# SECTION 2 - PLUMES: SOURCE, TRANSPORT & FATE

## 2.1 The Importance Of Plumes

Suspended sediment plumes created by dredging operations are of interest in physical, biological and general environmental terms. A plume may be considered to have both positive and negative effects. Any effect will vary in its importance according to its location. What is important in one location may not be so important in another. A plume may have effects whilst it is in suspension, and further, different effects during and following settlement. The detailed study of the impacts of plumes is therefore site-specific. Generic guidelines may be produced to standardise the requirements and specifications for site specific studies of plumes contributing to the competent conduct of an Environmental Assessment (EA). Examination of the impact of a sediment plume attributable to aggregate dredging forms *part* of the Environmental Statement (ES).

| **Mode** | **Effect** | **Perceived Impact** |
|---|---|---|
| SUSPENSION | reduced light penetration | reduced algal growth<br>reduced visibility<br>reduced primary productivity |
| | increased suspended solids | visual impact<br>decreased respiratory capacity<br>decreased reproductive capacity<br>decreased feeding capacity<br>deterrence of spawning<br>modification of migration routes |
| | increased nutrient flux | increased feeding opportunity<br>increased reproduction rates |
| SETTLEMENT | increased sedimentation rates | smothering of slow moving bottom dwellers<br>blocking of filter feeders<br>smothering of seabed fauna<br>smothering of hard bottom communities<br>silting of crab and lobster holes |
| | changes in sediment type | alteration of seabed sediment particle size distribution<br>alteration in character of sediment supply to beaches |
| | new sedimentation regimes | smothering of archaeological sites |

**Table 2.1** *Summary of the impact of plumes generated by aggregate dredging operations in particular, which generally concern only non-cohesive, granular sediments. Dredging of cohesive sediments have further implications, but detailed consideration is outwith the scope of this report.*

The field studies and comprehensive world-wide review of recently published literature strongly confirm the importance of recognising the specific interactions between the type of dredging activity, the geology and the environment. It is therefore necessary to consider the specific types of dredging technology that is applicable to the UK marine aggregate industry. The geological, biological and oceanographic environment in which the disturbance occurs will determine the impacts and the consequential relative significance of those impacts on the environment and other users of the environment.

## 2.2 Aggregate Dredging Methods

### 2.2.1 Trailing Suction Hopper Dredgers

Currently, aggregate dredging in the United Kingdom is predominantly undertaken by trailing suction hopper dredges (TSHD) (Plate 2.2.1a TSHD Sand Heron). These seagoing vessels contain all the necessary plant for highly automated and efficient operations including self discharge in port. Specifications for some of the U.K. marine aggregate mining fleet are reproduced in Table 2.2.1. For dredging in waters deeper than about 32m, the dredge pump may be mounted on the dredge pipe, rather than in the hull of the dredger.

**Plate 2.2.1a** *TSHD Sand Heron*

During loading, one or two suction pipes are trailed across the seabed at slow speed (<4m/s) whilst the sediment/water mixture is pumped aboard the vessel. The draghead at the end of the suction pipe in contact with the seabed may in its simplest form be of a plain pipe-end arrangement such as the ‘Sharks Mouth’ with a size little more than the diameter of the suction pipe. More commonly either a ‘Fixed Visor’ (varies from approximately 1.5m to 2.5m in width) or a ‘California’ type adjustable visor (1.75m to 2.75m width) (plate 2.2.1b) are used. Modern dredgers tend to favour the latter type.

**Plate 2.2.1b** *‘California’ Type draghead*

During loading, excess seawater is allowed to overflow from the hopper either by deck level spillways or a central chute. Overflow of lean mixture, predominantly containing some clays, silts and fine sands promotes retention of a full cargo of solids (Plate 2.2.1c).

There are some exceptions to permissible overflow, usually encountered when dealing with cohesive sediments, predominantly of silt/clay fractions, whilst undertaking capital or maintenance dredging of ports or harbours. In these cases there may be a risk of remobilising heavy metal contaminants bound to the sediment into the water column or creating very dense clouds of fine sediment. Such scenarios are unlikely during the mining of marine aggregate.

Economic *in situ* gravel/sand assays may contain 15-55% gravel, whereas most commercial cargo requirements will dictate 35-70% gravel content (A.R. Hermiston, *pers. comm.*) depending on customer requirements, local geology and ship performance. In order to improve the quality of the cargo, ‘screening’ techniques during loading are often used to reject the fractions of the pumped mixture not required. Such beneficiation improves the overall load/unload & process cycle timings considerably whilst not raising problems of generating large quantities of unwanted materials on land. Cargoes containing incorrect proportions of aggregate sizes will be difficult for the dredging company to sell. Some extraction licences in the U.K. do not permit screening during loading (*e.g.* Shingle Bank, Hastings).

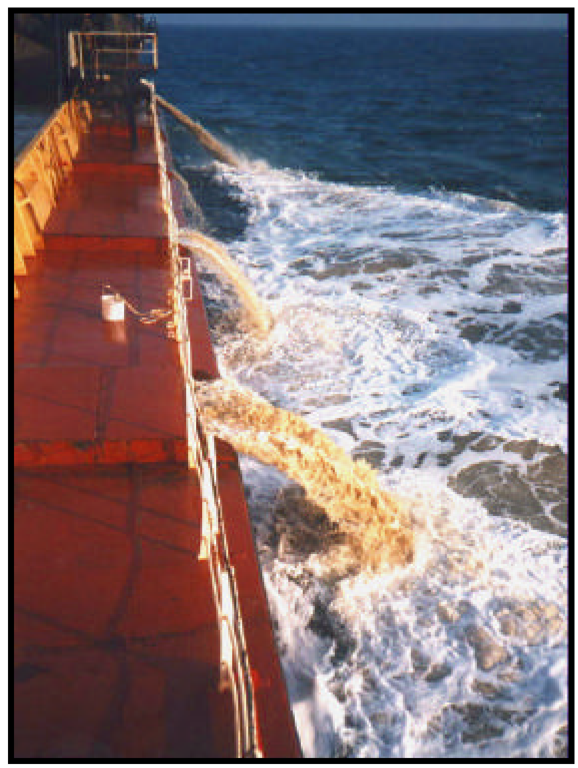

**Plate 2.2.1c** *Overflow from the ARCO Severn*

The vessel Master has the ability to raise and lower the draghead from the seabed to alter the density of the pumped mixture (to avoid ‘choking’ the dredge pump) and to wash-off any contamination of the cargo, for example by silts and clays *etc*. The draghead may also be lifted clear of the bottom to avoid any known obstacles or patches of poor materials, the locations of which will be recorded on the navigation plotting system. Special 'dump valves' may be fitted within the loading pipes which allow the pumped mixture to be instantaneously returned overboard, should contaminants, such as clays, be seen by the dredge Master before the material enters the hopper. On board instrumentation is becoming more widespread for semi-automation.

To facilitate fast turnaround in port, most vessels are equipped with self-discharge machinery, in the form of bucket wheels (*see* Plate 2.1.1a), scraper buckets, grabs or 'back-actors'. Cargoes can be discharged direct to wharfage without shore based plant costs. The larger trailing suction hopper dredgers are expected to work on a year round basis, with only limited interruptions due to the severest weather conditions.

The idealised concept of 'strip mining' using trailing suction hopper dredgers (*for example*, promulgated in Nunny & Chillingworth, 1986), is seldom realised. In practice, the dredge vessel will operate within a prescribed dredge run (based on geological prospecting & monitoring) with the track of the vessel scribing an 'hour glass' appearance (Davies & Hitchcock, 1992).

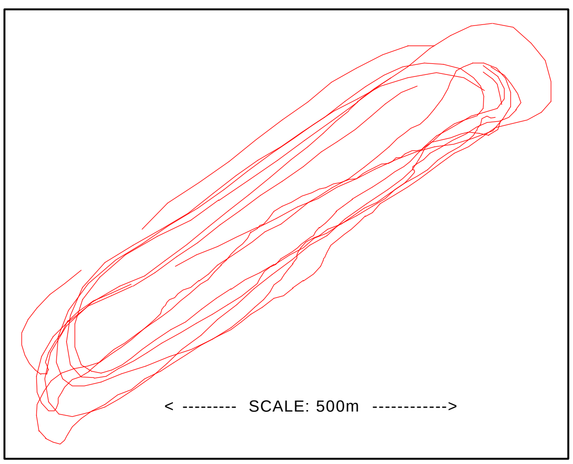


**Figure 2.2.1** *Navigation plot from the ARCO Severn Electronic Monitoring System (EMS) working an English Channel Licence, 21st August 1995. The proportion of the seabed remaining undisturbed between successive passes is clear. At the ends of the dredge run, superimposition of some successive passes occur. The size of the dredge run is limited (approximately 1100m x 250m), taking advantage of a localised channel deposit amongst a surrounding seabed of poorer grade deposits. The dredge run is oriented parallel to the dominant ebb and flow tidal currents.*

Within a licence area, there will be numerous discrete 'dredge-runs' and these will not usually encompass the whole licence footprint due to geological and operational constraints, for example, pockets of silt or clay, contamination by wreck debris, turning circles, navigation, pipelines/cables, exclusion zones (Figure 2.2.1). There will be an amount of seabed not physically disturbed by the dredging process, although this may be impacted in other ways. This has important ecological implications (*see* Section 6.7). At the ends of the dredge-run, when the vessel is turning, and near the middle of the run, lowering of the seabed may be slightly more than in other parts of the run, as successive trails superimpose on one another. The development of a 'trailer track' (Nunny & Chillingworth, 1986) does not appear widespread (*pers. obs. and* Davies & Hitchcock, 1992).

### 2.2.2 Anchor Dredging

The trailing suction hopper dredgers technique has largely superceded the practice of 'anchor dredging', although it can be favoured in certain circumstances. During anchor dredging the vessel lies at anchor whilst loading. The dredge pipe is forward facing, and the draghead of simple form. During the loading process, the dredger swings in an arc at the end of the anchor line, and/or moves forward slowly by hauling in the anchor chain. Anchor dredge vessels are generally smaller (Plate 2.2.2 Sand Swan) and often older than the majority of trailing suction hopper dredgers. Presently, there are only two dedicated anchor dredgers (Sand Swan and Sand Swift; G Singleton, *pers.comm.*), although some smaller existing dredgers can operate under both modes and there are new vessels under construction capable of both anchor and trailer dredging.

**Plate 2.2.2** *Anchor dredger Sand Swan*

The static nature of anchor dredging allows small, localised deposits to be worked where permitted. Sometimes this may be to some considerable depth below the surrounding seabed, although in the U.K. present licensing arrangements restrict removal to a maximum of 3m below surrounding seabed level. This is advantageous on small licences or where the resource is patchily distributed. On even or thin but extensive resources the trailing suction hopper dredgers is the preferred method.

| | Dredge Pipe Diameter | Hopper Capacity | Power | Type |
|---|---|---|---|---|
| ARCO ‘A’ Class x 4 | 700mm | 4500 t | 3942hp | TSHD |
| ARCO ‘T’ Class x 2 | 700mm | 3500 t | 3400hp | TSHD |
| ARCO ‘S’ Class (Severn) | 700mm | 2200 t | 2460hp | TSHD |
| ARCO ‘D’ Class x 2 | 450mm | 1300 t | 1550hp | TSHD |
| Camdijk | | 3110 $m^3$ | 5400hp | TSHD |
| Cambrae | | 3000 $m^3$ | 5840hp | TSHD |
| Cambeck | | 2740 $m^3$ | 4400hp | TSHD |
| Cambourne | | 2600 $m^3$ | 4400hp | TSHD |
| Peterston | | 483.7 $m^3$ | 810hp | SHD |
| Bowcross | | 765 $m^3$ | 1000hp | SHD |
| Welsh Piper | | 785 $m^3$ | 1329hp | SHD |
| Kaibeyar | 400mm | | 595hp | SHD |
| KB II | 450mm | | 660hp | TSHD |
| Sospan | | 700 $m^3$ | 1750hp | TSHD |
| Solent Lee | | 525 $m^3$ | 875hp | SHD |
| Sand ‘H’ Class | 850mm | 2500/2700 $m^3$ | 3823kW | TSHD |
| Sand ‘W’ Class | | 2227 $m^3$ | 1942/3529kW | TSHD |
| Sand ‘K’ Class | | 2070 $m^3$ | 3382kW | TSHD |
| Sand Swan | | 890 $m^3$ | 846kW | SHD |
| Sand ‘S’ Class | | 818 $m^3$ | 861kW | SHD |
| City of Westminster | | 2793 $m^3$ | 3790kW | TSHD |
| City of London | | 2652 $m^3$ | 3790kW | TSHD |
| City of Rochester | | 1271 $m^3$ | 2104kW | T/SHD |
| City of Portsmouth | | 770 $m^3$ | 932kW | TSHD |
| City of Southampton | | 751 $m^3$ | 783kW | TSHD |
| City of Bristol | | 751 $m^3$ | 783kW | TSHD |
| City of Swansea | | 570 $m^3$ | 634kW | TSHD |
| City of Chichester & Cardiff | | 1425 $m^3$ | 2720kW | TSHD |
| Britannia Beaver | 700mm | | 3942hp | TSHD |

TSHD = Trailing Suction Hopper Dredger SHD = Suction Hopper Dredger

**Table 2.2.1** *United Kingdom Marine Aggregate Dredgers (modified from*: World Dredging, Mining & Construction, *March 1997)*

## 2.3 Key Terminology

*Seston* may be considered as the total particulate matter suspended in seawater and includes plankton, detritus, inorganic solids *etc*. This may also be referred to as Suspended Particulate Matter (SPM). The terms ‘turbidity’ and ‘suspended solids concentrations’ are different, although commonly interchanged:

*Turbidity* is a measure of the ability of a liquid to transmit light *i.e.* it’s ‘cloudiness’. It is often expressed in terms of the light extinction coefficient, ‘k’, and is an indicator of the total amount of matter in suspension, the *seston*. Turbidity cannot be consistently correlated with a mass of sediment in suspension due to changes in the optical characteristics of different sediments according to size, shape and refractive index.
*Suspended solids concentration* is the mass of solids in a given weight or volume of fluid, referred to as concentration by weight ($C_w$) or by volume ($C_v$). Increases in suspended solids and turbidity are not proportional, and will vary according to the sediment properties. Conversion of turbidity to suspended solids concentrations is possible only when turbidity sensors are calibrated with a turbidity standard and with suspended matter from the monitoring site.

Suspended Solids Concentration (SSC) may be considered that part of the seston which is of inorganic origin. Strictly, SSC and SPM are therefore not an interchangeable or comparable quantity. The difference between them will depend on the amount of pre-treatment in the laboratory that is undertaken to remove the organic material from SPM before weighing and recording the SSC. Most data do not make the distinction between the two figures, and commercial laboratories will not undertake the extensive pre-treatment required unless expressly required to do so.

## 2.4 Plume Sources

During dredging operations, 'plumes' of disturbed sediment will be created within the water body mass. The form and magnitude of these are governed by three principal components (Figure 2.4a).

- the dredging technique, including type of dredging plant in operation, method of overboard returns, operational conditions such as speed over the ground
- sensitivity to suspension and resuspension of the bed material i.e. the ease at which bed material will be disturbed and will remain in suspension, largely determined by the characteristics of the sediment (geotechnical, rheological and micro-biological)
- condition of the surface waters i.e. water depth, current velocity, turbulence, salinity *etc*.

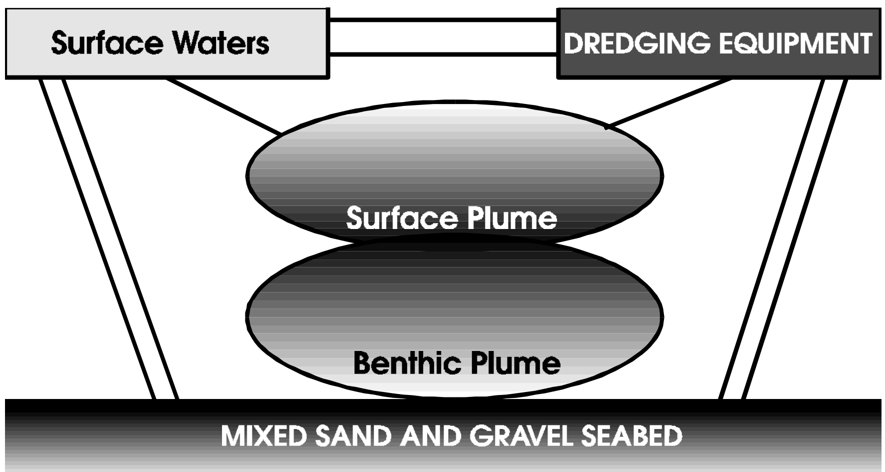


**Figure 2.4a** *Interaction between dredging plant, the seabed and the water column affecting turbidity (from Pennekamp* et al, *1996 modified)*

### 2.4.1 Benthic Plumes

Hydrodynamic and mechanical interaction of the draghead with the seabed will 'throw' finer grained sediment into suspension around the draghead from where it can be transported before settling out. Plumes thus created have been termed '*Benthic*' plumes.

If the draghead pushes material aside, rather than sucking sediments up, small levées are formed (Davies & Hitchcock, 1992). These will stand up above the surrounding levels of the seabed, and hence be more prone to erosion and entrainment into suspension (*see* Section 4, Figure 4.1.1). Although not strictly forming the benthic plume, the levée sediments are likely to be eroded soon after the draghead has passed, depending on local conditions, and so may add to the overall plume development. The volume of material within such levées may be significant, with up to 12% of the material displaced by the draghead (Davies & Hitchcock, 1992).

'*Secondary*' benthic plumes may be formed when fine material which has settled out immediately following cessation of the dredging operation, is eroded by peak tidal currents. In the pre-dredging condition, this material would already have been eroded and deposited in protected areas behind the lee of larger particles or micro-topographical structures, and so would otherwise not be available for creation of a secondary plume. It is conceivable that a cycle of erosion, deposition and re-erosion over the successive tidal cycles may continue to expand the areal impact of the dredging operation, beyond the immediate formation zone of the plumes by the dredge vessel (if the magnitudes of the tidal currents are asymmetric). At some point however, this must be considered as equating to a natural process.

### 2.4.2 Surface Plumes

'*Surface*' plumes are created by the overboard discharge of excess pumped waters containing sediment ('overspill') and by the process of onboard screening, '*beneficiation*', during the loading operation. During the latter, the gravel or sand content of the cargo is improved through rejection of the unwanted fractions overboard continuously during loading ('rejection').

Overspilling is necessary to allow the hopper to fill with solids to an economic level. The overspill will contain fine sediments that are maintained in suspension by the turbulence within the hopper. Commonly there are three to five deck level spillways on each side of the vessel for overspill. The material freefalls over the side of the vessel. As the draught of the vessel changes during the loading cycle, the distance of freefall will decrease, reducing entrainment of air, but also reducing the momentum of the discharge.

Some larger (*for example* TSHD Geopotes XIV) and newbuild (*for example* TSHD City of Cardiff) vessels are fitted with a central single spillway, which decreases the surface area of the discharge available to entrain air. Such discharges are usually subsurface, exiting the vessel through the keel and consequently releasing material some 5-10m below the sea surface (depending on vessel draught). Whilst clearly reducing some of the overspill characteristics previously mentioned, a paradox exists in that the plume so formed is immediately in front of the ship propellers, which will induce considerable turbulence and will often force the plume back to the surface. This will significantly interrupt the density current settling effect which otherwise plays an important role in reducing the overall impact of plume dynamics.

Several overseas vessels have been fitted with a secondary pipe similar to the main dredge pipe which returns the overspill or rejected material to immediately above the seabed. Whilst this is a relatively common option for trench mining vessels, this has not been undertaken within the U.K. aggregate dredging fleet. Although costly, investigation of this option may prove to limit the extent of plume development at the surface and be particularly useful for dredging in sensitive areas or areas with high fines contents. It is unlikely to be technically realistic as a retrofit option due to limitations on power availability. Recycling of the overspill/reject sediment-laden waters back into the draghead may both increase the solids/water content and recycle any material that had otherwise been lost, some of which may be desired cargo.

During the loading process sediments are therefore placed into suspension about the dredging operation by the action of the draghead on the seabed and the overboard return of surplus or rejected mixtures. Initially two distinct forms of plumes are recognised. After a short time interval, of the order of seconds to minutes in shallow coastal water depths of 15-35m, these will combine to form one continuous plume within the water column.

## 2.5 Plume Transport

The finer sediment fractions of the overspill and reject surface plumes will move away from the point of discharge by three separate mechanisms: advection by tidal currents; diffusion by turbulence; and settling. Coarser sediments will be transported a lesser distance away from the point of discharge. The location of settlement will be dependent on the settling velocity of the sediment, the carrying capacity of the water column and (dependent on wave-induced turbulence) the distance the tidal currents are consequently capable of advecting the sediments before deposition.

### 2.5.1 Advection Of Cohesive Sediments

Advection of a plume containing suspended sediments and any other particulate or suspensates will be dependent predominantly on the velocity of the tidal currents at the site concerned and the velocity and direction of the dredge vessel itself. The consummate velocity vector will determine the excursion of the plume before settlement permits the sediment to reach the seabed. Mathematical modelling applied to dredging scenarios in the UK commonly considers the tidal flows as constant depth-averaged or surface current vectors obtained by the British Hydrographic Office. Unless detailed and complex models are applied, any non-linearity in the tidal flows, reduction in velocity with depth or vertical velocity components are not included.

### 2.5.2 Diffusion Of Cohesive Sediments

Diffusion of the suspended sediments will occur due to natural turbulence within the water column Ignoring the turbulence induced by the action of the outwash from the dredger and by the vessel propellers themselves, the concentration distribution through space and time of a slug of cohesive sediment can be assumed to follow a Gaussian distribution (*see, for example*, HR Wallingford, 1993). It is assumed that the water velocity, water depth and diffusion coefficients remain constant throughout the plume. Tidal velocities are assumed to remain in line with the x-axis.

$$c(x,y,z) = c_b + \frac{m}{4\pi t h \sqrt{(D_x D_y)}} \exp\left[ -\frac{1}{4t}\left[\frac{x^2}{D_x} + \frac{y^2}{D_y}\right] - \frac{w_s t}{h} \right]$$

where; $c_b$ = background concentration
m = mass of material released at t=0
h = water depth
$D_x, D_y$ = diffusion coefficients
$w_s$ = settling velocity

The x & y axes are horizontal with the x-axis aligned with the current flow and the y-axis perpendicular to it. The origin x=y=0 is always taken to be the centre of the plume and is hence mobile due to advection. (HR Wallingford, 1993) The models commonly allow for a number of distinct release events which simulates the continued release of material from the dredger in different locations (when trailer dredging).

### 2.5.3 Settling Of Cohesive Sediments

Much of the plume modelling work which has been carried out in the UK over recent years (largely by HR Wallingford) incorporates the settling of cohesive sediment into the Gaussian diffusion calculations within the term;

$$\left[\frac{-w_s t}{h}\right]$$

It is generally assumed that constant settling rates of the order 0.1mm/s - 1.0mm/s are suitable for the cohesive material (*c.f.* Section 4.2.3).

Only recently (*see* Section 5.2) and following field observations (*see* Section 4.2) that the excursion of the plume did not in reality extend as far as the Gaussian models suggested (*see*, Land *et al*, 1995; Whiteside *et al*, 1995), have *in situ* attempts been made to quantify a realistic figure that is specific to the aggregate dredging scenario and which reflects the special hydrodynamic and physical conditions under which the sediments are released (*see* Section 4.4). These studies are ongoing, and indicate that the settling velocities of excess dredged sediments during aggregate extraction are not uniform between areas observed, with considerable variability within areas (M. P. Dearnaley, *pers. comm*.).

### 2.5.4 Transport Of Sand

A simplified but comprehensive set of empirical formulae have been established by van Rijn (1987) and modified following Grass (1981; *In:* HR Wallingford, 1993) to estimate the sediment transport rate $Q_t$.

$$Q_t = A.U.\left(\sqrt{U^2 + B.U^2_{rms}} - U_{crit}\right)^{n-1}$$

where; n = 3.4
U = depth averaged velocity (m/s)
$U_{rms}$ = rms orbital velocity

and where A, B and $U_{crit}$ are defined by;

$$A = \frac{\rho_s d_{50}\{0.005(d_{50}/h)^2 + 0.012 D_*^{-0.6}\}}{\{(g_s-1)g d_{50}\}^{1.2}}$$

$$B = 0.08/C_D$$

for 0.1m<=$d_{50}$<=0.5mm;

$$U_{crit} = 0.19(d_{50})^{0.1}\log(4h/d_{90})$$

for $d_{50}$>0.5mm;

$$U_{crit} = 8.5(d_{50})^{0.6}\log(4h/d_{90})$$

$$D_* = d_{50}\{((g_s-1)g/\nu^2)^{1/3}$$

$$C_D = \left[\frac{0.4}{\ln(h/z_o)^{-1}}\right]^2$$

where; $\rho_s$ = sediment density (kg/m³)
$d_{50}$ = median particle diameter (m)
$d_{90}$ = 90 percentile particle diameter (m)
h = water depth (m)
$g_s$ = particle specific gravity (~2.65)
g = gravitational acceleration (m/s²)
$C_D$ = drag coefficient of the seabed ($z_0 = 0$)
ν = kinematic viscosity of water at 10°C ($\nu = 1.4\times10^{-6}$ m²/s)

### 2.5.5 Settling Of Non-Cohesive Sediments

Particles greater than sand sizes (>2mm) are generally assumed in the context of aggregate dredging to fall to the seabed instantaneously and consequently are ignored.

In a clear, still fluid, the particle fall velocity ($w_s$) of a solitary fine particle of 100µm or less (Stoke's Range) can be described by:

$$w_s = 1/18.\ ((g_s - 1).g_w.D^2_s / \nu))$$

where: $w_s$ = particle fall velocity
$g_s$ = particle specific gravity (~2.65)
$g_w$ = water specific gravity (~1.026)
g = gravitational acceleration (m/s²)
$D_s$ = particle size
ν = kinematic viscosity coefficient

For suspended sand particles in the range 200-1000μm, the following equation can be used (Zanke, 1977; *In:* van Rijn, 1987):

$$w_s = 10\,(\nu / D_s)\left\{\left[1 + \frac{0.01(g_s-1)gD_s^3}{\nu^2}\right]^{0.5} - 1\right\}$$

For particles larger than 1000μm, the following can be used (van Rijn, 1987):

$$w_s = 1.1\,((g_s - 1).g_w.D_s)^{0.5}$$

These formulae are applicable for suspension concentrations of less than approximately 400ppm. For higher concentrations, the presence of the surrounding particles will reduce the particle fall velocity. For normal flow conditions with particles in the range 50-500μm, the reduced particle fall velocity can be described by the following (van Rijn, 1987):

$$w_{s,m} = (1-c)^m\, w_s$$

where m = 4.65 - 2.32 for large & small particles respectively (Maude & Whitmore, 1958)
= 4 for sand particles(van Rijn, 1987)
c = sediment concentration

However, it must be noted that counteracting, or replacing, the reduced particle fall velocity, $w_{s,m}$ , will be the development of settlement enhancing 'Density Current' effects at high suspended sediment concentrations. Further consideration is outwith this report, but the role and the theory of 'Density Currents' within the dredged sediments plume is receiving detailed investigation elsewhere (*see, for example*, Whiteside *et al*, 1995; HR Wallingford, 1996). The traditional treatment of density currents applies more usually to fine-grained, cohesive sediments. However it is the specific discharge manner of the aggregate dredging operation which appears to create such a phenomenon best described also as a density current.

## 2.6 Plume Settlement

Plumes of suspended sediment created by dredging activities will augment existing concentrations of suspended sediment before decaying to background levels. The time required for the concentration levels to return to background will be a function of:

(i) the length of time for the water body at that point to be replaced by unimpacted waters with background levels of sediment. This will be directly dependent on water body current velocities (flushing time)

(ii) time taken for sediment to settle out of suspension. This is dependent on characteristics of the receiving medium such as water depth, salinity, density, viscosity, turbulence; of the sediment itself such as structure (i.e. as individual particles or as flocs), grain size, shape and density; and of other influences such as hindrance, buoyancy (entrapped air), gas content of sediments, initial sediment velocity (momentum) on entering the water body, *etc*.

The greater the density contrast between the discharge plume and surrounding waters and the less diffuse the discharge source, the more likely the plume is to behave as a density current and rapidly descend to the base of the water column. Impacts will tend to be more localised. During descent of the plume, friction at the edges of the plume may entrain sediment into the surrounding waters.

When dealing with density currents associated with dumping of dredging material (maintenance and capital dredging of principally cohesive fine sediments), observations of resuspension on impact with the seabed have commonly been made (*see* Lavell, 1981). However, it is likely that the magnitude of any density currents formed by aggregate mining overboard returns using present techniques will not cause significant resupension on impact with the seabed.

Table 2.6.1a presents a range of traditional theoretical and laboratory determined settling velocities for potential suspensates that may be encountered and which have been of direct relevance to plume studies. Material coarser than sand may be assumed to settle virtually immediately.

From observations within this project and by others (*for example*, HR Wallingford, 1996) the presence of flocs is now considered important. The settling velocity of flocs is not related directly to their size, and so does not follow Stokes Law.

Gibbs (1985) presents the following relationship to define the settling velocity of flocs:

$$U = 1.73\, D_f^{0.78}$$

where $U$ is the settling velocity ($cms^{-1}$) and $D_f$ is the floc diameter. Using this equation, the settling velocities for a range of flocs can be determined (Table 2.6.1b). The terminology microflocs (<100µm) and macroflocs (>100µm) is that proposed by Eisma (1986).

| **Particle Description** | | **Size (µm)** | **Settling Velocity (cms$^{-1}$)** |
|---|---|---|---|
| Sand | Fine | 200 | 2.1417 |
| | Very fine | 100 | 0.67 |
| Silt | Coarse | 50 | 0.1816 |
| | Medium | 20 | 0.0298 |
| | Fine | 10 | 0.00749 |
| Clay | Very fine | 5 | 0.00187 |
| | | 1 | 0.0000748 |

**Table 2.6.1a** *Settling velocities of unhindered discrete particles (grain size descriptions based on Folk, 1980)*

Density gradients of the receiving waters may make an (unknown) contribution to the variation in settling velocities observed. It is known that the water temperature near the seabed may be *circa.* 1$^{o}$ C less than the surface waters (A.R. Hermiston, *pers. comm.*). Rapid and intense mixing of these cooler bottom waters with the warmer surface waters may cause density driven micro-currents. Coupled with changes in pressure, it is postulated that some physico-chemical precipitation may occur under calm conditions which is a component of the surface froth and 'sheen', visible for some time at the surface. This may also be observed by the CBP techniques (*see* Sections 4.2.2, 4.2.3 and 4.4).

| **Floc Description** | **Size (µm)** | **Settling Velocity (cms-1)** |
|---|---|---|
| Macroflocs | 2000 | 0.493 |
| | 1000 | 0.28711 |
| | 500 | 0.1672 |
| | 200 | 0.08182 |
| Microflocs | 100 | 0.04765 |
| | 50 | 0.02775 |
| | 20 | 0.01358 |
| | 5 | 0.0046 |

**Table 2.6.1b** *Settling velocities of unhindered flocs (floc descriptions based on Eisma (1980)*

Particles in suspension will settle in different ways depending on the suspension concentration. Based on the concentration and the tendency of the particles to interact, there are four principal type of sedimentation (Paris & Martinez, 1996);

(i) discrete: in low SSC the particles settle individually without grouping, according to more classical sedimentation theories

(ii) flocculant: in dilute suspensions particles group together increasing their mass and settling at a faster rate, especially applicable for fine cohesive sediments

(iii) zone: in intermediate suspensions the particle forces are sufficient to hinder settling of neighbouring particles so that they tend to stay in relatively fixed positions and they tend to settle as a unit

(iv) compression: high concentrations which encourage the particles to form a structure

If discharge is slow, or at little differential to surrounding waters, entrainment is likely to occur more rapidly and the plume will quickly diffuse throughout the water column. The particles will then behave more characteristically according to the principles of *Stokes Law*. Such a plume will reside in the water column for longer, will be advected further by tidal currents and hence will impact wider area. However, deposition per m$^2$ will be correspondingly lower assuming a given quantity of material entering the water column. The opposing perspectives on the benefits or otherwise of slow settling rates are summarised in Table 2.6.1c.

Of importance in terms of evaluating the effect of suspended sediment plumes is the distance that sediment can travel before settling out of suspension (i.e. gross excursion and hence area of impact). The gross area of impact may then be subdivided into smaller zones of reducing impact away from the source, which will be dependent on the different settling rates for different particle sizes and hence accumulation rates at different points.

| Fast Settling Rate | Slow Settling Rate |
|---|---|
| Impacts limited seabed area | Impacts far wider seabed area |
| Higher accumulation rate | Lower accumulation rate |
| Greater smothering | Lower smothering |
| Over-sanding of resource | Carries unwanted fines away from resource |
| Limits potential for cumulative effect | Cumulative effect potential with neighbouring licences |
| Unable to reach sensitive areas | May reach sensitive areas |

**Table 2.6.1c** *Pros and cons of the development of plumes and transport away from the immediate dredge site. Dredging companies may prefer transport of fines away from the actively dredged area to avoid "oversanding" of the resource and re-screening on subsequent loading.*

It is known that inorganic sediment is present in the sea as flocculated aggregate with settling speeds many times greater than those of the constituent grains (McCave, 1975, *in* Moore, 1977). Particles of different sizes are known to respond differently to gravity and turbulent forces. In an initial, unflocculated suspension this will cause random variations in particle movement accompanied by abundant particle collisions. Because of their larger relative surface area and proportionally greater adhesive force, the smaller particles will tend to flocculate most rapidly. Larger grains are not sufficiently active to flocculate to other single grains but they do adhere to the soft and irregularly shaped flocs composed of smaller grains. As the particles become larger, the movements become more uniform and the suspension reaches a steady state where the movements of the largest grains equal that of the largest flocs and further flocculation ceases (Kranck, 1973 *in* Moore 1977).

Muschenheim (*cited in:* Messieh *et al,* 1991) noted that rapid flocculation of clay-sized particles and/or intense vertical mixing may accelerate the particle settling velocity, thus allowing sediment to reach the seabed at lesser distances from discharge platforms. Davies (1984) records similar observations occurring within 500m radius of a dredger, although he does not specify water depths and/or current velocities.

J. Rees (*pers. comm.*) has noted a far-field near-bed extension to the range of elevated suspended concentration levels reported herein. Few details appear to date within the press. It is considered that this 'benthic boundary layer plume' reported in the far-field may be the result of floc formation, maintained in suspension by turbulence within the boundary layer. The existence of such flocs will vary geographically in response to the geological nature of the substrate, in particular the mineralogy of the clay constituents. Further, flocculation at the same site will vary over time, in response to seawater temperature, salinity and overall viscosity. This is an important feature which may have further ramifications, but knowledge is at an early stage and research is ongoing.