaining fine material. The extracted water was then returned to the main body of the river downstream of the reach. This continued for the duration of the test.

4.2 Determination of bed deposition

The deposition of material on the bed is dependent on particle properties and localised flow characteristics, therefore in areas of low velocity – close to the channel banks and areas where vegetation and sand banks occur – it was anticipated that the smaller sized fraction may fall out of suspension, so-called ‘hot spots’. Conversely, if the larger particles remain within the main flow body, they may well be transported out of the reach by the processes of saltation. Hence any technique needs to be able to determine the load and location of each fraction.

Two techniques were considered, a survey of the bed material using a magnetic susceptibility sensor or collecting discrete core samples. As the first is only able to determine a total load and not size fraction at each location, numerous discrete samples were collected. The samples taken were coincident with the grid system previously set up. i.e. at 0.5 m intervals on each cross section, Fig. 10. Additional ‘intelligently located’ samples were obtained for the identification of ‘hot spots’.

Fig. 7 Suspended sediment sample extraction

Fig. 8 Settling tubes

Fig. 9 Magnet housing

Fig. 10 Discrete bed core samples taken at 0.5m intervals

4.3 Sediment Tracer Studies - Results

Visual evidence shows deposition of the coarse ‘red’ sediment both in the outfall pipe, Fig. 11 and adjacent to the outfall bank within the first 5 m downstream from the outfall, Fig. 12. Photographs taken during the introduction of the sediment at the manhole show a plume of predominantly fine ‘green’ particles emerging from the outfall pipe, Fig. 13, and being conveyed through the reach. Unfortunately, analysis of the discrete bed cores collected subsequent to the trace failed to quantify the amount of sediment tracer deposited. Some of the naturally occurring particles were found to be magnetic and this prevented the use of magnetic forces to easily separate the sediment tracer and, after an extended storage period, oxidation of the tracer particles prohibited fluorescent detection methods from being employed.

The suspended sediment settling tubes located at the downstream boundary of the reach failed to collect any of the coarse ‘red’ sediment. All the material collected on the magnets, Fig. 14, was fine 'green' particles. It is inferred that the coarse 'red' sediment was all deposited close to the outfall. From the four sampling systems a total of 6 g of material was collected. Knowledge of the sampling flow rate, channel cross-sectional area and velocity, allows an estimate to be made of the quantity that passed through the whole system. This gives an estimated total mass of 500 g passing through the downstream boundary (i.e. 1/30th the mass input).

Fig. 11 Coarse sediment deposited in outfall pipe

Fig. 12 Coarse sediment deposited on channel bed in the vicinity of the outfall

Fig. 13 Sediment tracer at 40.0 m downstream from outfall

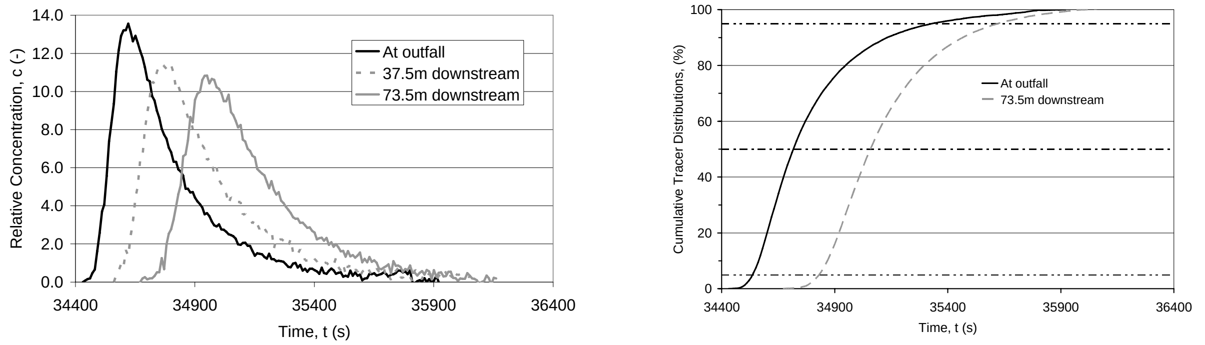
Fig. 14 Fine sediment retained on magnet

There is an upper limit to the amount of sediment that can be retained on the magnet and this limitation, together with the inability to separate sediment tracer particles within the discrete bed cores, prevented the reliable determination of the location of the unaccounted mass. However, the in-situ SCUFAs, which were installed to monitor the Rhodamine WT solute trace and have fixed excitation and emission wave lengths, record both fluorescence and turbidity. The data are available from the instruments located at 40 m and 80 m downstream from the outfall, Fig. 6. This clearly shows both the solute traces before and after the introduction of the 15 discrete inputs of sediment tracer and confirms that fluorescent sediment tracer passed through the downstream section at 80 m, as indicated by raised concentration levels between 10:00 and 10:30 hrs. A significantly lower response was detected 40 m downstream from the outfall, probably because the material was not fully cross-sectionally mixed.

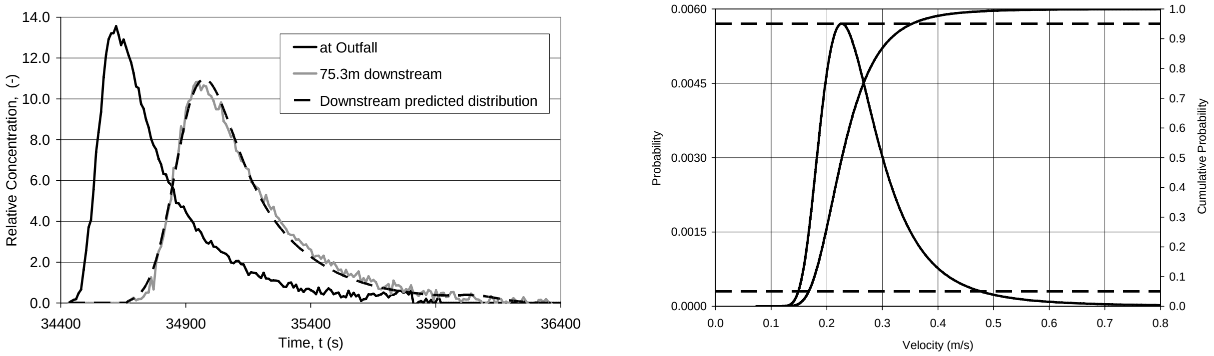
In summary, the sediment tracing results show that none of the coarse 'red' particles were detected in the suspended sediment settling tube sampling system at the downstream boundary. A significant quantity of the coarse 'red' sediment was deposited in the outfall pipe and large quantities were deposited on the receiving channel bed within first 5 m of the outfall. It is inferred that none of the coarse 'red' particles exited the reach. Of the fine 'green' particles, a few were observed to have been deposited on the channel bed, but not in large quantities. Most fine 'green' particles were observed to be conveyed through the reach and the in-stream measurements detected their transport in suspension. However, improved sampling and detection procedures are required to reliably quantify the reach scale sediment dynamics. Note that, although the site had originally been classified as 'dispersing' (i.e. reach mean velocity > 0.1 m/s), the velocity measurements included point values which fell below 0.1 m/s, and the sediment tracer tests clearly showed significant deposition of material in the 63-150 µm size fraction.

5. ESTIMATING THE REACH VELOCITY DISTRIBUTION

Whenever possible during the extended monitoring programme, solute tracing was conducted at all of the 6 study sites (Gaskell *et al.,* 2007). At HA08, three downstream measurement locations were used, situated at the highway outfall, at 37.5 m (Fig. 1) and at 73.5m (Fig. 2) downstream from the outfall. The temporal concentration distributions recorded at HA08 on 7th July 2005 are presented in Fig. 14a.



a) Recorded Temporal Concentration Distributions b) Cumulative Tracer Distribution Plots



c) Analysis for ADE Parameters d) ADE Predicted Velocity distribution

Fig. 14 Example of Solute Tracing Results and Analysis

The traces have been utilized to derive velocities using two alternative methods: 1) based on the difference between the upstream and downstream cumulative temporal concentration profiles; and 2) based on a fitted advection diffusion equation (ADE) model.

The first approach uses parameters derived from cumulative tracer distributions to estimate the range of velocities within a flow. This is a relatively simple approach that directly uses the raw data without making any assumptions on the type of model required to describe to processes. It assumes that on average the particles retain their spatial position within the tracer cloud. Over such short reaches and timescales this may be an acceptable assumption. An estimate of the flow velocity has been made by considering the time difference for 5, 50 and 95 %ile of the tracer mass between the outfall and the most downstream measurement site, illustrated in Fig. 14b. The difference in the median (50%) travel times at the two locations (339 s) suggests a reach-averaged mean velocity of 0.217 m/s.

River water quality models often use the ADE to describe the transport and spreading of soluble material within the flow. This assumes that all the processes are random and the spatial distribution from an instantaneous release of material may be described by a Gaussian distribution. This technique has also been used to analyse the traces, and an example of the predicted distribution for the same trace is provided in Fig. 14c. This employs a fitting routine described in Guymer (2002) and predicts a reach mean velocity of 0.227 m/s and a longitudinal dispersion coefficient of 0.391 m^2/s. Using these two parameters, a prediction of the reach velocity distribution may be made (Fig. 14d)

A comparison between the predictions obtained from both techniques is provided in Fig. 15 for all data sets collected from this study site. The symbols show the velocities for 5, 50 and 95 %ile of the tracer mass. This shows clearly that the minimum and mean velocities predicted using either technique are similar. However, the maximum velocities predicted by the application of the ADE are significantly larger. Inspection of the individual predictions, Table 1, shows that this mainly occurs when the longitudinal dispersion coefficient is large relative to the travel time for the reach length considered. This indicates that the ADE assumptions, particularly the 'frozen cloud' assumption that advection is significantly greater than dispersive mechanisms (Rutherford, 1994), is a limitation. The cumulative tracer distribution-based approach probably provides a more realistic estimate of the upper velocity (5% travel time).

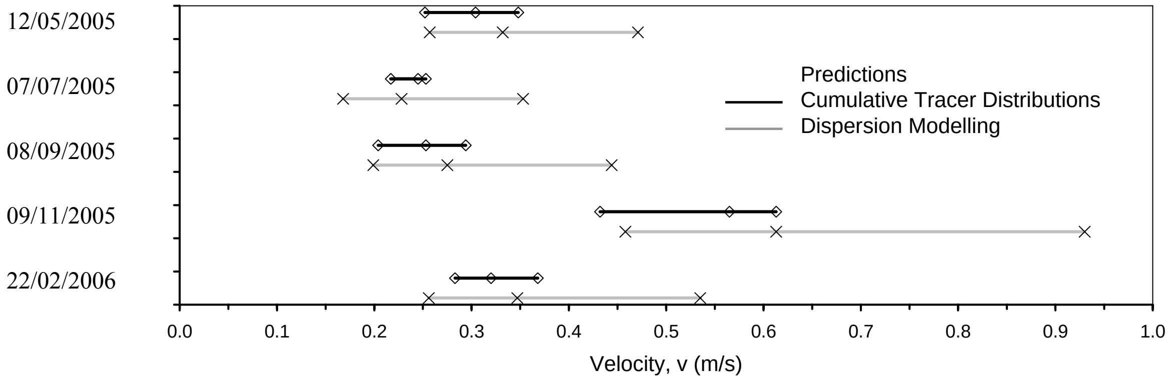


Fig. 15 Comparison of Predicted Velocity Ranges for all Traces Performed

Whilst both techniques allow estimates of the effects of spatial variation in velocity to be made, further comparisons and validation with field measurements are required to assess the most appropriate technique. The next section outlines how the velocity distributions may be utilized to predict the likelihood of sediment deposition.

	ADE Fitted Parameters		Dispersion Modelling			Cumulative Tracer		
Date	Mean travel time (s)	Longitudinal dispersion coefficient (m^2/s)	Upper Velocity 5% (m/s)	Mean Velocity 50% (m/s)	Lower Velocity 95% (m/s)	Upper Velocity 5% (m/s)	Mean Velocity 50% (m/s)	Lower Velocity 95% (m/s)
12/05/2005	220	0.385	0.471	0.332	0.257	0.348	0.304	0.252
07/07/2005	323	0.391	0.353	0.228	0.168	0.253	0.217	0.245
08/09/2005	268	0.542	0.444	0.275	0.199	0.294	0.253	0.204
09/11/2005	120	0.958	0.930	0.613	0.458	0.613	0.565	0.432
22/02/2006	212	0.581	0.535	0.347	0.256	0.368	0.320	0.283

Table 1 Summary of Predicted Velocity Ranges

6. PREDICTING SEDIMENT DEPOSITION

A simple settling tank calculation (Tchobanoglous and Schroeder, 1987) has been performed using knowledge of the sediment characteristics (diameter, density and particle size distribution); together with an estimate of the reach mean flow depth. From the survey data, Fig. 3, this was estimated as 200 mm. This has been performed in conjunction with velocity probability distributions obtained from solute tracing and allows estimates of the deposition potential to be made. For the study undertaken at site HA08, all the coarse 'red' sediment is predicted to deposit. For the fine 'green' sediment around 10% is estimated to deposit within the reach. A further 20%, in the size range 20 to 30 µm, may settle, but only if it experiences low velocities of less than 0.1 m/s. 70% of the input mass is estimated to pass through the reach. There are several simplifications in this approach, however, and the assumption that the material is cross-sectionally well-mixed and experiences the same range of velocities within the reach as the solute tracer is a limitation. The predictions do however, agree with the sediment tracing results and allow the effect of spatial variations in channel velocity to be incorporated within an estimation technique.

7 CONCLUSIONS

A novel sediment tracing study was undertaken, using two different types of fluorescent and magnetic particles to reveal the fate of sediments discharged from a highway outfall into a small receiving watercourse. The study provided useful visual and qualitative information, although it failed to generate any robust quantitative data. It was observed that whilst most of the fine (<63 µm) material was transported out of the study reach (80 m downstream from the outfall), the majority of the coarser sediments (63-150 µm) were deposited close to the outfall.

A technique has been proposed that has the potential to estimate the proportion of material likely to deposit within a predefined reach. This utilises typical sediment properties, channel flow depth and the variation of velocities within the reach. It has been shown that the latter could be obtained through solute tracer measurements within the reach. In this case the model predictions are consistent with the field sediment trace.

8.0 ACKNOWLEDGEMENTS

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