7. Suspended Particulate Matter and Turbidity

1. Key points

i. **Introduction**

Suspended Particulate Matter (SPM) carries pollutants, shades light and so inhibits primary production, and embodies particulate organic matter forming part of the marine ecosystem (section 2). It is highly variable according to depth and physical processes in the area (i.e. tide and current regimes and wind; sections 2.1 and 3).

ii. **How has the assessment been undertaken?**

Traditional assessment methodologies are still used successfully, but various optical techniques are increasingly being used, for particle size as well as weight of SPM. This has increased understanding of the dynamics and processes associated with SPM in shelf seas, especially tidal stirring of sediments (sections 2.2, 3.1, 4). Remote sensing measurements of ocean colour provide time series for studying variability of suspended material, phytoplankton pigments and coloured dissolved material.

iii. **Current and likely future status of suspended particulate matter and turbidity**

Trends in SPM concentrations and therefore turbidity for UK waters show no significant change between *Charting Progress* (Defra et al., 2005) and *Charting Progress 2*.

iv. **What has driven change?**

Not applicable.

v. **What are the uncertainties?**

Remote sensing measurements are still hampered by weather (especially cloud) and by a lack of understanding of optics in (turbid) coastal and shelf waters (section 4).

vi. **Forward look**

For improved shoreline management plans there is a need for more quantitative information, especially on shoreline processes, wave interactions (inshore wave climate) and water flow along coasts (section 5). There is much interest and activity in SPM within coastal regions of the UK and Europe with EU Integrated Coastal Zone Management recommendations and a number of large EU-funded projects studying turbidity in coastal regions (section 6). The improved methods of assessment provide added data on suspended sediments, to allow better mapping of UK waters for environmental quality through turbidity measurements (section 5).

2. Introduction

Suspended particulate matter (SPM) in shelf seas is important because its properties determine turbidity in the water column (which constrains primary production and influences heat transfer), material transfers to the seabed (which determines sedimentation rates, biogeochemical transfers from water to seabed, and productivity of the benthos), and the flux and fate of associated pollutants and contaminants. Shifts in the fate of SPM between export to the pelagic food web or deposition to the benthos are critical in the assessment of eutrophication. Very close to a sandy seabed, suspended matter consists of resuspended mineral matter, but elsewhere in the water column SPM is typically in the form of flocs – loosely bound aggregates composed of mineral matter (e.g. clay minerals), organic matter (living and dead components of phytoplankton, heterotrophic organisms, bacteria, faecal matter), and water. While the primary components of flocs may be of the order of 1 to 5 μm in size, fully developed flocs grow to 600 μm or more. Because of their structure, flocs have a high surface-area to volume ratio, high water content and low density. Flocs are formed by collisions of smaller particles in low-turbulence regimes, and are ruptured by shear in high-turbulence regimes. Consequently, they vary in size and properties on short-time scales (significantly during a tidal cycle). Their fragility makes them difficult to sample conventionally so interrogation of floc properties relies on *in situ* techniques.

This section of the OPEG Feeder Report deals with SPM and turbidity but not specifically with the biological components of SPM: living plankton and phyto-detritus (plankton are considered in another chapter of this report). However, given the composition of flocs, it is impossible to ignore the profound biological influence on floc properties, dynamics, and fate. 'Turbidity' is a measure of the concentration of SPM in the water, which includes both biological and mineral material; SPM causes scattering and absorption of light rays and hence affects water 'clarity'. Light is scattered mainly by mineral suspended solids, whereas light is absorbed by mineral suspended solids, phytoplankton pigments, dissolved organic matter and the water itself (Bowers et al., 2002). Hence any consideration of suspended matter in shelf seas necessarily encompasses the biological components and phyto-detritus that at times in the seasonal cycle comprise the bulk of SPM.

Much of the information about suspended material in UK waters, as presented in *Charting Progress* (Defra et al., 2005), is still current. This section will show examples of new (more recent) data and highlight how this improves current knowledge. Key additions include recent instrumental developments that provide new measurements and fresh insights on SPM properties and dynamics.

Although there are a number of recent papers looking at SPM in the North Sea (e.g. Gayer et al., 2006; Eleveld et al., 2007; Fettweis et al., 2007), these largely focus on the Dutch and German areas of the North Sea, especially in regions of sand extraction and are based on pre-2004 data. Modelling SPM is a major contributor to new work, especially linked to the higher resolution satellite imagery from MODIS and MERIS, but also based on older data and imagery.

2.1 Processes controlling suspended particulate matter and turbidity

The concentration of SPM in UK shelf seas depends on a range of physical forcings, biological mediation, and the characteristics of the seabed. Suspended sediment concentration (SSC) is the net result of the competition between resuspension and deposition on which is superimposed the effect of advecting horizontal gradients.

Resuspension is due to the bed shear stress caused by horizontal momentum changes experienced by fluid parcels as they move up or down in turbulent eddies into faster or slower moving levels in the boundary layer. In large areas of UK shelf seas, tidal currents are the primary forcing of resuspension, while waves become the dominant agent in shallow water. Waves and tidal currents combine to generate bed shear stress over much of the shelf; waves enhance the bed stress so that sediment is mobilised and currents determine the magnitude and direction of transport. For non-cohesive beds, the threshold shear stress for initiation of grain movement and for suspension can be predicted, the important sediment property being grain size. For cohesive beds (i.e. a bed containing at least 10% clay), prediction becomes increasingly difficult as the proportion of cohesive clay increases. At present there is no reliable empirical or theoretical criterion for estimation of the threshold condition for cohesive beds. Furthermore, some or much of the resuspended material is benthic fluff (Jago et al., 1993), a low density surficial layer on the seabed derived in large part from phyto-detritus and other organic matter. Benthic fluff is resuspended by much smaller shear stresses than the bed sediment itself, and is the source of a significant part of the resuspension signal in the water column. The fluff layer generates anoxia at the sediment-water interface changing the biogeochemical regime at the seabed.

Deposition depends on settling of SPM which is governed by the size and density of the particles. Settling can be considered as 'sinking rate', i.e. the net downward flux as might be captured in a sediment trap, but is better conceptualised as 'settling velocity', the velocity with which particles settle in still, non-turbulent water since this absolute parameter can be used in numerical models of vertical exchange. The settling velocity of flocs is very variable (and difficult to measure) with values in the range 10^{-4} to 2×10^{-2} m/s (Jago et al., 2007); the upper part of this range exceeds that of fine quartz sand grains. Since flocs are prone to aggregation and rupture in a fluctuating turbulence regime, the settling velocity may vary over orders of magnitude on tidal time scales. The response of flocs to turbulence depends on floc strength – also very variable depending on how the flocs were formed in the first place. Consequently it is difficult to assign settling velocities to flocs in real shelf conditions. There is evidence that floc size and settling velocity have upper limits due to floc rupture by sinking stresses (Hill, 1998), but field observations show that, at least in the short term, flocs significantly exceed such limits.

Biological mediation of floc size and floc strength is well documented but not easy to quantify. A range of microbiota exude extracellular polysaccharides which, when associated with flocs, increase their propensity to aggregate. This process is variable: for example, the nutrient status of plankton cells probably affects their stickiness, and different types of biota undoubtedly give rise to flocs of different structure and strength. Biological mediation is seasonally variable and is probably most significant towards the end of the spring phytoplankton bloom. Its impact may also be spatially variable: limited data suggest that stratified waters are characterised by small, weak, slow-settling flocs while mixed waters are characterised by larger, stronger, fast-settling flocs, but how much of this is due to biological mediation is not clear (Jago et al., 2007).

2.2 Measurement of suspended particulate matter and turbidity

Measuring SPM *in situ* is difficult and can be subject to large sampling (including methodological) errors (Ellis et al., 2005); satellite-derived and modelled SPM data are more compatible (Binding et al., 2005). It is particularly difficult to make discrete *in situ* SPM measurements in tidal waters largely due to water movements and small-scale mixing processes which lead to significant variability in samples. *In situ* measurements are important for validation of optical measurements and for modelling, especially issues of size distribution which are key inputs to any SPM model.

Studies in CASIX (the NERC Centre for observation of Air-Sea Interactions and fluxes) showed that models of the UK shelf seas need to consider the effects of turbulence and how the SPM and coloured dissolved organic matter (CDOM) impact the light in the sea. The largest errors in shelf sea models are in the coastal and shelf-sea waters, due to their complexity in terms of light and physical processes. Turbulence is a key issue for the physics of models due to the interactions of coastal processes. Seabed type and particle size also need to be included when considering shallow waters.

High-resolution measurement of SPM concentration is achieved using optical and acoustic techniques. Optical sensors employ light transmission or backscatter (transmissometers, optical backscatter sensors OBS, respectively) as proxies for SSC. Since transmittance and backscatter are influenced by the size of particles as well as by their concentration, these optical instruments must be calibrated *in situ* for every deployment. Acoustic methods (e.g. Acoustic Doppler Current Profiler ADCP) can also be used but these too need calibration for specific applications. There are inherent problems in interpreting optical and acoustic data when SPM properties are changing on short time scales and/or when plankton cells augment SPM in the water column (Bunt et al., 1999) as calibration becomes increasingly uncertain. Nevertheless, such instruments have greatly increased understanding of the processes that determine SSC in shelf seas.

3. Progress since *Charting Progress*

A more recent innovation is *in situ* particle sizing using lasers (e.g. LISST; Agrawal and Pottsmith, 2000). These instruments provide, for the first time, the ability to monitor particle-size spectra of SPM with high temporal and spatial resolutions. LISST also provides volume concentration of SPM which in association with determination of SSC allows for calculation of floc effective density (Mikkelsen and Pejrup, 2000). However, LISST data need to be interpreted with caution in stratified regions of the shelf since water density differences can cause light scattering – schlieren – even though only few particulate scatterers may be present (Mikkelsen et al., 2008). Moreover, the veracity of optical and acoustic techniques for sensing SPM properties is uncertain when the particles are mostly flocs.

Remotely-sensed data using Earth Observation techniques potentially overcome some of the difficulties in measuring SPM properties on a regional scale, but the ability to use remotely-sensed ocean colour depends on the atmospheric correction, and the inherent optical properties (IOPs) of the water – the absorption and scattering properties which are highly variable in the so-called Case 2 waters of turbid coastal seas. (Case 2 waters are those waters whose optical properties are dominated by suspended particulate matter, dissolved organic matter and phytoplankton pigments; Case 1 waters are optically clear and the optical properties are determined only by phytoplankton.) Attenuation, being the sum of scattering and absorption, a measure of turbidity, encompasses all particles in the water, both the suspended sediment and the biological particles (e.g. phytoplankton), and all the dissolved material in the water. Disentangling the various contributors is problematic (e.g. Bowers et al., 2002). The diffuse attenuation coefficient, 'k_d', is one of the most accurate remotely-sensed measurements available. The NERC Earth Observation Data Acquisition and Analysis Service (NEODAAS) is able to produce time series of imagery from a number of ocean colour sensors to cover the whole UK shelf region or specific seas. Imagery can be presented as normalised water-leaving radiance at 551 nm, $nL_w(551)$, or any other similar wavelength which is considered to represent the concentrations of suspended sediment in the top optical depth of the water column. This depth is retrievable from the attenuation coefficient and for recent satellite sensors, k_d at 490 nm provides plots of this. This attenuation coefficient relates to the 'turbidity' of the water, and so includes all suspended material (of both inorganic and organic origin). Time series of $nL_w(551)$ and $k_d(490)$ from NEODAAS, for the whole UK shelf for January, April, July and October 2003 to 2007, derived from MODIS AQUA data, are shown in Appendix 1. For $nL_w(551)$ these plots highlight the higher turbidity closer inshore that is associated with certain large river outputs (e.g. the Thames), with shallow bank areas (e.g. Arklow Bank in the Irish Sea) and areas of strong tidal mixing (e.g. off Holyhead in the Irish Sea). The $k_d(490)$ plots show a more usual seasonal signal associated with phytoplankton blooms.

3.1 New evidence for suspended particulate matter in UK waters

The spatial distribution of suspended sediments is a consequence of hydrodynamic forcings acting on the unconsolidated sediments of the shelf and the coastline. In general, waves are more important for resuspension in shallow water (< 10 m) and currents become more important in deeper water (> 10 m). However, waves can be important at greater depths; for example, at the Liverpool Bay SmartBuoy which is a mooring at about 20 m depth, the variability in SPM is dominated by storms/waves, and the effect of these on turbidity is much longer than the storm events themselves. The sedimentary nature of the seabed is the result of an inherited relict distribution of glacial and fluvio-glacial deposits, much modified by waves and currents during and since the post-glacial transgression.

The complex interactions of process and response result in marked temporal variations of SSC superimposed on strong spatial gradients. The simplest model of SSC variation is the 'twin peaks' model (Weeks et al., 1992) whereby a time series of SSC at any location is composed of tidal signals – an M_4 signal (four tides per lunar day) due to resuspension superimposed on the semi-diurnal M_2 signal (two tides per lunar day) due to advection of a horizontal concentration gradient. The combination gives rise to a twin peaks signature with varying concentration minima at successive slack waters. This signature is best developed during spring tides; it may disappear on neap tides and during storms. Much of the signal is due to resuspension of benthic fluff and, in areas where there is a finite supply of fluff, peak SSC in the lower part of the water column occurs in advance of the peak current velocity (Jago and Jones, 1998).

Subsequent observations using LISST have shown that disaggregation of flocs, with M_4 frequency, is an additional major contributor to SPM properties over tidal cycles (see below).

On a regional scale, SSC is greatest in coastal zones due to enhanced supply from resuspension of bed material, fluvial inputs, and direct erosion of the shoreline (most important in areas where the shore is composed of poorly consolidated glacial deposits). The seasonal variation of wave conditions gives rise to a comparable variation of SSC and turbidity in those areas dominated by waves. There are also biological factors controlling turbidity which increases during phyoplankton blooms. There is a marked reduction in turbidity after the spring bloom; a possible explanation is that enhanced biological mediation of aggregation creates rapidly settling flocs which are sedimented to the seabed.

4. Presentation of the evidence

4.1 Irish Sea

The Irish Sea continues to be a test-bed for UK shelf sea processes, with easy access for the R.V. *Prince Madog*. There have been several Irish Sea initiatives concerned with SPM in the Irish Sea since *Charting Progress* (Defra et al., 2005). These include INTERREG projects such as MATSIS and "the use of ferries to monitor water quality in the Irish Sea", and the NERC-funded CASIX and TURBSED. There are ongoing studies as part of the NOC-led Irish Sea Observatory with regular cruises, and linked modelling and remote sensing studies.

Using satellite reflectance imagery, White et al. (2003) have shown that there was no overall trend in near-surface turbidity between 1987 and 1997 in the Irish Sea, but that year-to-year variability was positively correlated with changes in the mean annual regional wind strength, controlled by the north-south atmospheric pressure gradients and related to the North Atlantic Oscillation (NAO) Index. However, there is evidence that water clarity in the Irish Sea deteriorated between the mid-1960s and the late 1980s – the mean annual Secchi depth in the Menai Straits decreased from around 2.3 m to less than 1.5 m during that period (Lumb, 1990). More recent measurements (Kratzer, 2000; Kratzer et al., 2000) indicate that this decrease has reversed and unpublished measurements made as part of MSc practical work support this.

An overview of SPM seasonal variability can be seen at:
http://www.oceannet.org/library/publications/documents/marine_processes_and_climate.pdf
The images are composites at a resolution of 1.1 km, from a 1998 time series of NASA SeaWiFS satellite images for reflectance at 555 nm (closely related to SPM concentrations). More recent data are available through the MATSIS project, provided by NEODAAS, for $nL_w(551)$ bimonthly for 2005 (Figure 7.1) and 2006 (Figure 7.2), and for $k_d(490)$ bimonthly for 2005 (Figure 7.3) and 2006 (Figure 7.4).

Seasonal SeaWiFS data from the CASIX archive shows a very clear cycle of SPM for a site off Anglesey (Figure 7.5), but models are currently unable to reproduce this with a fixed settling velocity. The water is more turbid in the winter months, becoming clearer in the spring, reaching a low over the summer months and increasing again in autumn as autumnal winds induce more mixing. A seasonally-varying settling velocity resulting from aggregation/disaggregation linked to turbulence and biological mediation is required. This SeaWiFS output is an average value for a box around the Anglesey *in situ* sampling station (52.9°N, 5.525°W to 53.82°N, 4.15°W)) derived from the Moore-Aiken algorithm (Moore et al., 1999). The error bars represent one standard deviation, i.e. the spatial variability. This algorithm, however, produces SPM values which are less than the *in situ* data measurements.

Analysis of Irish Sea satellite imagery by Bowers et al. (1998, 2002) shows that isolated, persistent turbid patches of SPM occur in regions of enhanced tidal currents, for example, the presence of two separate turbidity maxima, one off Wicklow Bay, the other off Anglesey. These areas correspond to the areas of strongest tidal currents, and it is considered that the high reflectance is produced by fine sediments maintained in suspension throughout the water column by tidal stirring. However, the seabed sediment at these localities is predominantly coarse grained. Ellis et al. (2008) ascribed the persistence of these patches to a conservative balance of diffusion of small particles out of the turbid patch and diffusion of aggregated material towards it. An alternative explanation is that the patches result from throughput of SPM by advection plus settling, resuspension and disaggregation by turbulence within the patch.

Novel interpretation of satellite data by Bowers et al. (2007) provides a synoptic overview of particle size of surface SPM (Figure 7.6). The particle size appears to be limited by the Kolmogorov turbulence scale.

A major advance since *Charting Progress* has been the extensive deployments of LISST instruments providing both spatial gradients and temporal variations in particle size. New methods for measurement of turbulence properties (Rippeth et al., 2003) have provided insights into the physical controls of SPM properties in response to tidal forcing. These measurements provide previously unavailable information on how SPM responds to physical processes (especially water movements) and therefore provides new data on the reasons for the variations in turbidity in UK shelf waters. The influence of tides on turbidity is better defined, with information relating to resuspension of bottom sediments, as well to potential aggregation of material in suspension.

Extensive measurements in fast tidal streams off Anglesey have demonstrated that the particle size of SPM is due to a combination of time-varying turbulence at any point superimposed on space-varying turbulence advecting through the site (Jago et al., 2006). Time asymmetry in the turbulence field gives rise to an asymmetric M_4 signal in SPM volume concentration (Figure 7.7) due to asymmetric resuspension and disaggregation of flocs at times of peak turbulent energy.

Harmonic analysis of LISST time series (Figure 7.8) shows that aggregation of flocs occurs at high and low slack waters but the largest flocs occur at low slack water. This is due to space-varying ambient turbulence which produces a horizontal gradient in floc size with small and large flocs at opposite ends of the gradient (Figure 7.9); hence there is an M_2 signal in floc size.

Superimposed on this is the effect of time-varying turbulence at the observational site: resuspension and disaggregation occur at peak turbulence generation with M_4 frequency. At this particular site, the disaggregation contribution was ~ 40% as much as the resuspension component near the bed and ~ 20% integrated through the water column. Thus the time series shows a more complex interaction of processes than proposed by the simple twin-peaks model.

Resuspension occurs in deeper, stratified waters during spring tides. Thus in the gyre of the western Irish Sea, in water depth ~ 65 m, there is a clear M_4 resuspension signal on spring tides (Figure 7.10) but this is not seen on neap tides.

CASIX data (unpublished) shows the strong link between turbidity and phytoplankton (see Figure 7.10). The transmissometer data show turbidity maxima in the surface layer of the Irish Sea gyre and in the bottom mixed layer. Comparison with the fluorescence signal (representative of phytoplankton concentrations) shows the turbidity in the upper layer to relate to the higher abundance of phytoplankton in the stratified surface waters in May 2004. Turbidity in the surface layer is clearly linked to phytoplankton activity, while in the bottom layer it is due to resuspension of benthic fluff.

The National Oceanography Centre (NOC) runs the Irish Sea Observatory with regular sampling cruises and fixed moorings. For up to date data and full details of the instrumentation used, go to the website http://cobs.pol.ac.uk. With Cefas, NOC maintains a SmartBuoy in Liverpool Bay from which time series of data measurements can be made. Figure 7.11 shows the Liverpool Bay time series of suspended load, with the monthly average, the climatology and the anomaly for the seven-year period from December 2001 to September 2008. The station in Liverpool Bay has high variability, as shown by the error bars for the monthly average and climatology.

A recently developed 1D model of the resuspension of a mixture of non-cohesive SPM size fractions has been used to simulate successfully several years of the observed SPM in Liverpool Bay on supra-annual timescales, as shown in Figure 7.12 (van der Molen et al., 2009).

Studies in 2004-2006 piloted a scheme for using above-water radiometers mounted on ships of opportunity to monitor water quality in the Irish Sea (Mitchelson-Jacob et al., in preparation). Figure 7.13 shows the variation in remote sensing reflectance across the Irish Sea over the range of wavelengths of the above-water radiometers mounted on the Irish Ferries' ship *Ulysses* crossing between Dublin and Holyhead twice daily. The plot from 23 September 2004 shows high reflectance in the east, off Holyhead, generally lower in the central Irish Sea and slightly elevated reflectance towards Dublin, indicating that suspended loads are higher closer inshore and lowest in the central region.

From long-term *in situ* measurements carried out in the Irish Sea, a robust relationship has been observed between the reflectance ratio (665 nm / 555 nm) and the concentration of mineral suspended matter (MSS) (Binding et al. 2003, 2005). A relationship similar to this has been derived from the *in situ* data collected here – using the in-water samples collected to validate the optical measurements made. This relationship is used to retrieve MSS concentrations from the ferry radiometer data.

Monthly variations of turbidity with a daily resolution can be created using a kriging method for gridding the data in the Surfer Software. The results for September to November 2004 (Figure 7.14) show a number of features relating largely to the dynamical processes involved in the Irish Sea. There was minimum turbidity in the middle of the Irish Sea (~ 2 to 6 mg/l), with maximum values and variations close to the coasts (~ 6 to 30 mg/l). Distinct pulses, likely to be due to tidal resuspension or river inputs, can be seen off Dublin and Holyhead at times. Turbidity increased towards the winter.

4.2 North Sea

The southern North Sea, with stronger tidal currents and shallower water, has higher SPM concentrations than the northern North Sea. There is a strong seasonal signal in the southern part related to seasonality in the wave climate. A series of satellite images of reflectance at 555 nm during 1998, closely related to SPM concentrations, is at:
http://www.oceannet.org/library/publications/documents/marine_processes_and_climate.pdf
The images are NASA SeaWiFS composites for the North Sea 1998 at a resolution of 1.1 km. The scale is mg/l. The residual transport of SPM follows the anticlockwise gyre of the North Sea which, as a result, transports suspended matter eroded from the east coast of the UK (especially East Anglia). For comparison, more recent time series of $nL_w(551)$ and $k_d(490)$ for the UK shelf seas, as supplied by NEODAAS, are shown in Appendix 1.

As part of the Southern North Sea Sediment Transport Study Phase 2 (SNS2), from 2000 to 2002, historic measurements of SPM were compiled (including the measurements made under Phase 1 completed in 1996), new measurements were made (April-December 2001) and compared with sediment transport models. The SNS2 was designed to provide a broad appreciation and detailed understanding of sediment transport along the eastern coastline of England between Flamborough Head in Yorkshire and North Foreland in Kent, on the south side of the Thames Estuary.

SPM values held by Cefas (as at April 2002 including the data collected in the SNS2 project) were grouped into measurements taken in summer and winter. The summer and winter distributions of suspended fine sediments obtained by sampling the surface waters of the southern North Sea are shown in Figure 7.15.

Concentrations of suspended sediment in the southern North Sea in summer (Figure 7.15) are generally low in offshore areas (0 to 4 mg/l), with higher SPM concentrations found in estuaries, especially the

Thames and Humber with values over 300 mg/l. Some higher concentrations close to the coast were attributed to the Humber plume and the effect of high spring tidal currents off Great Yarmouth/Lowestoft.

The winter suspended sediment concentrations are higher, generally about double the summer concentrations (Figure 7.15) but with similar patterns in the coastal areas. There is a dominant plume-like feature, reported by Dyer and Moffat (1998); it extends north-east from Norfolk across the North Sea towards the Netherlands and also showed in the modelling for SNS2. This may be due to local resuspension by wave activity but the data density in this region is too low to make definitive judgements. Figure 7.16 shows a SeaWiFS image from 19 October 2000 with a distinctive strong reflectance plume indicative of higher levels of suspended sediment.

A study in the southern North Sea off the Dutch coast illustrates how SPM properties are governed by an interacting combination of physical and biological processes (McCandliss et al., 2002). The study area was in ~ 20 m water depth and influenced by outflow from the Rhine. The observations in spring showed SPM and chlorophyll concentrations characterised by a two-layer structure with low concentration in the surface layer and higher concentrations near the bed. The surface layer, of relatively low salinity, contained larger particles than the more saline bottom layer (Figure 7.17).

Near-surface SPM was characterised by slow-settling particles (modal settling velocity 10^{-4} to 10^{-3} mm/s). Resuspension of relatively small, fast-settling (> 10^{-1} mm/s), predominantly inorganic particles occurred during spring tides and storms. During calm, neap tide periods, settling and deposition occurred (modal settling velocity 10^{-2} mm/s). The remaining SPM was dominated by large slow-settling particles, especially in the surface layer. In spring, phytoplankton formed a major slow-settling component of near-bed SPM, which was maintained in suspension during spring tides and storms but settled to form an aggregated phyto-detrital fluff layer during at least two calm neap tide periods. The observations show the relatively rapid rate at which fluff layers are formed and dispersed, and highlight the need for high frequency measurements during studies of vertical exchange processes.

Fettweis et al. (2006) showed the strong relationship between the floc size of SPM and the turbulence regime over tidal cycles in the Belgian coastal zone (Figure 7.18). As a result, floc size increases offshore as turbulent stresses diminish.

Resuspension of benthic fluff also occurs in much deeper water. A study in the northern North Sea (water depth > 100 m) shows that a threshold bed shear stress of 0.02 to 0.03 Pa was needed to resuspend fluff so that resuspension occurred on spring tides (Jago et al., 2002). However, peak bottom-layer SPM concentrations preceded peak tides by three days due to a finite supply of fluff at the site. Modal settling velocities of SPM in long-term suspension were 10^{-4} to 10^{-3} mm/s while the resuspension component had modal values 0.2 to 5.7 mm/s (Figure 7.19).

Cefas SmartBuoy data from the southern North Sea (Figures 7.20 and 7.21) show the time-variation in suspended load, its monthly average, climatology and the anomaly over the seven-year period from December 2001 to September 2008. This shows the annual peaks of suspended load increasing from 2001 to 2007 for Warp (TH1) NMMP, from the outer Thames Estuary, with higher (~ two-fold) concentrations than at West Gabbard to the north. The peak concentrations occur in the winter months, highest in March, with the lowest concentrations occurring after the spring phytoplankton bloom in May/June. All plots indicate that suspended load is highly variable.

4.3 English Channel

Seasonal observations of the nature and concentration of SPM for the western boundary of the eastern English Channel were reported by Velegrakis et al. (1999). The highest concentrations were found adjacent to the English coastline, with lower concentrations offshore (Figure 7.22). The highest concentrations occurred in winter when SPM was enriched with coarse silt particles. The diatom communities found within SPM indicate that material resuspended in the coastal zone was transported offshore. SPM fluxes (based upon the observed SPM concentrations and the output from a 2-D hydrodynamic model) from the western Channel ranged between 2 and 71×10^6 t/y with a mean of around 20×10^6 t/y over the period of the observations (1994–1995). These fluxes are comparable to the mean values previously reported (Defra, 2005) as output through the Dover Strait. Therefore, it is possible that the eastern English Channel may be characterised as an area of fine-grained sediment bypass.

5. What the evidence tells us about environmental status

The main changes associated with suspended material and turbidity are from new developments in methods for sensing SPM, for example the LISST, measurements of turbulence, and developments and new sensors in Earth Observation.

- Trends in SPM concentrations and turbidity, identified in *Charting Progress* (Defra, 2005), show no significant change.
- Traditional methodologies are still used successfully, although more emphasis is on optical techniques, such as transmissometers and radiometers. Each of these provides limited data due to the current lack of understanding of marine optics, especially in turbid waters. Many optical studies relate to weight of SPM – but particle size is also important.
- New optical instrumentation is now available to study particle size, such as LISST – low-angle laser scattering or laser diffraction instruments. This has increased understanding of the dynamics and processes associated with suspended particles in shelf seas, especially tidal stirring of sediments.
- Remote sensing measurements of ocean colour provide time series for studying variability at a higher resolution than previously. Two parameters are used: water-leaving radiance in the green, for example $nL_w(551)$ and diffuse attenuation, $k_d(490)$. However, these measurements are still hampered by limitations such as weather and by a lack of understanding of the coastal and shelf water marine optics ('Case 2' problem).

Good-quality waters are needed to sustain a fully-functioning healthy ecosystem. Recent data improve understanding of coastal and shelf sea processes, especially with respect to particle size and SPM. Current evidence is that the concentrations of suspended material, and therefore the turbidity, have not significantly changed since *Charting Progress*. Specific, localised, inshore high-turbidity events have been seen following heavy rain events and localised flooding, but this has always been the case.

Satellite monitoring, although an attractive approach for broad-scale assessments of water quality with the higher spatial and spectral resolution of current sensors, is limited by the difficulty of obtaining high-quality images, by cloud conditions over the UK shelf seas; also it can only assess surface waters. Despite the limitations, through its easy method, with a good spatial scale for UK shelf seas, the use of colour satellite imagery can be a contributor to monitoring environmental status and its change over time.

The summary table (Table 7.1) includes an assessment of trend but not status ('traffic-light') because (1) no accepted criteria apply for suspended material giving significant risk of adverse effects; and (2) the UK (government), or even the EU, cannot itself take measures to improve the status.

Suspended sediment is subject to a wide range of natural variability on many time scales, reacting quickly to local flow (circulation) and conditions for phytoplankton production. There is no reason to suppose that this variability or typical suspended concentrations have changed significantly to have an impact on the environment or human health. Local construction has the potential to introduce local changes and significant impacts on the spatial scale of the construction, such as in harbours and around wind turbine pylons. Climate change, given the expected changes of sea-level rise and a potential increase in storminess, will impact on suspended load, with many coastal areas becoming more turbid through direct impact of both these scenarios. The higher sea level rises, the more upper-beach/terrestrial sediment will enter the marine environment, adding to the sediment load and potentially changing the type (and particle size) of sediments in suspension in coastal regions. Any increase in storminess through wind and or wave action will impact on shallow water regions in particular by increasing the resuspension of bottom material.

6. Forward look and need for further work

Both new and previous data of SPM and turbidity variations in UK waters show that there are gaps in understanding and that a clear picture of the spatial and temporal variability of SPM and turbidity is missing – largely due to the rate of change in the dynamic processes that control these. To assess how this relates to environmental status needs an understanding of the role of SPM in the marine environment. SPM controls the entry of light into the sea, and binds pollutants and nutrients, such as phosphate. Better knowledge is needed of how these bindings occur and under what conditions release occurs.

The main questions to be addressed are therefore:

- What is the role of SPM in determining, and therefore changing, environmental status?
- Are background levels of SPM changing and, if so, is the change significant?
- What is the role of SPM in the diagenetic processes that bind nutrients to it; what happens to these nutrients; how are they released back into the environment?

For the future, the impacts of SPM on environmental quality need to be assessed under climate change scenarios:

- Will increased storminess increase mobilisation of sediments and release pollutants back to the water column and how might this impact on marine ecosystems and human health?
- How could these increased levels of turbidity affect optical properties of the shelf seas and what will be the impact of this on phytoplankton blooms and productivity?
- How might changes in catchment affect coastal waters – impacts of climate change on both catchments and coastal regions?
- How will raised water temperature affect phytoplankton biogeochemistry and how will that feed back upon SPM through flocculation processes?

Advances in marine optics and use of in-water and remotely-sensed data for monitoring SPM and turbidity in coastal and turbid waters highlight areas of uncertainty and limitations in their use. Although improvements have been made, the 'Case 2' problem for use of ocean colour satellite data in turbid waters is still unresolved and inhibits the derivation of precise ocean colour data due to a poor atmospheric correction; SPM is a major inhibitor in the ability to derive phytoplankton measurements in sediment-laden waters.

Integrated coastal zone management (ICZM) is being rolled out in many regions, each with 'new' indicators for this. For example, the Wales Coastal Maritime Partnership has compiled ICZM indicators for Wales – see the draft list at www.walescoastalpartnership.org.uk/images_client/resource/Draft%20List%20of%20Welsh%20ICZM%20%20Indicators.pdf. These bring to the fore management issues for coastal waters where SPM levels can have negative socio-economic impacts; from impacts on human health to the aesthetics of bathing waters.

CETaSS – the Wirral Shoreline Management Plan (SMP) – Stage 1 Scoping study (Cell Eleven Tidal and Sediment Study; Faber Maunsell, 2005) recommends the need for more quantitative information, especially on shoreline processes, wave interactions (inshore wave climate) and water flow along coasts for improved shoreline management plans.

6.1 Conclusions

The present state shows little change since *Charting Progress*. However, given recognised climate change impacts for coastal regions, changes are anticipated in the future. Several proposed studies aim to assess how climate change will impact coastal regions and model the scenarios for this. There is a lot of interest and activity in coastal regions with the EU ICZM recommendations and a number of large EU-funded projects studying turbidity in coastal regions, for example, IMCORE - Innovative Management for Europe's Changing Coastal Resource.

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Figure captions

Figure 7.1 Bimonthly MODIS Aqua images for 2005 showing $nL_w(551)$ for the Irish Sea. Data supplied by NEODAAS to the MATSIS project. Land and cloud and edge of scene are masked in black. Higher suspended loads are indicated by the green to red colourations.

Figure 7.2 Bimonthly MODIS Aqua images for 2006 showing $nL_w(551)$ for the Irish Sea. Data supplied by NEODAAS to the MATSIS project. Land and cloud and edge of scene are masked in black. Higher suspended loads are indicated by the green to red colourations.

Figure 7.3 Bimonthly MODIS Aqua images for 2005 showing $k_d(490)$ for the Irish Sea. Data supplied by NEODAAS to the MATSIS project. Land and cloud and edge of scene are masked in black. Higher turbidity is indicated by the green to red colourations. The July image illustrates the high turbidity associated with phytoplankton blooms in Liverpool Bay.

Figure 7.4 Bimonthly MODIS Aqua images for 2006 showing $k_d(490)$ for the Irish Sea. Data supplied by NEODAAS to the MATSIS project. Land and cloud and edge of scene are masked in black. Higher suspended loads are indicated by the green to red colourations, with periods of phytoplankton activity having the highest values.

Figure 7.5 SPM concentrations derived from SeaWiFS data from 2001, for Holyhead, Anglesey. The error bars represent one standard deviation. From Mitchelson-Jacob et al. (2006).

Figure 7.6 Near-surface median particle size by volume estimated from satellite images for (a) summer (contour interval 50 µm), and (b) winter (contour interval 20 µm). From Bowers et al. (2007).

Figure 7.7 Turbulence and SPM properties at a site off Anglesey, Irish Sea. (A) Turbulence production from seabed ADCP; (B) Turbulence dissipation from profiling FLY; (C) SPM volume concentration from profiling LISST. Measurements at 1 h intervals. Turbulence in $\log_{10} W/m^3$ and volume concentration in µl/l (= ppm). From Jago et al. (2006).

Figure 7.8. Variation in SPM properties over a 50 h period. (A) Median particle diameter (µm), (B) volume concentration (µl/l) of particles < 100 µm (arrows indicate peak values corresponding to times of peak turbulence; the signal diminishes over time as neap tides are approached), (C) volume concentration (µl/l) of particles > 100 µm (arrows indicate peak values corresponding to times of minimum turbulence (slack waters): red arrows at low water slack, yellow arrows at high water slack; high water signal disappears towards neap tides). Time scale is in hours after the first low water slack. Width of arrows approximates to magnitude of signal. From Jago et al. (2006).

Figure 7.9 Spatial variation in median particle diameter (µm) along a transect off Anglesey. From Mitchelson-Jacob et al. (2006).

Figure 7.10. Fluorescence (top) and beam attenuation (bottom) during spring tides in the gyre of the Irish Sea. From unpublished CASIX data; courtesy of G. Mitchelson-Jacob, Bangor University.

Figure 7.11 Liverpool Bay time series for suspended load from the Cefas SmartBuoy for December 2001 to September 2008. The upper panels show the time-series of (left panel) half-hourly data and (right panel) monthly mean and standard deviation (blue error bars) of the half-hourly data. The lower left panel shows the seasonal cycle by mean and standard deviation (red error bars) of the monthly means, and also (blue error bars) the mean monthly standard deviation of the half-hourly data. The lower right panel shows the anomaly time-series of the monthly mean to the climatology. Courtesy of J. van der Molen and N. Greenwood, Cefas.

Figure 7.12 SPM concentrations at 1 m below the surface in Liverpool Bay. a) Total concentration (grey: observations, black: model); b) 10 µm fraction (model); c) 31 µm fraction (model); d) 60 µm fraction (model). The total concentration in the model is the sum of the three size fractions. All fractions were assumed to be non-cohesive quartz. The gaps in the model results represent times for which wave data were not available to force the model. The finest fraction rarely settles and provides a background concentration. The 31 µm fraction provides a seasonally varying background. The 60 µm fraction primarily responds to wave events because of its larger settling velocity. Reproduced from van der Molen et al. (2009).

Figure 7.13 Variation across a spectrum (350 to 950 nm) of remote sensing reflectance measurements along a transect across the Irish Sea from Dublin to Holyhead. From Mitchelson-Jacob et al. (in prep.).

Figure 7.14 Monthly variations of turbidity (represented as mineral suspended sediment, mg/l) with a daily resolution for September to November 2004. From Mitchelson-Jacob et al. (in prep.).

Figure 7.15 Suspended load based on SPM data in the CEFAS archive for April 2002 for winter and summer months. The data are from discrete water samples. From SNS2 (2002).

Figure 7.16 Large-scale transport of suspended matter depicted by a SeaWiFS image from 19 October 2000, clearly showing the extent of the Thames plume. From SNS2 (2002); data supplied by NEODAAS.

Figure 7.17 (a) SPM concentration (mg/l), (b) chlorophyll concentration (mg/m^3), (c) median particle diameter (µm) and (d) salinity in the southern North Sea, spring 1999. From McCandliss et al. (2002).

Figure 7.18 Through-tide measurements in September 2003: (A) SPM concentration (mg/l), water depth (m) and vertically averaged current velocity (m/s) and (B) averaged particle size (μm) and Kolmogorov microscale of turbulence (μm; from model result). Measurements at ~ 3 m above bed. From Fettweiss et al. (2006).

Figure 7.19. Settling velocity spectra (a) near-surface and (b) 1 m above bed showing enhanced tidal resuspension component (fluff) near the bed; (c) near-surface and (d) 1 m above bed four days later at peak spring tide after total removal of the fluff layer, so low SPM concentration and minimal resuspension. From Jago et al. (2002).

Figure 7.20 Warp (TH1) NMMP time series for suspended load from the Cefas SmartBuoy for December 2001 to September 2008. The upper panels show the time-series of (left panel) half-hourly data and (right panel) monthly mean and standard deviation (blue error bars) of the half-hourly data. The lower left panel shows the seasonal cycle by mean and standard deviation (red error bars) of the monthly means, and also (blue error bars) the mean monthly standard deviation of the half-hourly data. The lower right panel shows the anomaly time-series of the monthly mean to the climatology. Courtesy of J. van der Molen and N. Greenwood, Cefas.

Figure 7.21 West Gabbard time series for suspended load from the Cefas SmartBuoy for December 2001 to September 2008. The upper panels show the time-series of (left panel) half-hourly data and (right panel) monthly mean and standard deviation (blue error bars) of the half-hourly data. The lower left panel shows the seasonal cycle by mean and standard deviation (red error bars) of the monthly means, and also (blue error bars) the mean monthly standard deviation of the half-hourly data. The lower right panel shows the anomaly time-series of the monthly mean to the climatology. Courtesy of J. van der Molen and N. Greenwood, Cefas.

Figure 7.22 SPM concentrations (in mg/l) in the surficial waters of the eastern English Channel (early September 1994). The open circles show the locations of the sampling stations. From Velegrakis et al. (1999).

APPENDIX 1 NEODAAS imagery - $nL_w(551)$ and $k_d(490)$ for UK Shelf Seas

Figure 7.A1. Turbidity maps from Earth Observation data for selected months from each season, 2003-2007. These show Aqua-MODIS diffuse attenuation coefficient $k_d(490)$, which indicates the fraction of blue-green light that is attenuated per metre depth. CONTINUED ON NEXT TWO PAGES.

Figure 7.A1 (cont.) Turbidity indicates the presence of both suspended sediments and phytoplankton, and so there is large interannual variability in this parameter. Low light in January prevents the reliable use of Aqua-MODIS data at higher latitudes. In April the turbidity is dominated by suspended sediment, particularly in the southern North Sea, though the spring bloom is often present in the Celtic Sea. In July the sediment is at a minimum so the turbidity indicates phytoplankton in the NE Atlantic. With less phytoplankton growth, October turbidity is mostly influenced by sediment.

Figure 7.A1 (cont). Although the seasonal patterns are similar across 2003-2007, bloom events provide the most noticeable differences, for instance in the Atlantic NW Approaches in July 2005 and northern North Sea in April 2007.

Figure 7.A2. Maps of monthly suspended sediment concentration from Earth Observation data. These are Aqua-MODIS water-leaving radiance at 551nm - $nL_w(551)$, which may be used as a proxy for suspended sediment, though note that it also highlights scattering particulates such as coccoliths. These maps clearly

show the spatial distribution of suspended sediment in UK waters seasonally from 2003 to 2007. CONTINUED ON NEXT TWO PAGES.

Figure 7.A2 (cont.) The seasonal pattern is consistent across these years, with much less interannual variability than the corresponding turbidity maps. It can be seen that the Irish Sea, southern North Sea, and northern English Channel are subject to high sediment loads for most of the year except summer. Coccolithophore blooms are often present in the North Sea in July.

Table 7.1 Summary assessment of trends

Parameter	**CP2 Region**	**Key factors and impact**	**What the evidence shows**	**Trend**	**Confidence in assessment**	**Forward look**
Suspended Particles	1, 2, 3, 4, 5 (North Sea, Channel, Celtic Sea, Irish Sea)	Tides, winds, waves, site. Affects primary production	Varies on short scales	No clear trend	Medium	Nearshore increase?
Suspended Particles	6, 7 (Scottish shelf seas)	Tides, winds, waves, site. Affects primary production	Varies on short scales	No clear trend	Medium – no new data identified	Nearshore increase?
Suspended Particles	8 (Adjacent Atlantic)	Tides, winds, waves, site. Affects primary production	Varies on short scales	No clear trend	Medium – no new data identified	No clear trend