TURBIDITY DUE TO DREDGING AND DUMPING OF SEDIMENTS

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Content

1. Introduction

Dredging of sediments deposited in harbour basins and approach channels is known as maintenance dredging and is a basic element of the economic performance of many ports. Usually, the dredged materials consist of clay, silt and sand particles/flocs. The fraction with particles < 63 μm is known as mud, the fraction between 63 μm and 2000 μm (2 mm) is known as sand.
The mud fraction < 63 μm can be subdivided in:

- fraction < 4 μm; colloidal fraction (remaining in suspension in all conditions);
- fraction < 4-8 μm; settling velocity 0.03 mm/s (flocculation limit 0.25 mm/s);
- fraction 8-16 μm; settling velocity 0.12 mm/s; (flocculation limit 0.25 mm/s);
- fraction 16-32 μm; settling velocity 0.45 mm/s;
- fraction 32-63 μm; settling velocity 1.8 mm/s.

The three essential elements of dredging are: excavation, transport and disposal. Often, the most critical elements are the excavation and the disposal (dumping) of sediments at the disposal site due to environmental pollution problems. In many cases the dredged material has to be dumped in the outer estuary or at open sea. Dumping in rivers and inner estuaries is most often not allowed if the dredged material is polluted.

Efficient management of dredging works requires:

- detailed and regular monitoring of the area considered;
- sufficient knowledge of the sediment transport processes in the area considered;
- sufficient knowledge of dredging and disposal methods;
- sufficient knowledge of cost and price factors of various dredging methods.

Maintenance dredging in a navigation channel requires knowledge of dredging accuracy, which depends on the type of soil and the type of dredging method, see Table 1.1. The mean depth in the area considered after dredging consists of the required depth plus the accuracy involved. When maintenance dredging is performed by a hopper dredger in a sandy area with a required depth of 10 m, the actual mean depth after dredging needs to be 10.6 ± 0.6 m, given the accuracies involved. The minimum depth in the area will be about 10 m and the maximum depth will be about 11.2 m after dredging.

Type of dredger	Sand	Mud
Grab dredger	± 0.3 m	± 0.2 m
Cutter dredger	± 0.4 m	± 0.3 m
Hopper dredger	± 0.6 m	± 0.5 m

Table 1.1 *Accuracy of various dredging methods*

2. Dredging methods

Each type of dredger has its own typical characteristics such as:

- sensitivity to waves and currents (operational conditions);
- minimum water depth required for excavation (dredging) and sailing;
- minimum horizontal channel dimensions required for manoeuvering;
- type of soils that can be dredged;
- production in relation to soil composition;
- vertical accuracy of dredged bed profile.

The following three main types of dredging methods are available:

- **Cutter suction dredging CSD (hydraulic);**
  - positioned by anchors (hindrance to ships);
  - sensitive to waves and currents;
  - connected to floating pipe line (removal of dredged materials);
  - large range of soils (soft to consolidated, rocky soils);
  - large production range (upto 10,000 m^3/hour); 10% to 20% solids (by weight) in slurry;
  - reasonably smooth bed profile after dredging;
  - wide suction mouth can be used to remove a wide, but thin layer (dustpan dredger);

- **Trailing-suction hopper dredging THSD (hydraulic);**
  - self sailing with suction pipes and draghead suspended from cables (midships alongside);
  - sediment is pumped into hopper and excess water is ultimately forced to flow overboard;
  - no hindrance to other ships (no floating pipeline);
  - not very sensitive to waves and currents;
  - minimum water depth required for dredging and sailing (approx. 7 m);
  - suitable for relatively soft unconsolidated soils;
  - very suitable for large channel maintenance projects;
  - large production range (up to 10,000 m^3/hour);
  - unloading through pipeline pumping; by rainbowing or by bottom-doors;
  - rough bed profile after dredging;
  - environmental problems due to overflow;

- **Grab dredging by crane/backhoe (mechanical);**
  - dredging from a fixed platform (hindrance);
  - able to work close to structures (piers, quays);
  - not sensitive to waves and currents;
  - closed clamshell bucket for minimum turbidity levels;
  - removal of dredged material by barges for off-site transport;
  - small production range (500 m^3/hour);
  - large range of soils (soft clay to soft rock);
  - smooth bed profile after dredging.

During dredging and dumping activities, mud is most often released in the system as spill (side effect). Two types of mud spill sources can be distinguished (see also **Table 2.1**):

- single point-spill event (< 1 hour; spill area of 10x10 m^2) generating a mud cloud; the mud cloud is carried downstream by the current and the mud concentration decreases due to settling and mixing (vertical , longitudinal and lateral);
  Examples: mud overflow from a hopper dredger; mud dumping though bottom doors of barge
- (semi)continuous point-spill over a certain period (hours to days; spill area 10x10 m^2);
  Examples: free fall spraying of sand-mud into the water (rainbowing) to make land.

Dredging and dumping activities can be seen as (semi) continuous mud sources.
Loading and unloading times of dredging/dumping equipment are given in **Table 2.1**.

Type of dredger	**Dredging activity**	**Dumping activity**			
		Pump-line exit	**Spraying pontoon**	**Rainbowing**	**Bottom doors**
Grab	Semi-continuous Loading time= 8-24 hours per day	Semi-continuous; Grab fills barges which connect to pipeline Unloading time= 1-2 hours per event	Semi-continuous; Grab fills barges which connect to spraying pontoon Unloading time= 1-2 hours per event	-	Single release Grab fills barges; Barges sail to dumping site Unloading time < 10 minutes per event
Cutter	Continuous	Continuous Cutter is connected to pipeline	Continuous Cutter is connected to pipeline	-	-
	Semi-continuous Loading time= 1-2 hours per event	Semi-continuous Cutter fills barges which connect to pipeline Unloading time= 1-2 hours per event	Semi-continuous Cutter fills barges which connect to pipeline Unloading time= 1-2 hours per event	-	Single release Cutter fills barges with bottom doors Unloading time < 10 minutes per event
Hopper-small/large	Semi-continuous Hopper dredges at borrow site Loading time= 1-2 hours per event (cycle time depends on distance between dredging and dumping sites)	Semi-continuous Hopper connects to pipeline Unloading time= 1-2 hours per event	Semi-continuous Hopper connects to spraying boat Unloading time= 1-2 hours per event	Semi-continuous Hopper sails to dumping site Unloading time= 1-2 hours per event	Single release Hopper has bottom doors Unloading time < 10 minutes per event

Table 2.1 *Loading and unloading times of dredging equipment*

3. Turbidity caused by dredging

3.1 General aspects

The increase of suspended sediment concentrations due to the dredging process is generally expressed as a total suspended solids concentration (TSS or SSC in kg/m^3; gr/l or in mg/l).
TSS is a simple measure of the dry-weight mass of non-dissolved solids suspended per unit volume of water. TSS includes inorganic solids such as clay, silt, sand, etc. It may also include organic solids such as algae, zooplankton, and detritus, depending on the type of analysis method. When direct measurement of the quantity of suspended particulate matter present in water is needed, TSS mass determination in a laboratory is the most common method.
Turbidity is a common standard method used to describe the cloudy or muddy appearance of water. Turbidity measurements have often been used for water quality studies because they are relatively quick and easy to perform in the field. The concept of turbidity involves optical properties of the water and is not a direct measure of the concentration of suspended sediments. Turbidity has been defined as an optical measurement of light that is scattered and absorbed. The standard unit of measurement for turbidity is the Nephelometric Turbidity Unit (NTU) measured with a nephelometer. NTUs are based on a standard suspension of formazin in water, which is used to calibrate nephelometers. According to this model, the lower the measured NTU value is, the clearer and less turbid the water will be.
Thus: turbidity and light transmission measure the presence of particles indirectly through their optical properties, while TSS measurements directly quantify the mass of particulates present in the water.
Figure 3.1 shows a plot of Turbidity (NTU) against TSS (mg/l) based on various studies.
Roughly: TSS= (0.2-0.8) Turbidity

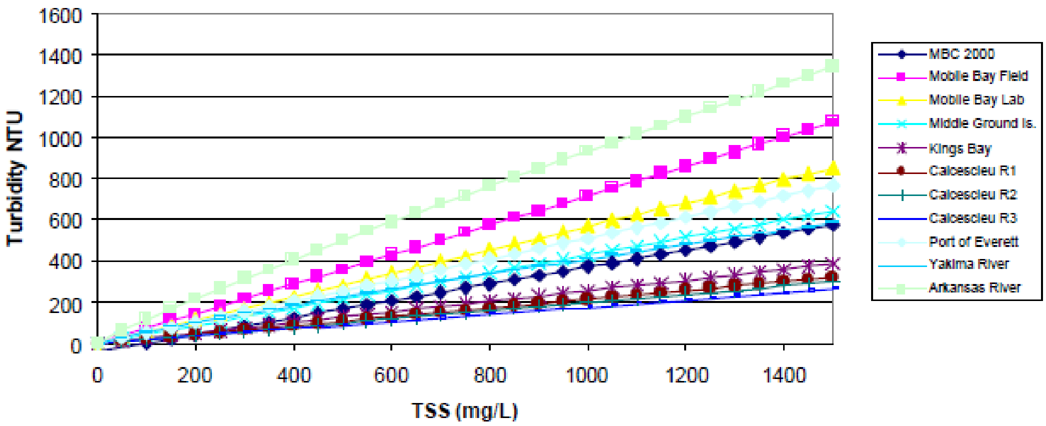


Figure 3.1 *Relationship Turbidity (NTU) and Total Suspended Solid concentration (TSS in mg/l); LASC 2003*

Sediment concentration plumes generated by dredging may have strong adverse effects on biological resources either through impact to water quality or increased siltation. The most important environmental problems are:
- siltation outside dredging area and impact on near-bed fauna and flora (benthic organisms);
- uncontrolled movement of attached pollutants and hence pollution of clean areas;
- release of nutrients; reductions in dissolved oxygen in surface water;
- flocculation and clogging of micro-organisms;
- blocking of sunlight due to increased turbidity levels.

All types of dredging operations create some form of turbidity in the water column, depending on the:
- applied dredging method (mechanical dredging using grab, bucket, clamshell; hydraulic dredging using pipeline cutterhead, hopper including overflow; agitation dredging);
- nature of the sediment bed (soil conditions, gas content);
- hydrodynamic conditions (water depth, mean currents, salinity, waves).

Turbidity during dredging activities is caused by the:

- actual dredging/excavation process at the sediment bed (resuspension effect), including gas releases from disturbed bed;
- spillage during vertical transportation from bed to vessel or barge;
  - grab dredger and bucket dredger: sediments washed off during vertical movements; impact on bed, losses during emptying in barge;
  - hopper dredger: movement of suction pipes through bed, return flow under vessel during sailing, jet flow due to propeller of vessel, emptying of suction pipes after blockings (flow reversal in pipe), overflow during filling process (pumping continues after hopper is full in order to displace the water and increase the material density in the hopper, excess sediment-laden water overflows and re-enters the water column);
- spillage during horizontal transportation from dredging to dumping site.

The two most turbidity generating dredging methods are: Grab dredging and Hopper dredging

Grab dredging

Sediment leakage and resuspension are caused by (**Figure 3.2**):

- resuspension when the bucket impacts the sediment bed, closes, and is pulled off the bottom;
- sediment losses as the bucket is pulled through the water column (either raised from the bottom or lowered from the surface);
- sediment losses when the bucket breaks the water surface;
- sediment/water spillage or leakage as the bucket is hoisted and swung from the water to the barge.

In addition, losses of sediment can occur if the barge is allowed to overflow (to increase the effective load) and it is likely that this practice increases suspended sediment concentrations around the dredging operation. Closed clamshell buckets of 5 and 7 m^3 are available for low-turbidity dredging.

Figure 3.2 *Grab dredging (The Grab Specialist; www.tgs-grabs.nl; Almere, The Netherlands)*
Upper: open grabs with heavy mud spill during hoisting
Lower: closed clamshell grabs (left:hydraulic for backhoe and Right: mechanical for crane)

Hopper dredging

Basically, the loading process consists of three phases (**Van Rhee, 2002**):

- filling phase to overflow level; three layers are present in the hopper: a lower layer of settled sand, a sediment-water mixture and a top layer of clear water;
- overflow phase (5 to 15 min); the hopper is filled with sand and the excess water is forced out of the hopper by overflow through a pipe system; a high-concentration density current is present above the bed gradually reducing in time; a low-concentration top layer is present near the water surface flowing in horizontal direction to the overflow system;
- final phase; high-concentration layer reaches the water surface and the overflow losses of sediment increase considerably; the maximum sediment concentrations in the overflow pipeline may be as large as 30% by volume when the hopper approaches its capacity .

In fine sandy conditions, the total overflow generally is of the order of 5% to 10%.
In muddy conditions, the overflow can reach values up to 30% of the total volume of sediment pumped into the hopper and may cause significant environmental problems.

Van Rhee (2002) performed large-scale laboratory tests (fine sand of 0.105 mm and 0.14 mm) of the hopper filling process and the associated overflow processes. The maximum overflow loss of sediment was about 40% in the tests with fine sand of 0.115 mm. A field hopper test at the sandy Dutch shoreface (Hopper Cornelia of Boskalis Westminster Dredging: B=11.5 m, L=52 m, Q=6 m^3/s, d_{50}=0.24 mm) showed an overflow loss of sand of about 8%.

Van Parys et al. (2001) compared various techniques to reduce the turbidity during hopper dredging operations in the outer Port of Zeebrugge (Belgium). The turbidity levels were reduced by a factor 5 in case of dredging without overflow.

Spearman et al. (2011) have measured the in-situ sediment concentrations of the overflow discharge (about 1 to 5 m^3/s) on three different hopper dredgers (capacity between 6000 and 16000 m^3). The solid concentration of fine silts and sands increases from 0 at the start of the dredging process to about 500 kg/m^3 at the end after about 1 hour when the hopper is almost full of sand. The overall mean value is about 200 to 300 kg/m^3 during the overflow process. The overflow (pump) discharge of sediment is about 300 to 500 kg/s, which is released into the water column. The high-concentration slurry descends towards the bed as a dynamic plume. Simultaneously, a passive low-concentration plume is generated in the water column by mixing/entrainment processes along the surface of the high-concentration slurry. The sediment source flux of the passive plume is of the order of 5% (≅15 kg/s) of the overflow discharge (≅ 300 kg/s). The descending slurry eventually collapses onto the bed to form a density current propagating and settling out along the seabed over some distance (< 50 m). The passive plume with source input of about 15 kg/s ($Q_{s,source}$) is slowly diluted/dispersed in the ambient current by advection, lateral mixing and settling out of sediments to the bed. The source concentration of the passive plume at some distance (say 30 to 50 m) down-current of the dredger can be estimated as $c_{source}=Q_{s,source}/(b_o hu)$ with b_o=plume width at source, h= water depth and u= ambient current velocity. Using: $Q_{s,source}$= 15 kg/s, b_o=10 m, h=10 m and u=0.5 m/s, it follows that $c_{source}\cong 0.3$ kg/m^3.

3.2 Turbidity values measured at field dredging sites

Herein, various study results are summarized. A detailed overview of field data is given by Mills and Kemp 2016).

Stuber (1976) presented data of turbidity studies during agitation dredging works near wharves, slips and docks (using drag beams behind tugs) in the Savannah River channel in the USA. The slips and wharves (siltation areas of 100x300 m^2; water depths of about 10 m) are located adjacent to the main river channel and experience siltation rates in the range of 0.2 to 1 m per month. The tidal range varies in the range of 1.5 to 3 m; the peak tidal currents in the middle of the channel are in the range of 1 to 1.5 m/s. The background concentrations are in the range of 500 mg/l (near bed) to 50 mg/l (near surface). Agitation dredging is performed during ebb tidal flow. Suspended solids were measured at sampling control stations located at about 100 to 300 m downcurrent from the dredging sites and at a slightly greater distance from the bank than the centerline of the dredging area. Samples were taken at the water surface and at depths of about 4.5 m and 9 m from the water surface. The background concentrations varied in the range of 20 to 100 mg/l at most sites. The maximum silt concentrations in the downcurrent control stations varied in the range of 100 to 200 mg/l at a depth of 4.5 m and in the range of 200 to 400 mg/l near the bed (at depth of 9 m). The largest increase observed was from a background value of 30 mg/l to 300 mg/l during dredging (factor 10).

Sosnowski (1984) studied the sediment resuspension near grab dredging works in the New Thames River and Eastern Long Island Sound (USA). The tidal range is about 1 m; the tidal currents are in the range of 0.5 to 0.8 m/s in the Thames River and in the range of 1.3 to 2 m/s in the Sound. The dredging operation consisted of a barge-mounted crane using an open clamshell bucket. Samples were taken at three depths (surface, mid-depth and near-bottom) in the dredge plume at 30 to 300 m downstream from the dredging site. Background concentrations were taken about 100 m upstream of the dredging site. Near the bottom the sediment concentrations were in the range of 100 to 1000 mg/l within 50 m from the dredging site. At a distance of about 300 m the near-bottom sediment concentrations were back to the background values of about 10 to 20 mg/l. Near the water surface the sediment concentrations were in the range of 10 to 100 mg/l within 50 m from the dredging site. At a distance of about 200 m the surface sediment concentrations were back to the background values of about 5 mg/l.

Hayes et al. (1984) present results of field studies into sediment resuspension caused by cutterhead, clamshell and hopper dredging methods at various USA sites. Suspended sediment concentrations near the cutterhead (within 6 m) were found to be in the range of 100 to 1000 mg/l depending on cutterhead tip speed, swing speed and type of cut (full or partial). Suspended concentrations were found to much lower (factor 2) when a closed clamshell bucket was used in stead of an open bucket. Turbidity values in the plume of a hopper dredger showed values of about 900 m/l near the bed and 350 mg/l near the surface at 30 m from the dredger with overflow and values of about 50 mg/l without overflow.

Wakeman et al. (1975) describe the results of turbidity studies conducted during the 1974 maintenance work at Mare Island Strait (San Francisco Bay, USA) using hopper and cutterhead dredgers and at Oakland Inner Harbour using a grapple or clamshell dredger. Water turbidity monitoring at various distances downcurrent from the dredging site was performed based on water sampling. A special experiment was designed to determine the impact of overflowing during hopper dredging on the surrounding water column. The sediment concentration monitoring results are given in **Tables 3.1 to 3.3**.
The cutterhead dredger was found to have the least effect on water turbidity during dredging operations. The hopper dredger without overflow also showed a relatively low effect on turbidity levels. The open grab dredger and the hopper dredger with overflow produced relatively high levels of turbidity and suspended solids in the water column. These values were however much smaller than those generated during natural high run-off periods and high wind-wave events.

Station downcurrent (m)	Depth below water surface (m)	Background concentration (mg/l)	Concentration during dredging operation (mg/l)
50	1	18	80
	5	20	50
	9	22	280
100	1	18	40
	5	20	60
	9	22	100
400	1	18	25
	5	20	10
	9	22	40

Table 3.1 *Crab dredging*

Station downcurrent (m)	Depth below water surface (m)	Background concentration (mg/l)	Concentration during dredging operation (mg/l)
50	10	40	70
100	10	40	55
400	10	40	50

Table 3.2 *Cutterhead dredging*

Station downcurrent (m)	Depth below water surface (m)	Background concen tration (mg/l)	Concentration during dredging operation without overflow (mg/l)	Concentration during dredging operation with overflow (mg/l)
50	1	150-200	210	350 at start of overflow 75 after 3 min 350 after 6 min 315 after 9 min
	10	150-200	230	250 at start of overflow 165 after 3 min 870 after 6 min 390 after 9 min

Table 3.3 *Trailing suction hopper dredging with and without overflow*

Bernard (1978) synthesizes the results of eight research studies into sediment resuspension and turbidity levels near various dredging sites in the USA. Water-column turbidity generated by dredging operations is usually restricted to the vicinity of the operation and decreases rapidly with increasing distance from the operation. The results can be summarized, as follows:

- **Grab (Clamshell)**: maximum concentrations of suspended solids within 50 to 100 m from the dredging site will be less than about 200 mg/l; the visible plume will be about 300 m long at the surface and approximately 500 m near the bottom; maximum concentrations will decrease rapidly to background values within 500 m;
- **Cutter**: the increase of suspended concentrations around cutterhead dredges is restricted to the immediate vicinity of the cutter, where concentrations may be as high as 10 gr/l within 3 m of the cutter; near-bottom levels of 100 to 200 mg/l may be found within a few hundred metres of the cutter;
- **Hopper**: during overflow operations, turbidity plumes with concentrations of 200 to 300 mg/l may extend behind the dredge for distances up to 1200 m; without overflow the concentrations are considerably smaller (factor 3 to 5); near-bottom concentrations of 1 to 2 gr/l are generated near the dragheads.

Turbidity levels around dredging operations can be reduced when necessary, but not without appreciable cost, by improving existing cutterhead dredging equipment techniques (large sets and very thick cuts should be avoided), using watertight buckets and eliminating hopper dredge overflow, or using a submerged overflow system. The dispersion of near-surface turbidity can be controlled, to a certain extent, by placing a silt curtain downstream or around certain types of dredging/disposal operations. Under quiescent current conditions (<0.1 m/s) turbidity levels in the water column outside the curtain may be reduced by as much as 80 to 90 percent. Silt curtains can not be used in conditions with currents larger than 0.5 m/s.

Willoughby and Crabb (1983) studied the behaviour of dredge-generated sediment plumes in Moreton Bay, Australia. The data were collected during June and July 1982 in the overflow plume generated from a trailing suction hopper dredger during sand (0.25 mm) dredging at Middle Banks in the Bay area. Close to the dredge, the measured concentrations ranged between about 500 mg/l (near the bed) and 50 mg/l (near the surface). The background concentration were of the order of about 5 mg/l. The concentrations in the plume were found to be reduced to at or just above background levels within approximately one hour. About 90% of this reduction occurred within the first 20 minutes. Given the local current velocity of about 0.6 m/s, the major proportion of the dredge suspended material settled within about 600 to 700 m downcurrent from the dredge.

Battisto and Friedrichs (2003) studied the suspended sediment plume characteristics during oyster shell dredging (on 22 August 2001; northeast of Hogg Island in the James River estuary, Virginia, USA) using ADCP, OBS and bottle samples. During strong tidal flow, the dredge plume was confined mainly to the bottom of the estuary channel with a width of about 200 m and an estimated maximum length of 5 km. At distances of 100 to 400 m downstream of the dredge, the plume was about 1 to 2 m thick with concentrations of 50 to 100 mg/l higher than the background values of about 100 mg/l. At distances of 700 m downstream of the dredge, the plume was about 3 to 4 m thick with concentrations of 30 to 50 mg/l higher than the background values (100 mg/l). Active dredging around slack water produced a spatially less extensive but higher concentration suspension in the immediate vicinity of the dredge. During slack after ebb, a plume of 8 m thick, 200 m wide and concentration of 100 mg/l was formed near the dredge before collapsing and spreading along the bottom of the main channel as a layer of 1.5 m thick, concentrations up to 150 to 200 mg/l and an estimated length of 500 m. This concentration pool was then advanced landward with the flood tide. When dredging was stopped at slack after flood, the plume outside the immediate vicinity of the dredge settled to below detection levels within an hour. Comparison of OBS and ADCP profiles showed good agreement. A typical ADCP transect across the dredge plume provides better visualization of the extent of the dredge plume than is possible with only OBS profiles.

Clarke et al. (2007) measured suspended sediment concentrations (ssc) in the sediment plume of mechanical dredge with an environmental bucket operating in Arthur Kill Waterway, New Yersey, USA. The background concentration was 10 mg/l in an ambient current of 0.3 to 0.4 m/s. The maximum plume concentration in the lower third of the water column was about 300 mg/l at 10 m from the dredger, 100 to 200 mg/l at 60 m down-current, < 100 mg/l at 100 m down-current, < 20 mg/l at 350 m. The plume width was about 70 m at at about 300 m due to lateral mixing
Clarke et al. (2007) also summarized ssc in plumes at various other USA-sites. The ssc very close to the dredger was in the range of 200 to 400 mg/l with some values up to 1000 mg/l and values of 100 to 200 mg/l at about 100 m from the dredger.

Since 1985 various turbidity studies **(Blokland, 1988; Pennekamp and Quaak, 1990; Pennekamp et al., 1996)** have been performed around dredging vessels in several harbour basins in the Netherlands (Port of Rotterdam). Local currents were quite small (<0.5 m/s). The measurements were carried out before, during and after the dredging activities. A network of measurement stations was set up within and around the dredging area (grid interval of 50 m). Sediment concentrations were measured at depth intervals of 1 to 3 m using optical sensors. The duration between consecutive measurements over the full water depth was about 30 minutes. Iso-concentration contours were made and from this the quantity of sediment brought into suspension was determined by integrating the mean concentration over space and time.
Three aspects were considered: the level of turbidity in the dredging area, the horizontal dispersion of the sediment cloud (in absence of local currents; mean currents were small at dredging sites considered), and the settling time of the sediment cloud after cessation of dredging.
The results were expressed in the following four basic parameters (**Pennekamp et al., 1996; Kirby and Land, 1991**):

- depth-averaged background concentration (C);
- characteristic increase of depth-averaged concentration (ΔC) at a distance of 50 m from centre of dredging activity;
- decay time (ΔT) of the increase of the concentration after cessation of dredging activity; time after which the turbidity has diminished to background values at 0.5 m above the bed at 50 m from dredging centre;
- spill, loss or resuspension parameter S_{spill}, which is the mass of sediment brough into suspension per m^3 of dredged material (see also **Table 3.4**).

The S_{spill}-parameter is defined as:
$S_{spill}=M_{spill}/V_{dm}=M_{spill}/(M_{dm}/\rho_{dry,insitu})= \rho_{dry,insitu}M_{spill}/M_{dm}=\rho_{dry,insitu}$ (R/100)

The production of spill (kg/s) is related to the dredging production (m^3/hour), as follows:
$P_{spill}=S_{spill}\ P_{insitu}=\rho_{dry,insitu}$ (R/100) (P_{insitu}/3600)

with:
M_{spill}= mass of spilled material brought into suspension (kg);
M_{dm}=total mass of dredged materials (kg);
V_{dm}=Volume of dredged materials (m^3);
$\rho_{dry,insitu}$= in-situ dry density of dredged materials;
$\rho_{dry,pumped}= \alpha\ \rho_{dry,insitu}$= dry bulk density of pumped sediment (during/after dredging in pumpline, kg/m^3);
α=factor (0.3-0.5);
$R_{spill}=M_{spill}/M_{dm}x100\%=100\ S/\rho_{dry,insitu}$ =spill percentage= resuspension/spill percentage (1% to 10%); about 1% to 10% of dry sediment mass (per m^3 of in-situ (source) material dredged out of the system; water+sediment);
$P_{insitu\ dredged}$= production of dredging equipment of insitu volume (m^3/hour); volume of soil to be removed;
$P_{pumped}=[\rho_{dry,insitu}/\rho_{dry,pumped}]P_{insitu}$ =volume production rate of (added) water + sediment material (m^3/hour);
P_{spill}= production rate of spill of fines brought into suspension (input for dispersion models, see **Section 5.2.2**).

The effectivity of the dredging process can be evaluated from the dry mass of dredged sediment derived from the pre and post bathymetric surveys and the dry mass of sediment passing through the pumpline of the dredger.

$$\rho_{dry,insitu}\ V_{dredged}= Q_{mixture}\ \rho_{dry,pumped}\ \Delta t_{dredged}\ \alpha_{eff}$$

$$(\rho_{wet,insitu} - \rho_w)/\alpha_s\ V_{dredged}= (\rho_{wet,pumped} - \rho_w)/\alpha_s\ Q_{mixture}\ \Delta t_{pumped}\ \alpha_{eff}$$

$$V_{dredged}= [(\rho_{wet,pumped} - \rho_w)/(\rho_{wet,insitu} - \rho_w)]\ Q_{mixture}\ \Delta t_{pumped}\ \alpha_{eff}$$

$$\alpha_{eff} = [(\rho_{wet,pumped} - \rho_w)/(\rho_{wet,insitu} - \rho_w)]\ [Q_{mixture}\ \Delta t_{pumped}/V_{dredged}]$$

$$\alpha_{eff} = [V_{pumped}/V_{dredged}]$$

with:
$V_{dredged}$=volume of removed water and sediment based on pre- and post bathymetric surveys;
$V_{pumped}= [(\rho_{wet,piumped} - \rho_w)/(\rho_{wet,insitu} - \rho_w)]\ Q_{mixture}\ \Delta t_{pumped}$ =volume of water and sediment through pump line;
$Q_{mixture}$= pump discharge of all dredgers involved;
Δt_{pumped}= total pump time;
$\rho_{wet,insitu}$=wet density of in-situ material;
$\rho_{wet,insitu}$=wet density of pumped mixture (range of 1200-1300 kg/m^3);
$\alpha_s=(\rho_s - \rho_w)/\rho_s$= coefficient
α_{eff}= coefficient (known as effectivity or agitation coefficient; loss/gain coefficient=1-α_{eff}; range 0.5-0.9)

$\alpha_{eff} < 1$ if $V_{pumped} > V_{dredged}$; in case of heavy natural infill during dredging and/or infill from overflow or side-casting processes in the period between the pre- and post surveys.

$\alpha_{eff} > 1$ if $V_{pumped} < V_{dredged}$; in case of natural scour or removal of in-situ sediment by propeller action of moving vessels in the period between the pre- and post surveys.

Example: Cutter dredger with P_{insitu}=2000 m^3/hour; $\rho_{dry,insitu}$=1200 kg/m^3; R_{spill}=2%.
S_{spill}=1200x2/100=24 kg/m^3 (2% of 1200 kg/m^3)
P_{spill}=1200x(2/100) (2000/3600)=13.3 kg/s

Table 3.4 shows S_{pill}-values for various dredging methods.

Dredging method	Production of dredged material (m^3/hour)	$C_{background}$ (mg/l)	ΔC at 50 m from centre (mg/l)	ΔT_{decay} after cessation of dredging (hr)	S_{spill} of fines (kg/m^3)
Large suction hopper (maximum overflow)	4000-6000	50-100	300-1000	1.5	20-50
Large suction hopper (limited overflow)	4000-6000	50-100	200-400	1	10-20
Large suction hopper (no overflow)	4000-6000	50-100	50-200	0.5-1	5-15
Small suction hopper (limited overflow)	1500-2500	20-50	50-200	0.5-1	5-15
Grab (open)	100-500	20-50	50-200	1	5-15
Grab (closed)	100-500	20-50	20-100	0.5-1	3-10
Bucket	300-600	20-50	50-200	0.5-1	5-15
Large cutter	>1000	20-50	50-200	0.5-1	5-15
Medium cutter	200-1000	20-50	50-200	0.5-1	5-15
Small cutter	100-200	20-50	20-100	0-0.5	3-10
Hydraulic crane (various backhoes)	100-200	20-50	100-500	1	5-50

Table 3.4 *Sediment resuspension/loss parameter S_{spill} of dredging equipment.*

LACS (Los Angeles Contaminated Sediments) Task Force (2003) has analysed the available data (40 to 50 cases) on the loss or resuspension of sediments during dredging operations without overflow from various dredging studies of the international literature. **Figure 3.3** shows the cumulative probability distribution of the loss/resuspension coefficient R_{spill} (as a percentage) on the horizontal axis of hydraulic (without overflow) and mechanical dredging methods, see also **Table 3.5.** It is shown that hydraulic dredging methods tend to resuspend less sediment into the water column than do mechanical dredging methods.
To include the uncertainties involved, it is wise to use the 90%-values. For example: $R_{spill, 90\%}$ = 2% for hydraulic dredging, which means that in 90% of the studied cases, the R-factor was < 2% and in 10% > 2%.
The R-parameter (derived from water samples) of hydraulic dredges represent the spill of fines at some distance (10 to 30 m) from the dredging point and which are washed away by local currents (input for dispersion models). The R-values close to the dredging point may be much higher (5% to 10%) but most of the coarser spilled sediments will settle immediately close to the dredging point (within 30 m).

Parameter	**Hydraulic dredging (no overflow)**	**Mechanical dredging**
Spill (resuspension/loss of fines) percentage $R_{spill,mean}$	0.8%	2%
Spill (resuspension/loss of fines) percentage $R_{spill,50\%}$	0.5%	1.5%
Spill (resuspension/loss of fines) percentage $R_{spill,90\%}$	2%	8%
Spill (resuspension/loss of fines) percentage $R_{spill,extreme}$	8%	10%
Turbidity concentration increase $\Delta c_{50\%}$	20 mg/l	70 mg/l
Turbidity concentration increase $\Delta c_{90\%}$	500 mg/l	150 mg/l
Turbidity concentration increase $\Delta c_{extreme}$	5000 mg/l	500 mg/l

Table 3.5 *Some characteristic values of resuspension factor and turbidity concentration increase; LASC Task Force 2003*

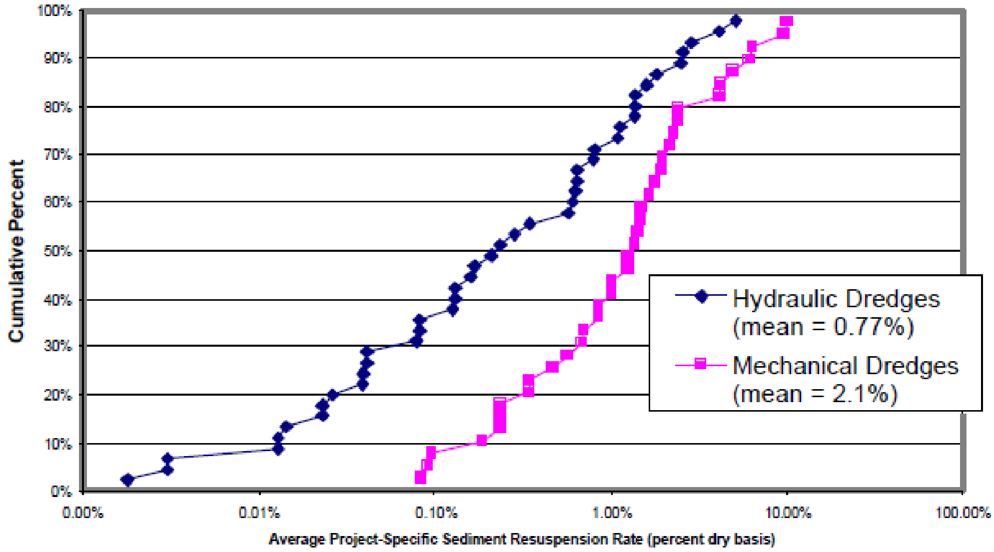


Figure 3.3 *Probability distribution (vertical) of R_{spill}-percentage (horizontal); LASC Task Force 2003*

Figure 3.4 shows the measured suspended sediment concentrations (above the background concentrations) at a distance of about 35 m (100 feet) from the dredge point based on data summarized by the LASC Task Force (2003). The turbidity concentrations produced by mechanical dredging methods are, on average, larger than those produced by hydraulic dredging methods. This may be caused by the fact that turbidy concentrations are generated at almost any point in the water column.

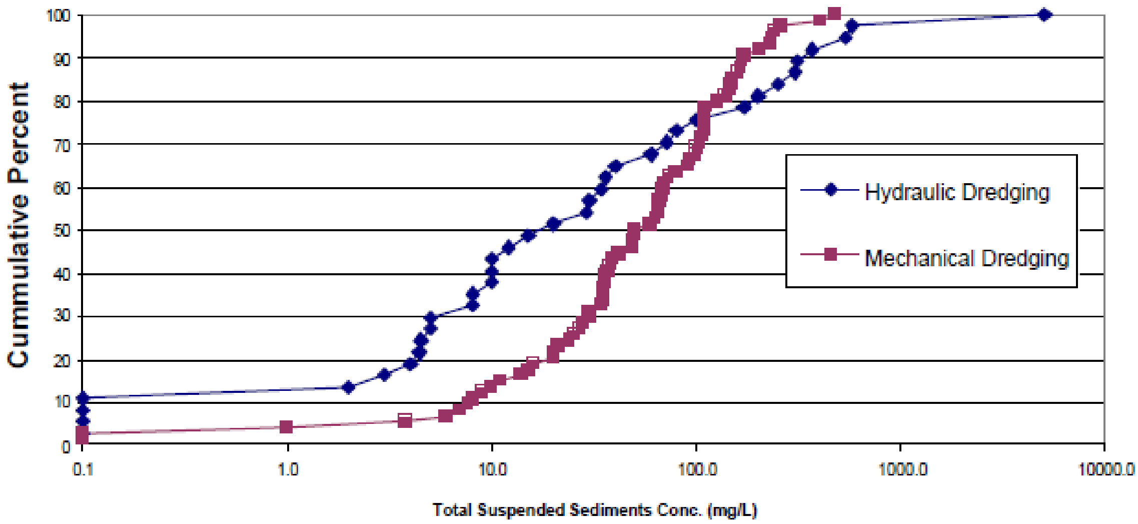


Figure 3.4 *Probability distribution of turbidity concentrations at 35 m from dredger; LASC Task Force 2003*

Becker et al. (2015) from **Van Oord dredging company** have proposed generic formulations for the source terms related to dredging and dumping of sediments. Realistic estimation of source terms, that define the suspended sediment input for far field dredge plume modelling, is key to any assessment. Their method is based on soil characteristics and dredge production rates, combined with empirically derived, equipment and condition specific 'source term fractions'. A source term fraction relates the suspended fine sediment that is available for dispersion, to the amount of fine sediment that is present in the soil and the way it is dredged.

The parameters involved are:

$M_{fines,total} = \rho_{dry,insitu}\ p_{fines}\ V_{insitu}$= total mass of fines to be dredged (kg);

$\rho_{dry,insitu}$ = dry density of insitu sediments;

p_{fines}= fraction of particles < 63 μm;

V_{insitu}= total insitu volume to be dredged.

The production rate of a dredger can be formulated as:

$P_{insitu} = V_{insitu}/(N_{days}\ N_{loading}\ \Delta T_{loading})$ = production rate of dredger of insitu volume(m^3/s);

N_{days}= number of days with dredging work;

$N_{loadings}$= number of loadings per day (24 hours);

$\Delta T_{loading}$ = loading time of dredger (seconds).

The required initial dredging volume for a hopper dredger is: $V_{hopper,o} = V_{insitu}/(N_{loadings}\ N_{days}) = P_{insitu}\ \Delta T_{loading}$
The mass of fines for hopper dredger with initial volume $V_{hopper,o}$ is: $M_{fines,hopper,o} = \rho_{dry,insitu}\ p_{fines}\ P_{insitu}\ \Delta T_{loading}$
The cycle time consists of: loading without overflow (≅ 0.2 hr) + loading with overflow (≅ 1 hr) + sailing to dump location (≅ 1 to 3 hrs) + dumping of load (≅ 0.1 hr) + sailing to dredging location (≅1 to 3 hrs) giving a total time of 3 to 6 hrs (N_{cycle} = 4 to 8).
In the case of hopper dredging, there are losses due to the loading (suction) processes and due to the overflow processes at the loading site. The dredged volume ($V_{hopper,o}$) is larger than the volume carried by the hopper dredger (V_{hopper}) to the dumpsite.
The mass M (kg) and flux F (kg/s) of fines brought into suspension due to the loading (drag head suction) and the overflow at the dredging site are:

$M_{fines,loading} = e_{loading}\ M_{fines,hopper,o}$ and $F_{fines,loading} = M_{fines,loading}/\Delta T_{loading}$;

$M_{fines,overflow} = e_{overflow}\ (M_{fones,hopper,o} - M_{fines,loading}) = e_{overflow}\ (1-e_{loading})\ M_{fines,hopper,o}$ and
$F_{fines,overflow} = M_{f,overflow}/\Delta T_{overflow}$;

The overflow generates two processes: passive plume of fines (most important for environmental dispersion) and a dynamic near-bed density current of fines. Thus:

$M_{fines,overflow} = M_{fines,plume} + M_{fines,dc1} = e_{plume1}\ M_{fines,overflow} + (1-e_{plume1})\ M_{fines,overflow}$

The flux related to the passive plume is: $F_{fines,plume} = e_{plume1}\ M_{fines,overflow}/\Delta T_{overflow}$
The mass of fines remaining in the hopper is:

$M_{fines,hopper} = M_{fines,hopper,o} - M_{fines,loading} - M_{fines,overflow} = [1- e_{loading} - e_{overflow}\ (1-e_{loading})]\ M_{fines,hopper,o}$

The hopper load is carried to the dumping site, where the load is dumped (by bottom doors) generating a passive plume and a near-bed density current (dc). Thus:
$M_{fines,hopper} = M_{fines,dumpplume} + M_{fines,dc2}$
$M_{f,dumpplume} = e_{plume2}\ M_{fines,hopper}$ and $F_{fines,dumpplume} = e_{plume2}\ M_{fines,hopper}/\Delta T_{dumping}$

with: e = efficiency or spill factor; $e_{loading}$ = 0.01-0.03; $e_{overflow}$ = 0.1-0.5; e_{plume1} = 0.1-0.3; e_{plume2} = 0.05-0.15;$\Delta T_{loading}$= duration of loading/suction processes (1 to 2 hours); $\Delta T_{overflow}$= duration of overflow (1 to 1.5 hours); $\Delta T_{dumping}$= duration of dumping process (10 minutes).
The source fluxes can be converted to a source concentration by using: $\Delta c= F/Q =F/(b\ h\ u)$,
with: F=flux of fines (kg/s), Q= b h u= water flow discharge (m^3/s), b= characteristic width (≅ 10-20 m); h= characteristic height (≅ 5-10 m); u= characteristic flow velocity (0.5 to 1 m/s); Δc = source concentration increase due to dredging activity (kg/m^3).
Similar formulations can be derived for other type of dredgers (grab dredger + barges, backhoe dredger + barges; cutterhead dredger + barges).

Example

$V_{hopper,o}$= 2400 m^3; $e_{loading}$= 0.03, $e_{overflow}$= 0.4; e_{plume1}= 0.2; e_{plume2}= 0.1; p_{fines}= 0.5; $\rho_{dry,insitu}$= 1185 kg/m^3; P_{insitu}= production insitu= 0.45 m^3/s; $\Delta T_{loading}$= 1.5 hr = 5400 s; $\Delta T_{overflow}$ = 1 hr= 3600 s; $\Delta T_{dumping}$ = 10 minutes = 600 s.

(subscript f refers to fines)

$M_{f,hopper,o} = \rho_{dry,insitu}\, p_{fines}\, P_{insitu}\, \Delta T_{loading}$ = 1185x0.5x0.45x5400= 1.44 10^6 kg

$M_{f,loading} = e_{loading}\, M_{f,hopper,o}$=0.03x1.44 10^6= 4.32 10^4 kg and $F_{f,loading} = M_{f,loading}/\Delta T_{loading}$=4.32 10^4/5400= 8 kg/s

$M_{f,overflow} = e_{overflow}\, (1-e_{loading})\, M_{f,hopper,o}$= 0.4x(1-0.03)x1.44 10^6=5.6 10^5 kg; $F_{f,overflow}$ = 5.6 10^5/3600= 155 kg/s

$M_{f,plume} = e_{plume1}\, M_{f,overflow}$=0.2x5.6 10^5=1.1 10^5 kg; $F_{f,plume}= M_{f,plume}/\Delta T_{overflow}$=1.1 10^5/3600= 30 kg/s

$M_{f,hopper} = [1- e_{loading} - e_{overflow}\, (1-e_{loading})]\, M_{f,hopper,o}$= [1-0.03-0.4(1-0.03)]x1.44 10^6= 0.84 10^6 kg

$M_{f,dumpplume} = e_{plume2}\, M_{f,hopper}$= 0.1x0.84 10^6= 8.4 10^5 kg;

$F_{f,dumpplume}= M_{f,dumpplume}/\Delta T_{dumping}$=8.4 10^5/600 = 140 kg/s.

Assuming an initial plume width of b=10 m, water depth of h= 10m, and local flow velocity u= 0.6 m/s, the concentration increase at the initial plume location is: Δc=140/(10x10x0.6) = 2.3 kg/m^3 = 2300 mg/l.

3.3 Measures reducing turbidity during dredging

Environmental dredging is a type of dredging focusing on operating either with minimal suspension of sediment or with particular accuracy. It can apply to specially adapted variants of any of the types of traditional dredgers. Typical environmental questions to be answered are whether suspended sediments will leave the dump site, where the material will go and how much material will remain in the water column after a certain time. Some types of dredgers have been specially designed for this purpose:

- Auger dredgers (**Figure 3.5**) using special equipment to move material towards the suction head; pumping by piston action to enable the transportation of high-density material;
- Disc-cutter dredgers with a cutter head which rests horizontally and rotates its vertical blades slowly (consolidated silt and sand; **Figure 3.5**);
- Scoop/sweep dredgers using special equipment to scrape the material towards the suction intake.

Mitigating measures to reduce environmental effects are (see also **John et al., 2000**):

- **Trailing suction hopper dredger**:
  - optimise trailing velocity, suction mouth and suction discharge;
  - limit or no overflow;
- **Cutter suction dredger (Figure 3.5)**:
  - optimise cutter speed, swing velocity and discharge;
  - use special cutterhead design;
- **Grab dredger**:
  - use watertight grab/clamshell (**Figures 3.2** and **3.6**);
  - use silt screen;
  - limit grab time above water;
  - limit grab dragging on bed;
- **Backhoe dredger**:
  - use special bucket for reducing sediment losses;
  - use silt screen (**Figure 3.6**); only if local current velocity < 0.5 m/s.

Figure 3.5 *Cutter head* *Screw-Auger head* *Disc cutter head*

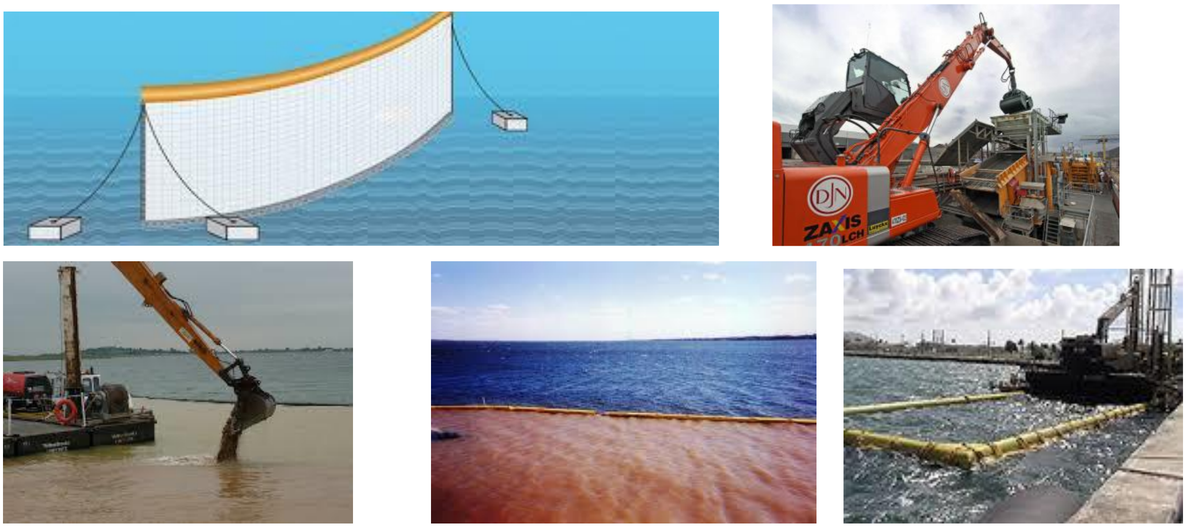


Figure 3.6 *Silt screens*

Cutter-suction dredgers generate a cloud of dredged material into the water, which is pumped/sucked into the mouth of the dredge pump. However, cutter-suction dredgers are not able to suck all that material up and may leave as much as 5% of all disturbed solids in the ambient water.
Horizontal hydraulic Auger dredgers push the dredged material into a shroud that directs the material into the pump's suction mouth. The shrouding of material enables horizontal hydraulic Auger dredgers to suck up almost all materials. Silt screens can be used to reduce the spreading of spilled mud.
A screw-Auger dredger operates like a cutter suction dredger, but the cutting tool is a rotating srew at right angles to the suction pipe (**Figures 3.5**). A horizontal hydraulic Auger dredger moves forward and dredges material away in broad lanes (dredge cuts), which are easy to track by echo-sounder. Self-propelled Auger dredgers are available that allows the system to propel itself without the use of anchors or cables. An Auger head (www.dopdredgepumps.com) can also be attached to a backhoe boom.

3.4 Summary

Mechanical dredgers cause increases of suspended sediment concentrations (SSC) in the range of 50 to 200 mg/l at about 50 m from the dredge point, but most data are less than 100 mg/l, see **Tables 3.6** and **3.7**. Generally, the larger the dredger the higher the SSC but, as the size increases, the overall volume of sediment lost as a percentage of the total volume dredged tends to decrease. The mechanical dredgers have relatively high S-values (close to the dredging point), but the concentration increase is not that high because the sediment is well dispersed throughout the water column and over a wide area at low concentrations before finally settling.

Table 3.8 shows dilution factors based on measured data and theoretical dispersion studies (**Section 5**). In most cases, the SSC decay to the background values within 500 m, except for hopper dredging with overflow.

Cutter suction dredgers produce SSC which are quite high near the cutterhead (about 1,000 to 10,000 mg/l), but are quite small away from the cutter.
Trailing suction hopper dredgers can inject considerable quantities of fines into the water column when overflowing. SSC close behind the dredger can reach up to 500 mg/l at the water surface and as much as

5000 mg/l near the bed. If operating without overflow, very little sediment is brought into suspension (generally smaller than about 200 mg/l). The overflow mixture tends to descend towards the bed quite rapidly as a dense plume due to its relatively high density and high rate of delivery.
Large suction hopper dredgers can produce just as much turbidity (in terms of S-values) as small Backhoe grab dredgers. The S-values do not depend greatly on production capacity.
The study results from various field sites show that the turbidity concentrations:

- are greatest near the bottom;
- decrease rapidly with distance from the dredger; decrease is less rapid if currents are relatively large;
- are greatest for very fine sediments.

The decay times (after cessation of dredging) is about 3 hours in depths of 5 to 10 m, which implies that the suspended sediments sink relatively quickly to the bed after cessation of dredging operations in conditions with relatively low currents (< 0.5 m/s). The effective settling velocities of fines/mud are in the range of 0.5 to 2 mm/s (due to flocculation effects).
The turbidity increase near dredgers in the harbour basins of Rotterdam was found to be of the same order of magnitude as the turbidity increase due to sailing and mooring of vessels (resuspension due to propeller of vessels with tugs and the return flows between bottom side of vessels and the bed in shallow water).
Turbidity increases up to 500 mg/l (background concentration of 20 mg/l) were measured at distances of about 50 to 200 m from a large bulk carrier during mooring at the quay wall with assistance of four tugs in one of the harbour basins of Rotterdam. The annual production of turbidity during maintenance dredging in the Botlek harbour basin of Rotterdam is of the same order as the production of turbidity due to the passage and mooring of all vessels in a year in this basin.
Turbidity can be greatly reduced by modification of the standard dredging procedures (overflow using special return pipes at bottom side of vessel; closed grab or clamshells; silt curtains or screens around mechanical dredgers).

<u>Turbidity parameters (see Tables 3.6, 3.7 and 3.8)</u>
The resuspension/loss rate of dry mass of fine sediment per hour (kg/hour) is given by:

$$P_{spill} = (R_{spill}/100)\ \rho_{dry,insitu}\ P_{insitu} = (R_{spill}/100)\ \rho_{dry,pumped}\ P_{pumped} \qquad (3.1)$$

The resuspension/loss rate per unit time and area (kg/m^2/hour):

$$P_{spill,area} = (R_{spill}/100)\ \rho_{dry,insitu}\ (P_{insitu}/A_d) = (R_{spill}/100)\ \rho_{dry,pumped}\ (P_{pumped}/A_d) \qquad (3.2)$$

with:
R_{spill}= 100 $S_{spill}/\rho_{dry,insitu}$ = spill percentage (1% to 10%); about 1% to 10% of dry sediment mass (per m^3 of insitu source material dredged out; water + sediment);
S_{spill}= dry sediment mass (kg/m^3) resuspended/lost for each m^3 of insitu (source) material dredged out;
P_{insitu} =production rate of insitu volume (500 to 5000 m^3/hour); total volume to be removed;
P_{pumped} =[$\rho_{dry,insitu}/\rho_{dry,pumped}$]$P_{insitu}$ =volume production rate of (added) water + sediment material (m^3/hour);
A_d = area where sediment is dredged (of the order of 100 to 1000 m^2; model grid area);
$\rho_{dry,insitu}$ = dry bulk density of insitu sediment before dredging (kg/m^3);
$\rho_{dry,pumped}$= dry bulk density of dredged sediment (during/after dredging), (kg/m^3).
Hopper dredger: $\rho_{dry,pumped}$= ratio of dry sediment mass in hopper (at end of overflow process) and hopper volume; about 300-600 kg/m^3 for mud and and 1500/1600 kg/m^3 for sand.
Cutter dredger with barges: $\rho_{dry,pumped}$= ratio of dry mass in barge and barge volume.
Cutter dredger with pipeline: $\rho_{dry,pumped}$= dry sediment concentration in pipeline (200 to 400 kg/m^3).
Grab dredger: $\rho_{dry,grabbed}$= dry mass in grab/grab volume (500-1500 kg/m^3 for mud and sand).

Dredging method	Production of dredged material (m^3/hour)	ΔC at 50 m from centre with respect to background (mg/l)		S_{spill} of fines close to dredger (kg/m^3)
		Dutch sites	USA sites	
Large suction hopper (maximum overflow)	>4000	300-1000 s 500-5000 b	300-1000	20-50
Large suction hopper (limited overflow)	>4000	200-400		10-20
Large suction hopper (no overflow)	>4000	50-200	50-300	5-15
Small suction hopper (no overflow)	1500-4000	50-200	50-200	5-15
Large cutter suction	>1000	50-200	50-200	5-15
Grab (open)	100-500	50-200	10-100 surface 100-1000 bed	5-15
Grab (closed)	100-500	20-50	10-50 surface 50-300 bed	3-10
Grab Backhoe	100-300	100-500		5-50

ΔC=concentration increase; s=surface, b=near bed

Table 3.6 *Sediment resuspension/loss parameters of dredging equipment.*

Parameter	Hydraulic dredging (no overflow)	Mechanical dredging
Spill (resuspension/loss of fines) percentage $R_{spill,mean}$	0.8%	2%
Spill (resuspension/loss of fines) percentage $R_{spill,50\%}$	0.5%	1.5%
Spill (resuspension/loss of fines) percentage $R_{spill,90\%}$	2%	8%
Spill (resuspension/loss of fines) percentage $R_{spill,extreme}$	8%	10%
Turbidity concentration increase $\Delta c_{50\%}$	20 mg/l	70 mg/l
Turbidity concentration increase $\Delta c_{90\%}$	500 mg/l	150 mg/l
Turbidity concentration increase $\Delta c_{extreme}$	5000 mg/l	500 mg/l

R_{spill}=spill percentage, ΔC=concentration increase

Table 3.7 *Resuspension factor and turbidity concentration increase; LASC Task Force 2003*

Current velocity	Dilution factor at about 200 m from source	Dilution factor at about 500 m from source	Dilution factor at about 5000 m from source
0.1-0.3 m/s	1/5	1/10	1/50
0.3-0.5 m/s	1/5	1/10	1/25
0.5-1 m/s	1/5	1/7	1/15
1-1.5 m/s	1/5	1/7	1/10

Dilution factor $\gamma_d = c_x/c_o$; c_x= concentration at location x; c_o=concentration at source location

Table 3.8 *Dilution factors of mud concentrations (8 to 16 μm; almost uniform distributed over water column) due to settling, longitudinal and lateral mixing/dispersion (see Table 5.5); continuous source in water depth of 10 m*

3.5 Examples of predicted turbidity values at dredging sites

Example 1: Turbidity generated by hopper cutter suction dredging in muddy conditions

Given: Production rate P_{pumped} = 2000 m^3/hour (sediment +added water); Overflow rate $R_{overflow}$= 0%
Dry bulk density of insitu mud $\rho_{dry,insitu}$= 800 kg/m^3
Dry bulk density of mud $\rho_{dry,pumped}$= 400 kg/m^3
Filling time= 0.5 hours; water depth= 15 m
$R_{spill,90\%}$=resuspension factor= 2%
Local current velocity= 0.7 m/s

Equation (3.1) yields:
P_{spill}= $(R_{spill}/100)\ \rho_{dry,pumped}\ P_{pumped}$ = (2/100)x400x2000 = 16000 kg/hour ≅ 5 kg/s

Maximum sediment concentration increase at 50 m from centre Δc_{max}≅ 500 mg/l
Maximum sediment concentration increase at 500 m from centre Δc_{max}≅ 1/5x500= 100 mg/l
Maximum sediment concentration increase at 5000 m from centre Δc_{max}≅ 1/50x500= 10 mg/l

Example 2: Turbidity generated by open Grab dredging in muddy conditions

Given: Production rate P_{grab} = 300 m^3/hour (sediment+added water); Overflow rate $R_{overflow}$= 0%
Dry bulk density of insitu mud $\rho_{dry,insitu}$= 800 kg/m^3
Dry bulk density of mud in grab bucket $\rho_{dry,grab}$= 700 kg/m^3
water depth= 15 m
$R_{spill,90\%}$=resuspension factor= 8%
Local current velocity= 0.3 m/s

Equation (3.1) yields:
P_{spill}= $(R_{spill}/100)\ \rho_{dry,grab}\ P_{grab}$ = (8/100)x700x300 = 17000 kg/hour ≅ 5 kg/s

Maximum sediment concentration increase at 50 m from centre Δc_{max}≅ 150 mg/l
Maximum sediment concentration increase at 500 m from centre Δc_{max}≅ 1/3x150= 50 mg/l
Maximum sediment concentration increase at 5000 m from centre Δc_{max}≅ 1/30x150= 5 mg/l

The spill or resuspension rate ($kg/m^2/s$) per unit time/area can be converted to a local concentration, as follows:

$P_{spill}/A_d = v_{current\ near\ bed}\ c_{nearbed}$
$c_{nearbed}= [P_{spill}/(A_d\ v_{current\ near\ bed})]$

Using: P_{spill} = 5 kg/s, A_d = 400 m^2 and $v_{current\ near\ bed}$= 0.1 m/s, it follows that:
$c_{nearbed}= [P_{spill}/(A_d\ v_{current\ near\ bed})]$= 5/(400x0.1) = 0.125 kg/m^3= 125 mg/l over an area of about 400 m^2.

In one hour a quantity of 17000 kg is brought into suspension by the grab.
Given a production rate of 300 m^3/hour and a layer thickness of 0.5 to 1 m, the grab can remove sediment from an area of about 300 to 600 m^2.
Given a water depth of 15 m, the volume of water within an area of 400 m^2 is about 6000 m^3.
Thus: the concentration increase is about 17000/6000 ≅ 3 kg/m^3 ≅ 3000 mg/l within an area of 20x20 m^2.
This value applies to the situation with no advection (current velocity= 0 m/s; no dilution) and no settlement of the fines within the dredging area.
If a silt screen around the area of 400 m^2 is used, the sediment concentration will go up to values of the order 3000 mg/l (brown water, see **Figure 3.5**).

Example 3: Turbidity generated by hopper overflow in muddy conditions

Given: Hopper volume V_{hopper}= 5000 m^3; Overflow rate $R_{overflow}$= 7%
Dry bulk density of mud in hopper $\rho_{dry,hopper}$= 400 kg/m^3; fraction fines < 63 μm= 0.8
Filling time= 0.5 hours; sailing speed during loading= 3 km/hour; water depth= 15 m
Local current velocity =0.6 m/s

The following formula can be used:

ΔC_{fines}= [e_{fines} ($R_{overflow}$/100) $\rho_{dry,hopper} V_{hopper}$]/[$L_{track}$ B_{track} h_{mixing}]

with:
e_{fines}= fraction of fines of hopper load (0.8);
L_{track}= sailing distance during dredging,
B_{track}= effective ship width (20 to 30 m),
h_{mixing}= effective water depth over which sediment is mixed (1 to 5 m).

The total overflow loss of a hopper with a volume of 5000 m^3 will be about 350 m^3 (assuming loss of 7%) or about 350x0.4=140 tons of sediment (assuming a dry density of 400 kg/m^3).
This amount of sediment will be released (mixed) in the water column during sailing over a distance of the order of 1500 m, a width of about 30 m (about 3 times the width of the vessel) and an effective mixing depth of 5 m (30% of water depth).
Most of this sediment (coarser fractions) will rapidly sink to the bed; the fines (80%) will remain in suspension for some time (15 to 30 minutes).
This yields: ΔC_{fines}= [0.2x(7/100)x400x5000]/[1500x30x5] $\cong$ 0.15 kg/m^3 $\cong$ 150 mg/l. This should be interpreted as an average value over the sailing track with area of 30x1500 m^2.

The method of Becker et al. (2015) yields (**Section 3.2**):
$F_{f,plume} = e_{plume1} M_{f,overflow}/\Delta T_{overflow}$ = 0.3x[(0.8x400x0.07x5000)/1800]= 20 kg/s
$\Delta c = F_{f,plume}/Q = F_{f,plume}/(B\ h\ u)$ = 20/(30x15x0.6)= 0.074 kg/m³= 75 mg/l

Table 3.6 shows values up to 1000 m/l in the vicinity (at 50 m) of the dredger.
Using a dilution factor of 1/10 (**Table 3.8**), the increase of the mud concentration at 500 m is about 100 m/l.

4. Turbidity at dumping sites

4.1 Dumping/disposal sites

Two options are available for disposal:
- on land (reclamation);
  - requiring design and construction of dikes;
  - requiring compaction and drainage of dumped materials;
- open water (river, estuary or coastal sea);
  - near-field dumping and far-field dumping.

The selection of a dumping site in open water depends on:
- hydrodynamic conditions at the disposal site (wave action and currents should be minimum);
- location of the disposal site with respect to the recirculation of fines to the dredging site (preferably on downdrift side of net current); some recirculation is acceptable as long as the cost of additional dredging is less than disposing it at another site without recirculation; the storage capacity should be sufficient;

Near-field dumping
This disposal method is a cheap solution and consists of:
- side-casting at dredging location (channel) resulting in a mound along the channel (relatively high mounds are more easily resuspended);
  downdrift bypassing (maintenance dredging in a channel through a large shoal can be best dumped at downdrift location so that the sand remains in the system);
- thin-layer disposal over wide area to prevent resuspension and backflow to dredging location (area should be much larger than the dredging area).

Far-field dumping
This disposal method is relatively expensive as it is aimed at dumping the sediments as far as possible from the dredging site to prevent sediments from returning to the dredging site.
The following methods can be distinguished;
- offshore mounds in deep water; it may be attractive to make an offshore reef protecting the coast landward of the reef (if dredged material is sand);
- nearshore feeder berm; it may be attactive to keep the dredged material (if sandy) in the nearshore system with possible effect of nourishing the beach system.

Unpolluted or lightly polluted dredged material can generally be dumped at a near-field or far-field disposal sites. Very polluted materials should preferably be dumped on land in confined areas.

4.2 Dumping processes in open water

4.2.1 General

The method of dumping strongly depends on the environmental effects (turbidity should be minimum); silts and clays are generally dispersed over relatively large areas in the presence of currents (mud plumes).
The resuspension potential at dumping site (stirring up of deposited sediment by local currents and storm waves) should be studied. Most of the disposed materials will sink relatively quickly to the bed as a density current. In shallow water, the deposited sediments can be stirred up easily in relatively shallow water by wind waves.

The thickness of the deposits at the dump site should remain relatively small (not more than 10% of local water depth) at the end of the project to minimize resuspension; preferably, the disposal site should be selected at a location where the wave and current-related bed-shear stresses remain relatively small so that the sediments are not dispersed or carried away from the designated limits of the site (**Scheffner, 1991**).

The available dumping methods are:

- free fall dumping (bulk load) using hopper or barges with bottom doors or split hull hopper/barges;
- continuous jet or plume disposal by pumping of mixture through a floating or submerged pipe (with or without a diffusor) into the water column;
- side casting at dumping site (sediment is pumped from the hopper into the water column at disposal site); submerged or emerged methods can be used;
- side casting at dredging site using a trailer sidecasting dredger (with or without a special boom of length up to 100 m), which directly pumps the dredged sediments into the water as far as possible away from the dredger; this is very efficient in situations with very weak tidal currents (lagoons) or unidirectional cross-currents away from the dredging site;
- continuous free fall disposal from a spray boat; which is often used in shallow water to make land reclamations by spraying thin layers of sand on the bottom and to minimize the spreading of turbidity.

4.2.1 Free fall loads through bottom doors

Dumping processes

In the literature there is an extensive amount of information on the spreading and dispersal of fine sediments (sediments < 63 μm) during the dumping process at disposal sites based on laboratory and field studies. Fines released during the dumping process descend to the seabed as a cloud while a minor amount of the fines (<3%) are striped from the cloud and are dispersed in the water column and carried away by local currents to be deposited on the seabed elsewhere (more quiescent locations with low velocities).

Sediments (mud) are released from hopper dredgers in the form of a high-concentration slurry of water sediments (concentrations of the order of 300 to 600 kg/m^3) through a pipe exits or through bottom openings. Hopper dredgers are equipped with bottom openings (bottom doors) for quick release of the sediment load on a time scale of 1 to 3 minutes. In the case of split hull barge or hopper, the hull of the vessel splits open to release the load almost instantaneously.

After release, the behaviour of dredged materials strongly depends on the sediment (cloud) concentrations during exit discharge, as follows (**Figure 4.2.1**):

- high-concentration dynamic jet-type plume; dredged materials of high concentration behave as a (negatively buoyant or downward moving) jet towards the seabed where it forms a density current radiating outwards from the point of impact;
- low-concentration passive plume: dredged materials of low concentration behave as a passive plume of sediments affected by local current velocities and turbulent mixing processes resulting in rapid dilution of the plume and rapid dispersal of fines in the water column.

The hopper load generally consists of a high-concentration slurry (dry density of 300 to 600 kg/m^3) dredged by hydraulic suction/pumping of fines with extensive reworking of the soil by the pump blades and relatively large volumes of water involved for transportation of materials.

Barge loads may consist of very dense sediment mixtures of cohesive blocks or clods produced by grab-type of bucket-type (clamshell) dredging resulting in mixtures with dry density values in the range of 600 to 1200 kg/m^3.

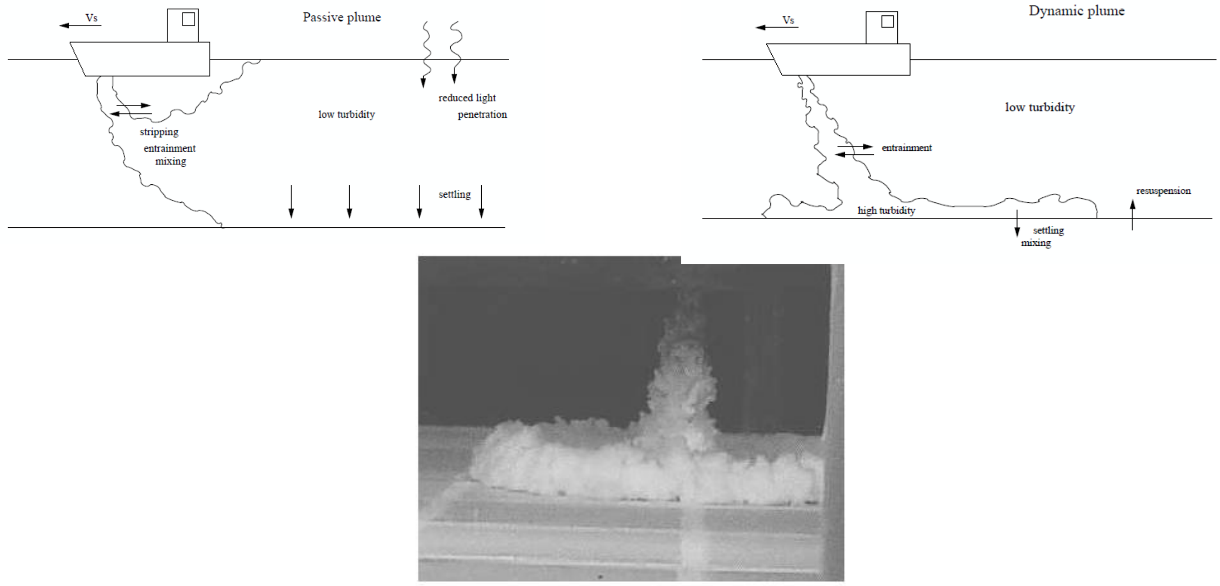


Figure 4.2.1 *Passive and dynamic plumes (Dankers 2002)*

Boot (2000) and **Winterwerp (2002)** performed an experimental laboratory study of continuous jet disposal. After release from the outflow pipe, the mixture forms a plume which is either directly mixed with the ambient water (passive plume; **Figure 4.2.2**) or behaves as a density current (dynamic plume; **Figure 4.2.2**) descending to the bed and flowing along the bed after impact.
They varied: the sailing speed of the outflow pipe at the hopper (0 to 2 m/s); the velocity of the mixture at the outflow pipe and the concentration of the mixture. A mixture of kaolinite and water was used. The geometrical scale was 1 to 60. The sailing velocity in the flume was varied between 0 and 0.26 m/s corresponding to 0 and 2 m/s in nature. The outflow velocity of the mixture in the model was varied between 0.06 and 0.25 m/s corresponding with 0.5 to 1.9 m/s in nature.
The density of the mixture in the outflow pipe was varied between 1148 and 1174 kg/m^3 (sediment volume concentration between 5% and 15%).
The following plume characteristics were studied: mixing over depth, thickness of plume, radial dispersal of sediment along bottom of flume and the radial dispersal velocity.
The type of plume can be expressed as a function of a velocity ratio (u/w) and Richardson number (Ri), as shown in **Figure 4.2**.

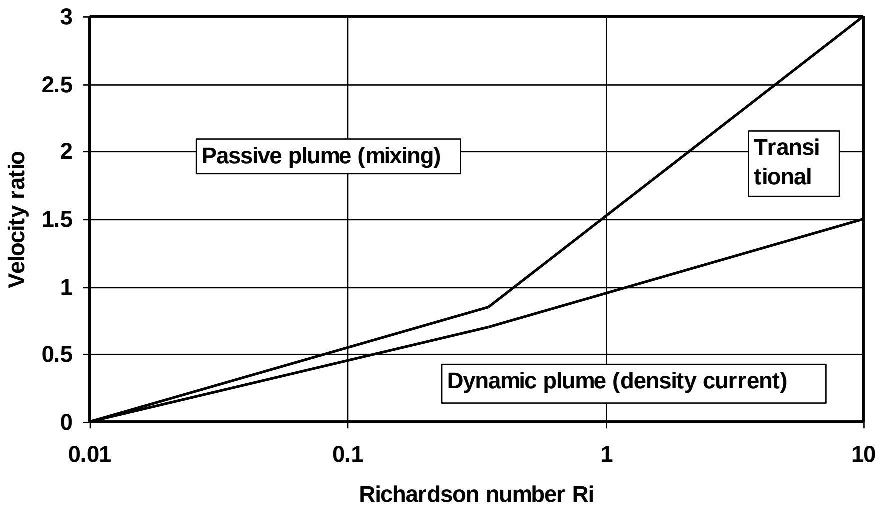


Figure 4.2.2 *Type of plume as function of Richardson number (Ri) and velocity ratio (u/w); Boot (2000) and Winterwerp (2002)*

The basic parameters are: u= velocity of ambient water relative to the ship sailing with or against the flow, w= outflow velocity of mixture (plume) at pipe; Ri= $\varepsilon gd/w^2$ with $\varepsilon = (\rho_{mixture}-\rho_{water})/\rho_{water}$, $\rho_{mixture}$= density of mixture in outflow pipe, g= acceleration of gravity, d= diameter of outflow pipe.
Given the following values as an example calculation: u= 1 m/s, w= 2 m/s, $\rho_{mixture}$= 1100 kg/m^3, ρ_{water}= 1025 kg/m^3, d= 1 m; the plume will behave as a density current (Ri= 0.18; u/w= 0.5).
Quick release dumping of dredged materials in shallow water < 100 m from a hopper dredger falls in the category of dynamic jets/plumes and consists of three steps (Bokuniewicz et al., 1978; USACE 2015; Mills and Kemp, 2016):

1. convective descent: dredged materials descent as a big and coherent cloud of sediment to the seabed under influence of gravity (excess density) with a velocity far greater than the settling velocity of the individual fines; the bulk of the dredged materials falls in a dense jet (and not as individual particles settling slowly downward) directly to the seabed with only minor losses of sediment to the water column; shear stresses developing along the interface between fluid and sediment cloud cause local turbulent eddies which entrain fluid into the cloud and sediment out of the cloud reducing the excess density (lower cloud concentrations) and increasing the volume of the cloud; fines are stripped/separated from the cloud by turbulent eddies resulting in suspended spill concentrations in the water column;
2. dynamic collapse into density current (underflow) after impact onto the seabed and radiating outwards with decreasing horizontal velocities and spreading as dominant processes; fines are stripped from the density plume and mixed into the overlying water as suspended spill;
3. passive spreading and transports by local currents if the dynamic plume is sufficiently diluted (only in very deep water).

Table 4.2.1 shows field data at dump sites in the USA determined by Bokuniewicz et al. (1978) based on detailed measurements using echo-sounding equipment and various electronic sensors for velocity and concentrations. Pumped water samples were used for calibration of sensors. Syringe samples were used for determination of the bulk density of the hopper loads.

Site	Water depth and currents	Dredged material	Insertion speed at exit and release time	Descent speed	Disposal radius and travel time	Spill from cloud
Ashtabula (Lake Erie)	15-18 m <0.2 m/s	700 m^3; sandy silt hopper 1300 kg/m^3	1.2 (38 s)		150 m after 600 s	<2%
New York Bight (open Ocean)	26 m <0.25 m/s	3000/6000 m^3; marine silt hopper and barges	hopper: 1 m/s (100 s) barges: 2 m/s (10 s)		hopper: 250 m after 500 s barge: 300 m after 500 s	<2%
Saybrook Long Island Sound)	52 m <0.7 m/s	1150 m^3; marine silt clamshell dredge 1300 kg/m^3	6.5 m/s (4 s)	2.8 m/s	150 m after100 s	<2%
Seattle (Duamish River)	67 m <0.2 m/s	400/500 m^3; sandy silt clamshell dredge 1600 kg/m^3	0.4 m/s (60 s)	0.5 m/s	60 m after 300 s	<2%
Rochester (Lake Ontario)	15-46 m <0.2 m/s	700 m^3; river silt hopper 1200 kg/m^3	mean: 1.2 initial: 4.5 m/s end: 0.5 m/s (45 s)	0.8 m/s (Surface: 2 m/s (Bed: 0.7 m/s) (depth 15 m)	90 m after 300 s	<2%
New Haven (Estuary)	18 m <0.4 m/s	1500 m^3; marine silt/clay clamshell dredge	3 (20 s)		70 m after 300 s	<2%

Table 4.2.1 *Field data of dynamic plume disposal sites (Bokuniewicz et al., 1978)*

Descent

The field data of **Table 4.2.1** show that the descent speed of a high-concentration cloud of fines is in the range of 1 to 3 m/s and strongly depends on the insertion speed which is the initial speed of the cloud after release from the dredger. The descent speed roughly is 0.4 to 0.8 times the insertion speed. The water depth has not much effect on the descent speed as long as the cloud is not disintegrated and behaves as dynamic plume (descent speed >> settling speed of individual cohesive aggregates). The descent speeds at the Seattle site and at the Saybrook site are very different, but the water depth is in the same range (50 to 70 m).
A sediment load of larger cohesive blocks or clods (>0.05 m) have a terminal settling speed in the range of 1 to 2 m/s and may fall as individual elements to the seabed rather than as bulk cloud, independent of the insertion speed.

The insertion speed can be derived from the emptying rate (discharge rate) and the open door area of the hopper. The emptying rate depends on the type of dredged materials in the hopper load (density, load thickness) the geometry and opening speed of the bottom doors. Some type of hoppers (or barges) have an almost instantaneous door opening resulting in a high insertion speed. Large hoppers with multiple doors produce multiple simultaneous jets.
The insertion speed and thus the descent speed is low (< 1 m/s) in the case of slow door opening and low density of the hopper load.

The insertion speed can to some extent be controlled by the dredge operator (door opening speed or area). A high insertion speed can be used to reduce the transit time (and minimize spill) to the seabed in conditions with a strong current and or large depth. A low insertion speed can be used to increase the transit time resulting in a smaller bed impact and bed surge.

An important process during descent of the high-concentration sediment cloud (slurry) to the seabed is the entrainment of water into the cloud due to the generation of a thin boundary layer flow with shear stresses along the interface of the cloud producing small-scale turbulent eddies which bring clear water into the cloud and sediment out of the cloud into the boundary layer. By this entrainment and dilution processes with clear ambient water, the cloud volume of water and sediment increases strongly during descent, but at the same time the bulk cloud density decreases due to dilution.

Bokuniewicz et al. (1978) measured the lateral spread due to entrainment by using horizontally scanning echo-sounding equipment and found that the cloud volume impacting the seabed was 70 times greater than the released volume at a site with depths up to 45 m (Rochester site, Table 4.1).In deep water, there is a relatively long descent path and thus more water can be entrained mixed into the descending cloud resulting stronger dilution. At a certain depth, the cloud is fully disintegrated and the decent speed becomes equal to the settling speed of the individual mud aggregates

Spill of fines along the interface of the cloud may occur during the descent of the cloud, but the spill outside the boundary layer along the cloud is found to be minor (<1 to 2% of the cloud mass) due to the absence of turbulence. Additional spill may occur due to flushing processes around the hopper bottom doors in the end phase of the load release.

The spill is somewhat higher (<3%) at dump sites with strong tide-/wind-induced currents > 0.7 m/s due to interaction of current-related turbulence with the descending cloud. Strong currents also cause significant (but predictable) displacement of the descending cloud, particularly in the zone where the cloud is decelerated sufficiently (to the velocity of the ambient current) and the cloud concentration is substantially reduced to values below 50 kg/m^3 and gradually becomes a passive cloud

Examples

The author has consulted (March 2022) two major dredging companies (Jan de Nul dredging, Belgium and Boskalis dredging, The Netherlands) to obtain more information of the dumping parameters related to soft dredged materials, see **Table 4.2.2**. The insertion speed varies in the range of 1 to 2 m/s for soft mud dredged materials (wet density of about 1250 kg/m^3), depending on the number of doors, the total effective door area and the opening time. The effective door area is somewhat less than the opening area due to the presence of opening machinery and the doors are not completely vertical in full opening position, see **Figure 4.2.4**.

The insertion speed is relatively high (> 1 m/s) for a hopper (AVH) with many doors (high percentage of door area in relation to the total load area). Hopper 1 (AVH) has 14 doors with a total effective door area of 210 m^2, which is 23% of the load area. Hopper 2 (G) has 4 doors with maximum effective area of 80 m^2.

Detailed information of the dumping process of hopper 1 (AVH) is given in **Figure 4.2.3** which shows the dumping of a hopper load as function of time (April 2021, Hamburg).

The hopper volume is 9130 m^3; the load is 11220 ton (wet bulk density=1.23 t/m^3).
The opening time is 180 s (16:42:10 to 16:45:25), see upper plot
The load release time is 60 sec (16.42:10 to 16:43:10, see blue line in lower plot
Load is released in 60 sec after the start the opening procedure (180 s).
Total open area of bottom doors after 60 s assumed to be 1/3 of total area=210/3=70 m^2,
The insertion speed is $9130/(60x70) \cong 2$ m/s

Detailed information of the dumping process of hopper 2 (G) is given in **Figure 4.2.5** which shows the dumping of a hopper load as function of time (28 July 2021, Rotterdam).
The hopper volume in 2 load areas is about 12000 m^3.
The load release time is about 2 minutes (around 23.51 hrs).
The insertion speed is $12000/(120x80) \cong 1.25$ m/s

Parameter	**Hopper 1 Alexander von Humboldt (Jan de Nul dredging)**	**Hopper 2 Gateway (BosKalis dredging)**
Hopper load volume (m^3)	9000	12000
Hopper load area (m^2)	900	1200
Number of double doors	7 (4.1x8.2 m^2)	4 (4x5.4 m^2)
Effective door area (m^2) and relative door area (%)	210 (23%)	80 (7%)
Opening time of doors (s)	70 m^2 after 60 s 140 m^2 after 120 s 210 m^2 after 180 s	60
Disposal time to release load (s)	60 to 100	180 to 300
Disposal discharge (m^3/s)	150 to 90	120 to 180
Insertion speed of load through doors (m/s)	2 to 1	1.25 to 0.85

Table 4.2.2 *Dumping parameters of hopper dredgers*

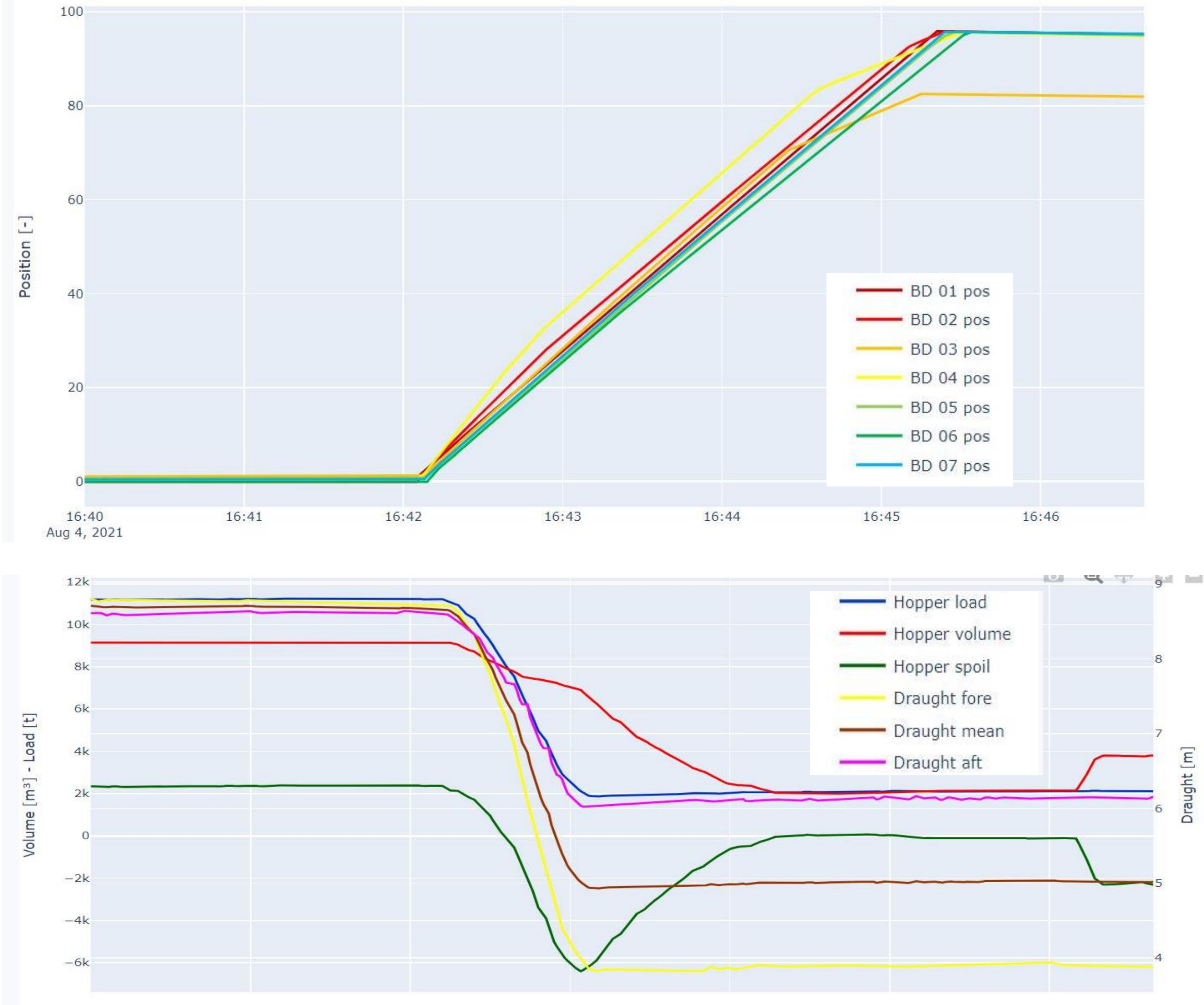


Figure 4.2.3 *Dumping processes as function of time (hopper 1: Alexander von Humboldt, Jan de Nul dredging)*
Upper: Opening of bottom doors (7 pairs) as function of time
Lower: Hopper load, volume and draught as function of time

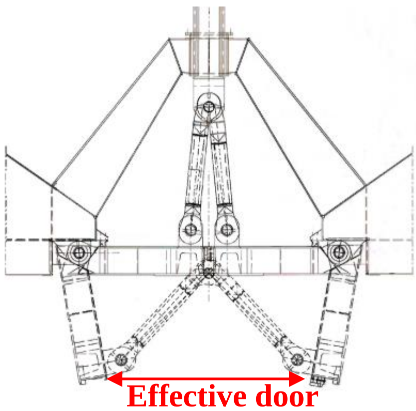
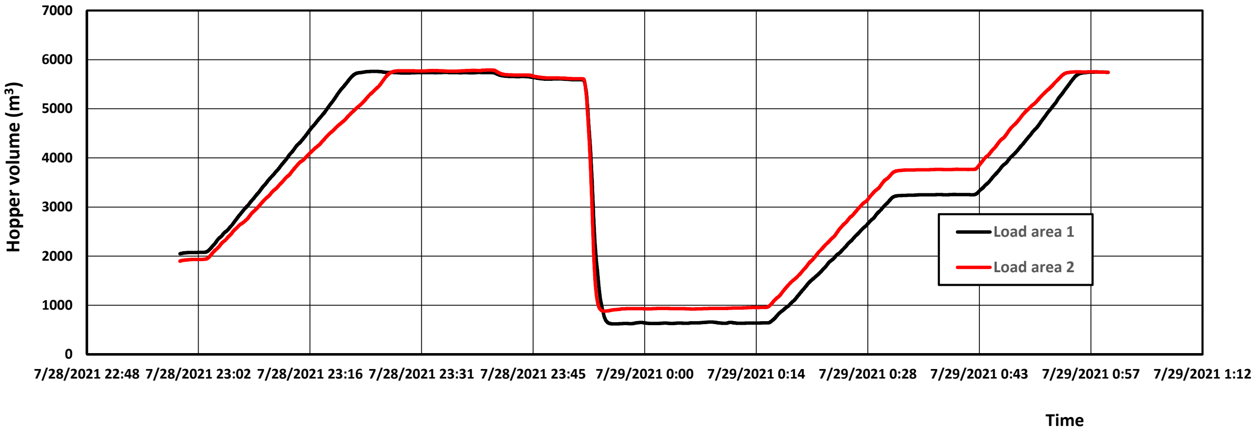


Figure 4.2.4 *Bottom doors of hopper 2*



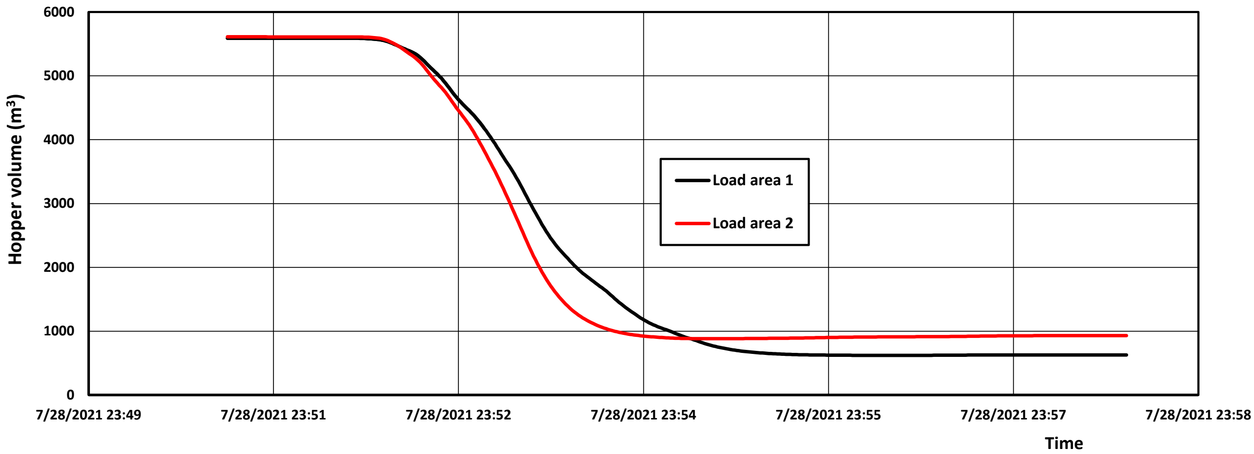


Figure 4.2.5 *Dumping processes as function of time (hopper 2 Gateway, BosKalis dredging))*
Upper: Dredging cycle as function of time
Lower: Dumping process as function of time

__Bed impact__

At most filed sites of **Table 4.2.1**, the dredged materials reached the seabed while travelling at speeds < 1 m/s. The jet plume is deflected after bed impact and runs radially away in all directions as a disk-type of density current (or density surge) at similar speeds of 1 m/s over hundreds of meters before coming to rest (see Table 2.1). The initial thickness of the spreading disk with supercritical flow is 3 to 4 m carrying a sediment load with concentrations of about 10 kg/m^3 and in the range of 1 to 5 kg/m^3 near the surge front. In deeper water the cloud diameter is larger due to dilution processes resulting in a higher initial thickness (4 to 6 m; <10% of water depth), but with lower sediment concentrations (< 5 kg/m^3). Higher quantities of dredged material released (larger hoppers) also lead to thicker density currents.
Both the thickness and the speed of the density current decrease at distances further away from the impact point with the sediments of the decelerating cloud gradually settling out (deposition). Most larger cohesive blocks are disintegrated during the impact process. The spread of the density current is radially symmetric around the point of impact with may lobes and indentations along the outer edge of the deposits.
Summarizing, the main findings of hopper load dumping based on data from field sites, are:

- descending cloud behaves as a coherent dynamic jet plume in depths up to 70 m without disintegration; larger cohesive blocks with settling speeds in the range of 1 to 2 m/s may settle as individual aggregates;
- descent speed is reasonably constant in water depths up to 70 m and depends strongly on the insertion speed through the hopper bottom doors;
- descending cloud is diluted strongly by water entrainment process along interface, but the cloud is not disintegrated in water depths up to 70 m;
- spill of fines from the descending cloud is minor (<1% of hopper load mass) in depths up to 70 m; spill may be somewhat higher (<3%) at sites with strong currents > 0.7 m/s due to interaction of current- related turbulence with the descending cloud; cloud is displaced by the current.

Depth of cloud disintegration

The convective descent stage can be subdivided into three phases, as follows:

- initial acceleration phase; after release, the closely packed and coherent cloud of sediment accelerates to its terminal speed and expands rapidly by entraining ambient water and reducing its excess density;
- thermal phase with ongoing entrainment of water and violent vortices around the cloud (vortex rings) reducing the cloud concentrations to values of the order of 10 kg/m^3 if there is sufficient depth of water (>50 m);
- passive disperse phase; the vertical velocity of the cloud is reduced to values of the order of the settling velocity of the individual aggregates (< 0.05 m/s) and particles individually settle out to the seabed under the influence of local currents and turbulence causing additional mixing.

Thus, at a certain depth below the water surface, the dynamic plume will be fully disintegrated due to dilution processes and behaves as a passive, dispersive plume of individual aggregates or particles each with its own individual settling velocity.

The depth on full cloud disintegration can be estimated by the following three methods, as follows:

A. dynamic plume behaviour (Annex II);
B. jet entrainment theory (Annex I);
C. mud erosion theory.

A. Dynamic plume behaviour

Two cases are considered:
A1. Mud cloud slurry without mud clods (slurry density=1250 kg/m^3);
A2. Mud cloud slurry with clods (slurry density=1200 kg/m^3).

A1. Mud cloud slurry without mud clods (slurry density=1250 kg/m^3)

The dynamic plume behaviour at dump site in a depth of 70 m from a hopper dredger is simulated by the SEDPLUME-model (Annex II).
The dynamic plume/cloud after release from the hopper vessel is assumed to have a cylinder-type of shape with diameter D.
The diameter is of the order of the bottom door opening (D= 3 to 4 m).
The length of the cylinder is of the order of the hopper draught (≅3D).
The initial cloud velocity is set to 1 m/s.
The cloud is assumed to consist of a mud slurry with initial wet bulk density ρ_c=1250 kg/m^3.
The water depth is 70 m and the fluid density at surface is 1020 kg/m^3 linearly increasing to 1030 kg/m^3 at bottom.
The most conservative results are obtained for:
-shape factors for cylinder, see **Table 4.2.3**;
-drag coefficient=C_D=2;
-skin friction coefficient=f_w=0.03;
-entrainment velocity=v_e=0.05 w_c with w_c= coherent cloud velocity.
These model settings are based on model calibration for field data (Bokuniewicz et al., 1978), see Annex II.

The model results are (**Figure 4.2.6**):

- cloud accelerates from 1 to 2 m/s within 2 sec;
- cloud decelerates from 2 m/s near surface to 0.2 m/s at bottom (70 m below surface);
- mud cloud concentration decreases from 300 kg/m^3 near the surface to about 3 kg/m^3.

The mud cloud velocity close the bottom is 0.2 m/s which is higher than the eddy velocity scale of about 0.1 m/s. Hence, the mud particles have velocities much higher than the individual settling velocity of mud particles (order 1 mm/s; passive behaviour). Based on this, the mud cloud behaviour is dynamic from surface to bottom. The dynamic behaviour is most pronounced in the upper 50 m of the water depth with downward mud cloud velocity >0.5 m/s. The dynamic behaviour is weaker in the lower 20 m of the water depth with velocities decreasing from 0.5 to 0.2 m/s.

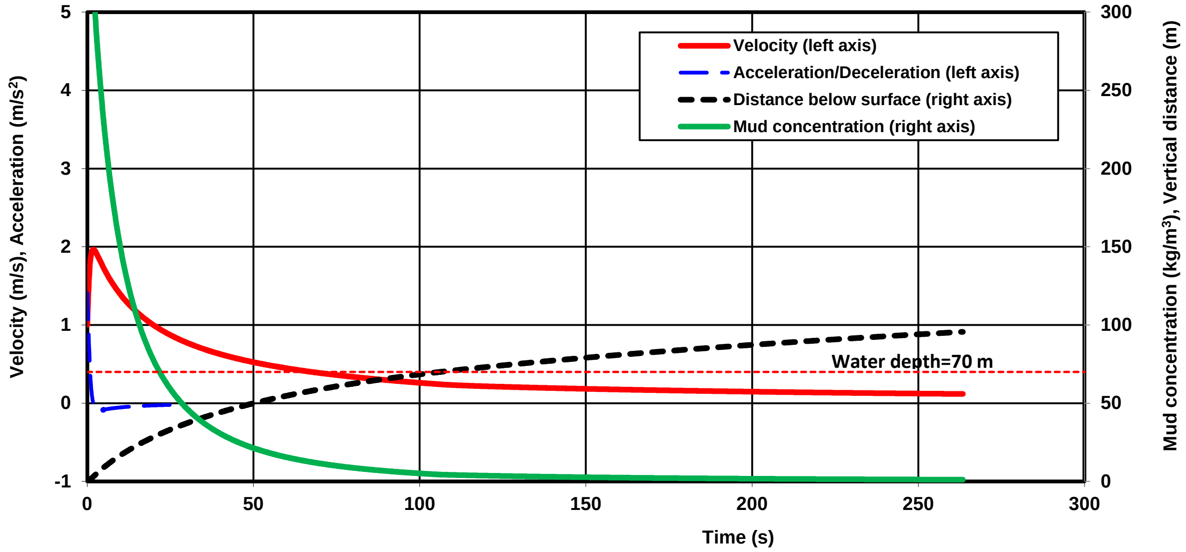


Figure 4.2.6 *Cloud velocity, cloud acceleration, mud cloud concentration and vertical distance as function of time*

Falling mud cloud in saline water		
Diameter D	3	(m)
Surface density of medium	1020	(kg/m3)
Maximum density of medium	1030	(kg/m3)
Density fall body	1250	(kg/m3)
Mixture viscosity at surface of medium	0.000001	(m2/s)
Surface viscosity of medium	0.000002	(m2/s)
Layer thickness	70	(m)
Alpha1 shape effect cross-area (pi/4=0.75 to 1)	0.75	(-)
Alpha2 shape effect volume (sphere=pi/6=0.52; cube=1, rectangle >1)	0.52	(-)
Alpha3 shape effect surface area friction (sphere=pi=3.14, cube=6; cilinder 2 to 4)	2.5	(-)
Alpha4 mixing entrainment parameter (0.01 to 0.05)	0.05	(-)
Alpha 5 surface area reduction coefficient for entrainment	0.7	
Friction factor	0.03	(-)
Drag coefficient for Reynoldsnumber > 10000	2	(-)
Time step dt	0.1	(s)
Initial velocity	1	m/s

Table 4.2.3 *Input data of SEDPLUME-model (Annex II)*

A2. Mud cloud slurry with clods (slurry density=1250 kg/m³)

The wet bulk density of the mixture of slurry and clods can be determined, as follows:

Volume: $V_{load} = V_{clod} + V_{slurry}$

Mass: $\rho_c V_{load} = \rho_{clod} V_{clod} + \rho_{slurry} V_{slurry}$

$\rho_c = \rho_{clod} (V_{clod}/V_{load}) + \rho_{slurry} (V_{slurry}/V_{load})$

$\rho_c = \rho_{clod} (V_{clod}/V_{load}) + \rho_{slurry} (1-V_{clod}/V_{load})$

The wet bulk density of mud slurry ≅ 1200 kg/m³

The wet bulk density of mud clods (including water within clod)≅ 1500 to 1700 kg/m³

The mixture density depends on then percentage of mud clods:

10% clods ρ_c =0.1x1600 + 0.9 x 1200=1240 kg/m^3

20% clods ρ_c =0.2x1600 + 0.8 x 1200=1280 kg/m^3

A realistic mixture of dredged materials from a site with a firm mud/clay bed consists of: 80% slurry; 10% clods of 0.05 m; 5% clods of 0.1 m; 3% clods of 0.2 m and 2% of clods of 0.3 m.
The fall velocity of the clods based on the SEDPLUME-model is given in **Table 4.2.4**. The values strongly depend on the wet bulk density of the clods and the clod shape (c_D-value). Measured values are given by Bukoniewicz et al. (1978).
Based on this, it follows that:

- mud clods of <0.1 m have settling velocity < 1 m/s and remain within the descending mud cloud in the upper part (25 m) of the depth; segregation occurs in the lower part of the water column (**Figure 4.2.3**);
- mud clods of 0.2 and 0.3 m have fall velocities in the range of 1 to 2 m/s and remain in the mud cloud in the upper 5 to 10 m; segregation will occur in lower 60 m; hence about 5% of the hopper load will fall through the cloud.

The fall of the slurry component of the mixture with initial density of 1200 kg/m^3 is found to decrease to about 0.15 m/s near the bottom based of SEDPLUME-model. The cloud behaves as a dynamic cloud over most part of the water column.

Diameter (m)	**Fall velocity (m/s)**					
	Measured	**ρ_{clod}=1500 kg/m^3**	**1600 kg/m^3**	**1700 kg/m^3**	**2000 kg/m^3**	**2650 kg/m^3**
0.02	0.35	0.35	0.39	0.42	0.50	0.65
0.05	0.79	0.56	0.61	0.66	0.80	1.03
0.11	1.26	0.83	0.91	0.98	1.18	1.52
0.20		1.11	1.22	1.59	1.59	2.05
0.30		1.36	1.50	1.95	1.95	2.51

Table 4.2.4 *Fall velocity of mud clods (SEDPLUME-model results; c_D=1; ρ_w=1020 kg/m^3; spherical shape) Measured field data of Bukoniewicz et al. (1978)*

B. Jet entrainment theory

The descending mud cloud is assumed to behave as downward sediment-laden mud jet with a Gaussian type of velocity distribution.
Based on jet flow theory (Annex I), the maximum jet velocity decreases in downward direction, as follows:

$u_{max,x}$= 2 u_{mean}=5(d_o/x) u_o

$u_{mean,x}$=2.5 (d_o/x) u_o

with: $u_{max,x}$= maximum jet velocity at location x, $u_{mean,x}$=jet-averaged mean velocity at location x.

The velocity scale of eddies generated by the local currents and the falling cloud is of the order of 0.1 m/s. When the mean jet velocity is decreased to the scale of the eddy velocities, the sediment particles can be easily carried away and diffused by the eddies.
The vertical distance below the water surface after which the jet velocity (d_o=3 m) is reduced from u_o=1 m/s to u_{mean}=0.1 m/s is by: $x_{passive}$=2.5 (u_o d_o/u_{mean})=2.5x1x3/0.1=75 m

The decrease of the initial mud slurry concentration ($c_o \cong$300 kg/m^3) can also be estimated based on jet flow theory (Annex I).
It follows that:

Q_x=α_{jet} (x/d_o) Q_o

with: Q_x=water discharge of jet at distance x from source; Q_o=jet discharge at source; d_o=jet diameter at source, α_{jet}= coefficient (≅0.5).

The sediment transport is given by:

$$Q_x c_{mean,x}=Q_o c_o$$

with: $c_{mean,x}$= jet-averaged mud slurry concentration at x, c_o=$c_{mean,o}$= concentration at source (constant across jet at x=0).

Both equations can be combined to give:

$$x=(1/\alpha_{jet})\ d_o\ (c_o/c_{mean,x})$$

Passive plume behaviour is assumed to occur for $c_{mean}\leq 10$ kg/m^3 (10,000 mg/l). Under these conditions, the individual particles are so far apart that they can settle individually, see **Figure 4.2.7**.

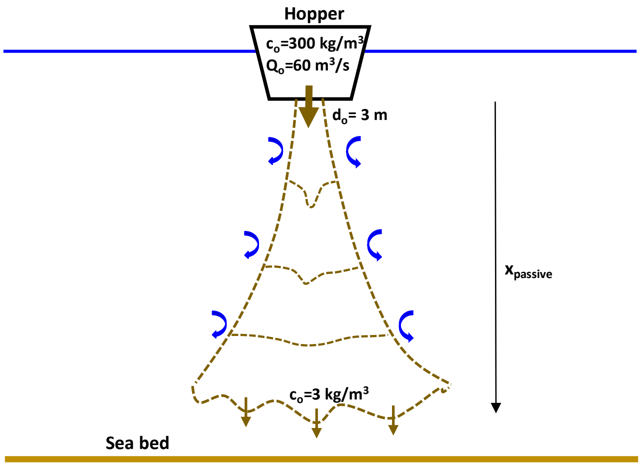


Figure 4.2.7 *Jet plume widening due to entrainment processes*

Using: d_o=3 m, Q_o=60 m^3/s and c_o=300 kg/m^3 (data of Section 1) it follows that: $x_{passive}\geq 180$ m.

Based on this, the dynamic plume will go over in a passive plume at a vertical distance of about 75 to 180 m below the water surface. In a water depth of 70 m, the plume will behave as a dynamic plume (cloud) with a descent speed much higher than the individual settling velocity (≅1 mm/s).
The descent speed of the jet cloud decreases from about 1 m/s near the water surface to about 0.1 m/s near the bottom.
To be conservative, the minimum transition distance to be used is 75 m based on jet entrainment theory. This value is in good agreement with the values found for the dynamic plume approach (SEDPLUME-model).

C. Mud erosion theory:
It is assumed that the discharge plume behaves as a dynamic plume with a descent speed of about 1 m/s. During descent, a boundary layer flow with velocities of the order of 1 m/s develops along the interface of the plume/jet, see **Figure 4.2.8**.
The shear stress τ_w along the plume interface are given by: $\tau_w=1/8\ \rho_w\ f_w\ u^2$
with: ρ_w = fluid density; f_w= friction coefficient (0.01); u= mean flow velocity in boundary layer.

Using: u=1 m/s, f_w=0.02 and ρ_w = =1020 kg/m^3, it follows that τ_w≅2.5 kg/m^3.
Based on this, the erosion rate is about 2000 gr/m^2/s =2 kg/m^2/s for soft mud with dry density of 400 kg/m^3 (Van Rijn 2019; Van Rijn et al., 2019).

For reasons of simplicity, the initial plume/cloud is schematized as a series of rectangular "blocks" with dry density of 300 kg/m^3.
Assuming an insertion speed of 1 m/s, a block (cloud) of fines with a length of 1 m is inserted each second after release. The horizontal dimensions are: 3 x20 m^2 resulting in a discharge of 60 m^3/s for an insertion speed of 1 m/s.

The mass of fines in each block is 60x1x300=18000 kg.
This block is gradually eroded by shear stress along the interface with area (20+3)x1x2=46 m^2.
The time required to fully disintegrate all sediments of each block is: 18000/(46x2)≅200 s.

Given a descent speed of 1 m/s, the vertical length scale for passive cloud behaviour is 200 m.

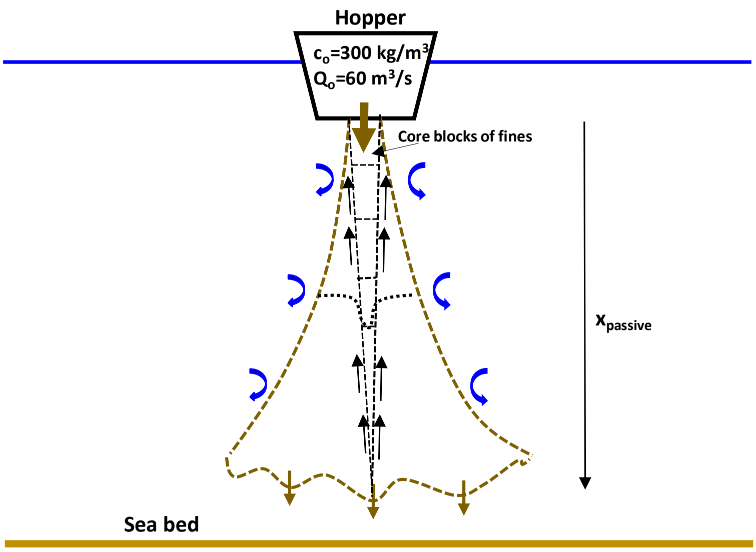


Figure 4.2.8 *Jet plume erosion due to shear stress along interface*

Summarizing, free fall dumping of a bulk load by using a barge with bottom doors depends on the insertion speed (quick or slow release), type of sediments, strength of local currents and water depth (see also **John et al., 2000**):

- coarse materials (gravel, clay balls/clods/blocks and coarse sand) will immediately settle to the bed at high settling speeds 0.5 to 2 m/s; if sand percentage is less than 30%, the sand will not settle out, but tends to stay within the slurry;
- the vast majority of the fines will also sink (descend) rapidly to the bottom as a bulk load with a cloud settling velocity (dynamic plume phase; see **Figure 4.2.2**); where it forms a low-gradient and low-density circular mound (fluid mud mound);
  - after impact upon the bed a sediment cloud with a thickness of about 3 to 5 m will be generated (settling to background concentrations takes about 1 hour) and the sediment load will radially flow away from the point of impact over the bed as a flow of low-density mud (dry density of 10 to 100 kg/m^3; bulk density of 1150 to 1200 kg/m^3);
  - the fluid mud front propagates in the form of a near-bottom head wave over a distance of about 100 to 500 m, depending on initial density and momentum of the sediment-water mixture and the strength of the local current flow;
  - a small amount of sediment (1% to 5%) is resuspended in a turbid layer behind the head wave by turbulence-induced upward mixing at the upper surface of the mud layer;
  - the local bed slope has a strong effect on the behaviour of the fluid mud flow (layer of 0.2 to 0.4 m); if the slope is larger than about 1 to 50/100, the fluid mud will flow downslope at a velocity of about 0.1 to 0.3 m/s; if the local slope is smaller than 1 to 100 the mud flow can not be maintained and it will tend

to settle out and the velocity of the head wave will decrease and form a mound with a density of 200 kg/m^3 and a surface slope of 1 to 500;
- the mud density in the center of the mound may become about 500 kg/m^3 due to consolidation processes;
- the surface of the mound close to the dumping center may be pocked with conical hills and scour pits with maximum slopes of 1 to 50 and a relief of about 0.5 m;

- a small amount (1% to 5%) of the bulk load will be eroded away as a cloud of spill from the outside of the bulk load during its descent to the bed and dispersed into the water column as a passive turbidity cloud; the cloud dispersion depends on the types of sediment and settling velocities of flocs and individual particles; direction and strength of the currents; local water depth; salinity-flocculation; the suspended sediment concentration along the centre line of the cloud will rapidly decrease with increasing distance down-stream from the disposal site due to settling and lateral dispersal by turbulence; under tidal conditions the cloud/plume will extend in the flood and ebb directions; the maximum cloud/plume length will be equal to the tidal excursion; the adjustment length to background concentrations generally is of the order of 100 to 300 times the local water depth; the horizontal movement is known as advection and the process whereby the plume spreads in width and depth is termed dispersion or diffusion (mainly due to turbulence and variation of current velocities over the depth).

4.2.3 Jet disposal through submerged pipeline

Continuous jet disposal through horizontal or vertical submerged pipelines can take place in two modes (see **Figures 4.2.9, 4.2.10, 4.2.11**);

- low-concentration mixture pumped into the water column and dispersed over the depth by turbulence and settling due to individual sediments (passive plume moving due to external forces);
  basic processes are:
  - segregation of fractions (heterogeneous sediments); larger particles have larger settling velocities;
  - horizontal advection by wind-driven, tide-driven and wave-driven currents;
  - lateral diffusion due to turbulent forces generated by currents;
  modelling techniques are:
  - random walk models including advection and diffusion;
  - gaussian diffusion models;
  - numerical transport models including advection and diffusion;
- high-concentration mixture pumped into the water column behaving as a density jet or as a cloud/plume of particles (cloud settling) descending rapidly to the bed (dynamic plume moving due to internal forces);
  basic processes are:
  - initial descent of plume to bottom (cloud or convective settling);
  - settling from high-concentration near-bottom layers as density current;
  - horizontal flow of density current along bed;
  dynamic plume behaviour depends on:
  - nature of sediment;
  - density and momentum in descent phase;
  - degree of aggregation during descent (increased settling velocity).

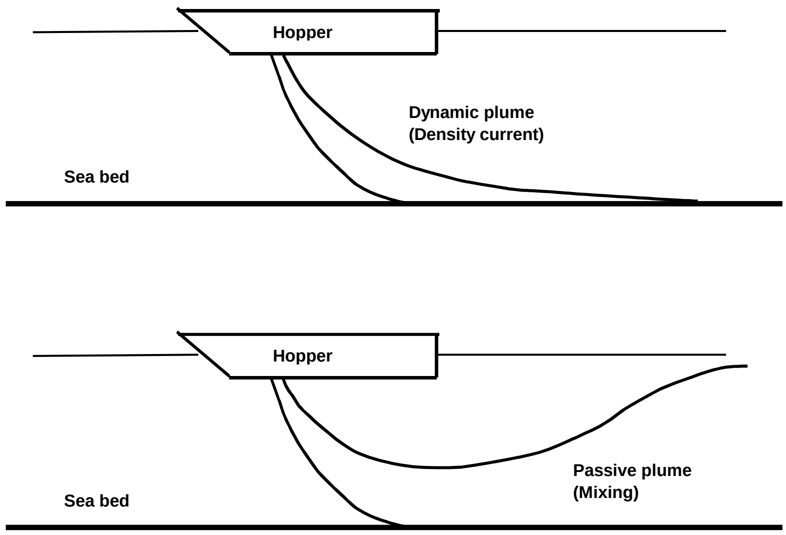


Figure 4.2.9 *Dynamic and passive plumes at hopper disposal site*

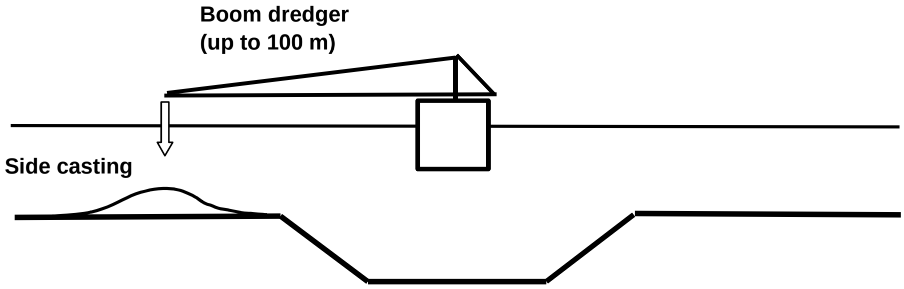


Figure 4.2.10 *Side casting of maintenance dredging using a boom dredger in channel*

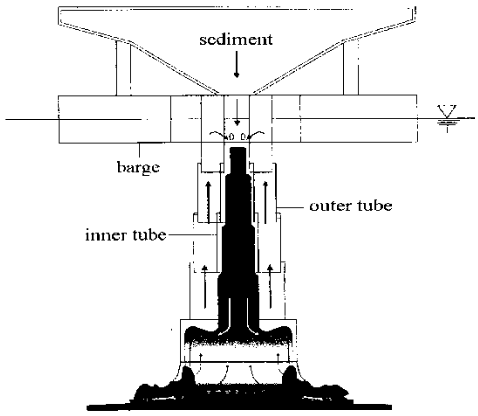


Figure 4.2.11 *Vertically movable diffuser pipe to reduce environmental effects during dumping of sediment.*

The environmental effects of sediment dumping can be greatly reduced by using special equipment (vertically movable diffuser pipe, see **Figure 4.2.11**). The pipe outlet should be placed close to the bed to prevent the generation of a thick suspension cloud. Another method is a diffuser pipe connected to a pivot-boom system, which can be lowered overboard (from hopper of barge) to a position near the bottom.

4.2.4 Free fall spraying

Land reclamations in shallow waters (< 3 m) are often made by using a spraying system connected to a pipeline, see **Figures 4.2.12** and **4.2.13**. The production rate of water + sand is about 0.5 to 1 m^3/s for one

pipeline. The pipeline concentration of sand is of the order of 200 to 300 kg/m^3. The spraying system continuously moves forward along the land reclamation area. Thin layers of sand are produced until the top level of the new sand area is close to the waterline. After that, the spraying boat is removed and the pipeline exit is placed directly on the sediment bottom. Small dikes are made by bulldozers and excavators to prevent the lateral spreading of the sediment mixture. The spraying method is prefered in conditions with relatively soft subsoils so that the consolidation process of the subsoil can proceed gradually.
The vertical spraying system is most suitable for small-scale land reclamations (in lakes) and produces less turbidity in the surroundings. The horizontal spraying system is most suitable for marine conditions (nearshore mounds; nearshore bars; under water nourishments).

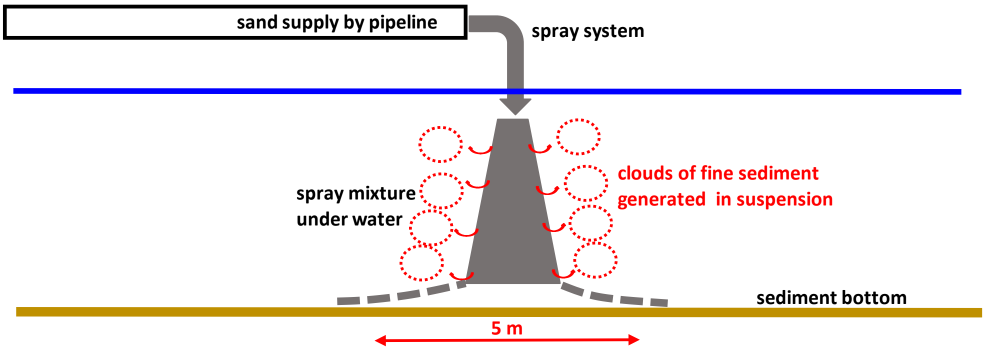


Figure 4.2.12 *Vertical spraying system*

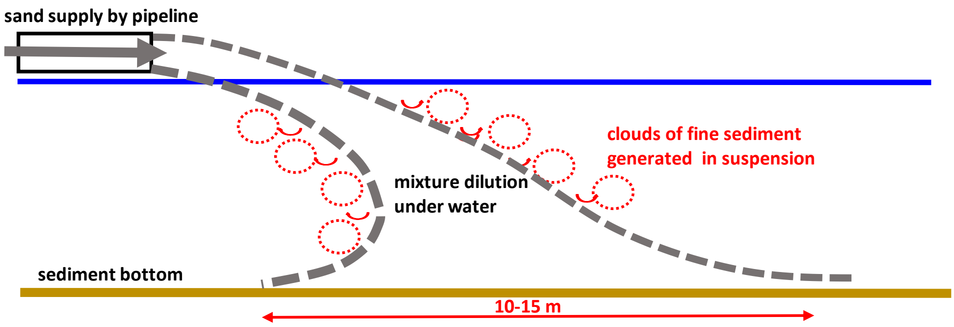


Figure 4.2.13 *Horizontal spraying system*

4.3 Turbidity of spill measured at field dumping sites

4.3.1 Spill from free fall dumping (bottom doors; pipeline exit)

Wolanski et al (1992) studied the offshore dumping of mud dredged from the Port of Townsville, Australia. The sediment material was dumped offshore in typically 12 m depth. The hopper suction dredger usually dumps about 2500 m^3 of material while underway at about 2.5 m/s by opening trap doors in the bottom of the hull at the dump site. After dumping from a moving vessel, the sediment plume settled down rapidly (velocities between 0.1 and 1 m/s) as a dome with some radial motions resulting in a widening of the plume. No internal bores were generated along the bottom. Additional mixing in the turbulent wake of the moving vessel caused rapid dilution. Following dumping a long muddy streak was visible at the surface of the water. During the dumping from a stationary vessel, two stages of settling were observed. Initially, there was a rapid descent as a negatively buoyant jet, forming a high-concentration suspension near the bottom, followed by a subsequent slower settling of mud flocs. After impact upon the bed, the jet spread laterally, with an internal hydraulic jump (bore) being present at its leading edge. In calm weather, mud flocs settled out of this layer in about 15 minutes and the suspension did not move out of the dump site. In rough weather, the settling of mud flocs was inhibited by wave-induced turbulence and the suspension was mobile and was transported away from the dump site.

Table 4.3.1 shows measured mud concentrations in the middle of the plume at various times after dumping. In calm weather (with very weak currents of 0.1 m/s) initially a layer of about 4 m thick had developed with concentrations of 5 to 6 gr/l. After 16 minutes the layer was less than 1 m thick with concentrations of about 0.25 gr/l. Thus, the sediment cloud settled out in about 15 minutes in 10 m water depth. The bottom turbid layer settled 3 m in 5 minutes with an effective settling velocity of about 1 cm/s. In rough weather conditions, a sharp interface (lutocline) was generated during the dumping process, which remained sharp after 15 minutes. Reversals were observed with higher concentrations at 15 min than at 8 min suggesting effects of wave-induced near-bottom turbulence and patchiness. In these conditions the dumped material formed a long-lived, turbid, bottom layer of about 1 m thick. This mobile layer was carried away in landward direction by wind-induced bottom currents of about 0.3 m/s. The waves played an essential role in keeping the sediment in suspension. In quiescent waters, this suspension settled out and was compacted to about 11% of its original volume in about 4 days. The compacted sediments were resuspended by long wave action forming a mobile, 1 m thick, high-concentration suspension at the bottom.

Height above bottom (m)	Calm weather			Rough weather		
	t=3 min	t=8 min	t=16 min	t=3 min	t=8 min	t=15 min
0.5	c=5.5 gr/l	2	0.2	c=10 gr/l	2.5	2.5
1	5	0.5	0	5	1.5	2
2	4	0.1	0	1	0.3	0.6
3	2	0	0	0.3	0	0.3
4	0.25	0	0	0.1	0	0
Depth-averaged	<1	<0.5	<0.1	<1	<0.5	<0.5

Table 4.3.1 *Mud concentrations in middle of plume of dumped mud after dumping from moving vessel (time refer to the time after dumping) based on Wolanski et al. (1992)*

Healy et al. (1999) studied the dumping of muddy sediments dredged from a nearby Marina (Pine Harbour, New Zealand). The marina approach channel (depth of 2.4 m below C.D.) crosses a 1 km wide intertidal zone. As there was public opposition to disposal of the dredgings in the littoral (beach) environment, two alternative disposal methods were studied: (1) side-casting into a mound alongside the channel and (2) thin-layer disposal at an offshore location at the end of the approach channel. The dredging was carried out by a digger mounted on a barge. Initially, the dredged sediment was side-casted into a mound of muddy material (50 m wide, 0.5 m high) alongside the channel. Monitoring results showed that some of the muddy sediments were transported back into the channel. Secondly, the dredged material was dumped as a thin-layer disposal over an offshore area of similarly muddy adjacent sea floor. The disposal site (500x500 m^2) was situated at the offshore end of the approach channel and was about 11 times larger than the total channel area.

Monitoring of mud concentrations during dredging operations showed values of about 60 mg/l in the dredging plume just north of the channel, while background values were of the order of 30 mg/l. Monitoring of mud concentrations during dumping of sediments (from a barge) at the disposal site showed values of 50 to 70 mg/l in the trailing plume from the barge. At distances greater than 250 m from the barge the mud concentrations were close to background values (about 20 mg/l). The turbid plume was observed to be a transient feature which typically lasted 5 to 15 minutes. The maximum thickness of the mud layer on the sea floor was about 0.3 m per year in the central disposal area and no mounds of muddy deposits accumulated.

Spanhoff et al., 1990 studied the recirculation of fine sediments dumped at an offshore mud disposal site 'Loswal Noord' near the entrance (at about 11 km) to the Port of Rotterdam, The Netherlands.
Large quantities (15 to 20 million m^3 per year) of sediment (mud and fine sand) dredged from the harbour basins are dumped at this site. The sea bottom at the site is relatively flat outside the dump area. The water depths vary in the range of 15 to 20 m below mean sea level. The tidal range is about 2 m; the peak tidal flood currents to the north are about 0.7 m/s and the peak tidal ebb currents to the south are about 0.6 m/s. The fresh-water river outflow from the Rhine is about 1500 m^3/s generating a stratified flow system over an offshore distance of about 11 km from the entrance. Residual currents (order of 0.05 m/s) near the bottom at the dump site are found to be directed landward to the river outlet. As the sediments at the dump sites are confined to the lower layers, there is a potential for recirculation of sediment back to the dredging sites (harbour basins). Results from mass balance studies (comparison of total dumped volume and sedimentation volume of the in-situ mound at seabed) over about 20 years show that about 50% to 80% of the dumped mud and about 30% of the fine sand has been carried away from the dump site in alongshore directions. Mathematical model studies (3D) suggest the presence of a relatively strong return flow of mud from the dump site towards the harbour entrance largely due to the generation of a large-scale horizontal gyre and the presence of vertical circulation due to sainity-induced density gradients.

4.3.2 Spill from free fall spraying

Svasek (2011) has studied the spreading of turbidity (particles < 63 μm) around a spraying system of sand (**Figure 4.3.1**) at the dumping site of a land reclamation in a shallow lake (Marker lake) in The Netherlands. The natural bed of the lake is covered with a thin mud layer. The production rate of sand was 2000 m^3/day. A silt screen around the spraying boat was used to reduce the turbidity pollution as much as possible (see **Figure 4.3.2**). The concentration of fines in the water column was measured using an optical OBS-sensor from a small survey boat. The settlement of fines was measured by using small mud trapping bottles attached to fixed poles at about 0.25 m above the bottom (see **Figure 4.3.1**). The bottles were emptied and replaced every week over a period of 1 year (2010). The poles with trapping bottles were situated in rows at about 200 to 1100 m from the mud screen (**Figure 4.3.1**).
Based on measured data (Svasek 2011, 2017), the flow velocities in depths of 2.5 to 3 m are strongly winddriven and vary with the strength of the wind. The flow direction is approximatley equal to the wind direction. The flow velocity is about 0.05 m/s for conditions with Beaufort 3 (wind velocity=4 m/s) and increases to about 0.15 m/s for Beaufort 6 (wind velocity= 12 m/s).

The concentration of the spraying mixture is about equal to that of the supply pipe ($Q_{pipe}\, c_{pipe} = Q_{spray}\, c_{spray}$ = constant and $Q_{pipe} = Q_{spray}$).

The mud concentration ($c_{mud\text{-}cloud}$; see **Figure 4.2.9**) close to the spraying system can be estimated from:

$$c_{mud\text{-}cloud} = e_{mud1}\, p_{mud}\, c_{spray} = e_{mud1}\, p_{mud}\, c_{pipe}$$

Another method is:

$$c_{mud\text{-}cloud} = e_{mud2}\, p_{mud}\, \rho_{bulk}\, P/Q_{flow}$$

with:
$c_{pipe} \cong c_{spray} \cong$ 200 to 300 kg/m^3;

P= total production rate of sand+ mud (m^3/s); range 0.5-1.5 m^3/s;
p_{mud}= fraction of mud (< 32 μm) of sand-mud mixture (ca. 0.01-0.1); fraction 32-63 μm will settle rapidly;
c_{pipe} = mud concentration in supply pipeline (200 to 300 kg/m^3);
ρ_{bulk}= bulk density of sand-mud mixture (≅ 1600 kg/m^3);
Q_{flow}= b h u= flow discharge passing the spraying boat;
b= size of spraying boat (≅ 10 m); h= local water depth; u= local flow velocity;
e_{mud1}= mud loss factor (0.01-0.05); mud loss from outer spray layer under water (about 10%);
outer layer is about 20% of total spray layer;
e_{mud2}= mud loss factor (0.01-0.05).

The coefficients e_{mud1} and e_{mud2} can be determined from the measured data of Savsek (2011):
$c_{mud\text{-}cloud} \cong 150$ mg/l $\cong 0.15$ kg/m^3; $p_{mud} \cong 0.05$, P= 0.11 m^3/s (16000 m^3/week; 40 hours);
Q_{flow}=bhu=10x3x0.1 = 3 m^3/s; $c_{pipe} \cong 250$ kg/m^3 yielding: $e_{mud1} \cong 0.15/(0.05x250) \cong 0.01$;
$e_{mud2} \cong 0.15x3/(0.05x1600x0.11) = 0.05$

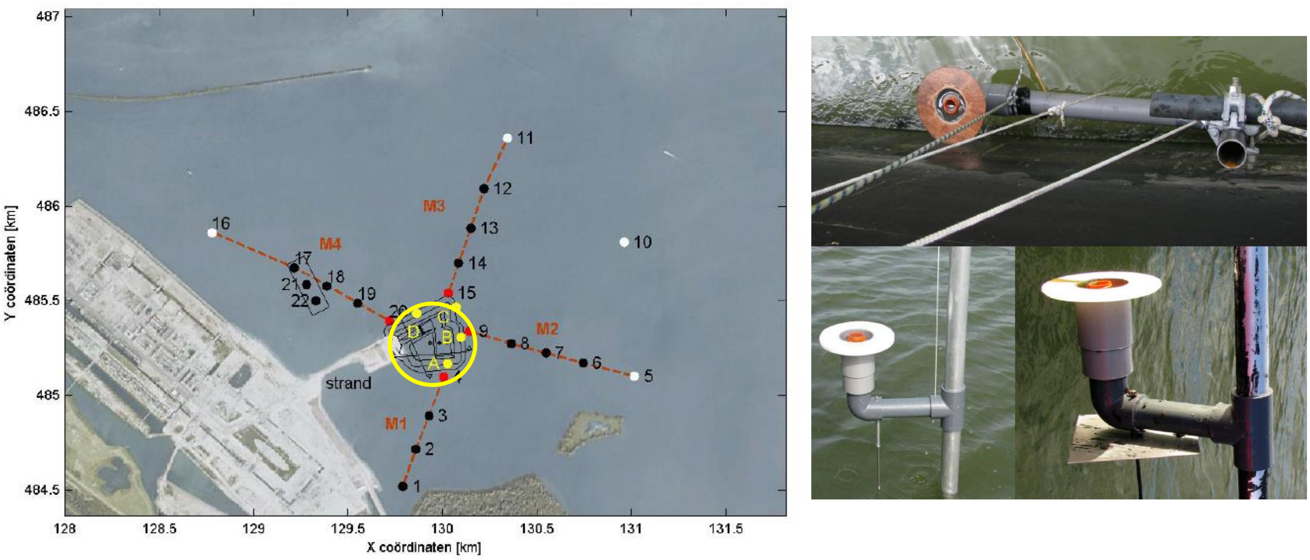


Figure 4.3.1 *Location of measuring poles (black dots) with mud trapping bottles (right) and mud screen (yellow); A, B, C and D are fixed poles within the screen area (Svasek 2011)*

Based on the analysis of measured mud concentrations (in mg/liter) and mud settling rates (in mm/day), the following conclusions are given (see also **Table 4.3.2**):

- mud concentrations are approximately uniform over the water depth (2.5 to 3 m); the natural mud concentrations in conditions without spraying of sand are about 10 mg/l in conditions with almost no wind (BF <3) and about 40 mg/l with much wind (BF 6);
- mud settlement in conditions without spraying of sand is about 0 to 4 mm/day with little wind and 8-14 mm/day with much wind;
- mud settlement values at a distance of 200 to 1100 m from the mud screen are:
  - average settlement over a year of about 3 mm/day; variation of 0 mm/days in periods with no wind to 14 mm/day in periods with much wind;
  - variation of settlement is relatively large due to influence of waves stirring mud from the bottom at windy days;
  - influence of spraying system on the turbidity levels outside the screen is limited to a circle of about 200 m around the screen, where increased mud settling rates and concentrations do occur;
- maximum mud concentrations inside the screen area are 60 to 120 mg/l at distance of 25 to 50 m from the spraying boat; mud settling close to spraying boat is 9-11 mm/day and 1-3 mm/day at distance of 25 to 50 m from spraying boat;

- maximum mud concentrations just outside mud screen are 30 tot 60 mg/l during conditions with no wind (BF < 3) and 100 mg/l with much wind (BF 5-6); mud settlement just outside screen is 2 mm/day with no wind and 8 mm/day with much wind;
- mud screen yields maximum concentration reduction of 50% in conditions with no wind and 25% reduction in conditions with much wind; relatively much turbidity passes the sreen on windy days;
- mud clouds with initial concentration of about 100 mg/l inside the mud screen reduce to about 10 mg/l (natural background concentration) over distance of about 200 m (dilution factor 1/10); natural concentrations are present at distances > 200 m from the screen;
- mud clouds with initial concentration of about 100 mg/l near the spraying boat (without mud screen) reduce to about 10 mg/l (natural background concentration) over distance of about 400 m (dilution factor 1/10);
- mud clouds are local and temporary phenomena; areas with relatively clear water (concentrations < 10 mg/l) are present inside and outside the screen at arbitrary locations and times.

Figure 4.3.2 *Mud clouds inside and outside mud screen near IJburg in Marker lake, The Netherlands (Upper: 5 June 2010; Middle: 25 June 2010; Lower: 19 July 2010)*

Conditions	**Mud concentrations (mg/l) and mud settling rates (mm/day) inside mud screen**		**Mud concentrations and mud settling rates outside mud screen**		**Mud concentrations and mud settling rates with half open screen (2 weeks)**			**Mud concentrations without screen**
	close to spraying boat	**further away from boat at 50 m**	**close to screen at 10 to 20 m**	**further away at 200 to 1100 m from screen**	**inside scree**	**just outside screen**	**further away > 100 m**	
Period of 1 year (2010)			average: 2-4 mm/day maximum: 6-10 mm/d	wk11: 4-6 mm/d wk18-19: 6-8 mm/d wk21: 2-4 mm/d wk24-25: 6-8 mm/d wk33: 8-10 mm/d wk35-36: 6-8 mm/d wk41-42: 6-8 mm/d wk45-46: 8-10 mm/d other: < 2 mm/d				
Mud cloud 19 March 2010 BF3 from SW								10-100 mg/l at 100 m; 40 mg/l at 500 m from spraying
Mud cloud 19 May 2010 BF4 from NNW			40-80 mg/l	20 mg/l at 150 m 10 mg/l at 300 m				
Mud cloud 27 May 2010 BF3 from NW			50-80 mg/l	30 mg/l at 150 m 20 mg/l at 200 m 10 mg/l at 600 m				
Mud cloud 18 Aug 2010 BF5 from W		80 mg/l	20-80 mg/l	10 mg/l at 100 m				
Mud cloud 25 Aug 2010 BF4 from W			20-80 mg/l	20 mg/l at 100 m 10 mg/l at 200 m				
10 June 2010 BF2		80-100 mg/l; 3-9 mm/d	50-70 mg/l	5.5-7 mm/d				
24 June 2010 BF4 NW		120 mg/l; 2-9 mm/d	70 mg/l	0-1 mm/d				
1 July 2010 BF3 WNW		80-120 mg/l; 1-11 mm/d	50-100 mg/l	0-1 mm/d				
10 June-19 July 2010	60-140 mg/l; 20 mg/l after cessation of spraying			wk24: 6-8 mm/d (w) wk25: 6-8 mm/d (w) wk26: 0-1 mm/d (nw) wk27: 0-1 mm/d (nw) wk28: 0-1 mm/d (nw) wk29: 0-1 mm/d (nw)				
13 July-19 July BF2 to BF6					100-120 mg/l	50-100 mg/l	50-100 mg/l at 100 m; 10-20 mg/l at 300 m	

s.b.=spraying boat; w=much wind; nw= no wind; BF= Beaufort wind scale; wk=week

Table 4.3.2 *Mud concentrations (in mg/l) and mud settling rates (in mm/day) around spraying boat; IJburg, Marker lake, The Netherlands*

4.4 Examples of predicted turbidity values at dumping sites

Example 1: **Dumping of sand through a pipeline exit of a hopper dredger**
Production: Pump discharge at exit = 5500 m^3/hour
Sediment: Mixture of sand and mud; 3% fines < 63 μm; 1% < 32 μm.
Dry sediment concentration during pumping though pipeline= 200 kg/m^3
Tide: Local current velocity of 1 m/s

The following formula can be used: $\Delta C_{fines}= e_{fines}\, p_{fines}\, c_{pipe}$

with: p_{fines}= fraction of fines < 32 μm of hopper load (0.01); $c_{pipe}=\rho_{dry,sediment}$= dry density of the sediments leaving the pipeline exit (200 kg/m^3); e_{fines}=0.01-0.1= efficicency factor related to the dilution and mixing close to the pipelin exit.
The sediment concentration of the water-sediment mixture leaving the pipe-outlet will be about 300 kg/m^3. Assuming a mud fraction (< 32 μm) of about p_{fines}= 0.01 and e_{fines}= 0.1, the mud concentration of the sediment plume will be about 0.2 kg/m^3 or 200 mg/l in an area with horizontal dimensions of about 10 m. The fraction 32-63 μm (settling velocity=1.8 mm/s) will settle rapidly close to the dumping site.

The sand fraction will settle rapidly within 100 m from the dumping site, but the fines/mud will be carried away by the local currents.
The exit concentration of fines/mud of 200 mg/l will be diluted rapidly as the fine sediments are carried away by the flow with velocity of about 1 m/s. After 100 s the fines are about 100 m away from the pipeline and are diluted to about 50 mg/l (dilution factor 4).
After 1000 s the fines are about 1000 m away from the pipeline and are diluted to about 20 mg/l (dilution factor 10).
In the case of model simulations using a grid size of 100 m at the dumping site, the fine sediment concentrations to be specified as input at the model grid cell should be of the order of 50 mg/l during the dumping time period (order of 0.5 to 1 hours).

Example 2: **Dumping of mud through bottom doors of a barge**
Dry density: Dry density of sediment load in barge = 400 kg/m^3
Sediment: Mixture of mud; 30% fines < 32 μm, 40% fines of 32-63 μm and 30% sand > 63 μm
Barge: Volume=1000 m^3; dumping time= 10 min= 600s, vessel length=70 m, vessel width= 10 m
Annual dumping volume= 10 million m^3
Tide: Maximum tidal flow velocity at site= 0.7 m/s; water depth= 3 m; discharge=2.1 m^2/s
Tidal volume= 10^8 m^3

The sediments are brought in the flow by direct dumping through bottom doors of the barge. Using this method, a coherent load of sediment with a dry density of about 400 kg/m^3 will move from below of the dredger to the bed at relatively high speed (group fall velocity of about 0.5 m/s) without much dispersion of fines, as most of the fines are enclosed within the load. Fine sediments can only be dispersed from the outer layer of the load. The fraction 34-63 μm (settling velocity=1.8 mm/s) will settle rapidly close to the dumping site. The fraction < 34 μm (settling velocity <0.45 mm/s) will remain in suspension.

The almost instantaneous concentration increase (Δc) immediately after dumping of the load of sediment can be estimated, as follows: $\Delta c_{dumping} \cong M_{fines,dump}/V_{water,dump}= e\, p_{fines}\, \rho_{dry,sediment}\, (V_{dump}/V_{water,dump})$
with:
e= efficiency factor (0.1) as only fines are dispersed from the outer layer of the load,
p_{fines}= fraction of fines < 32 μm (≅0.3), $\rho_{dry,sediment}$ = dry density of dumped sediment load (≅ 400 kg/m^3),
$M_{fines,dump}$= dry load of dumped material (kg), V_{dump}= dumping volume of dumper barge (≅ 1000 m^3),
$V_{water,dump}$= water volume in the area of dumper (5 to 10 times the volume of the dump barge; L_{vessel}x3W_{vessel}xwater depth).

Using these values, the concentration increase (Δc) immediately after dumping is estimated to be about $\Delta c \cong 1.2$ kg/m^3 over a horizontal domain of about 100 m (model grid size). This concentrations will be diluted rapidly by the mixing capacity of the flow (velocity= 0.7 m/s).
After 1 hour, the concentration increase is reduced to about 100 mg/l (factor 1/10) over an area of about 3 to 5 km.

The method of Becker et al. 2015 yields (see Section 3.2):
$F_{f,dumpplume}= e_{plume2}\ M_{f,hopper}/\Delta T_{dumping}= e_{plume2}\ (\rho_{dry,hopper}\ p_{fines}\ V_{hopper})/\Delta T_{dumping}=$ 0.1x(400x0.3x1000)/600= 20 kg/s.
Source concentration increase is $\Delta c= F_{f,dumpplume}/Q = F_{f,dumpplume}/(b\ h\ u)$= 20/(0.5x10x3x0.7)= 2 kg/m^3= 2000 mg/l. Effective plume width is assumed to be half the vessel width.
Both methods yield a source concentration increase in the range of 1000 to 2000 mg/l at the dump site.

Another method is the spill method: maximum spill=3% of mass= 0.03x1000x400=12,000 kg
The spill concentration= spill mass/volume of water around hopper (use effective width=3 vessel width)
Volume of water around hopper (length 70 m; width 10 m; depth=3 m)=70x3x(3x10)x3=6300 m^3
Spill concentration=12000 kg/6300 m^3 $\cong$2 kg/m^3=2000 mg/l, which is of the right order of magnitude compared to available data from field observations. Most likely, the spill concentration will be of the order of 1000 to 2000 mg/l.

The long term increase of the concentration of fines (< 32 μm) at the dumping site (length of about 5 km; width of about 2 km) and surroundings can be estimated, as follows:
$\Delta c_{fines} \cong M_{fines}/(N_{tide}\ V_{water,1\ tide}) = [p_{fines}\ V_{dump}\ \rho_{dry,sediment}]/[N_{tide}\ V_{water,1tide}]$
with: $M_{fines}= p_{fines}\ V_{dump}\ \rho_{dry,sediment}$; p_{fines}= fraction of fines < 32 μm ($\cong$0.3), V_{dump}= annual dumping volume ($\cong$ 10 million m^3), $\rho_{dry,sediment}$ = dry density of dumped sediment ($\cong$ 400 kg/m^3), N_{tide}= number of tides per year (730),
$V_{water,1tide}$= volume of water passing site during 1 tide.

The water volume passing the dumping area during one tide can be estimated as:
$V_{water,1tide}= b\ q_{mean}\ T$
with: b= width of dumping site ($\cong$ 1000 m), q_{mean}= mean discharge during flood and ebb ($\cong$ 1 m^2/s),
T= tidal period (12 hours or 45000 s), N_{tide}= number of tides per year ($\cong$ 730).

Using these values, the concentration increase is of the order of :
$\Delta c_{fines} \cong$ (0.3x10x10^{6}x400)/(730x1000x1x45000) $\cong$ 0.035 kg/m^3 $\cong$ 35 mg/l for a tidal flow tube of 1 km wide.
In practice, this concentration increase of fines (in addition to the background concentrations of fines) will be much smaller (< 10 mg/l) due to additional lateral dispersion.
The sediment concentration increase can also be computed by using the tidal volume.
Using: $\Delta c_{fines} \cong M_{fines,total}/[N_{tide}\ V_{tidalvolume}]$ = (0.3x10x10^{6}x400)/(730x 10^8) $\cong$ 0.02 kg/m^3 $\cong$ 20 mg/l.

Example 3: **Dumping of mud through bottom doors of a hopper**
Dry density: Dry density of sediment load in barge = 300 kg/m^3
Sediment: Mixture of mud; 30% fines < 32 μm, 40% fines of 32-63 μm and 30% sand > 63 μm
Hopper: Volume=7000 m^3; dumping time= 2 min= 120 s, vessel width= 20 m
Insertion discharge=7000/120$\cong$ 60 m^3/s; Insertion speed$\cong$ 1 m/s
Tide: Maximum tidal flow velocity at site= 0.5 m/s; water depth= 70 m;

Mass of release load=7000x300=2.1 10^6 kg
Maximum spill=5% of mass= 0.05x2.1 10^6 =105 10^3 kg
Spill concentration= spill mass/volume of water around hopper (use effective width of 3 x vessel width).
Volume of water around hopper (length 100 m; width 20 m)=100x(3x20)x70=420 10^3 m^3
Spill concentration=105 10^3 kg/420 10^3 m^3 =0.25 kg/m^3=250 mg/l, which is of the right order of magnitude compared to available data from field observations.

5. Numerical simulation of dispersion and settling processes

5.1 Theory of diffusion/dispersion/dilution processes

The spreading (decay) of suspended sediment concentrations (ssc) originating from dredging activities are called dredge turbidity plumes.
Two types of dredge plumes can be distinguished; dyanimc and passive plumes. Dynamic high-concenration plumes (near-field plumes with ssc in the range of 1,000 to 10,000 mg/l) descend rapidly to the seabed since the sediment-water mixture is much denser than the ambient water. The bulk behaviour, rather than the settling velocity of individual sediment particles is important in a dynamic plume. The zone of impact is small, since the settling velocity of the bulk is relatively high. Passive far-field plumes (with ssc < 1,000 mg/l) arise due to mixing of the dredge plume with ambient water. Mixing will occur when the current velocities of the ambient water are strong enough, transporting and mixing particles through the whole water column. In passive plumes the settling velocity of individual particles is low, so passive plumes can be present on long time and spatial scales.

Generally, the modelling of passive types of plumes is based on the numerical solution of a diffusion type of equation in which the spreading or dispersal of the suspended sediment concentration is represented by a the temporal and spatial gradients of the sediments concentrations in all directions (Fickian Law: suspended sediment flux= $\varepsilon_i \partial c/\partial x_i$).

Dispersion refers to the spreading of very fine sediment mass with a very small settling velocity (almost zero) as a bulk property (averaged concentrations) integrating all spreading/dispersion processes. Generally, the dispersion coefficient including all effects is larger than the turbulent mixing coefficient. Diffusive type of transport ($\varepsilon_i \partial c/\partial x_i$) is also known as Fickian transport.
The 2DV-dimensional advection-dispersion process of fine sediments < 63 μm in a horizontally uniform flow (dh/dx=0, du/dx=0) can be described by:

$$\partial c/\partial t + u\, \partial c/\partial x - w_s\, \partial c/\partial z - \varepsilon_z\, \partial^2 c/\partial z^2 - \varepsilon_x\, \partial^2 c/\partial x^2 = 0 \qquad (5.1)$$

with: c= sediment concentration, u= flow velocity (constant in space and time), w_s= settling velocity of sediment, ε= effective diffusion/mixing coefficient (assumed to be constant in space and time; about 0.1 to 10 m^2/s; K= dispersion coefficient including other effects), x=longitudinal coordinate, z=vertical coordinate.
Equation (5.1) can only be solved numerically.
The concentration of very fine mud (< 8 μm) with almost zero settling velocity (< 0.1 m/s) is uniform over the depth.
Neglecting the settling velocity and vertical diffusive transport, Equation (5.1) can be expressed as:

$$\partial c/\partial t + u\, \partial c/\partial x - \varepsilon_x\, \partial^2 c/\partial x^2 = 0 \qquad (5.2)$$

Assuming a fluid at rest (u= 0), the expression becomes:

$$\partial c/\partial t - \varepsilon\, \partial^2 c/\partial x^2 = 0 \qquad (5.3)$$

When a mass M (in kg/m^2) is released at x= 0 at time t= 0 as a line source (per unit width) in a channel with constant depth h (channel width=1 m), the solution of the 1-dimensional diffusion equation is:

$$c = M/(4\pi\, \varepsilon\, t)^{0.5} \exp[-\{x/(4\, \varepsilon\, t)^{0.5}\}^2] \qquad (5.4)$$

with: c= depth-mean concentration (kg/m^3), t= time, ε = constant diffusion/mixing coefficient (m^2/s).
Continuity requires that: $M = h \int_{-\infty}^{\infty} c\, dx$ (in kg/m^2).
Using: x=ut, it follows that: $M = h \int_{t1}^{t2} uc\, dt = uh \int_{t1}^{t2} c\, dt = q \int_{t1}^{t2} c\, dt$, with t_1 and t_2 being the leading and trailing edges of the cloud.

If the coordinate system is moving with the mean velocity u, then the solution of Equation (5.4) representing a symmetrical solution is also valid with respect to the moving coordinate system.
The solution reads:

$$c= M/(4\pi\, \varepsilon\, t)^{0.5} \exp[-\{x'/(4\, \varepsilon\, t)^{0.5}\}^2] \qquad (5.5)$$

Defining x = ut + x' (see **Figure 5.1**) and thus x'= x-ut, it follows that:

$$c= M/(4\pi\, \varepsilon\, t)^{0.5} \exp[-\{(x-ut)/(4\, \varepsilon\, t)^{0.5}\}^2] = c_{max} \exp[-\{(x-ut)/(4\, \varepsilon\, t)^{0.5}\}^2] \qquad (5.6)$$

with: $c_{max} = M/(4\pi\, \varepsilon\, t)^{0.5}$= peak value of the concentration at x=ut.
Thus: $c_{max} = \infty$ at t= 0 and c_{max} decreases with $1/(\varepsilon\, t)^{0.5}$; see **Table 5.1**. Using x=ut: c_{max} decreases with $1/x^{0.5}$.

The solution represents a Gaussian distribution, which reads as: $y=[2\pi\sigma^2]^{-0.5} \exp\{-(x-\mu)^2/(2\sigma^2\}$.
This yields: $2\sigma^2 = 4\, \varepsilon\, t$ or $\varepsilon = \sigma^2/(2t)$

The diffusion coefficient can be determined from the travel time (Δt) between 2 stations and the standard deviation of the dispersed cloud size in longitudinal direction at both stations: $\varepsilon =(\sigma_2{}^2-\sigma_1{}^2)/(2\, \Delta t)$.
The transport and dispersion of pollutants has been extensively studied in USA-rivers using fluorescent dyes as water tracers (Wilson 1968, Kilpatrick and Wilson 1989, Jobson 1996).

The dispersion and mixing of a tracer in a receiving stream take place in all three dimensions of the channel (**Figure 5.1**). The elongation of the tracer-response cloud longitudinally is defined as longitudinal dispersion. Vertical mixing is normally completed rather rapidly at section I (Figure 5.1), within a distance of a few river depths (h); say within 10h to 30h.
Lateral mixing is much slower but is usually completed within 10 to 30 times the river width (B) from the source point; say within 10B to 30B (at Section III, Figure 5.1). The effect of lateral mixing can be reduced by applying a line source injection (dye injection by multiple boats across the river width at the same time).
Longitudinal dispersion having no boundaries continues indefinitely along the river; downstream of section III the dominant mixing process is longitudinal dispersion, so the tracer concentration can generally be assumed to be uniform in the cross section.
A unit peak concentration has been defined as: $c_{max,unit}=[Q/(r\, M)]\, 10^6\, c_{max}$,
with: $c_{max,unit}$= unit peak concentration (s^{-1}), Q= river discharge (m^3/s), M= injected mass (kg), r= loss factor of injected mass (usually$\cong$ 0.9 to 1; losses due to the presences of dead zones and harbours etc).
Based on analysis of many river data, it was found that: $c_{max,unit,T}= 1000\, T^{-0.9}$ with T= travel time after injection (in hours) and $c_{max,unit,T}$= unit peak concentration at time T after injection (in s^{-1}).

If Fickian diffusion correctly represents the total longitudinal mixing in rivers, the unit-peak concentration decreases in proportion to the square root of time ($c_{unit} \sim t^{-\beta}$ or $c_{unit} \sim x^{-\beta}$ and β= 0.5; see Equation 5.6). Measured data show that the unit-peak concentration in natural rivers generally decreases more rapidly with time than predicted by the Fickian law. The presence of pools and riffles, dead zones, bends, and other channel and reach characteristics will increase the rate of longitudinal mixing and almost always yield a value of β greater than the Fickian value of 0.5. The value of β is approximately 1.5 for very short dispersion times (section I of Figure 5.1) and decreases to 0.5 for very long dispersion times (Jobson 1996).

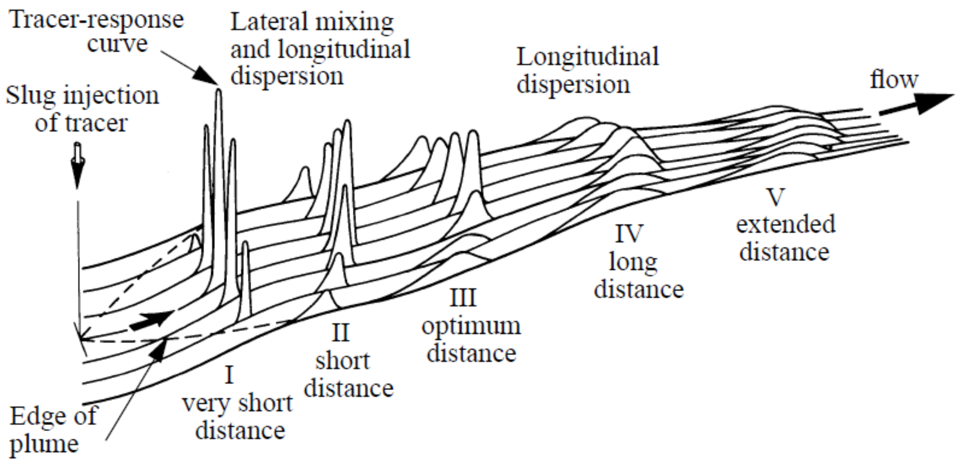


Figure 5.1 *Dispersion processes in a river from a single-point injection (Jobson 1996)*

A dilution factor can be defined as:

$$\gamma_d = \gamma_{d,longitudinal}\,\gamma_{d,lateral} = c_x/c_o \qquad (5.7)$$

with: c_x= concentration at location x and c_o= source concentration; γ_d- values in **Table 5.1**.

The dilution effect is relatively large close to the source because the longitudinal concentration gradient is relatively large resulting in a relatively large diffusive transport ($\varepsilon\, \partial c/\partial x$). Further away from the source, the concentration gradient decreases and hence the diffusive transport decreases.

<u>**Longitudinal mixing (constant width)**</u>

Equation (5.6) is shown in **Figure 5.1** for a point sourece M=10 kg/m^2 (being a spike-type release at x= 0 at t= 0; single release event) and u= 0.5 m/s, ε= 0.1 m^2/s at t = 5, 20 and 100 seconds, showing the gradual spreading of the (fine sediment) mass M in horizontal direction away from the source.
The maximum concentration (c_{max}) can be obtained for x=ut yielding: $\exp[-\{(x-ut)/(4\,\varepsilon\, t)^{0.5}\}^2] = 1$.
The maximum concentration decreases in downstream direction due to diffusion, **Figure 5.2**.
The maximum concentration in the 1D case decreases as: $c_{max}\sim(\varepsilon\, t)^{-0.5}$

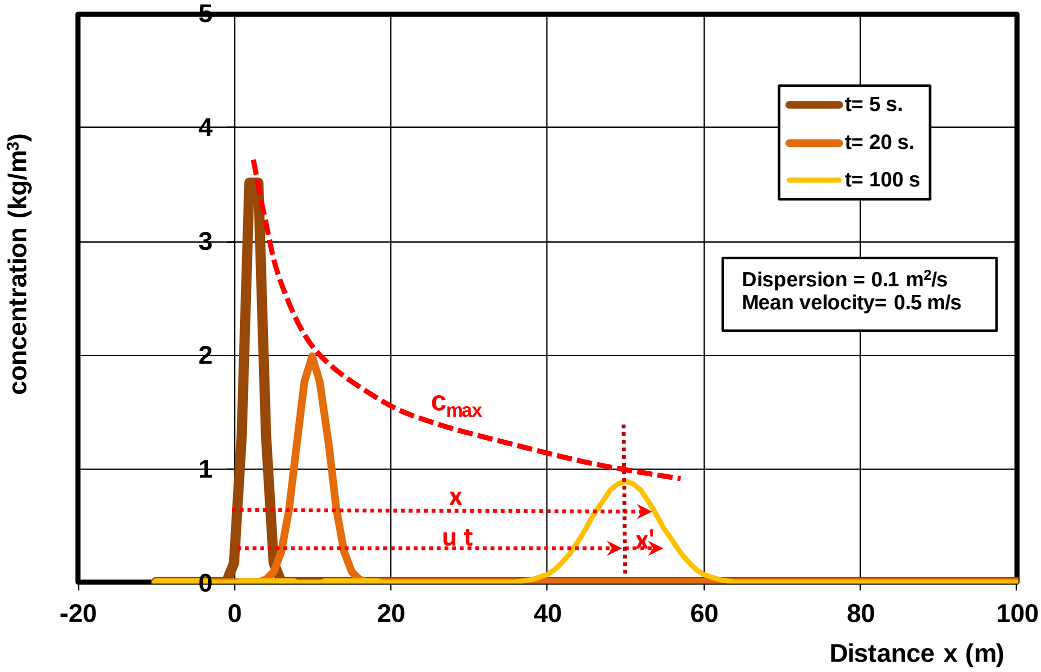


Figure 5.2 *Dispersion/diffusion of concentration as function of x (horizontal) and t*

Table 5.1 shows some theoretical results based on Equation (5.6). The computed concentrations and dilution factors are very small for large dispersion coefficients (100 m^2/s) due to longitudinal spreading. Most of the spreading occurs in the initial phase (over a small distance from the source location).

Ideally, the ε-value can be determined from a dye tracer experiment in unidirectional flow with a constant velocity. In practice, dye tracer experiments are often done in river flow, where the velocities near the bottom and near the banks are much smaller resulting in additional velocity gradients and mixing processes. The combined effect is known as the dispersion coefficient (K) with values in the range of 1 to 100 m^2/s.

Time	Distance (m)		Dilution factor			
	Current=	Current=	1D case; longitudinal mixing in main flow direction; no lateral mixing			
(s)	0.5 m/s	1 m/s	Mixing 0.1 m^2/s	1 m^2/s	10 m^2/s	100 m^2/s
0.1			c≅ 1 kg/m^3	≅ 1 kg/m^3	≅ 1 kg/m^3	≅ 1 kg/m^3
1	0.5	1	c=0.9	0.3	0.09	0.03
10	5	10	c=0.3 (γ_d≅1/3)	0.09 (γ_d≅1/10)	0.03 (γ_d≅1/30)	0.01 (γ_d≅1/100)
100	50	100	c=0.09 (γ_d≅1/10)	0.03 (γ_d≅1/30)	0.009 (γ_d≅1/100)	0.003 (γ_d≅1/300)
1000	500	1000	c=0.03 (γ_d≅1/30)	0.01 (γ_d≅1/100)	0.003 (γ_d≅1/300)	0.001 (γ_d≅1/1000)
10000	5000	10000	c=0.01 (γ_d≅1/100)	0.003 (γ_d≅1/300)	0.0009 (γ_d≅1/1000)	0.0003 γ_d≅1/3000)

Table 5.1 *Dilution factors for a mud cloud (fines with settling velocity < 0.1 mm/s); M = 1 kg/m² at t=0; single release event at source location*

Example 1

University of Karlsruhe (Germany) reports data of a dye tracer experiment in the Cowaleson Creek in the USA. The mean velocity is about 0.2 m/s, water depth is about 0.3 m, the creek width is 10 m.

The results are:

x_1= 700 m after t_1≅ 1 hour: $c_{max,1}$= 140 μg/l (mg/m^3); $\sigma_1 \cong$ 150 m (longitudinal cloud size≅ 2σ);

x_2= 2800 m after t_2≅ 5 hours: : $c_{max,2}$= 35 μg/l (mg/m^3); $\sigma_2 \cong$ 250 m;

x_3= 5200 m after t_3≅ 9 hours: $c_{max,3}$= 20 μg/l (mg/m^3); $\sigma_3 \cong$ 450 m.

The travel time Δt between station 1 and 2 is about 2100/0.2= 10500 s.

The travel time Δt between station 2 and 3 is about 2400/0.2= 12000 s.

The dispersion coefficient can be estimated as: $\varepsilon_{1-2}= [\sigma_2^2-\sigma_1^2]/(2\ \Delta t)= [250^2-150^2]/(2x10500) \cong 2\ m^2/s$

$\varepsilon_{2-3}= [\sigma_2^2-\sigma_1^2]/(2\ \Delta t)= [450^2-250^2]/(2x12000) \cong 5\ m^2/s$

The dilution factor between station 1 and station 3 is: γ_d = 20/140 = 1/7.

Example 2

Leibundgut et al. (1993) report a dye experiment in the Rhine River in Switserland. The mean velocity is about 0.8 m/s. The maximum concentration is 9 mg/m^3 (μg/l) at the upstream station and 5 mg/m^3 at the downstream station at distance of about 30 km. The travel time between the stations is about 10 hours. The dispersion coefficient was determined from the longitudinal cloud size (order of 5 km) at both stations and the travel time resulting in about $\varepsilon \cong$ 75 m^2/s. The dilution factor is about γ_d= 5/9 ≅ 1/2.

Example 3

In 1965, a large injection of 1800 kilograms of 40 percent dye solution was used to measure the travel time in a 202-kilometer reach (width of about 1 km) of the Mississippi River from Baton Rouge to New Orleans, Louisiana (Stewart, 1967). Most likely, 3 to 5 injection points with lateral spacing of about 200 m have been used across the wide river (Wilson 1968). Lateral mixing generally goes fairly quickly within a few kilometres from the injection points (Wilson 1968). The average discharge was approximately 6700 m^3/sec. The river width near Baton Rouge is about 1000 m. The dispersion patterns for the mid-stream sampling points at each of the four cross- sections sampled are shown in **Figure 5.3**.

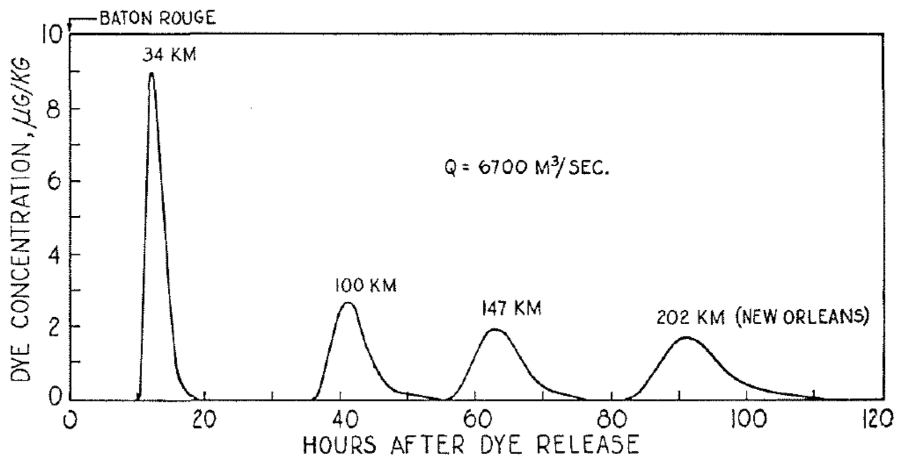


Figure 5.3 *Distribution of dye concentration (µg/kg ≅ µg/l = 10^{-6} kg/l = 10^{-3} kg/m³) with time at midstream sampling points, Mississippi River, Louisiana, September 1965 (Wilson 1968, Stewart 1967)*

The travel time between station 34 km and station 202 km is about 80 hours, which is a travel velocity of about 0.6 m/s (approximately the cross-section averaged flow velocity). The dye dilution is largest (estimated factor 100 to 1000 due to lateral mixing) over the initial traject 0-34 km and a factor of 4 between station 34-202 km.

Equation (5.6) has been used to estimate the dye concentration for dispersion coefficients in the range K=1 to 1000 m^2/s, see **Table 5.2**. A problem is the estimation of the initial load M (in kg/m^2).

The total dye mass is 1800 kg or 1.8 kg/m using a river width of 1000 m.

Assuming that the dye is released quickly (< 1 minute), the longitudinal distance covered by the flow is about 20 m resulting in M= 1.8/20 ≅ 0.1 kg/m^2.

Assuming a water depth of 10 m, the initial dye concentration is 0.1/10= 0.01 kg/m^3= 10^4 µg/l= 10 mg/l.

The best estimate of the initial concentration close to the injection point (within 1 km) is about 10-100 mg/l or 10,000-100,000 µg/l. The estimated dilution between stations 0 and 200 km is about 1/5000, see column 2 of **Table 5.2**.

A dispersion coefficient of about 100 to 300 m^2/s yields the best agreement with the measured data (at about 30 km and 200 km), see **Table 5.2**. The dispersion coefficient can also be estimated from the longitudinal cloud sizes at the observation stations and the travel time Δt of about 50 hours between the two stations at 100 and 200 km:

σ_1= 2 hours= 7200x0.6 = 4320 m at station 100 km;

σ_2= 4 hours=14400x0.6 = 8640 m at station 200 km.

The dispersion coefficient is: $\varepsilon_{1\text{-}2}= [\sigma_2^2-\sigma_1^2]/(2\,\Delta t)= [8640^2-4320^2]/(2x50000x3600) \cong 150$ m^2/s.

Station	**Measured dye concentration (µg/l=10^{-6} kg/m³)**	**Computed dye concentration (µg/l=0.001 mg/l=10^{-6} kg/m³)**				
		K=1 m²/s	**K=10 m²/s**	**K=100 m²/s**	**K=300 m²/s**	**K=1000 m²/s**
t=1000 s (15 min) x=0.6 km	not measured ≅ 10000 µg/l (≅ 10 mg/)	900 µg/l	280	90	52	28
t=50000 s (14 hours) x=30 km	≅ 9 µg/l	126 µg/l	40	13	7	4
t=350000 s (97 hours) x=200 km	≅ 2 µg/l (estimated dilution factor 1/5000)	48 µg/l	15	5	2.7	1.5

K= dispersion coefficient; M= 0.1 kg/m² as initial dye load; 1 µg/l= 1 microgram/l= 0.001 mg/l

Table 5.2 *Measured and computed dye concentrations for dye experiment, Mississippi River, USA, 1965*

Vertical mixing

A cloud of fine sediment (M= 10 kg/m^2; single release event) is injected at 2 m above the bed in a water depth of 100 m. The cloud is assumed to settle to the bed with advection velocity of -0.002 m/s (-2 mm/s). The fines will also be mixed vertically due to turbulence with a mixing coefficient of ε= 0.1 m^2/s.

Figure 5.4 shows the development of the concentrations as function of time in vertical direction (above the source point) using u = w_s = -0.002 m/s (advection velocity=settling velocity) and ε= mixing coefficient= 0.1 m^2/s. The mean concentration cloud at the source location (at 2 m above the bed) will slowly sink to the bed due to the settling velocity, while the concentrations are mixed vertically by turbulence.

After 1000 s: concentration at a level of 30 m above the injection point is 0.02 (dilution= 1/50).
After 10000 s: concentration at a level of 60 m above the injection point is 0.015 (dilution=1/70).
Hence, sediments can reach to the surface due to upward mixing processes.

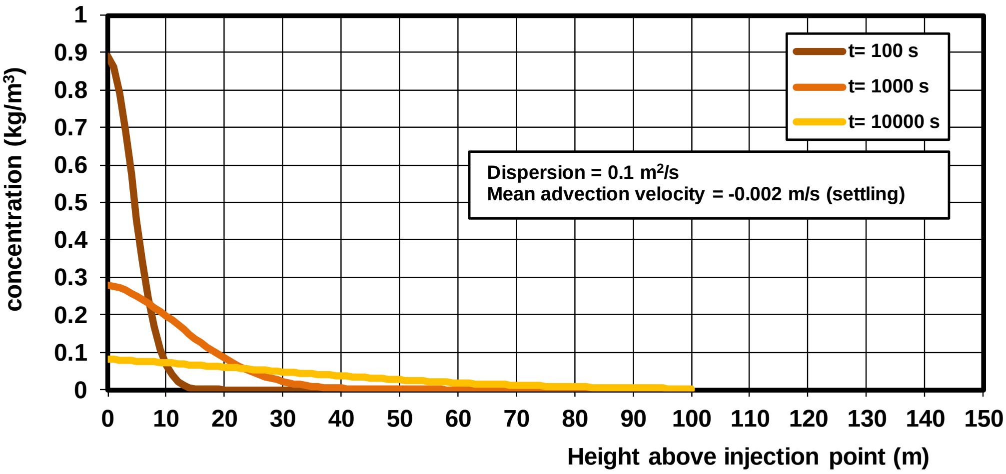


Figure 5.4 *Dispersion/diffusion of concentration as function of z (vertical) and t*

Lateral mixing

A continuous mud release source with initial width b_o will be spread out (diluted) due to lateral mixing and dispersion processes.

Based on available knowledge (Jirka et al., 2004), the lateral spreading due to mixing processes in a river flow can be described by (**Figures 5.5A,B**):

$$b_x=b_o+2x^{\beta} \qquad (5.8a)$$

with: b_o=width of mud source, b_x= width at location x, x= longitudinal coordinate, β= 0.5 to 1 (default=0.5).

Figure 5.5B shows a dredging-related plume. The plume width increases from about 10 m at the source location to about 60 m at x=500 m, which corresponds to a β-value of 0.5 to 0.6; $b_{500}=10+(2x500)^{0.6}=73$ m.

The dilution factor due to lateral mixing processes is: $\gamma_{d,lateral} = b_o/b_x= 1/[1+(2/b_o)x^{\beta}]$ (5.8b)

Using: $b_o \cong 10$ m (width of mud source), it follows that: $\gamma_{d,lateral} = b_o/b_x= 1/[1+0.2x^{\beta}]$ (5.8c)

Table 5.3 shows dilution factors for β=0.5 and β=0.7.

Distance from mud source location (m)	**β= 0.5**	**β= 0.7**
200	$\gamma_{d,lateral}$ = 1/4	$\gamma_{d,lateral}$ = 1/9
500	$\gamma_{d,lateral}$ = 1/6	$\gamma_{d,lateral}$ = 1/15
1500	$\gamma_{d,lateral}$ = 1/10	$\gamma_{d,lateral}$ = 1/35
5000	$\gamma_{d,lateral}$ = 1/15	$\gamma_{d,lateral}$ = 1/80
10000	$\gamma_{d,lateral}$ = 1/20	$\gamma_{d,lateral}$ = 1/125

Table 5.3 *Dilution factors related to lateral mixing (b_o=10 m)*

In the case of a river width of B=500 m, complete mixing of dye across the river width is accomplished after $500=10+2x^{\beta}$, yielding: x≅ 60000 m (60 km), which is about 120B for β=0.5;
x≅ 3000 m (3 km), which is about 6B for β=0.7.

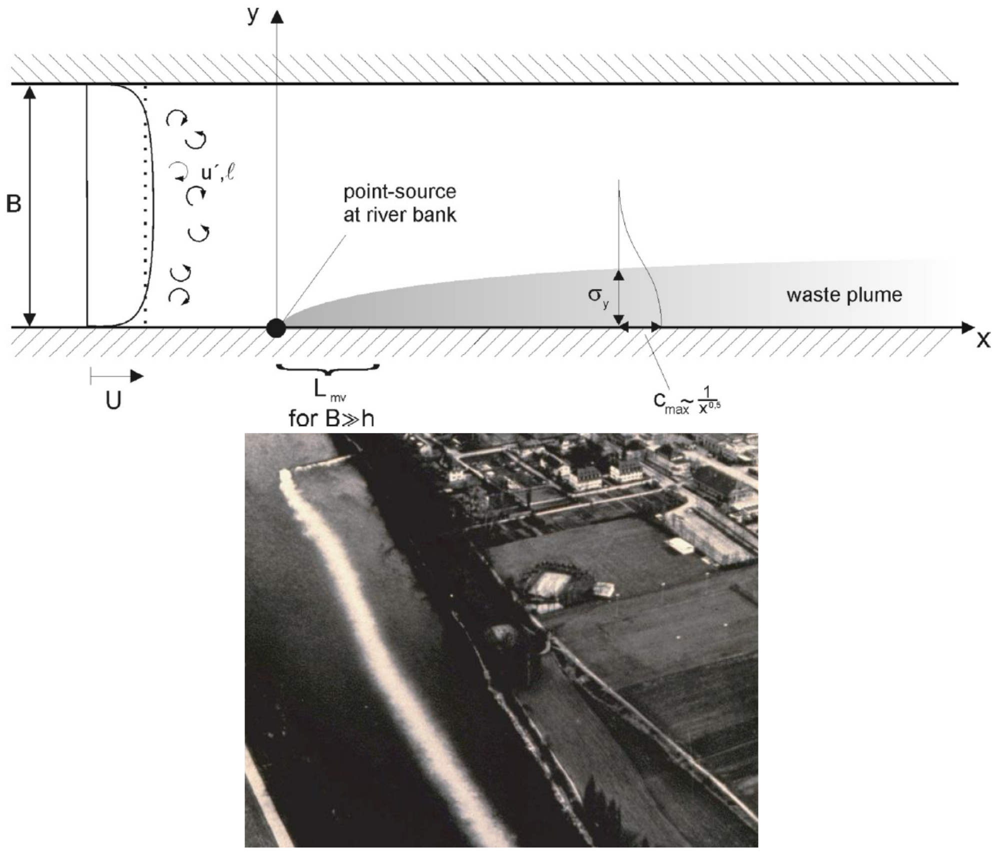


Figure 5.5A *Lateral mixing processes in river flow (Jirka et al. 2004)*
Upper: schematic lateral mixing (L_{mv}= length of full vertical mixing);
Lower: waste water release in Rhine river Switzerland (1960)

Figure 5.5B *Lateral mixing of dredging plume*

5.2 Settling and dispersion processes in uniform flow with and without lateral mixing

5.2.1 Longitudinal dispersion without lateral mixing

Three models have been used:

1. numerical SUSTIM2DV-model;
2. semi-analytical SEDTUBE1D-model;
3. analytical SEDPLUME1D-model

<u>SUSTIM-model</u>

The SUSTIM2DV-model has been used to compute the adjustment of suspended sediment transport of fine silt and sand in the case of channel deepening in steady flow (no tide) and constant width.

The SUSTIM2DV-model is a numerical two-dimensional vertical model in Fortran-code for the computation of sediment concentrations and sediment deposition across a dredged channel and over the tidal cycle. The numerical model solves the two-dimensional vertical advection-diffusion equation for suspended sediments on a non-equidistant grid. In vertical direction, the grid cells have a logarithmic size distribution resulting in very small grid sizes close to the bed and larger sizes near the water surface. In horizontal direction, the grid sizes can be set to small values in and near the channel and larger sizes further away near the in- and outflow boundaries.

The SUSTIM-model has been used to compute the deposition of silt in the offshore section KP33-43 of the Payra navigation channel (Bangladesh) during one month in the monsoon period.

Two cases are considered (**Figure 5.6**) , as follows:

- Case 1: water depth of upstream channel h_o=10 m; water depth of downstream channel h_1=11 m; upstream depth-averaged current velocity=1 m/s; downstream current velocity=0.91 m/s;
- Case 2: water depth of upstream channel h_o=10 m; water depth of downstream channel h_1=20 m; upstream depth-averaged current velocity=1 m/s; downstream current velocity=0.5 m/s.

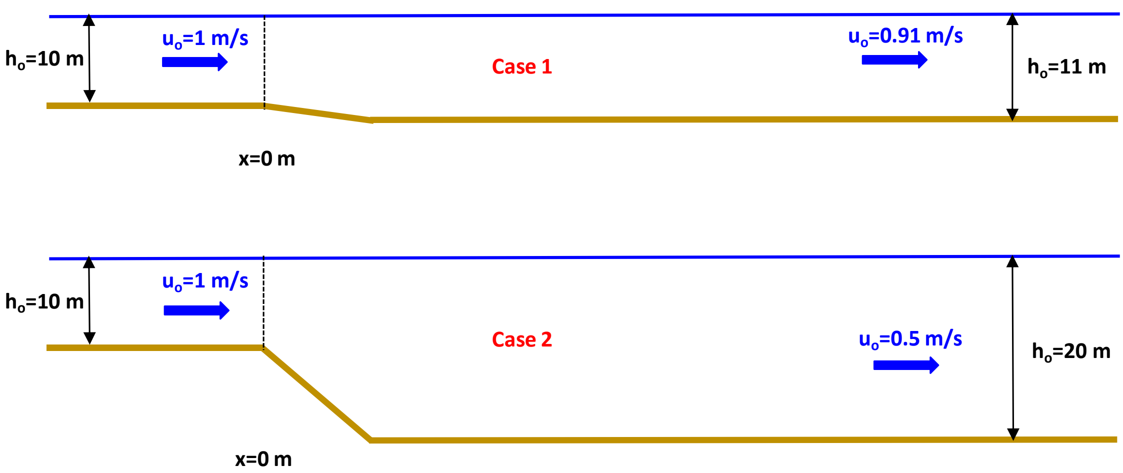


Figure 5.6 *Channel dimensions of Case 1 and Case 2 (constant width)*

These cases are used to determine the adjustment length of an overload of sediment (fine silt and sand) at the entrance of a straight channel (constant width and depth).

The sediment conditions are, as follows:

- sediment 8 µm; settling velocity=0.055 mm/s;
- sediment 16 µm; settling velocity=0.22 mm/s;
- sediment 32 µm; settling velocity=0.88 mm/s;
- sediment 63 µm; settling velocity=3.5 mm/s;
- sediment 125 µm; settling velocity=11.0 mm/s.

The other input data are:

- fluid/sediment density= 1025, 2650 kg/m^3;
- dry bed density= 1100 kg/m^3; critical bed-shear stress for initiation of erosion= 0.1 N/m^2;
- bed roughness k_s= 0.1 m;
- γ_1, γ_2= coefficients related to current-generated mixing of mud=0.05, 0.005;
- eta=1;
- NZ=25 (number of grid points vertical direction);
- Δx=2 m to 5 m (horizontal grid size), Δt=4 s (time step);
- slibc=coefficient reference mud concentration near bed=0.00000353.

The computed upstream sediment transport and depth-mean sediment concentration ($c_{mean}=q_s/(uh)$) are given in **Table 5.4**.

Sediment diameter (µm)	**Settling velocity (mm/s)**	**Upstream water depth (m) and current (m/s)**	**Upstream sediment transport (kg/m/s)**	**Upstream depth-mean concentration (mg/l)**	**Upstream sediment concentration (mg/l)**			
					bed	z=1 m	z=5 m	surface
8	0.055	10; 1	2.32	232	300	270	240	150
16	0.22	10; 1	2.15	215	300	263	222	110
32	0.88	10; 1	1.58	158	300	232	165	40
63	3.5	10; 1	0.524	52	300	132	45	1
125	11.0	10; 1	0.074	7	300	25	1	0

Table 5.4 *Upstream sediment parameters of Case 1, 2; SUSTIM-model*

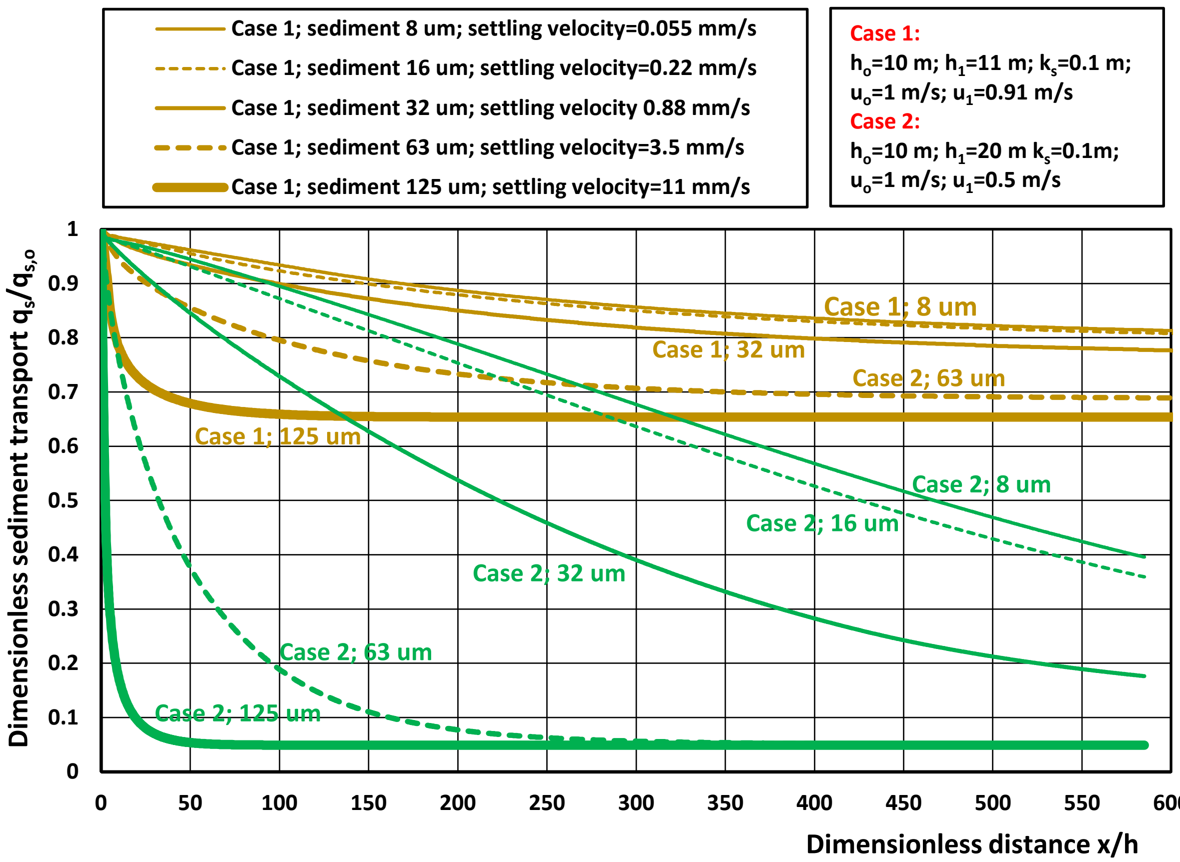


Figure 5.7 *Adjustment of sediment transport of mud, silt and fine sand, Case1 and 1; SUSTIM-model*

The decrease of the computed sediment transport values to the new flow conditions in the downstream deeper channel based on the SUSTIM-model is shown in **Figure 5.7**. The vertical axis represents the dimensionless sediment transport ($q_s/q_{s,o}$); the horizontal axis represents the dimensionless coordinate (x/h) with h=water depth of downstream channel.
The dimensionless adjustment length scales (L_a/h; h=water depth) to reach about 90% of the new equilibrium transport are given in **Table 5.5**.
Fine mud-silt transport (8 to 32 μm) has a very long adjustment length scale of the order of 1000 h.
Fine sand transport (63 to 125 μm) has a short adjustment length scale of the order of 100 h.

Sediment diameter (um)	Adjustment length scale (L_a/h)	
Settling velocity (mm/s)	Case 1 (h=11 m)	Case 2 (h=20 m)
8 μm; 0.055 mm/s	>1000	>1000
16 μm; 0.22 mm/s	>1000	>1000
32 μm; 0.88 mm/s	≅700	≅600
63 μm; 3.5 mm/s	≅350	≅200
125 μm; 11 mm/s	≅70	≅30

Table 5.5 *Adjustment length scales of overload conditions; SUSTIM2DV-model*

SEDTUBE1D-model

The SEDTUBE1D-model is a simple 1D-model which is based on exponential adjustment of the sediment transport and concentrations (ANNEX II) in the case of overload/underload conditions in a channel of constant width (no lateral mixing effects).
This model has been used to compute the settling distance for two fine sand fractions of 63 and 125 μm.
Two flow velocities have been used: 1.5 and 1 m/s.
The water depth is 15 m and the bed roughness is k_s= 0.01 m.
It is assumed that the local suspended transport (q_s) of fine sediment at the dumping (source) site is about 10 times higher (overload conditions) than the equilibrium suspended transport ($q_{s,eq}$).

Figure 5.8 shows the excess suspended transport defined as (q_s-$q_{s,eq}$)/$q_{s,eq}$ as function of the longitudinal distance from the dumping site for two sand fractions. The equilibrium suspended transport is computed by a sediment transport formula (Van Rijn 2007) implemented in the model. The water depth is h=15 m.
The results of **Figure 5.8** show that the total settling distance for the finest sand fraction of 63 μm is about 1500 h (≅25 km) if the flow velocity is about 1.5 m/s and about 1000 h (≅15 km for) a flow velocity of 1 m/s.

Table 5.6 shows the dilution factors ($\gamma_{d,longitudinal}$) for fine sand in conditions with velocities in the range of 0.3 to 1.5 m/s based on the SEDTUBE-1D model. The dilution factor is defined as: $\gamma_{d,longitudinal}$ =$q_{s,x}/q_{s,o}$≅c_x/c_o, with q_s = sediment transport = q c and q= water discharge per unit width=constant and c= concentration.
The concentration is almost uniform over the water depth for fine sediments.
In strong flows (1 and 1.5 m/s), the dilution factor due to sedimentation processes (sediment from the water column settling on the bed) for sediment of 63 μm due to settling and vertical mixing (no lateral mixing) is about 1/3-1/6 after 5 km and about 1/10-1/30 after 10 km (**Table 5.6**).
These values are only valid for settling processes in a narrow channel (no lateral mixing).
In practice, the dilution factors are much smaller due to lateral mixing (based on SEDPLUME-model of Section 5.2.2).

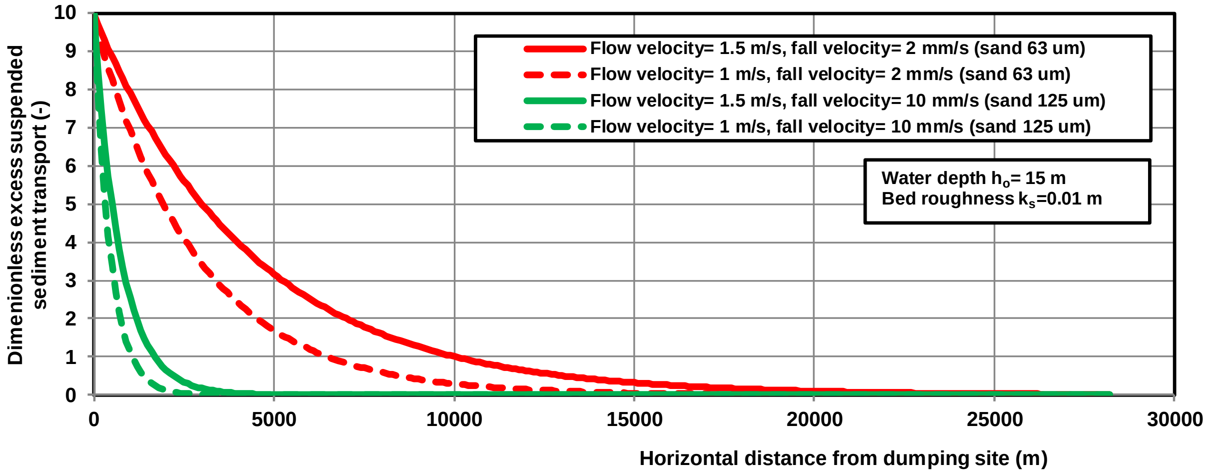


Figure 5.8 *Settling of fine sand as function of current velocity and fall velocity; water depth= 15 m; constant width (overloading conditions; continuous supply at source x=0); SEDTUBE1D-model (γ=0.1)*

Distance (m)		**Dilution factor γ_d for fine sand of 63 μm 1D case: settling and vertical mixing (constant width)**		
x	**x/h**	**Current = 0.3 m/s**	**Current= 1 m/s**	**Current= 1.5 m/s**
200	13	1/1.2	1.05	1/1.03
500	33	1/2	1/1.1	1/1.05
1500	150	1/5	1/1.5	1/1.2
5000	333	1/100	1/6	1/3

1D= line source in wide channel of constant width;

Table 5.6 *Dilution factors for settling of fine sand in channel of constant width; continuous line source of fine sand of 63 μm; settling velocity= 2 mm/s; water depth= 15 m; SEDTUBE-model (γ=0.1)*

The SEDTUBE1D-model has also been used to compute the settling distance of three mud fractions in a channel (constant width) with water depth of 3 m and current velocities in the range of 0.05 to 0.3 m/s. The settling distance is defined as the distance over which the sediment concentration reduces from 100 to 10 mg/l under the influence of settling processes. The width of mud source is equal to channel width.

The three mud fractions are:

- 32-64 μm with settling velocity=1.8 mm/s,
- 16-32 μm with settling velocity=0.45 mm/s,
- <16 μm with settling velocity of 0.25 mm/s (flocculated).

Figure 5.9 shows the computed dimensionless settling distance of the three mud fractions (L/h with h=water depth).

The coarsest fraction of 32-64 μm settles relatively quickly (within 150 h from the line source location). This means that the concentrations of the coarsest fraction are reduced from 100 to 10 mg/l after 150 h in a current of 0.3 m/s, which is a dilution factor of 1/10 for a water depth of 3 m.

The finest fraction < 16 μm has a settling distance of about 1300 h for velocity of 0.3 m/s.

Table 5.7 shows the dilution factors for the mud fraction 8-16 μm in conditions with velocities in the range of 0.1 to 0.5 m/s, based on the SEDTUBE1D-model (constant width; no lateral mixing).

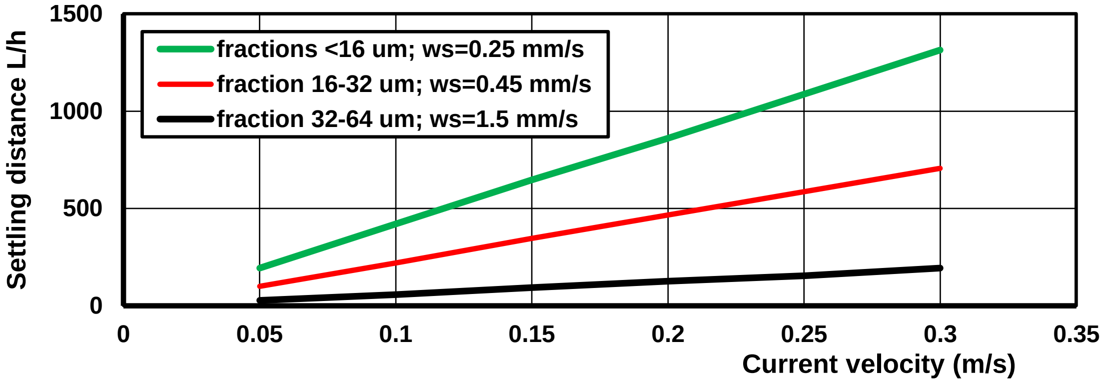


Figure 5.9 *Settling distance of mud as function of current velocity; water depth = 3 m; constant width; (overloading conditions; continuous supply at source x=0); SEDTUBE1D-model (γ=0.1)*

Distance (m)	Dilution factor γ_d for mud of 8-16 μm; w_s=0.25 mm/s 1D case: settling and vertical mixing (constant width); no lateral mixing					
	Water depth = 3 m			Water depth= 10 m		
	Current=0.1 m/s c_o=100 mg/l c_{eq}=10 mg/l	0.3 m/s c_o=100 mg/l c_{eq}=20 mg/l	0.5 m/s c_o=100 mg/l c_{eq}=30 mg/l	Current= 0.1 m/s c_o=300 mg/l c_{eq}=10 mg/l	0.3 m/s c_o=300 mg/l c_{eq}=20 mg/l	0.5 m/s c_o=300 mg/l c_{eq}=30 mg/l
200	1/1.5	1/1.2	1/1.05	1/1.1	1/1.03	1/1.01
500	1/2	1/1.5	1/1.2	1/1.5	1/1.1	1/1.05
1500	1/3	1/2	1/1.5	1/2	1/1.3	1/1.2
5000	1/15	1/5	1/3	1/10	1/2	1/1.8

c_o=source concentration; c_{eq}=equilibrium concentration
1D= line source in wide channel of constant width

Table 5.7 *Dilution factors for settling of mud in channel of constant width; water depth= 3 and 10 m; continuous source of mud of 8-16 μm; settling velocity= 0.25 mm/s; SEDTUBE1D-model (γ=0.1)*

<u>SEDPLUME-model</u>

The SEDPLUME-model (ANNEX II) is an analytical expression for exponential decay of the sediment concentrations (c) from the value c_o at x=0 to the equilibrium value c_{eq} further downstream. The sediment transport of the SEDPLUME-model is computed as q_{mud}=u h c. The channel width is constant (no lateral mixing; $f_{lateral}$=1). The SEDPLUME-model can be used for cases with or without lateral mixing.
The results of the SUSTIM2DV-model are compared to the results of the SEDPLUME-model for overload conditions of sediment with settling velocity of 1 mm/s in a channel with steady flow (constant width). The upstream water depth is 10 m; the water depth of the downstream section is 15 m. The approach flow velocity is 1.35 m/s (steady flow; no tide). The flow velocity in the downstream section is 0.9 m/s..
The input data of the SUSTIM2DV-model are: slibc=0.00005; γ_1=0.015; γ_2=0.0075; eta=1; dfm=0.01 m; k_s=0.03 m; fluid density=1025 kg/m^3, settling velocity=1 mm/s= constant.
The computed sediment transport at the entrance (x=0) of the downstream section with water depth of 15 m is 22.5 kg/m/s (SUSTIM2DV-model). The depth-mean concentration is 22.5/(0.9x15)=1.67 kg/m^3= 1670 mg/l.
The computed equilibrium transport in the downstream channel section is 7.45 kg/m/s (SUSTIM2DV-model). The depth-mean equilibrium concentration is 7.45/(0.9x15)=0.55 kg/m^3= 550 mg/l.
The values c_o=1670 mg/l and c_{eq}=550 mg/l are used in the SEDPLUME-model. The mud transport of the SEDPLUME-model is computed as: q_{mud}=u h c.

Figure 5.10 shows results of the SUSTIM2DV-model and SEDPLUME-model (SVM-approach) for overload conditions of sediment with settling velocity of 1 mm/s.
The decay of the mud transport of both models shows good agreement.

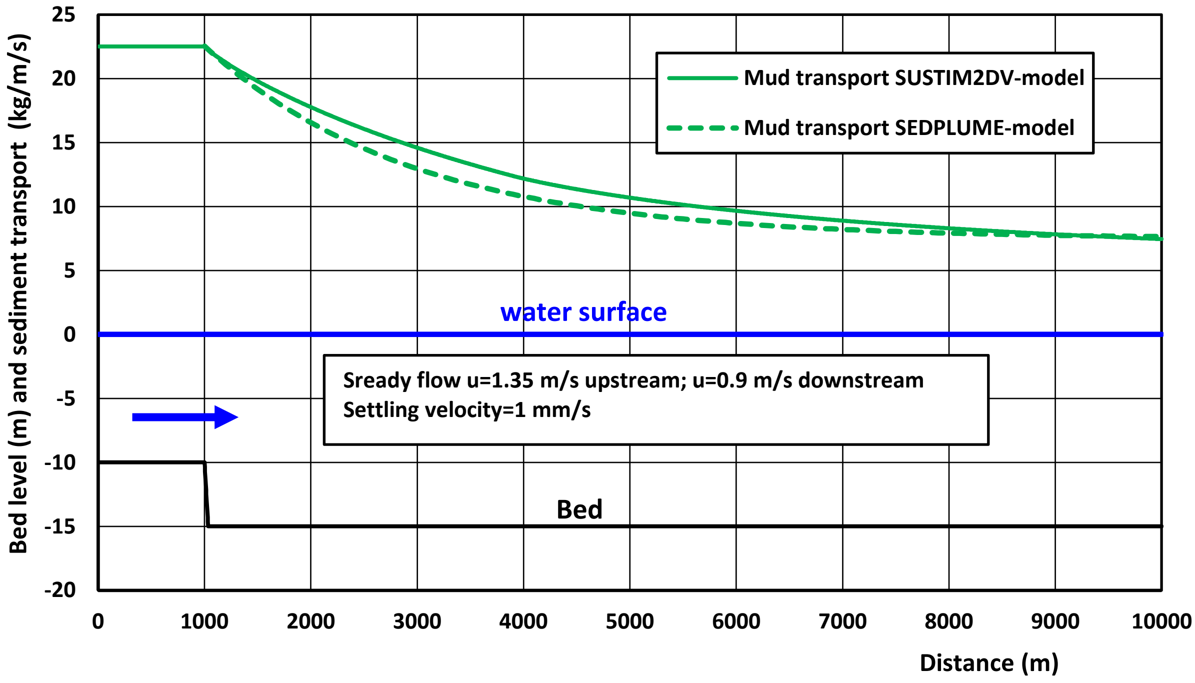


Figure 5.10 *Computed mud transport of SUSTIM2DV-model and SEDPLUME-model (SVM-approach) for overload conditions; settling velocity=1 mm/s*

5.2.2 Longitudinal dispersion with lateral mixing

SEDPLUME-model; simple model for sediment concentration decay in a plume

In ANNEX II, an analytical expression for the sediment concentration decrease in a plume is derived, which reads as::

$c= f_{time}\, f_{lateral}\, [c_{eq} + (c_o\text{-}c_{eq}) \exp(-A_S\, x)]$; S-approach (5.9a)

$c= f_{time}\, f_{lateral}\, [c_{eq} + (c_o\text{-}c_{eq}) \exp(-A_{SVM}\, x)]$; SVM-approach (5.9b)

with:

$A_s=\alpha w_s/(uh)$ for the S-approach;

$A_{svm}=\gamma(1/h)(w_s/u_*)(1+2w_s/u_*)(1+H_s/h)^2$ for the SVM-method;

c_o= concentration at x=0;

c_{eq}= equilibrium concentration at x=end (≥0).

$f_{lateral}=1/\{1+(2/b_o)x^{\beta}\}$= lateral mixing effect factor; no lateral mixing for β=0

f_{time}= time factor= dump time/interval time; dump time= duration of dumping process; interval time= time between two successive dumps;

b_o= width of mud source (≅10 m);

β = coefficient related to lateral mixing (range=0.5-0.7; lateral mixing is small for β=0 and b_o= very large).

w_s= settling velocity;

b_o= width of mud source;

α= calibration coefficient (>1);

γ=calibration coefficient (standard value=0.3; range 0.1-0.5; higher value gives shorter settling distance, quicker adjustment);

h= flow depth;

u_*= bed-shear velocity due to currents and waves ($=u_{mean}\, g^{0.5}/C$);

$C= 5.75\, g^{0.5} \log(12h/k_s)$= Chézy coefficient;

k_s= effective bed roughness height of Nikuradse;

u_{mean}= depth-averaged flow velocity;

H_s= significant wave height.

Equations (5.9a,b) are implemented in the SEDPLUME-model (S-approach and SVM-approach) for simulation of mud turbidity plumes and can be used for the simulation of the decrease of fine sediment concentrations from a line source or point source Lateral mixing can be included by a additional factor ($f_{lateral}$ and β-coefficient) and is mostly dominant. The effect of a discontinuous source can be taken into account by the f_{time}-factor (≤ 1).

The following examples are studied:

1. adjustment of fine sediment concentrations in overload conditions without lateral mixing (5 fractions);
2. adjustment of fine sediment concentrations in overload conditions without lateral mixing (3 fractions);
3. plume dispersion due to mud dumping with lateral mixing;
4. plume dispersion due to cutter dredging with lateral mixing.

Example 1: adjustment of fine sediment concentrations in overload conditions without lateral mixing

The SEDPLUME-model has been used to compute the dimensionless adjustment distance (L_a/h) of fine sediment fractions for the Cases 1 and 2 (overload of sediment transport in channel of constant width based on SUSTIM2DV-model), see **Section 5.2.1**. The β-factor is set to 0 (no lateral mixing). The initial concentration is set to 1000 mg/l. The ratio c_{eq}/c_o (SVM-method) is taken from **Figure 5.7**.
The results of the SUSTIM2DV-model and the SEDPLUME-model are given in **Table 5.8**.

The S-approach of the SEDPLUME-model gives much larger L_a/h-values than the SUSTIM2DV-model, which can be corrected by using a much higher effect settling velocity (α>>1).

The SVM-approach of the SEDPLUME-model gives larger L_a/h-values (factor 2) than the SUSTIM2DV-model for very fine sediments (8 and 16 μm), which can be corrected by using a higher γ-value (γ=0.5) or a higher settling velocity (factor 1.5 to 2).
The L_a/h-values of the SVM-approach are of the right order of magnitude for sediments of 32 to 125 um.

Based on this, it is concluded that the SVM-approach is the preferred method.

Sediment diameter Settling velocity	Adjustment length scale (L_a/h)			
	Case 1(u=0.91 m/s; h=11 m)			Case 2 (u=0.5 m/s; h=20 m)
8 μm; 0.055 mm/s	SUSTIM2DV-model		>1000	>1000
	SEDPLUME-model S	(settling only; α=1)	>3000	>3000
	SEDPLUME-model SVM	(settling+mixing; γ=0.3)	≅2500	≅2000
16 μm; 0.22 mm/s	SUSTIM2DV-model		>1000	>1000
	SEDPLUME-model S	(settling only; α=1)	>3000	>3000
	SEDPLUME-model SVM	(settling+mixing; γ=0.3)	≅2000	≅1500
32 μm; 0.88 mm/s	SUSTIM2DV-model		≅700	≅600
	SEDPLUME-model S	(settling only; α=1)	≅2500	≅2000
	SEDPLUME-model SVM	(settling+mixing; γ=0.1)	≅700	≅500
63 μm; 3.5 mm/s	SUSTIM2DV-model		≅350	≅200
	SEDPLUME-model S	(settling only; α=1)	≅1000	≅600
	SEDPLUME-model SVM	(settling+mixing; γ=0.1)	≅200	≅150
125 μm; 11 mm/s	SUSTIM2DV-model		≅70	≅30
	SEDPLUME-model S	(settling only; α=1)	≅400	≅200
	SEDPLUME-model SVM	(settling+mixing; γ=0.1)	≅50	≅20

Table 5.8 *Adjustment length scales of overload conditions for sediment of 8 to 125 μm*

Example 2: adjustment of fine sediment concentrations in overload conditions without lateral mixing

The SEDPLUME-model has been used to compute the settling distance of three mud fractions in a channel (constant width) with water depth of 10 m and current velocities of 0.1 and 1 m/s. The initial concentration is c_o= 1 kg/m^3= 1000 mg/l for all three fractions. The model coefficients are: α =1 for S-approach and γ=0.3 for SVM-approach. The three mud fractions are:

- 32-64 μm with settling velocity=1.8 mm/s,
- 16-32 μm with settling velocity=0.45 mm/s,
- <16 μm with settling velocity= 0.2 mm/s.

The computed decrease of the sediment concentrations based on the S-approach and the SVM-approach is shown in **Figure 5.11**. Analysis of the results gives:

- the decrease of the sediment concentrations proceeds more rapidly in the case of a weak current of 0.1 m/s compared to a strong current of 1 m/s;
- the decrease of the sediment concentrations according to the SVM-approach proceeds much more rapidly compared to the S-approach; the results of the S-approach can be improved by using α>1 (higher effective settling velocity).

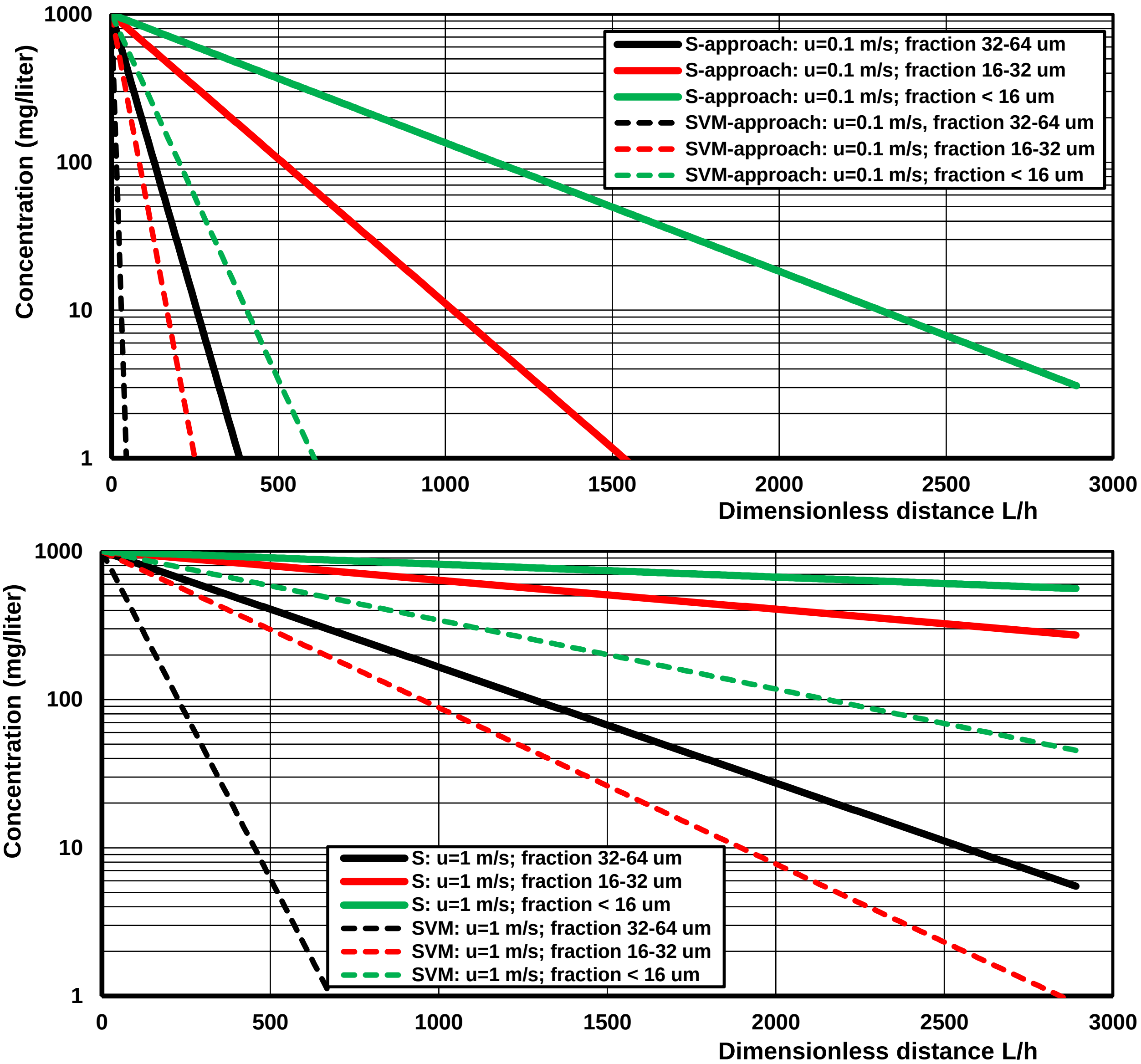


Figure 5.11 *Dimensionless settling distance of mud; water depth = 10 m; constant width; u=0.1 m/s (upper) and 1 m/s (lower); SEDPLUME-model (S and SVM approach) (overloading conditions; continuous supply at source x=0);*

Example 3: plume dispersion due to mud dumping with lateral mixing

Mud is dredged from a tunnel trench and dumped on both sides of the trench in a tidal river (water depth= 10 m; mean flow velocity= 1 m/s; **Figure 5.12**). The natural mud concentration in the tidal river is about 300 mg/l.
Four dump sites are used: A at 8.5 km from trench, B at 3 km, C at 3 km, and D at 10 km from trench.
Mud is dumped at the disposal sites by a dredger with bottom doors (dump time= 10 minutes; interval time= 120 minutes). Vessel length=100 m; width=20 m; water depth=10 m, hopper volume=5000 m^3.
What is the increase of the mud concentration at the tunnel trench due to dumping at the sites?

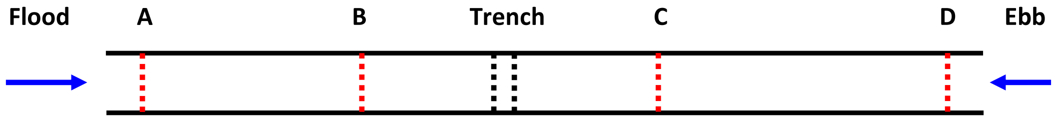


Figure 5.12 *Plan view of river with tunnel trench*

The initial mud concentration in the mud cloud at the dumping site can be estimated by using:
$\Delta c_{dump} = e\, f_{dump}\, p_{fines}\, \rho_{dry,sediment}$
with:
e= entrainment factor (≅0.05) of mud from the falling mud load;
p_{fines}= fraction fine silt/lutum < 32 μm;
$f_{dump}=(V_{dump}/V_{water,dump})$ = local mixing factor around dredger (≅ 1/3);
V_{dump}= dump volume of mud load;
$V_{water,dump}$= mixing water volume around dredger (2 to 3 $V_{dredger}$);
$\rho_{dry,sediment}$ = dry density of mud load (≅ 400-800 kg/m^3).
Using: e= 0.05, f_{dump}= 0.33; p_{fines}= 0.6 en $\rho_{dry,sediment}$ = 600 kg/m^3, it follows that the increase of the mud concentration at the dump sites is: Δc_{dump} ≅ 5 kg/m^3= 5000 mg/l.
The spill method yields: Δc_{dump}=(spill factor x dry load)/$V_{water\ around\ hopper}$= 0.03x600x5000/(100x(3x20)x10) =1.5 kg/m^3=1500 mg/l.
Both methods yield values which are somewhat higher than the observed values of Wolanski et al. (1992), see **Table 4.3.1**.

The SEDPLUME-model (SVM-approach) has been used to compute increase of the mud concentration at the tunnel trench location. The input data are: b_o= width of source= 50 m; f_{time}= time factor= dump time/interval time= 10/120=0.083; β = coefficient for lateral mixing (≅ 0.5); w_s= settling velocity (Table 5.9); h= water depth= 10 m; u= depth-averaged velocity = 1 m/s;
x= distance between disposal location and tunnel trench location (see **Table 5.9**).
Initial concentration=5 kg/m^3=5000 mg/l
Four sediment fractions are distinguished, as follows:

10% fraction 63-125 μm:	500 mg/l
30% fraction 32-63 μm:	1500 mg/l
40% fraction 16-32 μm:	2000 mg/l
20% fraction < 16 μm:	1000 mg/l
Total	5000 mg/l

Table 5.9 shows the increase of the concentrations due to the dumping of mud at sites A and B.
The most unfavorable coefficients are: β=0.5 (lateral mixing effect), γ=0.1.
In the most unfavorable situation, there is a mud concentration increase of about 75 mg/l at the tunnel trench location when mud is dumped at site B during flood flow resulting in extra maintenance dredging in the trench. The concentration increase is about 40 mg/l when mud is dumped at site A during flood flow. In reality, the mud concentration increase will fluctuate in time due to the intermittent dumping process (once every 2 hours). The results for dump sites C and D are similar.

Fraction sediment	Dump sites	
	Dump site A (flood) at 8.5 km	Dump site B (flood) at 3 km
Fraction 63-125 μm; w_s=6.5 mm/s; c_o=500 mg/l	< 1 mg/l	<1 mg/l
Fraction 32-63 μm; w_s=1.8 mm/s; c_o=1500 mg/l	3	15
Fraction <16-32 μm; w_s=0.45 m/s; c_o= 2000 mg/l	20	40
Fraction < 16 μm; w_s=0.25 m/s; c_o= 1000 mg/l	15	20
Total: c_o=5000 mg/l	≅40 mg/l	≅75 mg/l

Table 5.9 *Concentration increase at tunnel trench location; SEDPLUME (SVM-approach γ=0.1; β=0.5)*

Figure 5.13 shows the results of the DELFT3D-model for a scenario with dumping of mud at site A during flood and at site B during ebb. The average mud concentration increase over 6 hours is about 50 tot 60 mg/l, which is somewhat higher than the value of 40 mg/l based on the empirical SEDPLUME-model (SVM-approach).
The DELFT3D-model includes the erosion of fresh mud from the bottom at the dumping sites, which leads to somewhat higher mud concentrations.

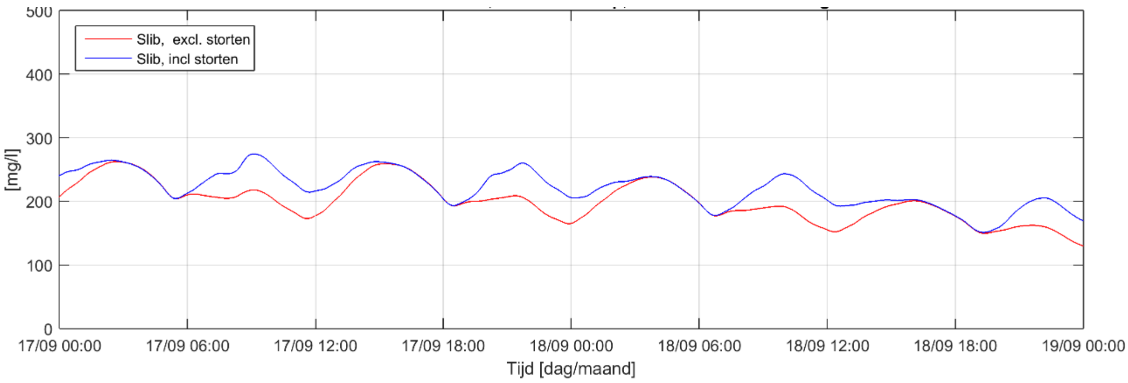


Figure 5.13 *Mud concentrations of DELFT3D-model at tunnel trench location due to dumping of mud at site A during flood and at site B during ebb.*

<u>Example 4: plume dispersion of cutter dredging with lateral mixing</u>

The cutter dredging (CSD) of hard sediments in a shipping channel section and the associated production of fines can be represented as a line source with length L_s and initial concentration $c_{o,flood}$ and $c_{o,ebb}$ over 1 tidal cycle, see **Figure 5.14**.

The local tidal cycle is represented as 2 blocks (each with duration of 12 hours; diurnal tide of 24 hours) with quasi-constant flow velocities u_{flood} and u_{ebb}.
The initial concentration $c_{o,flood}$ is computed as:

$$c_{o,flood}= Q_s N_{tides}/Q_{water}= Q_s N_{tides}/(L_s h_{flood} u_{flood}) = Q_s /[(L_{ch}/N_{tides}) \sin\alpha_{flood} h_{flood} u_{flood})]= Q_s /(r_p \sin\alpha_{flood} h_{flood} u_{flood})$$

with: Q_s=production of fines <250 μm by cutting process (in kg/s);
N_{tides}= total number of tides required to complete the cutter dredging in channel section with length L_s;
L_s= effective length of line source= $L_{ch} \sin\alpha_{flood}$;
L_{ch}= length of channel section (m);
α_{flood}= angle between channel axis and flood velocity vector (90°=flood velocity normal to channel axis);
h_{flood}= representative water depth (m);
u_{flood}= representative depth-averaged velocity during flood≅0.7 $u_{peak,flood}$ (m/s);
$r_p=L_{ch}/N_{tides}$= dredging progress rate along the channel section per tide (m/tide).

A similar function can be derived for the ebb flow.

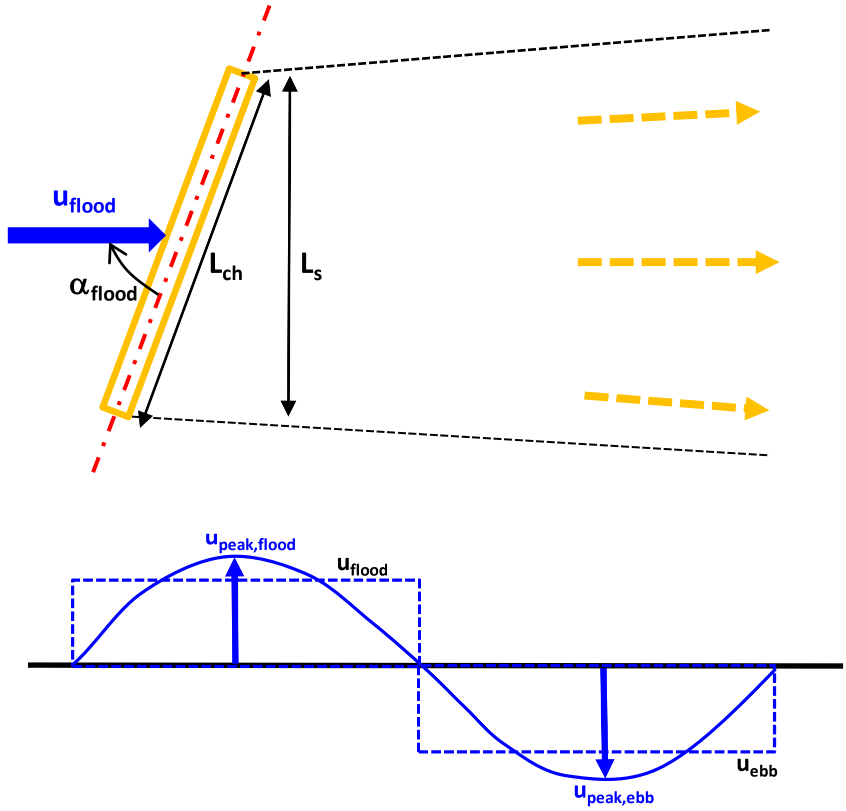


Figure 5.14 *Schematization of dispersion process in channel section with length L_{ch}*

The basic data: Q_s=50 kg/s, L_{ch}=3000 m= length of channel with hard bottom requiring CSD, α_{flood}= 45°, L_s≅2100 m, N_{tides}=100 (total dredging period=100 days; duration tidal cycle=24 hours; flood=12 hours; ebb=12 hours; diurnal tide), h_{flood}=12 m, u_{flood}=0.5 m/s give the following source concentration at some distance (about 100 m) from the cutter:

$c_{o,flood}$=50x100/(3000x0.7x12x0.5)≅0.4 kg/m^3.

The dredging progress per tide r_p= 3000/100=30 m/tide.

The input data of the SEDPLUME-model (SVM-approach) for the flood phase (duration of 12 hours) of the tidal cycle are given in **Table 5.10**.

The dispersion is computed for 5 sediment fractions with total initial concentration of 0.4 kg/m^3=400 mg/l and the following subdivision:

- 5% fraction 125-250 μm: 20 mg/l;
- 10% fraction 63-125 μm: 40 mg/l;
- 30% fraction 32-63 μm: 120 mg/l;
- 40% fraction 16-32 μm: 160 mg/l;
- 15% fraction < 16 μm: 60 mg/l.

The results of the SEDPLUME-model (SVM-approach) as function of distance for the flood phase of the tidal cycle with duration of 12 hours (diurnal tide) are given in **Figures 5.15, 5.16**.
The travel distance of a fluid particle with velocity of 0.5 m/s over the flood phase of 12 hours (diurnal tide) is 0.5 x12 x3600 ≅ 20 km.

The most important results for a production rate of fines of 50 kg/s are:

- plume width increases from 2.1 km to 7.5 km at 20 km from the cutter dredging site;
- maximum plume area over 20 km is about 100 km^2;
- deposited sediment layer is about 0.05 m close to the cutter dredging site and decreases exponentially to less than 1 mm at a distance of 7 km;
- total deposition volume in the plume area is about 200,000 m^3 (based on dry density of 800 kg/m^3); the area-mean deposition layer=200,000/100 10^6=0.002 m=2 mm;
- the long term total concentration of fines <62 μm outside a circle with radius of 5 km from the source location is maximum 20 mg/l (hardly visible cloud of fines); concentration < 3 mg/l at 10 km.

Similar results are obtained for ebb flow conditions.

3 MUD FRACTIONS+ 1 sand fraction		
Initial concentration co (fraction 1; 125-250 um)	20	(mg/l)
Initial concentration co (fraction 2; 63-125 um)	40	(mg/l)
Initial concentration co (fraction 3; 32-63 um)	120	(mg/l)
Initial concentration co (fraction 4; 16-32 um)	160	(mg/l)
Initial concentration co (fraction 5 <16 um)	60	(mg/l)
Settling velocity fraction 125-250 um	0.022	(m/s)
Settling velocity fraction 63-125 um	0.0065	(m/s)
Settling velocity fraction 32-64 um	0.0018	(m/s)
Settling velocity fraction 16-32 um	0.00045	(m/s)
Settling velocity fraction <16 um	0.00025	(m/s)
Gamma-coefficient of approach B	0.3	(-)
Water depth h	10	(m)
Flow velocity U	0.5	(m/s)
Bed roughness (ks)	0.1	(m)
Wave height	0	(m)
Width of line source bo	2100	(m)
Beta-coefficient lateral mixing (default=0.5; none=0)	0.8	(-)
Grid size	100	(m)
time factor = duration of dump/interval time	1	(-)
Time step for deposition	43200	(s)
Dry bulk density of deposited material	800	(kg/m³)
Computed values		
Cezy	**55.41756448**	**(m0.5/s)**
u*=bed-shear velocity	**0.028240144**	**(m/s)**
A-factor fraction 125-150 um	**0.059784517**	**(-)**
A-factor fraction 63-125 um	**0.010083724**	**(-)**
A-factor fraction 32-64 um	**0.002155932**	**(-)**
A-factor fraction 16-32 um	**0.000493278**	**(-)**
A-factor fraction < 16 um	**0.000270282**	**(-)**

Equilibrium conc. Fr 1	1	(mg/l)
Equilibrium conc. Fr 2	1	(mg/l)
Equilibrium conc. Fr 3	1	(mg/l)
Equilibrium conc. Fr 4	1	(mg/l)
Equilibrium conc. Fr 5	1	(mg/l)

Table 5.10 *Input data of SEDPLUME-model (SVM-approach)*

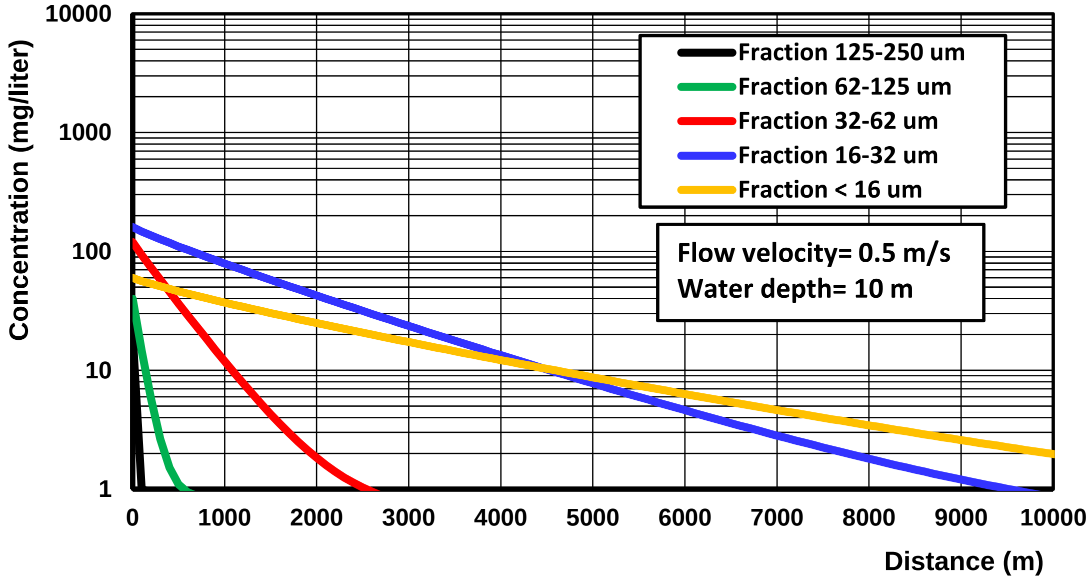


Figure 5.15 *Sediment concentrations as function of distance (m); tidal duration flood=12 hours; SEDPLUME-model (SVM-approach)*

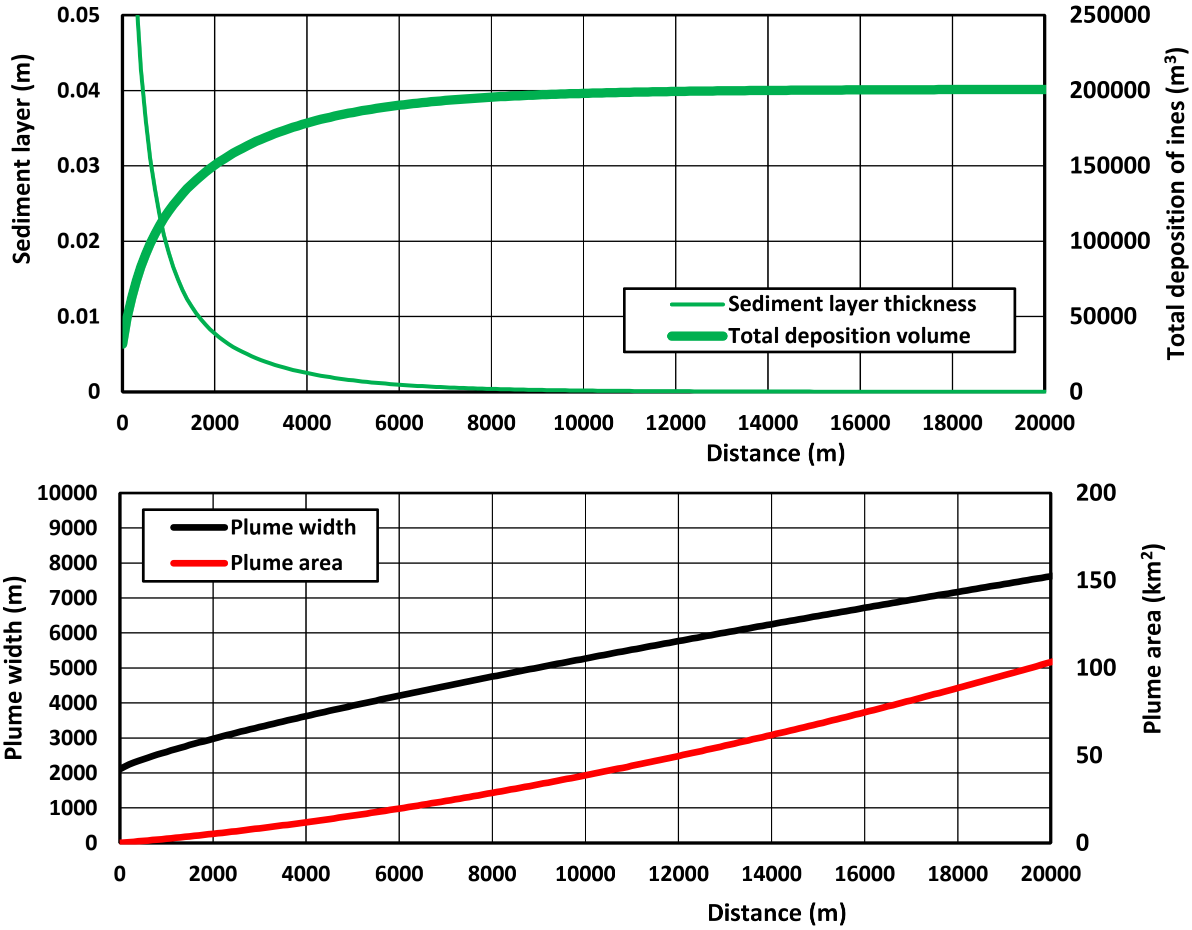


Figure 5.16 *Sediment layer thickness, deposition volume, plume width and plume area as function of distance (m); tidal duration flood=12 hours; SEDPLUME-model (SVM-approach)*

Validation case Jebel al Dhanna, Abu Dhabi

Measured suspended sediment concentrations of fines in the lee zone of a hopper dredger are shown in **Figure 5.17**. The computed results of the SEDPLUME-model based on the SVM approach are also shown.

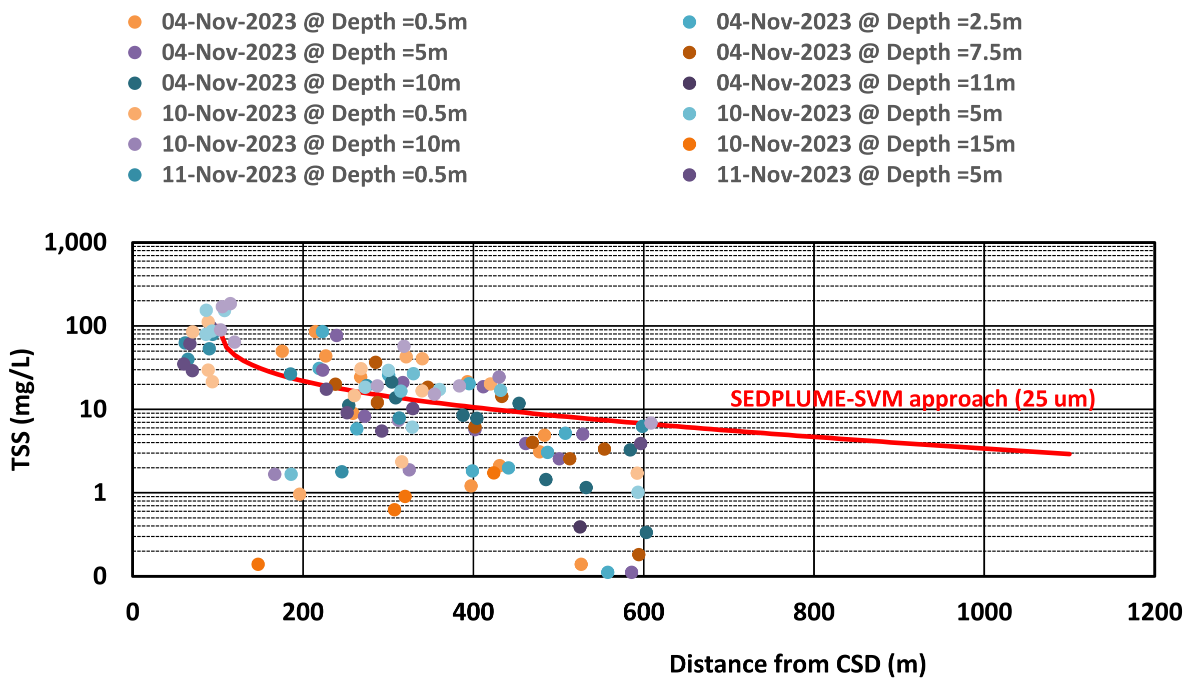


Figure 5.17 *Measured data in plume of dredger; simulation SEDPLUME (SVM) h=10 m; u=0.5 m/s; β=0.6, b_o=10 m c_o=100 mg/l, γ=0.3, ks=0.1 m, ws=0.5 mm/s (25 μm)*

5.3 Dispersion by three-dimensional models

Li and Ma (2001) show that the disposal of sediment in the water column can be very well simulated by using a 3D-numerical model based on the governing equations for the conservation of mass and momentum of the fluid and sediment phases. The turbulence was modeled by using the buoyancy-extended k-ε equations. The momentum equations of the particle phase were simplified by assuming that the drift velocity between the fluid phase and the sediment phase was constant and equal to the fall velocity. The erosion flux at the bed boundary was assumed to be zero. The model results were compared to experimental results obtained in a flume concerning the deposition of sediments (0.13 mm) discharged continuously at the surface of the flowing water. At the start of the calculations, a sand plume begins to form which gradually grows and reaches the bottom of the flume in less than 20 seconds for all of the runs. Two different deposition patterns developed. One is an oblong (elliptical) elongated shape and the other is a horseshoe shape, depending on the ratio of the initial negative buoyancy flux and the horizontal momentum flux of the sediments. The formation of these two deposition patterns is due to the intensity of the vortex rings in the plume. An intensive vortex can lead to the bifurcation of the sediment plume, dividing it into two separate horns and resulting in the horseshoe-shaped deposition pattern. Computed and measured deposition patterns on the bottom of the flume show reasonably good agreeement. The computed deposition pattern thickness at the longitudinal centerline section is roughly in agreement with that measured.

Sediment plume modelling for disposal of sand in the semi-enclosed Saldanha Bay (South Africa) using the DELFT3D model was performed by **Luger et al. (1998)**. Simulations were carried out for an extreme sediment leakage rate of 70 kg/s at the dredging site yielding sediment concentrations below 25 mg/l at the ecologically sensitive sites within the Bay. The maximum deposition thickness in the nearby lagoon was less than 2 mm over the dredging duration of 4 months which was acceptable.

A similar study using the DELFT3D-model was done by **Luger et al. (2002)** for the dredging and disposal of 2.4 million m^3 of muddy sediment from the Port of Richards Bay in South Africa.

Other examples of numerical studies related to the fate of dredged and dumped sediments are presented by **Teeter et al. (1999), Moritz et al. (1999) and Smith et al. (1999)**.

Using a 3D-model, the mud input in a certain cell at a fixed location need to be specified as mud discharge in kg/s, see **Figure 5.18**.

The mass balance equation of the cell is described by:

$$\partial(c\ V)/\partial t = \sum Q_{s,in} - \sum Q_{s,out}$$
$$\Delta c = (1/V)(\sum Q_{s,in} - \sum Q_{s,out})\ \Delta T$$

The mud input from external source: Q_s= input value
The advective transport terms are: $Q_{s,x}= A_x\ u\ c$; $Q_{s,y}= A_y\ v\ c$; $Q_{s,z}= A_z\ w\text{-}w_s\ c$
The diffusive transport terms are: $Q_{s,x}= A_x\ K_x\ \partial c/\partial x$; $Q_{s,y}= A_y\ K_y\ \partial c/\partial y$; $Q_{s,z}= A_z\ K_z\ \partial c/\partial z$

with: c= mud concentration (kg/m^3), V= volume of cell (m^3), Q_s= mud transport (kg/s); K= diffusivity coefficient (m^2/s), u,v,w= velocity components, w_s= settling velocity (m/s), A= area of cell planes (m^2).
Assuming that the mud concentration in the cell is much higher than that in the adjacent cells; all diffusive/dispersive transport components are outgoing.

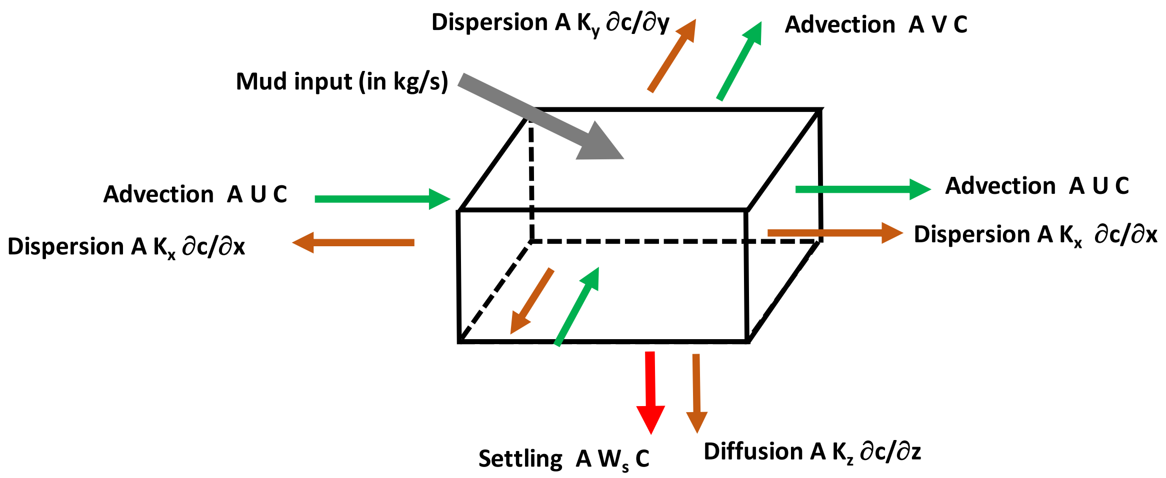


Figure 5.18 *Sediment transport terms in a cell of a 3D-model*

Example DELFT3D-model results
Figures 5.19, 5.20 and **5.21** show the results of mud cloud dilution computed by the DELFT3D-model with 8 layers in vertical direction. The local bed is assumed to non-erodible.
The mud source is the exit (red dots; Figures 5.19 and 5.20) of a pump-pipeline connected to hopper dredger vessel.
The mud input is the upper cell of the local water column (depth of about 1.5 to 2 m) at a location at about 2.2 km from the south corner point and about 0.4 km from the coastline (Figure 5.19).
The input cell dimensions are: 25x25 m^2 and cell thickness ≅ 0.2 m.
The tidal range is about 2 m.
The peak flood velocity is about 0.3 m/s (flood velocity from SW to NE).
The peak ebb velocity is about 0.1 m/s (ebb velocity from NE to SW).

Two mud fractions of 10 μm and 50 μm are considered: the settling velocities are $w_{s,10\,um}$= 0.06-0.075 mm/s and $w_{s,50\,um}$=1.8-1.9 mm/s.
The horizontal diffusivity is K_x=K_y= 10 m^2/s.
The vertical diffusivity is computed by the model from the hydrodynamics ($K_z \cong 0.01$ m^2/s).

The mud input of the fractions 10 μm and 50 μm are constant through the neap-spring tidal cycle during 1 month, as follows:
- fraction 10 μm; pump discharge= 2 m^3/s; concentration 15 kg/m^3; mud input= 2x15= 30 kg/s;
- fraction 50 μm; pump discharge= 2 m^3/s; concentration 115 kg/m^3; mud input= 2x115= 230 kg/s.

The transport terms of the fraction of 10 μm in the source cell can be estimated, as follows:
- cell areas: A_x=A_y= 25x0.2= 5 m^2; A_z= 25x25= 625 m^2;
- longitudinal velocity u=0.3 m/s; lateral velocity v≅0 m/s; vertical velocity w≅0 m/s;
- settling velocity of fraction 10 μm: w_s= 0.075 10^{-3} m/s;
- diffusivity: K_x=K_y= 10 m^2/s; Kz=0.1 m^2/s;
- upstream mud concentration ≅ 0 kg/m^3;
- mud concentration in mud source cell ≅ 5 kg/m^3 (Figure 5.11);
- horizontal concentration gradient $\Delta c/\Delta x \cong 1/25 \cong 0.04$ kg/m^4;
- vertical concentration gradient $\Delta c/\Delta z \cong 0.1/0.2 \cong 0.5$ kg/m^4;
- mud input from external source: $Q_{s,10\,um}$= 30 kg/s.

The longitudinal advective transport terms are:	$Q_{s,x,in} \cong 0$; $Q_{s,x,out}$= 5x0.3x5 ≅ 7.5 kg/s;
The lateral and vertical advective transport terms are:	$Q_{s,y} \cong 0$ kg/s; $Q_{s,z} \cong 0$ kg/s;
The vertical settling transport is:	$Q_{s,z,out}$= 625x 0.000075x1 ≅ 0.05 kg/s;
The horizontal diffusive/dispersive transport terms are:	$Q_{s,x,out} = Q_{s,y,out} \cong$ 2x(5x10x1/25) ≅ 4 kg/s;
The vertical diffusive transport terms are:	$Q_{s,z,out} \cong$ 625x0.01x0.1/0.2 ≅ 3 kg/s.

Based on this, the horizontal advective and the dispersive terms are dominant for very fine sediments; the vertical settling transport is relatively small. If the net transport is > 0, the cell will gradually be loaded over time until equilibrium is reached.

Figure 5.19 shows the mud concentration of 10 and 50 μm in the surface cell (with pump exit) at the source location and in the bottom cell at the source location through the tidal cycle.
The results are:
- fraction 10 μm: concentration in surface cell is in range 2000 mg/l to 6000 mg/l ($c_{mean} \cong$ 4000 mg/l);
- fraction 10 μm: concentration in bottom cell is in range 100 mg/l to 300 mg/l ($c_{mean} \cong$ 200 mg/l);
- fraction 50 μm: concentration in surface cell is in range 10000 mg/l to 30000 mg/l ($c_{mean} \cong$ 20000 mg/l);
- fraction 50 μm: concentration in bottom cell is in range 700 mg/l to 2500 mg/l ($c_{mean} \cong$ 1500 mg/l).

The concentration is maximum during the tidal slack periods when the flow velocities are almost zero (turning of horizontal tide) and minimum during the periods with significant flow velocities in the range of 0.3 to 0.4 m/s (maximum advection and dilution).
The concentrations in the surface cell with the pump exit are much larger (factor 10) than those in the bottom cell, which is caused by the relatively small settling velocities of the fine sediments. Furthermore, the vertical mixing is relatively small because the flow velocities are small (0.3 to 0.4 m/s). The additional mixing due to the pump jet is neglected. In practice, the difference between the surface and bottom concentrations in shallow depth of about 2 m will be much smaller.

Figure 5.20 shows the mud cloud movement of the fraction 10 μm along the coast from south-west to north-west during flood flow and back during ebb flow. The most important findings are:
- maximum mud concentration is < 100 mg/l at 750 m from mud source cell at surface;
- maximum mud concentration is < 30 mg/l at 1500 m from the mud source cell at the surface, which is the natural background mud concentration.

Figure 5.21 shows the mud cloud movement of fraction 50 μm along the coast from south-west to north-west during flood flow and back during ebb flow. The mud cloud is more circular and confined to the source location (pump exit)

The most important findings are:

- maximum mud concentration is < 100 mg/l at 500 m from mud source cell at the surface;
- maximum mud concentration is < 30 mg/l at 700 m from the mud source cell at the surface, which is the natural background mud concentration.

The simplified SEDPLUME-model (SVM-approach) has also been used to estimate the dilution factors of the fractions 10 μm and 50 μm for two values of the lateral mixing coefficient β=0.5 and β=0.7; see **Tables 5.11** and **5.12**. The input concentration is set equal to the tide-and depth-averaged concentration of the 3D-model, see **Tables 5.11, 5.12**.

The flow velocity is set equal to the mean velocity of about 0.3 m/s during the flood tide.

Very good agreement is obtained for the fraction 10 μm and β=0.7. A smaller β-coefficient of 0.5 yields larger concentrations compared to those of the 3D-model.

The agreement for the fraction 50 μm is less good. The SEDPLUME-model gives a concentration <1 mg/l at 500 and 750 m from the source location. The DELFT3D-model predicts much higher values of 100 and 30 mg/l. It is noted that a particle at the water surface with settling velocity w_s=1.8 m/s settles in 1.7x1000/1.8=1000 s to the bed. Given a flow velocity of 0.3 m/s, the path distance is 1000x0.3=300 m. Thus, this particle of 50 μm settles within 300 m from the source location to the bed.

Summarizing, it is included that the dilution factor of the very fine fraction of about 10 μm is in the range of

- 1/10 to 1/20 over a distance of about 500 m; 1/20 to 1/30 over a distance of about 1000 m;
- th 3D-model results show that the lateral mixing of very fines is relatively strong at short distances from the mud source location, which is in line with the findings of Kilpatrick and Wilson (1989) who state that the β-coefficient may close to 1 at short distance from the source location (data of Mississippi River, USA).

Distance from mud source location (m)	**SEDPLUME (SVM-approach) β= 0.5** c_o= 2000 mg/l; b_o=10 m h=1.7 m; u_{mean}=0.3 m/s w_s=0.075 mm/s (≅10 μm)	**SEDPLUME(SVM-approach) β= 0.7** c_o= 2000 mg/l; b_o=10 m h=1.7 m; u_{mean}=0.3 m/s w_s= 0.075 mm/s (≅10 μm)	**DELFT3D-model** c_o= 2000 mg/l (depth and tide-averaged)
750	c= 210 mg/l (dilution 1/10)	c= 60 mg/l (dilution 1/35)	c= 100 mg/l (dilution 1/20)
1500	c= 100 mg/l (dilution 1/20)	c= 25 mg/l (dilution 1/40)	c= 40 mg/l (dilution 1/50)

Table 5.11 *Dilution factors fraction 10 μm (parallel to main flow) of SEDPLUME and DELFT3D-model*

Distance from mud source location (m)	**SEDPLUME (SVM-approach) β= 0.5** c_o=10000 mg/l; b_o=10 m h=1.7 m; u_{mean}=0.3 m/s w_s=1.8 mm/s (≅50 μm)	**SEDPLUME (SVM-approach) β= 0.7** c_o=10000 mg/l; b_o=10 m h=1.7 m; u_{mean}=0.3 m/s w_s=1.8 mm/s (≅50 μm)	**DELFT3D-model** c_o= 10000 mg/l (depth and tide-averaged)
500	c<1 mg/l	c<1 mg/l	c= 100 mg/l (dilution 1/100)
700	c<1 mg/l	c<1 mg/l	c= 30 mg/l (dilution 1/300)

Table 5.12 *Dilution factors fraction 50 μm (parallel to main flow) of SEDPLUME and DELFT3D-model*

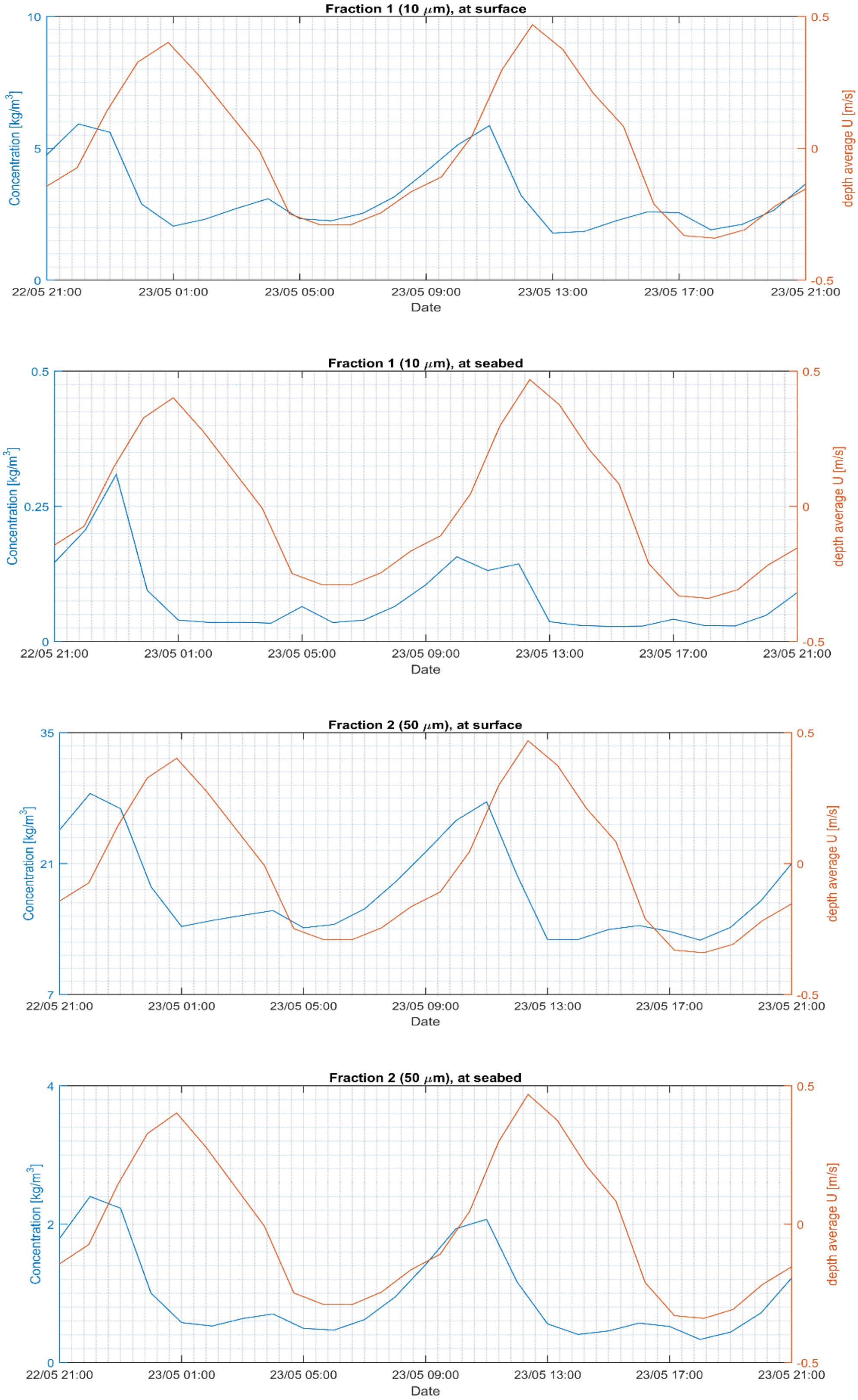


Figure 5.19 *Mud concentrations at source location; Peak flood velocity= 0.45 m/s; Peak ebb velocity= -0.3 m/s; Local water depth =1.7 m; Tidal range = 2 m*

Upper= fraction 10 μm in surface cell with pump exit;
Middle upper= fraction 10 μm in bottom cell beneath pump exit;
Middle lower= fraction 50 μm in surface cell with pump exit;
Lower= fraction 50 μm in bottom cell beneath pump exit.

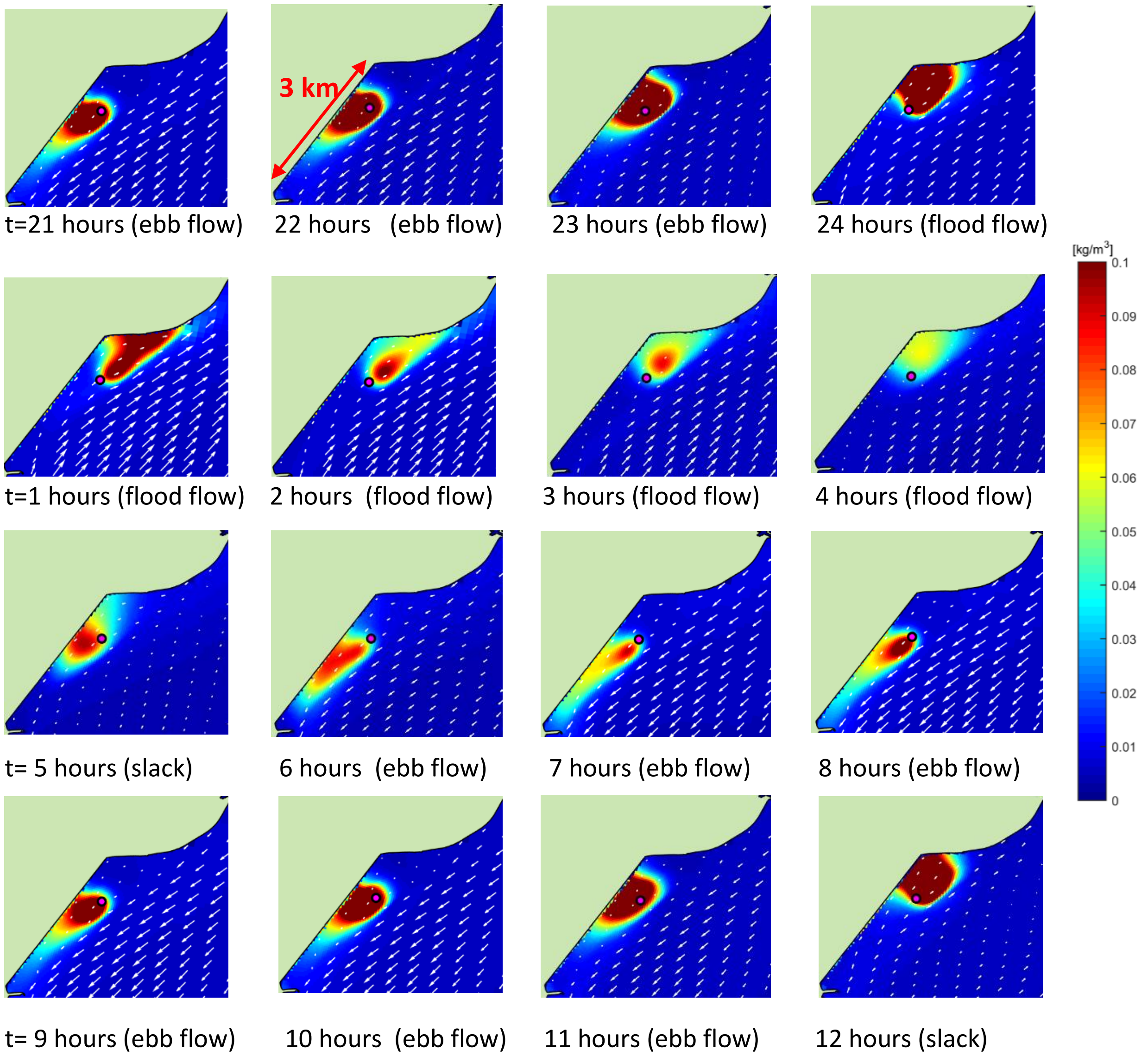


Figure 5.20 *Mud cloud of fraction 10 µm in bottom cell (mud source= red dot);*
Peak flood and ebb velocity= 0.3, 0.1 m/s; local water depth =1.7 m; tidal range = 2 m

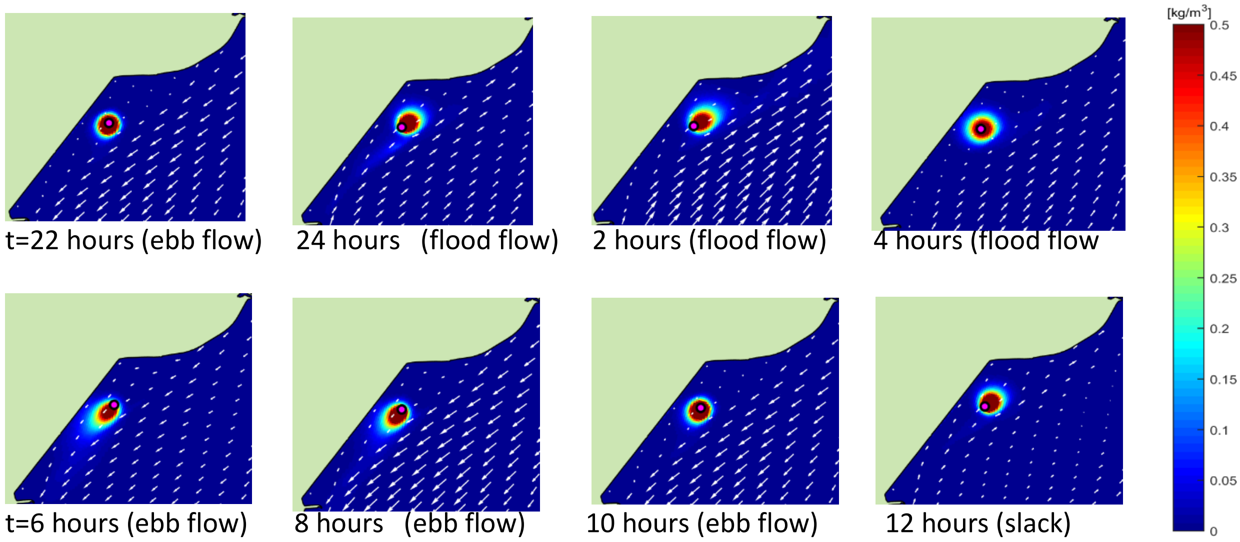


Figure 5.21 *Mud cloud of fraction 50 µm in bottom cell (mud source= red dot);*
Peak flood and ebb velocity= 0.3; 0.1 m/s; local water depth =1.7 m; tidal range = 2 m

6. References

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Annex I: Jet flow theory

Laboratory studies of jets penetrating into a quiescent fluid of the same density show that the jet envelope has a nearly conical shape (Abramovich, 1963; Rajaratnam, 1976; Pope, 2000). The radius R of the jet is proportional to the distance x downstream from the jet origin. The spreading angle of the jet is about 12° and about constant in longitudinal direction, see **Figures 1** and **2**. Thus: R=(tanα) x = (1/5) x.
The initial jet radius is equal to the nozzle radius (R_o= 0.5 d_o with d_o=nozzle diameter). The jet velocity is about constant over a distance of 2.5 to 6d_o (Rajaratnam, 1976) the distance x is counted not from the orifice but from a distance 2.5$_o$ into the conduit.

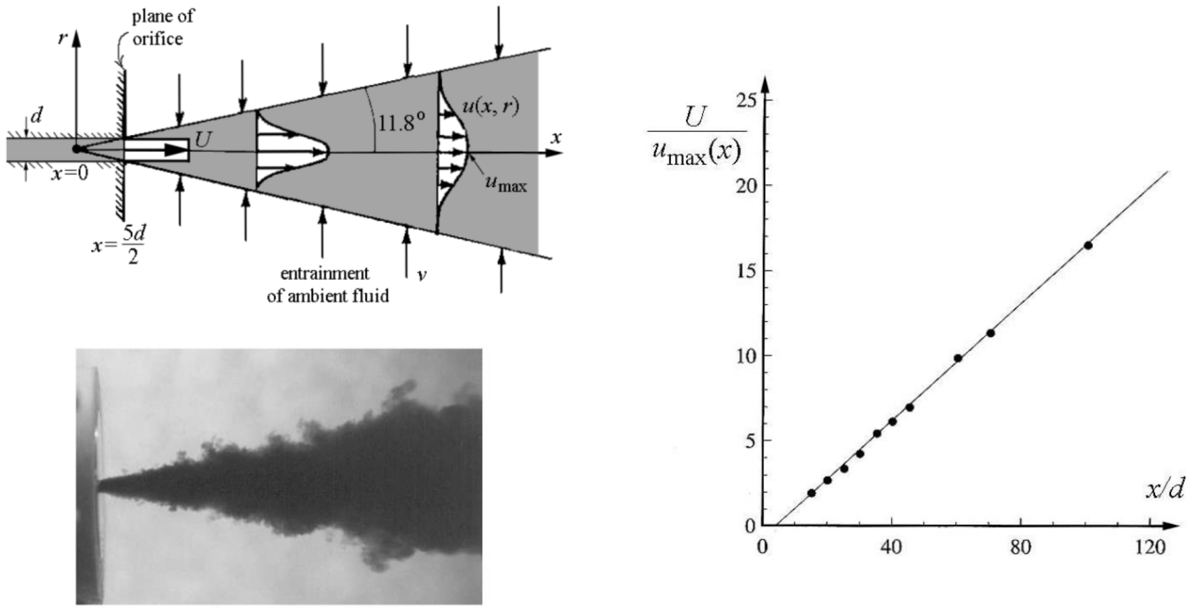

Figure 1 *Schematic jet development and measured jet velocities (U= jet velocity at x=0)*

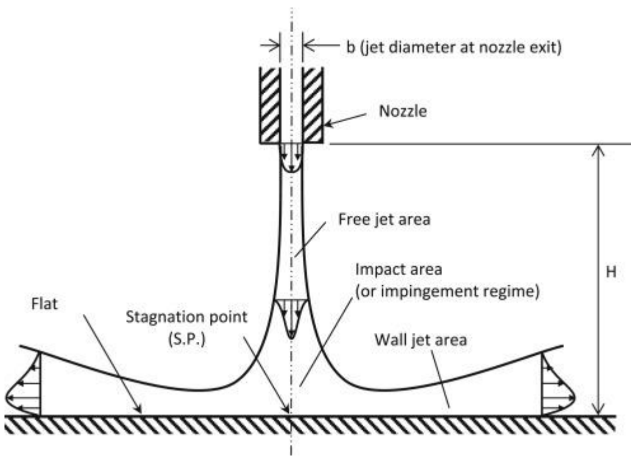

Figure 2 *Schematic impinging wall jet flow*

Observations shows that the velocity in the jet obeys a law of similarity: all cross-sections are identical and the velocity profile across the jet exhibits a nearly Gaussian shape (bell curve). This can be described by:

$$u_{x,r}=u_{max} \exp[-r^2/(2\sigma^2)] \qquad (1)$$

with: x=downstream distance (m), r=cross-jet radial distance from centerline (m), u_{max}= maximum velocity in the centerline, σ=standard deviation related to spread of the velocity distribution.

The diameter encompassing 95% of the area under the exponential curve is equal to 4σ resulting in: $d_x=2R_x=4\sigma$.

Thus: $\sigma=0.5R$ and $R=0.2$ x, it follows that: $\sigma=0.1$ x which leads to:

$$u_{x,r}=u_{max} \exp[-50r^2/x^2] \qquad (2)$$

When a jet enters a fluid at rest, the momentum is that of the jet itself, and the momentum flux in the jet's cross-section remains constant downstream. Since this flux is the momentum per unit volume ($M= \rho u$, with ρ=fluid density and u= velocity), times the velocity u itself cumulated over the jet's cross-section, this can be expressed as:

$$M={}_o\int^\infty \rho u^2 \,(2\pi r)\, dr = \rho\, (u_o)^2\, (0.25\, \pi d_o^2) \qquad (3)$$

Combining Equations (2) and (3) leads to: $u_{max}/u_o=5d_o/x$ for $x > 5\, d_o$ (4)

Measured data show: $u_{max}/u_o \cong 6d_o/x$ (Pope, 2000), which is in reasonable agreement with Equation (4).

The mean velocity over the jet follows from: $u_{mean}=1/(\pi R^2)\, {}_o\int^\infty \rho u\, (2\pi r)\, dr = 0.5\, u_{max}$.

The volumetric flux Q is not constant along the jet because of entrainment of quiescent surrounding fluid. It can be calculated, as follows:

$$Q= {}_o\int^\infty \rho u\, (2\pi r)\, dr = (\pi/50)\, u_{max}\, x = 0.1\, \pi\, d_o\, u_o\, x=0.1\, d_o\, [Q_o/(0.25\, \pi\, d_o)]\, x= 0.4\, Q_o\, (x/d_o) \qquad (5)$$

Thus: the volumetric discharge increases linearly with distance, as follows: $Q=4Q_o$ at $x/d_o=10$ and $Q=40Q_o$ at $x/d_o=100$.

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Annex II: SEDPLUME model

1. Dynamic behaviour of mud dump cloud from hopper vessel

The mud cloud is assumed to consist of (see **Figure 1**):

- cylinder-type of mud cloud core with cloud velocity (w_c) and cloud density (ρ_c); core cloud is gradually diluted due to entrainment of water into the cloud;
- diluted boundary layer mud cloud produced by vortices of the boundary layer; spill concentrations are generated by vortices from this boundary layer cloud into the water column.

Momentum balance cloud: $M_c\, dw/dt = \sum F$

$\rho_c V_c\, dw_c/dt = F_g - F_b - F_d - F_f$

$\rho_c V_c\, dw_c/dt = \rho_c g V_c - \rho_w g V_c - 0.5\ \alpha_1 \rho_w c_D D^2 w_c^2 - 0.125\, \alpha_3 \rho_w D^2 f_w w_c^2$

$dw_c/dt = g(\rho_c - \rho_w)/\rho_c - 0.5\,(\alpha_1/\alpha_2)(\rho_w/\rho_c)(c_D/D)\, w_c^2 - 0.125\,(\alpha_3/\alpha_2)(\rho_w/\rho_c)(f_w/D)\, w_c^2$

Assuming $dw_c/dt = 0$ and no skin friction, the terminal fall velcoity of a sphere is:

$0.5\ (\alpha_1/\alpha_2)(\rho_w/\rho_c)(c_D/D)\, w_c^2 = g(\rho_c - \rho_w)/\rho_c$

Using: $\alpha_1 = 0.25\pi$; $\alpha_2 = \pi/6$ for a sphere, it follows that:

$w_c^2 = c_D^{-1}\,(4/3)\,[(\rho_c - \rho_w)/\rho_w]\, g D$ (Stokes equation)

Mass balance cloud: $dM_c/dt = M_{f,in} - M_{s,out}$

$d(\rho_c V_c)/dt = v_e A_s \rho_w - v_e A_s \rho_c$
$d(\rho_c V_c)/dt = v_e A_s (\rho_w - \rho_c)$
$d(\rho_c \alpha_2 D^3)/dt = v_e (\alpha_5 \alpha_3) D^2 (\rho_w - \rho_c)$
$d(\rho_c)/dt = (\alpha_5 \alpha_3/\alpha_2)(v_e/D)(\rho_w - \rho_c)$

with:
$M = \rho_c V_c$ = mass of cloud with sediment;
ρ_c =wet bulk density of cloud (kg/m^3); ρ_w= fluid density (kg/m^3); g= gravity acceleration (m/s^2);
$V_c = \alpha_2 D^3$=volume of core cloud (m^3); $\alpha_2 = \pi/6 = 0.52$ for sphere; $\alpha_2 = 1$ for cube;
$A_c = \alpha_1 D^2$=area of cross-section of cloud normal to velocity (m^2); $\alpha_1 = 0.25\pi = 0.79$ for sphere; $\alpha_1 = 1$ for cube;
$A_s = \alpha_3 D^2$= area of surface of of cloud (m^2); $\alpha_3 = \pi = 3.14$ for sphere; $\alpha_3 = 6$ for cube;
D= representative size (effective diameter) of core cloud (m);
w_c= vertical cloud velocity;
$F_g = \rho_c g V_c$ = gravity force;
$F_b = \rho_w g V_c$ =buoyancy force;
$F_d = 0.5\, \rho_w c_D A_c w_c^2 = 0.5\ \alpha_1 \rho_w c_D D^2 w_c^2$ = drag force;
$F_f = \alpha_5 A_s \tau_f = \alpha_3 D^2\, 0.125\, \rho_w f_w w_c^2$ = skin friction force;
c_D= drag coefficient (0.5 to 2); f_w= skin friction factor (0.005 to 0.12);
τ_f= shear stress;
$M_{f,in}$ = mass of water entering cloud due to dilution processes; $M_{s,out}$= mass of sediment leaving cloud;
v_e= entrainment velocity=$\alpha_4 w_c$; α_4= entrainment coefficient (0.01 to 0.05);
α_5= reduction coefficient (most entrainment at front and lower part of cloud; range 0.5 to 0.7).

Model calibration

Based on field data of Rochester site, USA (Bokuniewicz et al. (1978), see **Table 1**.
Dump from hopper vessel in water depth ≅15 m
Model parameters: drag coefficient c_D=2; entrainment coefficient=0.05

Parameter	Measured value	Model value
Mud cloud density in hopper (kg/m^3) Mud cloud concentration (kg/m^3)	1200 320	1200 (input) 320 (input)
Initial cloud velocity (m/s)	2	2 (input)
Mean cloud velocity near bottom (m/s)	0.7	0.88
Mean cloud concentration near bottom (kg/m^3)	not measured	87

Falling body in fluid mud		
Diameter d	2	(m)
Surface density of medium	1000	(kg/m3)
Maximum density of medium	1000	(kg/m3)
Density fall body	1200	(kg/m3)
Mixture viscosity at surface of medium	0.000001	(m2/s)
Surface viscosity of medium	0.000002	(m2/s)
Layer thickness	14	(m)
Alpha1 shape effect cross-area (0.75 to 1)	0.75	(-)
Alpha2 shape effect volume (sphere=0.52; cube=1, rectangle >1)	0.52	(-)
Alpha3 shape effect surface area friction (sphere=3, cube=6; cilinder 3-10)	3	(-)
Alpha4 mixing entrainment parameter (0.01 to 0.05)	0.05	(-)
Alpha5 reduction coefficient surface area entrainment	0.7	(-)
Friction factor	0.03	(-)
Drag coefficient for Reynoldsnumber > 10000	2	(-)
Time step dt	0.1	(s)
Initial velocity	2	m/s

Table 1 *Model calibration parameters for Rochester site, USA (Bokuniewicz et al., 1978)*

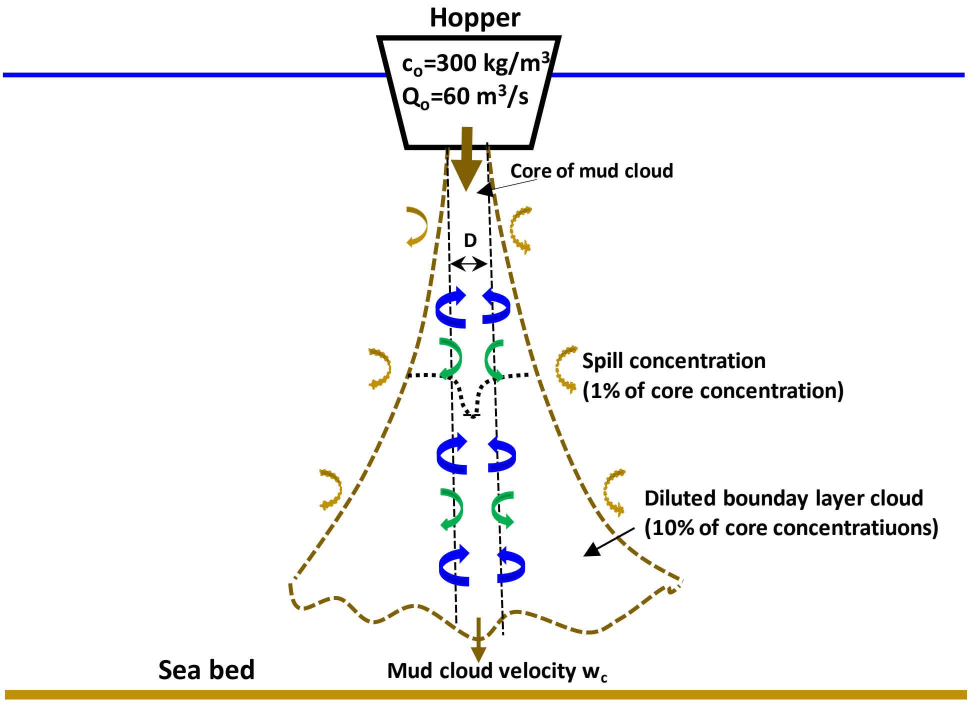

Figure 1 *Falling mud cloud schematization*

2 Passive plume behaviour

Settling model (S-approach)

A simple approach for the far-field development of mud cloud/plume concentrations can be obtained by considering the settling of mud in overload conditions with no flow velocity ($u \cong 0$), as follows:

$$h\, dc/dt + c\, \alpha w_s = 0$$

This Equation can be applied along a uniform flow field with velocity (u) by using a Langrangian approach with x=ut, yielding:

$$dc/dx + c\, \alpha w_s/(uh) = 0 \qquad (1)$$

with:
c= mud concentration; αw_s= effective settling velocity; h= water depth (constant);
u= flow velocity (constant); b_o= width of mud source;
α= calibration coefficient;
c_o= initial source concentration at t=0 (or x=0 at some distance from source);

Integration for a line mud source in unidirectional flow yields:

$$c_x = c_o \exp\{-\alpha(w_s/(uh))x\} \qquad (2)$$

Basically, Equation (2) is only valid for very fine mud (uniform concentrations over water depth) in very weak flows (<0.5 m/s) where upward mixing processes are of minor importance.

Based on available knowledge, the lateral spreading due to mixing processes in channel flow can be described by:

$$b_x=b_o+2x^{\beta} \qquad (3)$$

with: b_o=width of mud source, b_x= width at location x, x= longitudinal coordinate, β= 0.5 to 1 (default=0.5).

In the case of a line source in a wide uniform flow field, lateral mixing can be included, as follows:

$$c_x = f_{time}\, f_{lateral}\, c_o \exp(-A\, x) \qquad (4)$$

with:
c_o = initial concentration at t=0 (or x=0);
x = longitudinal coordinate along plume;
$A=\alpha w_s/(uh)$=adjustment coefficient;
$f_{lateral}=1/\{1+(2/b_o)x^{\beta}\}$= lateral mixing effect factor;
f_{time}= time factor= dump time/interval time; dump time= duration of dumping process; interval time= time between two successive dumps;
b_o= width of mud source ($\cong$10 m);
β = coefficient related to lateral mixing (range=0.5-0.7; lateral mixing is small for β=0 and b_o= very large).
w_s= settling velocity;
b_o= width of mud source.
α= reduction coefficient representing turbulence effects (α=1 for u<0.1 m/s; α= 0.1 for u>1 m/s).

This latter equation (4) is implemented in the SEDPLUME-model (S-approach) for simulation of mud turbidity plumes.
The $f_{lateral}$ term represents the lateral dilution effect; the last term represents the vertical settling effect.

The reduction effect due to the lateral mixing process (β-coefficient) is dominant; the reduction effect due to the exponential term is of less importance for fine sediments.

The daily deposition rate of mud (in m/day) follows from: $\Delta z_{b,x}= [\alpha\ w_s\ c_x/\rho_{dry,mud}]\ \Delta t$

with: $\rho_{dry,mud}$ = dry bulk density of mud deposit; Δt= time step (=86400 s for 1 day).

The deposition rate can also be computed as: $\Delta z_b= [(Q_{s,x}-Q_{s,x-\Delta x})\ \Delta t]/[0.5(b_x +b_{x-\Delta x})\ \Delta x\ \rho_{dry,mud}]$
with: $Q_{s,x}= b_x\ c_x\ u\ h$= mud transport at distance x, $b_x=b_o+2x^{\beta}$= width of plume at distance x.

Both equations yield almost the same results for small values of Δx (< 1 m).

The total deposited mud volume in the plume area is: $V_{deposition}= [Q_{s,L}-Q_{s,o}]\ \Delta t/\rho_{dry,mud}$

Settling and Vertical Mixing model (SVM-approach)

The settling of fine sediment particles from a continuous line source of mud in a turbulent flow with vertical mixing processes can be simulated by the SEDTUBE1D-model (Van Rijn 2005, 2017; www.leovanrijn-sediment.com), which describes the behaviour of suspended concentrations in a steady turbulent flow in a channel of constant width. The width of the sediment source is equal to the channel width.
The adjustment of the depth-averaged sediment concentration in a channel of constant width can be approximated by:

$$dc_x/dx= -A_{SVM}(c_x-c_{x,eq}) \qquad (5)$$

with:
c_x= depth-averaged sediment concentration (uniform over depth);
c_{eq}= depth-averaged equilibrium sediment concentration (input value ≥ 0);
Q= fluid discharge in channel (constant width);
Q_s= c Q = sediment transport in channel (in kg/s);
A_{SVM}= adjustment coefficient (in m^{-1}).

The adjustment factor (A_{SVM}) has been determined from computed results for a wide range of conditions based on a detailed 2DV-suspended transport model (Van Rijn 1987, 2005, 2017), yielding:

$$A_{SVM}= \gamma(1/h)(w_s/u_*)(1+2w_s/u_*)(1+H_s/h)^2 \qquad (6)$$

with:
γ=coefficient (standard value=0.3; range 0.1-0.5; higher value gives shorter settling distance, quicker adjustment);
h= flow depth;
w_s= fall velocity of suspended sediment (input value);
u_*= bed-shear velocity due to currents and waves (=$u_{mean}\ g^{0.5}/C$);
C= 5.75 $g^{0.5}$ log(12h/k_s)= Chézy coefficient;
k_s= effective bed roughness height of Nikuradse;
u_{mean}= depth-averaged flow velocity;
H_s= significant wave height.

The adjustment of the mud concentration proceeds relatively rapid in the presence of waves (see effect of H_s/h parameter). Higher A_{SVM}-values (higher fall velocity, smaller bed-shear velocity, higher relative wave height) lead to a more rapid adjustment to equilibrium conditions.

Equations (5) and (6) are used in the SEDTUBE1D-model, which can be applied to both mud and sand, because both equations are universal and includes the effect of vertical mixing processes due to turbulent processes (represented by u_*).

The analytical solution of Equation (5) is:

$$c = f_{time}\, f_{lateral}\, [c_{eq} + (c_o - c_{eq}) \exp(-A_{SVM}\, x)] \qquad (7)$$

with:
c_o= source concentration due to dredging/dumping process at x=0 (range of 100 to 1000 mg/l at about 100 m from the dredger);
c_{eq}= equilibrium (background; tide-averaged value in tidal flow; range of 10 to 100 mg/l) concentration at prevailing flow conditions.

It is noted that the sediment disposal processes close to the dredger (<100 m) with high initial concentrations (>>1 kg/m^3) and group-settling velocities (>> 10 mm/s) cannot be represented by Equation (7).

The deposition rate can also be computed as: $\Delta z_b= [(Q_{s,x}-Q_{s,x-\Delta x})\, \Delta t]/[0.5(b_x + b_{x-\Delta x})\, \Delta x\, \rho_{dry,mud}]$
with: $Q_{s,x}= b_x\, c_x\, u\, h$= mud transport at distance x, $b_x=b_o+2x^{\beta}$= width of plume at distance x.

The total deposited mud volume in the plume area is: $V_{deposition}= [Q_{s,L}-Q_{s,o}]\, \Delta t/\rho_{dry,mud}$

Summary

Both methods can be represented by:

$$c = f_{time}\, f_{lateral}\, [c_{eq} + (c_o - c_{eq}) \exp(-A\, x)] \qquad (8)$$

with:
$A=A_s=\alpha w_s/(u_{mean} h)$ for the S-approach;
$A= A_{svm}=\gamma(1/h)(w_s/u_*)(1+2w_s/u_*)(1+H_s/h)^2$ for the SVM-method;
c_o= concentration at x=0;
c_{eq}= equilibrium concentration at x=end ($\geq$0).
$f_{lateral}=1/\{1+(2/b_o)x^{\beta}\}$= lateral mixing effect factor;
f_{time}= time factor= dump time/interval time; dump time= duration of dumping process; interval time= time between two successive dumps;
b_o= width of mud source ($\cong$10 m);
β = coefficient related to lateral mixing (range=0.5-0.7; lateral mixing is small for β=0 and b_o= very large).
w_s= settling velocity;
b_o= width of mud source;
α= calibration coefficient (>1);
γ=calibration coefficient (standard value=0.3; range 0.1-0.5; higher value gives shorter settling distance, quicker adjustment);
h= flow depth;
u_*= bed-shear velocity due to currents and waves (=$u_{mean}\, g^{0.5}/C$);
C= 5.75 $g^{0.5}\log(12h/k_s)$= Chézy coefficient;
k_s= effective bed roughness height of Nikuradse;
u_{mean}= depth-averaged flow velocity;
H_s= significant wave height.