Particle Tracking: a new tool for coastal zone sediment management

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Abstract

A wide variety of contemporary environmental and socio-economic concerns are directly or indirectly associated with sediment transport in coastal regions. These include coastal flooding, contaminant storage/remobilisation, estuarine siltation, and longshore drift, amongst others. Sediment management policies attempt in the main to control or mitigate the negative affects of sediment migration. A fundamental understanding of sediment transport processes across the spectrum of energies (e.g. fair-weather, storms) and a spectrum of scales (days-years) is central to these efforts, and in spite of over 100 years' research there are, in fact, no unequivocal means of assessing sediment and contaminant transport pathways. Particle tracking technology in concept is not new, however, recent advances in manufacturing and monitoring technology have permitted sediment tracking to be undertaken in a way that permits visualisation and mapping of these pathways with increased logistic ease and increased statistical confidence. Particle tracking thus offers a new tool for such purposes, and is complementary to more conventional approaches such as process monitoring (e.g. of waves and tides) and numerical modelling. This paper describes the philosophy behind particle tracking methods, and outlines some of the approaches used in studies. The utility of particle tracking technology for sediment and coastal zone management, in particular to impact assessment, and to model calibration and verification, is discussed.

1. INTRODUCITON

Quantification of sediment transport has been of fundamental scientific and engineering interest since the early investigations of DuBoys (1879). Although basic, blue-skies research continues to be funded by governments and remains important (e.g. evidenced by the significant UK LOIS and EU LOICZ projects), a new focus based upon environmental management and underpinned by a wider environmental awareness has emerged. Now sediment transport research is used in a hitherto more applied fashion to solve issues and address problems of concern along the coastlines of the UK and elsewhere. 'Sediment management' is a central feature of many coastal zone management strategies and shoreline management plans, not least because of the role of sediment in pollution transport, the socio-economic and health risks associated with major sediment re-distribution during coastal flooding, and the impacts of sediment re-location (via dredging) on sensitive marine sites during port construction and expansion. Furthermore, incumbent and incoming pan-European legislation, such as the Habitats and Water Framework Directives, increasingly are driving fresh and innovative approaches to sediment management and must be included in management planning (Brooke, 2003).

Practical efforts to address sediment management problems in the coastal zone rely firstly upon a firm understanding of the physical processes involved (wave stirring, tidal advection etc.) together with access to appropriate tools. 'Tools' in this context includes widely differing products ranging from geographical information systems (GIS), to process measurement instrumentation e.g. coastal radar, instrumented benthic rigs, to numerical model prediction software e.g. storm surge prediction. This paper presents a relatively new tool – Particle Tracking - which is associated with *practical measurement* of sediment/contaminant pathways in coastal environments. Particle tracking is a powerful tool of itself for evaluating and visualising sediment transport pathways, but optimal information is forthcoming when tracking technology is used in conjunction with some or all of the tools mentioned above.

This presentation describes briefly the rationale and methodologies behind modern particle tracking methods, and outlines some of the approaches used in studies. The utility of particle tracking technology for sediment and coastal zone management, in particular to impact assessment, and to model calibration and verification, is discussed.

2. PATHWAY MAPPING USING PARTICLE TRACKING: A BRIEF OVERVIEW

Particle Tracking represents a powerful tool of use in coastal zone management. However, prior to consideration of the utility of the technology, it is first necessary to provide a brief overview of the technology in order that coastal managers, shoreline planners, marine consultants etc. may possess a general understanding of the principles involved as well as practical aspects of conducting tracking studies and it's scientific limitations.

Although the specific nature of studies inevitably varies, there are a number of steps common to all particle tracking studies. These are;

1. Assessment of the nature of ambient sedimentary material,
2. Manufacture of a particulate tracer of appropriate size, specific gravity and tracer signature,
3. Testing and verification of tracer properties (within accepted tolerances),
4. Introduction of the tracer into the environment (frequently termed 'injection' at the tracer 'drop zone'),
5. Collection/sampling of sediments and/or water samples in the surrounding region, and
6. Processing and analysis of environmental samples for tracer presence &/or quantity.

2.1 Tracer manufacture & characterisation

The first stage (assessment of sediment native to the environment of study) is a necessary pre-requisite for all studies. Samples must be taken from across the study environment in order to provide a statistical sample with which to design the tracer particle(s), although of course these samples also provide information on the nature of the sediment cover and the general character of sediment transport at the site. From direct measures of particle size spectra, settling velocity spectra and (clays only) surface charge, amongst others, a synthetic particle mimic is manufactured using modern methods. Whilst trade secrets must be respected, Partrac manufactures fluorescent, paramagnetic ('dual signature') tracer from non-toxic, natural materials (Fig. 1).

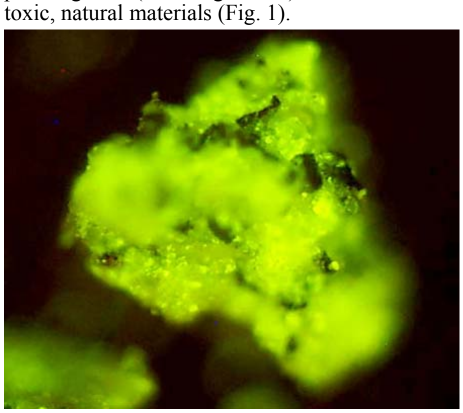

Figure 1: Partrac FM Series Tracer (scale: the particle is ~100 µm in diameter)

Up to 4 spectrally distinct fluorescent pigments may be encapsulated uniformly within particles, and magnetic inclusion technology is used during the manufacturing process to confer magnetic character to particles. 'Paramagnetic' means that the particles are attracted by strong permanent or electro-magnets (providing a simple and effective means with which to separate tracer from natural sediment), but they do not become permanent magnets themselves. No particle density adjustments are necessary since the foundation matrix is a natural mineral substance.

All tracer is routinely tested in a series of laboratory tests to assess similarity to the sediment to be tracked, a process termed 'hydraulic matching'. Similarity ratios e.g. of median grain diameter, are produced, and tolerances devised based in part on typical measurement errors and uncertainties associated with sediment transport research, together with sensitivity analyses of commonly used transport equations (after Soulsby, 1997; see Black et al. (b), in press, for a detailed discussion). The extensive bio-physical characterisation testing of both natural sediments and manufactured tracer provides an enhanced level of confidence that the tracer behaves like the natural sediments under fluid stress - the central, underpinning tenet of particle tracking technology.

2.2 Tracer injection

In order for a tracking experiment to follow, tracer is mixed (usually in a 50:50 wt.%) ratio with native sediment and formed into low profile blocks. Introduction or 'injection' of the tracer into the sea/river varies according to circumstance and may involve careful emplacement by divers, enclosure in water-soluble bags, ice encapsulation methods (in which the tracer admixture is entombed in a weighted ice block), remotely operated bottles or chambers lowered from a ship (White and Inman, 1987), or barge dumps for very large experiments (White, 1999). Sprinkling the tracer-sediment admixture represents perhaps the best method of tracer injection onto a shallow seabed (e.g. Ciavola et al., 1997), although, in fact, this is rarely performed. Within dredge impact studies the tracer is usually dosed directly into the dredge hopper and mixed thoroughly using the ship's pumps prior to release. Beachface environments (longshore sand transport experiments), in which disc-shaped areas of exposed sand are seeded with tracer particles, are perhaps the easiest environments in which to work.

The quantity of tracer necessary to yield useful results is also highly dependent on circumstance; it is a function primarily of the potential volume of water (or volume of sediment) within which tracer may become diluted and the analytical detection limit available. In every study efforts are made to utilise as great a quantity of tracer as permitted by the resources.

2.3 Sampling

Following release into the environment, particle tracking studies become wholly an exercise in sampling. In the case of fine sediment studies (e.g. dredge material dispersal), the sampling is dominantly directed at the suspended fraction using time-integrated suspended particle traps (a technological development to capture particles moving *horizontally* in a flow and which is described in detail in the accompanying presentation), vertical sediment traps (to measure downward particle flux), water samplers (most useful for instrument calibration) and fast-response optical and acoustic sensors e.g. optical backscatter sensors. For sediment which moves as bedload (including saltation) bottom sampling using grabs and coring devices is the only means available since a marine sand bedload sensor awaits development. A number of differing techniques using grabs and cores are used to retrieve bottom sediments. In addition, a number of *in situ* techniques such as benthic and profile photography (which capture an image of the sediment-water interface, Solan, 2000) have been developed and these have direct application with modification to assessment of tracer presence in seabed sediment. Photographic methods provide only a presence-absence (binary) indicator, although this is most useful in a 'reconnaissance' sampling context. Note coring devices provide, in addition, the depth of the mobile layer - a key variable governing the mass transport rate of sands (Soulsby, 1997).

Sediment transport is inherently a geo-spatial topic involving sampling across both time and space. Although sampling design undoubtedly varies widely between studies, appropriate and statistically robust sampling design is critical and thus always necessary. This is especially important in instances where contaminant impact in sensitive areas e.g. SSSI or SPA sites is of interest. However, statistically well founded sampling design is not a trivial problem; frequently it may consume a fair proportion of the financial resources available and practical restrictions can limit the number of samples possible. For these reasons it is essential that any sampling programme is very carefully designed. Ill-advised or poor sampling schemes at best give rise to low information content datasets, and at worst produce results from which it is almost impossible to derive any sensible conclusions (Black et al. (b), in press).

Probability (statistical) or search benthic sampling is preferred in tracer-based seabed mobility studies or impact assessment projects, and a variety of sampling schemes may be used (random, stratified random, two-stage, nested, cluster etc.). In situations where information is desired across large geographic distances often the 'nested-sampling grids' concept is useful. Nested-grids are localised, smaller scale sampling grids that contain a sufficient level of sample duplication to assess mean and variance in tracer content properly (facilitating time-series analysis). These nested-grids can be distributed across the region of interest so encompassing the geographical extent of interest. It is important to recognise that particle tracking has limitations; chief amongst these is dilution, which can rapidly reduce the signal to noise ratio to ~1. At this point there is little utility in continued sampling, so bringing an end to the experiment. Sampling, therefore, needs to be undertaken well before this point is reached, and in practice this means sampling in the near-field before excessive dilution has a chance to occur. This point reiterates the need for intelligent and adaptive sampling

3. DISCUSSION

Particle tracking represents a powerful tool for use in coastal zone sedimentary research, and recent advances (e.g. the authors' dual signature' technical innovation) have significantly simplified tracking studies to the point where there now exists a diverse, generic application; the technology may be applied to a range of marine engineering and marine environmental problems including beach replenishment efficacy, longshore sand transport rate assessment, impact assessment in sensitive sites, impact of marine aggregate extraction on benthic habit morphology and integrity, contaminant storage and transport time-scales, and estuarine siltation rates. Clearly, particle tracking is a flexible and adaptable tool. Particle tracking is also particularly useful since after certain assumptions surrounding use of tracer are satisfied, it records transport on a spatio-temporal basis (unlike most other available technologies) and is representative of the real-world processes. Tracer studies integrate biological effects on sediment transport such as microbial binding and bioturbation (e.g. Black et al., 2002), and reflects the influence of the range of wave-current combinations and seabed morphologies found in nature. It is quite impossible to represent or reproduce these effects accurately in laboratory or model simulations.

There are, however, as there are with any technology, limitations and chief amongst these is excessive dilution. This can be circumvented or at least reduced in importance through intelligent sampling design. Perhaps of greater importance in the wider context, and one which is indirectly related to the dilution problem, is the fact that particle tracking technology provides an indication of the sediment or contaminant transport under a limited set of hydrodynamic conditions only. In practice, one often selects the field conditions during which transport is most likely exacerbated e.g. during storms or during construction (e.g. adjacent to marine conservation sites), therby using particle tracking as a proxy for the worst case scenario. Ideally, one would conduct a series

series of tracking studies across a range of hydrodynamic conditions in order to encompass the range of environmental conditions.

3.1 Model Validation

The simplest solution to address the 'single conditions' problem is to combine particle tracking studies with sediment transport modelling. The major advantage of numerical models is the ease with which one can examine a wide variety of forcing wave-current and sediment response scenarios; however, in the absence of even partial validation, models represent at best an exercise in mathematics (Black et al. (b), in press). In order to correctly validate numerical models they should be run for the duration of the tracking experiment with the prevailing (measured) hydrodynamic conditions as inputs to the model runs and subsequently an analysis of the statistical similarity of predicted and measured sediment transport (Dyke, 1996).

The routine combination of particle tracking with numerical modelling is yet to come, in spite of the plethora of available model shells and codes and the widespread use of models by academics, consultants and marine professionals. It is not difficult to understand that such a combination would be mutually beneficial to both modellers and the 'measurers' of sediment transport, but clearly would provide a major benefit to coastal zone managers. Non-specialists should in principle be able to take full advantage of such a tool and run the validated model – with confidence – for the range of conditions relevant to their circumstances. Currently, modelling analyses of this sort remain in the domain of the larger consultants.

Development of a model validation exercise using particle tracking is a specialist endeavour (Dyke, 1996). Models operate on grids, for example, and necessarily use interpolation between grid nodes to define sediment transport at intermediate locations, and yet sediment transport can, and often does, occur at many localities simultaneously. Models often need to be re-defined in order that they specifically address point source release of tracer or, for example, calculate the sediment flux at the height of a suspended particle trap. This should not present insuperable difficulties for the modelling community.

Particle tracking (Lagrangian) models (Hunter, 1987), devised originally to model oil slick dispersal and in which particle positions are constantly updated, conceptually appear attractive as the mathematical equivalent of particle tracking experiments, however this is somewhat misleading. In the model case, the user tracks the location of introduced particles ad infinitum or over a specified period; this remains true whether particles are momentarily suspended or buried and enables the centre of mass of the released cloud of tracer (and hence the sediment transport rate) to be consecutively defined. On the other hand, the majority of particles in a particle tracking experiment can often be lost, precluding computation of the centre of mass. One practical approach here may be to model and measure the rate of loss of tracer (specifically bedload studies) over a period of time from a specific location, an approach commonly used in longshore sand transport studies (e.g. Ingle, 1966). The use of specialised benthic and profile photography may be particularly useful here in sub-tidal environments, especially as it can also provide data on mobile layer thickness (through the depth of burial of tracer in images) to compare with model burial/de-burial algorithms. Indeed, in the previous example this interaction of field measurement and model data is the process of model validation. Integration of modelling and field particle tracking offers improved confidence in model outputs, and therefore, provides a more useful decision making tool to both coastal scientists and coastal managers.

3.2 Impact assessment

Particle tracking is also an appropriate method with which to evaluate physical impacts onto sensitive marine sites. Currently, for example there are some 80 sensitive marine sites adjacent to port and harbour developments in which routine maintenance dredging occurs. Although increasingly marine disposal of dredge material is a secondary option to beneficial re-use (e.g. intertidal habitat creation), in those areas where marine disposal is exercised (e.g. offshore Milford Haven, SW Wales) the potential for smothering of the marine site exists. Since 1994, the EU Habitats Directive states that the port authority must demonstrate 'no adverse effect' of this material with respect to the marine site (Brooke, 2003). The prominent scientific challenge here relates to the fact that the dredge material - once influenced by the ambient tidal and wave currents - becomes indistinguishable from the native suspended sediments, and therefore a tracer is necessary to define transport from the source area (dredge placement zone) toward and into the marine site. Black et al (a) (submitted) describe the use of tracking technology in detail with specific reference to this context.

Experimental design can be framed around the dominant hydrodynamic processes at work cf. advection toward the marine site and sedimentation within the site. The use of time-integrated, autononomously deployed suspended particle traps located both in the nearfield (with respect to the dredger) and at the marine site boundary/farfield (Fig. 2) represents an appropriate monitoring strategy to measure the horizontal movement of dredge material. These traps accumulate sediments through time and then provide a time stamp on a user-defined basis, and thus the time of arrival of tracer together with the tracer mass can be used to judge whether the physical impact is likely significant or not. The use of two traps in a linear alignment in particular can provide additional information on rates of dilution between the source point and the marine site (using tracer data and associated current and turbidity information, both of which are logged by the traps).

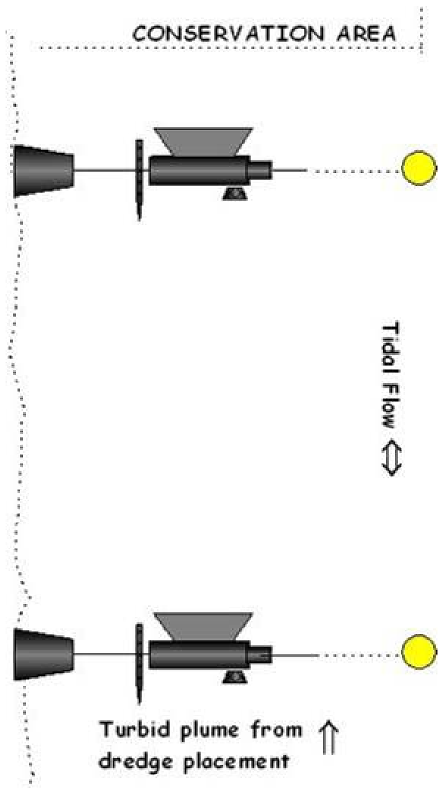

Figure 2. Combination nearfield-farfield sampling of suspended sediments (and tracer) using the time-series traps. This deployment/sampling strategy enables a wealth of information on the local sediment dynamics to be recorded, and for physical impacts to sensitive sites to be assessed with some confidence

The time-integrated horizontal particle traps can be used in conjunction with time-series vertical sediment traps to assess the relative importance of advection vs sedimentation within the marine site (Black et al. (a), submitted), and therefore provide firm evidence as to whether dredge material passes through a marine site or conversely settles onto the flora and fauna. Conventionally, significant operational problems have been associated with the use of vertical traps been associated with the use of vertical traps in shallow coastal zones where the hydrodynamic energy is greater (Gardner, 1980), but technical innovations by the authors now circumvent these limitations.

The use of (horizontal and vertical) sediment traps together with use of particle tracers presents a formidable tool for the direct assessment of the physical impact of seabed dredging operations. It is this type of information - hitherto unavailable - that is relevant to both coastal zone managers and conservation agencies.

4. CONCLUSIONS

A wide variety of contemporary environmental and socio-economic concerns are directly or indirectly associated with sediment transport in coastal regions, and increasingly there is a need to manage these in an environmentally sustainable manner. This paper has described briefly Particle Tracking Technology, which permits visualisation and mapping of sediment transport/contaminant pathways in coastal regions. Application of new methodologies together with the use of innovative technology now considerably enhance the utility of this approach. Two case studies highlighting the value inherent in the combination of particle tracking with numerical modelling analysis, and the practical means of assessment of dredge material impact on sensitive marine sites, have been presented.

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