GROUPE D'ETUDES ET D'OBSERVATION
SUR LES DRAGAGES ET L'ENVIRONNEMENT

WATER INJECTION DREDGING GUIDANCE DOCUMENT

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Contents

1 - INTRODUCTION

1.1 - Context

Siltation of ports is an issue of the greatest importance on account of the ensuing socio-economic and environmental impacts. A certain depth of water has to be maintained to operate ports efficiently and ensure safety for the ships and their crews, while respecting environmental sensitivities as far as possible.

Every year, roughly 35 to 40 million m^3 of sediments are dredged in France in maintenance operations, and 90% of this volume is dredged in the major ports on river estuaries. Dredging is also very often the principal item of expenditure in a port, whatever its size. Considering the economic and ecological stakes, choosing the optimum dredging technique is essential. It is of paramount importance to strike the right balance between cost, efficiency and environmental impact.

Water injection dredging is of increasing interest for many ports: not only the major seaports but also ports of more modest dimensions. The costs are generally lower compared to other techniques, and its efficiency appears to be greater under the conditions where its use is recommended.

Many full-scale operations or experiments have been conducted in the last 20 years, in various countries more recently including France, with a view to analysing this technique in greater depth and evaluating its impacts. Water injection dredging, in particular, has thus been the subject of many studies and experiments, on account of its limited impacts by comparison with the other hydrodynamic techniques.

1.2 - Purpose of the guidance document

This guide, produced by the group GEODE (*Groupe d'Etude et d'Observation sur les Dragages et l'Environnement*), sets out to collect and compile the bibliography and to analyse all the experiments carried out on water injection dredging to date, albeit in an uncoordinated manner, in France and throughout the world. Recognising that each dredging project needs to be studied individually on account of the specific site characteristics, the guide aims to provide decision-aid and analysis tools to be used during the preparation of any project, as well as the ranges of tools necessary for studying and monitoring a water injection dredging project.

The contents of this document are based on the results of experiments analysed by Artelia in collaboration with Dr Kate Spencer of Queen Mary, University of London.

This guide is not aimed at imposing strict analysis criteria, but elements of methods and analysis, with illustrations to provide a more immediate understanding of the mechanisms involved. It is intended for all the players involved in implementing water injection dredging operations, but also those contributing to research on the associated environmental impacts: project owners, project engineers, state regulatory authorities, the technical departments of local authorities, consulting engineers, associations, etc.

The document breaks down into six chapters, as follows:

- a general overview of hydrodynamic dredging,
- technical aspects and conditions of application of water injection dredging,
- potential impacts of water injection dredging,
- preliminary evaluation and post-project monitoring methods for such operations,
- recommendations regarding project monitoring based on analysis of case studies,
- focus on regulatory/legal aspects.

2 - GENERAL OVERVIEW OF HYDRODYNAMIC DREDGING

Water injection dredging belongs to the family of hydrodynamic dredging procedures. This family includes all those dredging techniques where the basic principle is to remobilise the sediments, especially using the action of natural currents, i.e.:

- agitation dredging,
- air injection dredging,
- plough dredging,
- auger dredging,
- water injection dredging, the subject of the present guide.

Clear distinctions have to be made between the various techniques since their applications, conditions of use and environmental impacts may be quite fundamentally different. A study by the CETMEF (2009) presents these various techniques and their uses in France.

2.1 - Agitation dredging (so-called 'American' dredging)

The objective of this process is to put the targeted sediments back into suspension. Agitation may be effected by:

- stirring the sediments in the water column with a powerful jet of water and/or by dragging an instrument along the sea or river bed,
- lifting by a pumping system. This technique may be used, for example, in the following cases:
  - a stationary suction dredger that lifts up and discharges the sediments within the water stream,
  - a trailing suction hopper dredger that maintains a constant overflow (US Army Corps of Engineers, 1983) or discharges the dredged materials on one side (side casting).

The latter technique was used for example by the Port of Nantes-Saint-Nazaire Authority until the early 2000s (the technique was abandoned completely in 2006). The yield here depends directly on the dredger's pumping rate (which may reach 10 000 m³ of sediment per hour for the biggest units) and not only on the hopper volume, by contrast with the traditional use of trailing suction hopper dredgers (TSHD).

Figure 2-1: The agitation dredger *Neptune* (*source: terra et aqua*), and the dredger *Side Cast Merrit* (US Army Corps of Engineers)

The sediment plume generated is taken up by the currents and reinserted into the local sediment transport. This method can therefore only be used in zones that are characterised by a strong local current or during spring tide periods.

The choice of jet power is a compromise between cost, efficiency and environmental impact. It must be sufficient in regard to the type of sediment to be agitated and the desired resuspension rate.

Agitation dredging is recognised as being extremely efficient and relatively inexpensive. The dredgers used are generally smaller than those used for hydraulic or mechanical dredging, easy to handle, and capable of dredging in zones that are otherwise difficult to reach, such as close to quays.

2.2 - Air injection dredging

This type of dredging uses an air injection system to re-suspend deposited sediments. The compressed air is propelled into the sediments, reducing the cohesion of the sediment particles and dispersing it throughout the water column.

This technique is little used, however, since it is less efficient than water injection dredging.

Figure 2-2: The dredger *Airset* (Dutch Dredging)

2.3 - Plough dredging

The passage of a plough or leveller enables limited quantities of sediments to be shifted from one site to another. The area where the materials are deposited may either be ‘conservative’, meaning that the materials are retained in the zone for subsequent extraction using one of the conventional techniques, or ‘dispersive’, meaning that final disposal of materials is dependent upon erosion and the natural sedimentary processes of the site.

Figure 2-3: The plough dredger *Alligator* (DEME) and detailed view of a leveller (source Anthony Bates Partnership)

The plough accumulates sediment as it is drawn along the sea bottom. It then leaves the pile of sediment in the target zone, and repeats the run as often as necessary. It may also be equipped with a water jet or an air injection system to facilitate its passage.

The simplicity of operation means that the technique is often used for small-scale regular maintenance projects, thus avoiding having to install heavier and costlier plant.

Plough dredgers come in different sizes. The width of the plough may vary between 3 and 35 m, and the surface area between 1.5 and 50 m^2.

2.4 - Auger dredging

This dredging technique consists of mounting a rotary milling cutter on a beam at the front of the dredger. The rotating cutters put the sediment back into suspension, and it is then dispersed by the local currents.

Figure 2-4: Rotary milling cutter dredger *Le Rochevilaine* used in the Vilaine estuary (*source: CETMEF*)

This technique is used in particular in the estuary of the river Vilaine and in Charente-Maritime in France, in the relatively shallow channels of oyster farms.

2.5 - Water injection dredging

The water injection dredging technique is also based on the principle of remobilisation. A low-pressure water jet is directed into the sediment layer to create a density current. The sediments are then picked up by this current and taken to a ‘lower’ point situated downstream of the current.

Figure 2-5: Dredger HAM 307

The power of the jets has to be adapted to the distance to be covered by the density current, to the hydraulic characteristics of the site and to the nature of the in-situ sediment.

The water flow rate of an injection dredger generally varies between 1000 and 12 000 m^3 per hour depending on the dredgers. Use of the technique is now developing in France, particularly in the Loire estuary where the port of Nantes-Saint-Nazaire (GPMNSN) commissioned a dredger of this type in June 2011.

This technique is described in detail in the following chapter.

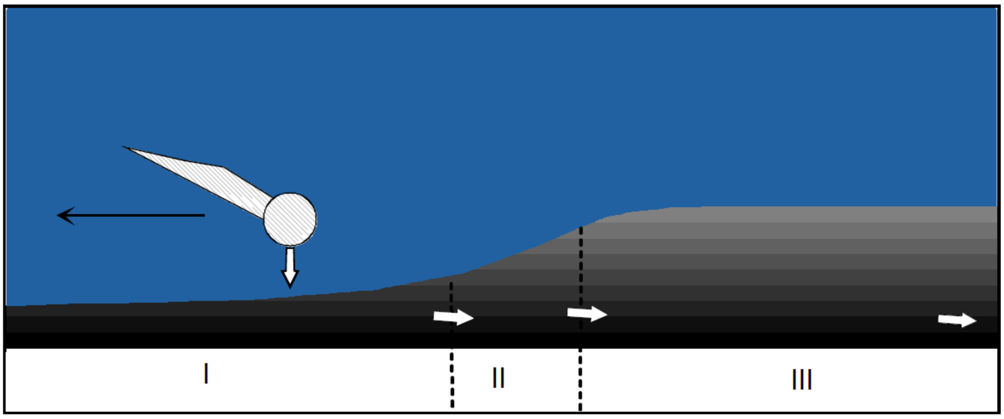
3 - TECHNIQUES AND USES OF WATER INJECTION DREDGING

This chapter presents the principal techniques of water injection dredging and the associated physical processes, as well as the conditions for its use.

3.1 - Physical processes

The action of a water injection dredger in a layer of sediment breaks down into three phases (see diagram below):

1. Low-pressure water injection,
2. Generation of the density current,
3. Displacement of the sediments.



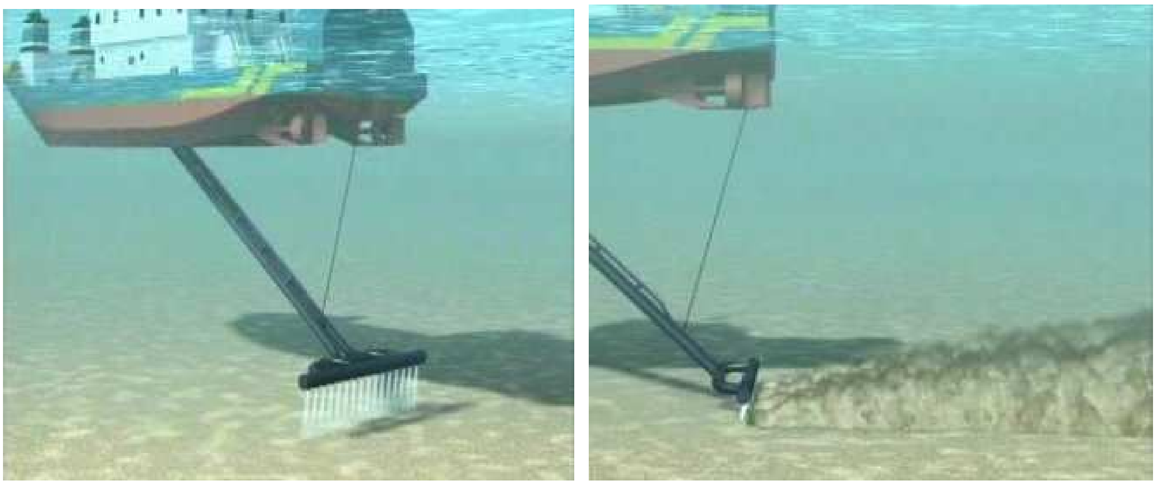


Figure 3-1: Principle of water injection dredging (MEYER 2000) and graphic representation of the density current (DELFT-VAN OORD)

Low-pressure water injection implies the introduction of large quantities of water. The water is pumped from the surface close to the dredger, and is then injected locally at low pressure (roughly 1.5 bars according to ESTOURGIE, 1989) into the sediment layer through a series of nozzles distributed along a horizontal beam (PIANC, 2012 – in press[1]). These water jets break down the cohesion between the sediment particles and create a turbulent mixture of water and sediment. This water-sediment mix has a higher density than the surrounding water and therefore has characteristics similar to those of a liquid with very low viscosity (Van Raalte & Bray, 1999). The water-sediment mix is transported horizontally along the sediment-water interface as a density current, under the influence of gravity and the currents related to the tide, waves or river discharges (Ospar Commission, 2004).

The sediments are thus remobilised: a density current is formed and moves close to the bed, and there is limited exchange with the water column. In this respect, the principle is totally different from that of agitation dredging, which involves resuspending the materials throughout the water column.

The density current is governed by an equilibrium between the injection force, the action of the local currents, gravity and the friction forces.

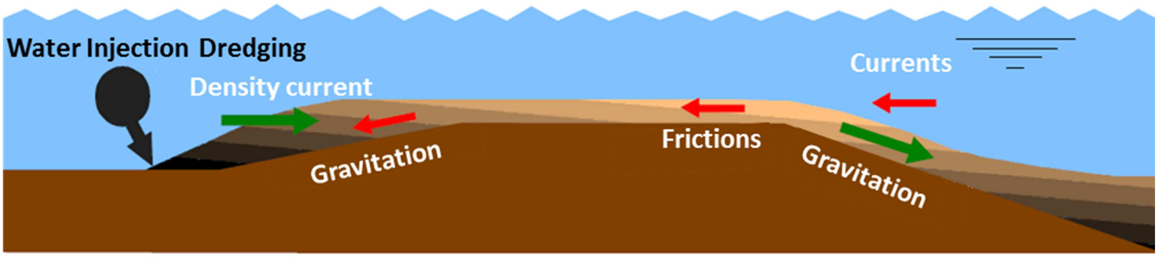


Figure 3-2: Forces liable to be exerted on the density current (after MEYER, 2000)

The final transport distance depends on several factors, including the density and composition of the sediments, and the slope and morphology of the bottom (Van Rallte & Bray, 1999). By contrast with other hydrodynamic techniques (such as agitation dredging), the vertical movement of the sediments during water injection dredging is limited and the sediments are not put into suspension, adopting instead the form of a density current just above the bottom (PIANC report in press).

There is no typical dredging zone configuration where water injection dredging may be automatically adopted. Each site needs to be analysed case by case, taking into account its specific characteristics.

3.1.1 - Density current characteristics

The density current moves across the sea bed over a thickness of between 1 and 3 m depending on the case, and does not affect the overall hydrodynamics of the site (experimentation at Port Edgar, Scotland, MACKIE ET AL. 1994). The speed of the density current varies according to the morphology of the zone and the velocity of the natural currents; it is generally between 0.3 and 2 m/s, (SOARES 2006, BORST 1994, MEYER 2000, GINGER 2011).

The density current is established temporarily, and solely for the duration of dredger operation. It may be propagated over a total distance ranging from a few hundred metres to several kilometres, depending on the nature of the sediments, the site morphology and local hydrodynamics (see table 3.1):

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[1] Published in 2013

Table 3-1: Examples of sediment transport distances

Site	Nature of sediments	Detection of remobilised matter	Source
Elbe estuary (Köhlfleet, Hamburg)	Mud	3 km	Meyer (2000)
Gironde estuary	Mud	300 m	Ginger (2011)
Weser estuary	Sand	50 m (levelling-off of dunes)	Stengel (2006)
Medway estuary	Mud or fine sand	200 m	HR Wallingford (2002)
River Don	Mud to coarse sand	6 km (tracer taken up by the sedimentary dynamics)	Harvey et al. (2007)

In most cases the distance over which the density current develops can only be estimated by a spot measurement of the turbidity identifying its presence. Its precise limits cannot therefore be determined; it is only possible to check whether or not it has attained a given sector.

In the case of the Gironde estuary, a different approach was adopted in 2010. The density current was monitored using an Acoustic Doppler Current Profiler (ADCP) installed on board a ship that could also monitor variations in real time. In this way the density current could be monitored until it was no longer detectable, thus giving a more precise indication of its exact limits.

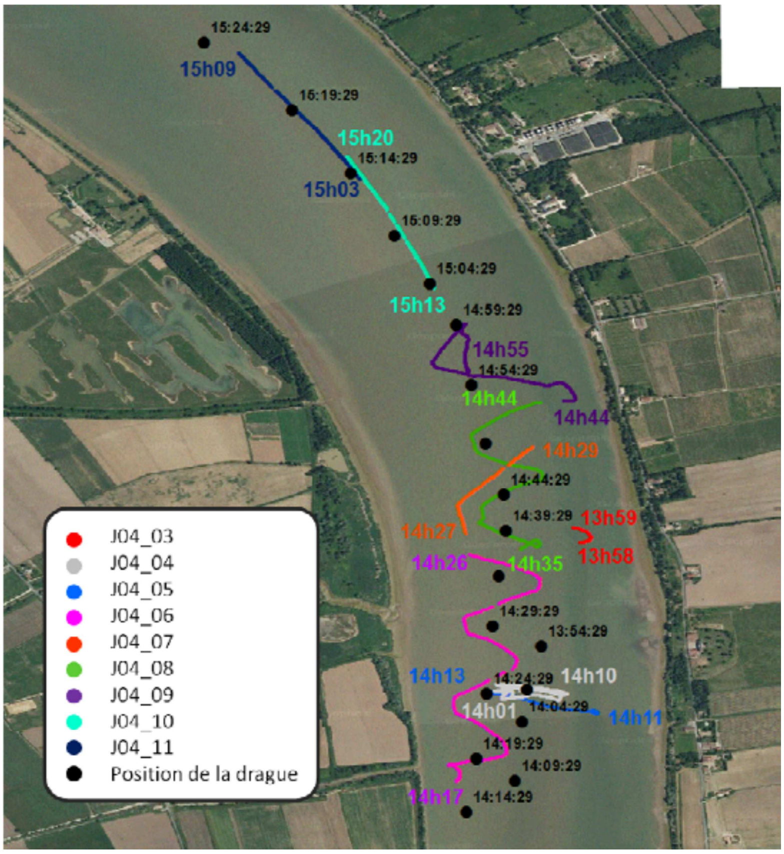


Figure 3-3: Movement of the ship equipped with ADCP in the Gironde estuary (GINGER 2011)

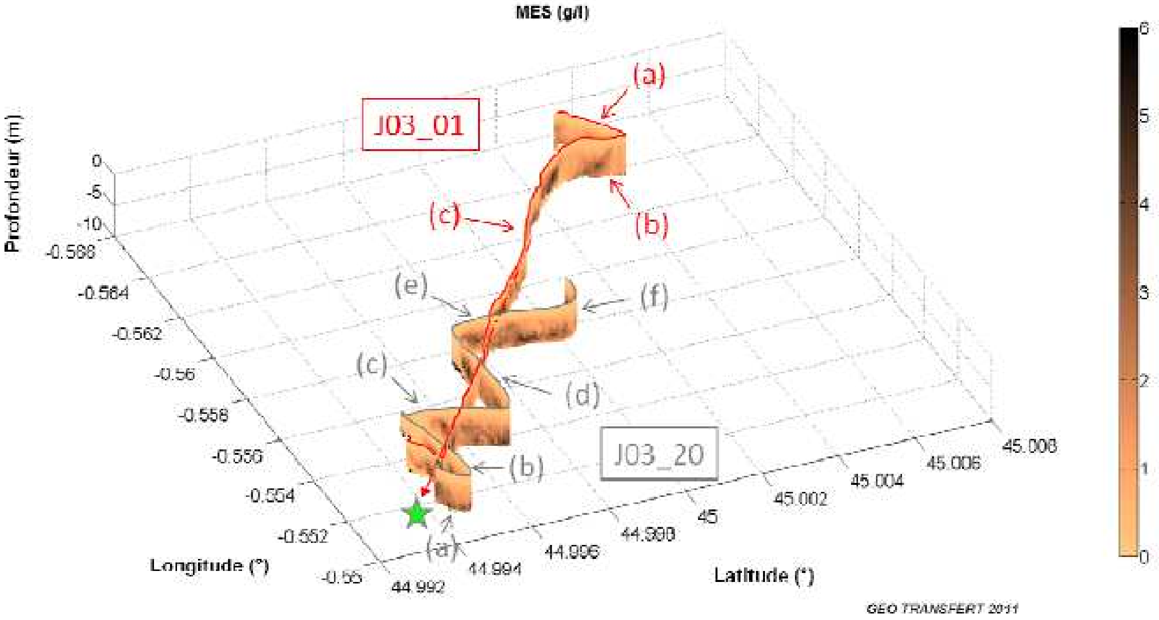


Figure 3-4: Example of pseudo-3D rendering of measurements made in the Gironde estuary (GINGER 2011)

A detailed map of the density current could thus be drawn up on completion of this measurement campaign, as shown in the following figure.

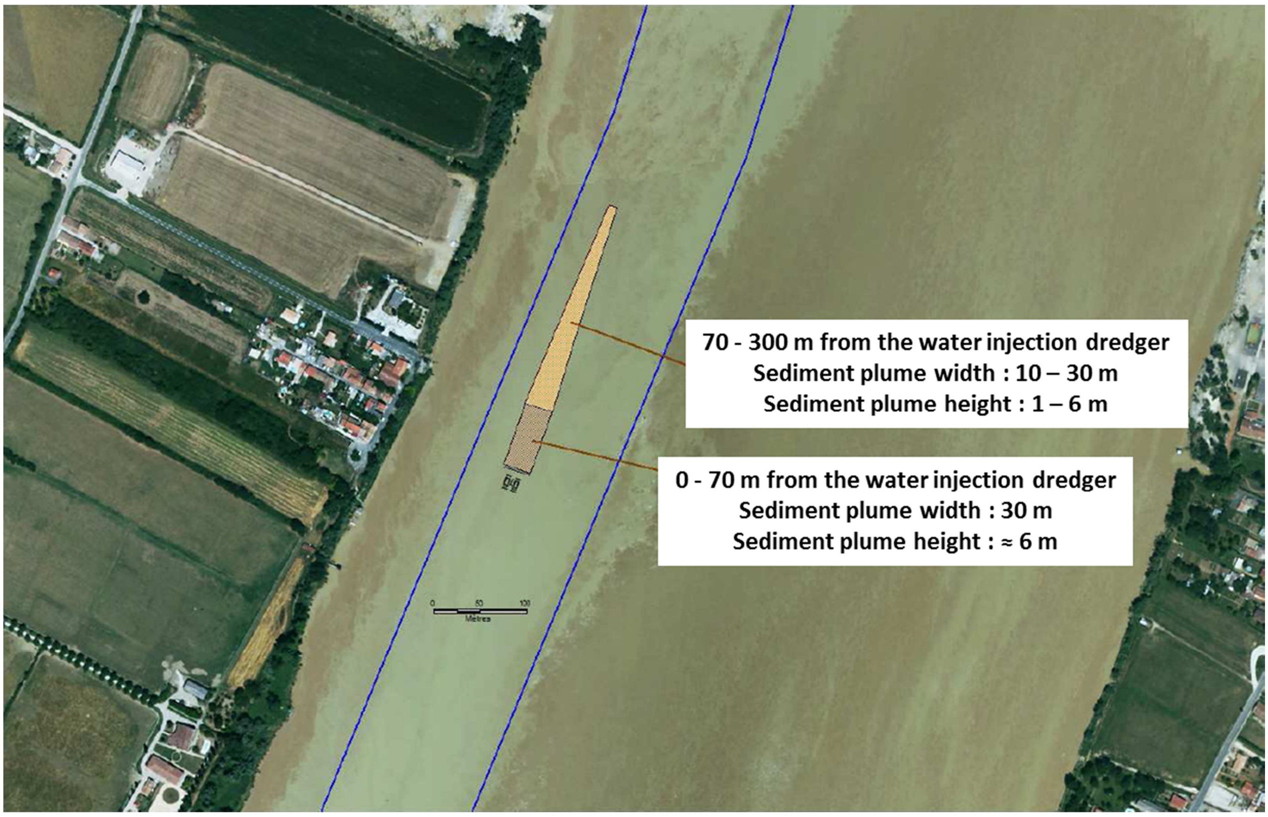


Figure 3-5: Spatial extent of the density current in the Gironde estuary (GINGER 2011)

3.1.2 - Quantification of dredged volumes

The quantification of dredged volumes is more complicated with water injection dredging than with other more ‘conventional’ techniques. This is because the fluidification process transforms the fine sediments into a liquid mud of low density, the limit of which is difficult to detect by a conventional bathymetric survey. This layer then gradually settles after the end of dredging operations, so that the resulting bottom level is variable over time, especially in an estuary environment where the river’s own action continues in the meantime, in the form of sedimentation or erosion.

For these reasons, dredging contractors and owners tend to prefer lump-sum or chartering (per hour or per day) contracts as the basis for payment. In order to check the elevations attained after dredging, the following procedures are recommended:

- fix in advance the density associated with the target ‘bed’, as well as the frequency of sampling by the measurement instruments,
- make additional soundings some time after dredging has been completed in order to take into account the subsequent sedimentation and settlement of the material (1 to 2 weeks depending on the case).

The methods used to quantify the dredged volumes therefore vary considerably from one site to another.

3.2 - History and practice of water injection dredging around the world

3.2.1 - History

The first theories suggesting the possibility of using local hydrodynamic forces for dredging operations date from the 1980s and were put forward in the Netherlands. A series of experiments were undertaken, the results of which were published in 1986, confirming the efficiency of a density current in transporting sediments. In 1987, the first hydrodynamic water injection dredger, the *Jetsed* (Van Oord), was built.

Since then the fleet of such vessels has grown constantly. The plant currently being operated is listed in Appendix 1.

3.2.2 - Recent uses of water injection dredging

3.2.2.1 - Uses in France

The water injection dredging technique has been used in France on an experimental basis since the 1990s, with a substantial increase in recent years. The table on the following page gives a concise summary of the operations completed:

Table 3-2: Use of water injection dredging in France

–: no data available X: monitoring carried out 0: no monitoring carried out

Site	Regime	Date	Duration (days or hours)	Volume (m^3)	Sediment	Contaminant	Monitoring		
							Phy	Chem	Bio
Dunkirk Gravelines	Coastal	1989 1991	–	–	–	–	–	–	–
Rouen	River	2001 to 2011	400 hours per year	50 000 to 150 000 m^3 per year	Mud and sand	–	X	X	0
Boulogne Calais	Coastal	2002	4 days	–	Mud	–	X	0	0
Nantes	Estuary	2006 to 2011	2009: 749h 2010: 650h 2011: 437h	1 - 2 million m^3/year	Mud	Low < N1[1]	X	X	0
Bordeaux	Estuary	2009 2011	2009: 10,5d 2011: 30 days	420 000m^3 in 2009	Mud	Low < N1	X	X	X
Bayonne	Estuary	2010 2011	2010: 5d 2011: 9d	60 000 m^3 in 2010	Mud and sand	Low <N1	X	X	X
Le Havre	Estuary	2002 to 2007	10 days per campaign (2-3 times per year)	20 000 to 30 000 m^3 per campaign	–	–	X	0	0

1 : Source : GEODE - "Arrêté du 9 août 2006 relatif aux niveaux à prendre en compte lors d'une analyse de rejets dans les eaux de surface ou de sédiments marins, estuariens ou extraits de cours d'eau". If the contamination is under N1, the impact is assumed to be negligible

3.2.2.2 - Uses in other countries

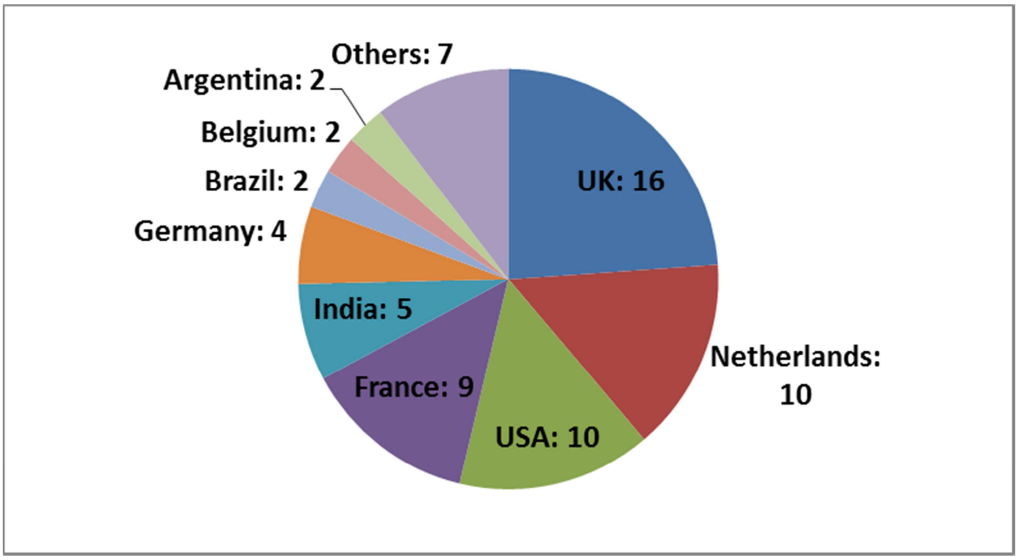
Water injection dredging is now commonly used in many countries, and particularly in Europe.

The UK, Netherlands, Germany and the USA are the four countries where the use of injection dredging is historically the most widespread. The first operations date from the late 1980s or early 1990s. Injection dredging is used particularly in river or estuarine environments.

On most sites, experimental monitoring was put in place before injection dredging was used on a large scale, in order to identify carefully the possible local impacts of using this technique. Depending on the conclusions of these preliminary studies, it was decided whether or not injection dredging could be applied on the site, with a reduced monitoring protocol if the conclusion was positive.

The monitoring put in place was initially aimed at determining the efficiency and economic performance of the technique, particularly with regard to the other types of dredging equipment available. It was not until the mid-1990s and the 2000s that environmental monitoring was put in place, including numerical modelling, with a view to identifying precisely the possible impacts of the dredging.

Today, injection dredging is commonly used for maintenance dredging operations and even occasionally for deepening navigation channels (e.g. Kakinda in India), sometimes in campaigns lasting several years (Mississippi), and throughout the world (see following figure).



Others = China, New Zealand, Bangladesh, Yemen, Ireland, Italy, Tanzania

Figure 3-6: Distribution of water injection dredging projects identified

The following map (completed by data from MEYER 2000, ATHMER 2004, WILSON 2008 and PIANC 2012 - in press) describes the situation of the various operations or experiments with water injection dredging that have been recorded to date (see table in Appendix 2 for more details).

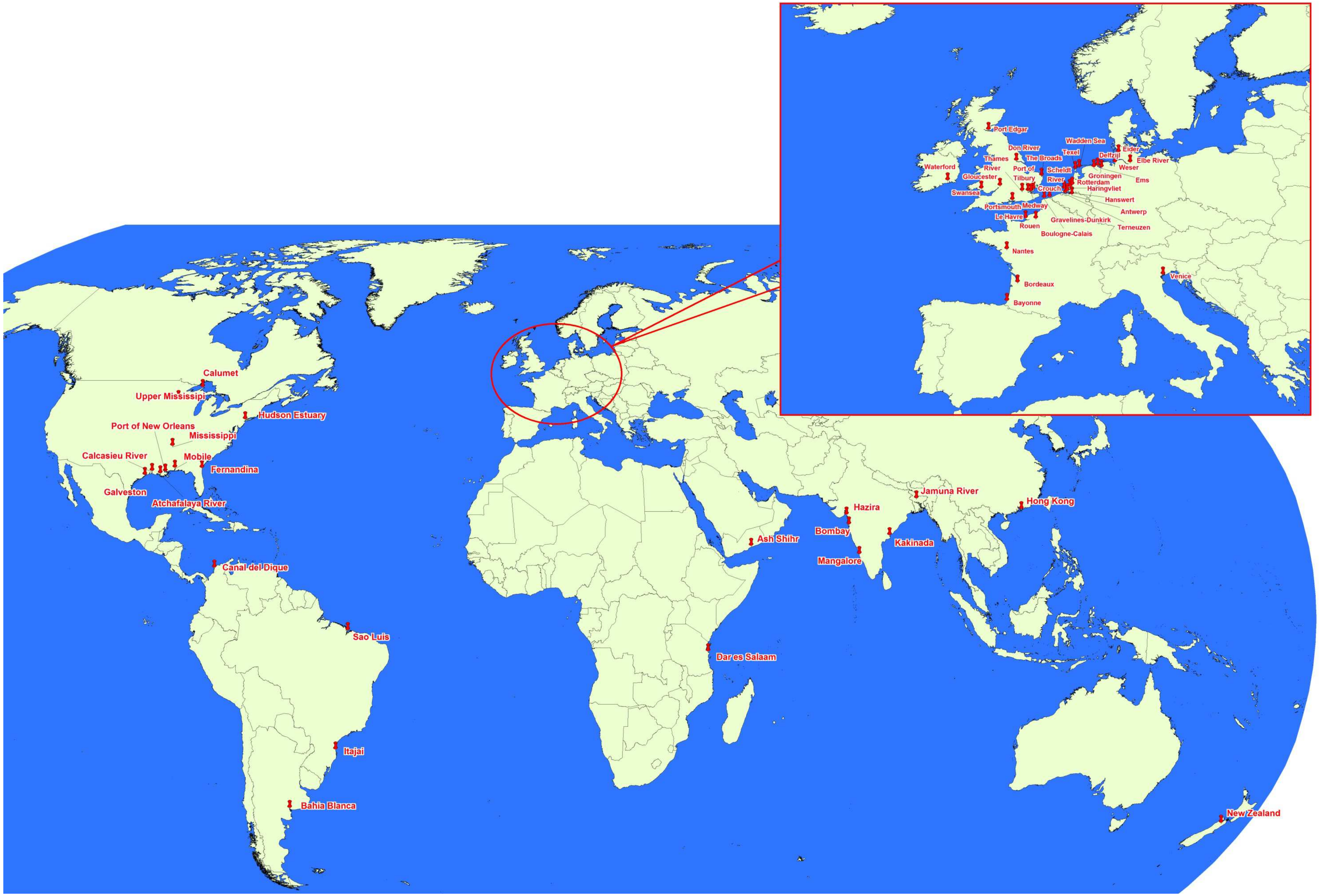


Figure 3-7: Locations of recent water injection dredging projects

3.2.2.3 - Site characteristics

The use of injection dredging on a specific site is principally governed by:

- the nature of sediments,
- the morphology of the site (slope, bathymetry),
- the hydrodynamics (river flows, tides).

Since these factors are independent and vary considerably from site to site, there is no ‘characteristic profile’ of a zone where injection dredging may ideally be carried out. The feasibility of proceeding by injection dredging therefore needs to be evaluated case by case (see following paragraphs).

3.3 - Implementation of water injection dredging

3.3.1 - General applications of water injection dredging

Based on the published results of experimental operations, the general applications of injection dredging may be listed as follows:

- general maintenance of channels (Loire, Gironde, Seine, Thames, Elbe, etc.),
- dredging of harbour berths or turning and anchoring basins (Medway, Loire, Gironde, Bayonne, Rouen, etc.),
- maintenance of a lock/wet dock (Antwerp, London, etc.),
- levelling-off of dunes/ridges/furrows using a trailing suction hopper dredger (Rouen, Weser estuary): short and localised operations on fine to coarse sediments,
- maintenance of local hydraulic conditions (Rouen),
- sediment nourishment schemes in the intertidal zone, mudflat or marsh (Medway): dredging and re-dispersal of very fine sediments towards the foreshore, taking advantage of the flood tide to reinforce the density current,
- used to support other dredging techniques (Boulogne/Calais, Kakinda, Mangalore, etc.): relocation of sediments to be extracted by trailing suction hopper dredgers,
- dredging in areas crossed by underwater cables or pipelines (Rouen, Terneuzen).

These operational cases are described in the following paragraphs.

3.3.2 - Applicability of the technique to a specific site

3.3.2.1 - Type and nature of the dredged sediments

The distance over which the materials are transported depends on the initial thickness of the density current, its propagation speed, and the sedimentation rate of the dredged materials, these parameters themselves being influenced by the depth to which water is injected into the sediment (PIANC 2012 – in press). The applications are therefore different depending on the nature of the sediments in the zone to be dredged and are highly dependent on the local configuration.

3.3.2.1.1 - Muddy to fine sediments

Injection dredging is most widely used on fine silt or mud, material that is easily fluidised and remobilised. However, materials that are too cohesive may reaggregate (flocculation) during the process and thus reduce the efficiency of the technique by increasing the sediment deposition rate.

Determining the shear stress of the materials present in the layer to be dredged is therefore an essential factor in assessing the feasibility of injection dredging in this case, and its potential efficiency.

Water injection dredging is particularly efficient in the case of maintenance operations, since the water jet penetrates more easily into relatively unconsolidated materials (PIANC 2012 - in press).

Propagation of the density current may range from a few hundred metres to several kilometres (PIANC 2012 - in press) under favourable hydrodynamic conditions. The sediments are projected either to a deeper zone where they are deposited permanently, or to a dynamic zone where they are reinserted into the sedimentary cycle.

The general practice is to start the dredging operations from the destination site in order to facilitate circulation of the density current.

3.3.2.1.2 - Medium to coarse sediments

For coarser, non-cohesive sediments, the mean diameter of the materials has a direct impact on their deposition rate once they have been fluidised (PIANC 2012 - in press). For particles more than 0.2 mm in diameter, the site morphology and the hydrodynamic conditions are of particular importance in allowing the use of water injection dredging (Knox et al. 1994). Sediments that are too coarse deposit too rapidly for the current to transport them satisfactorily.

The density current may only exist over short distances (< 50 m). In the case of levelling off dunes, the sediment will deposit on either side of the crests, in the corresponding furrows. The operation may be repeated a few times (but generally no more than two or three times) to complete the transport of the materials to the targeted zone.

3.3.2.2 - Hydromorphological context

Application of injection dredging on a particular site is principally governed by:

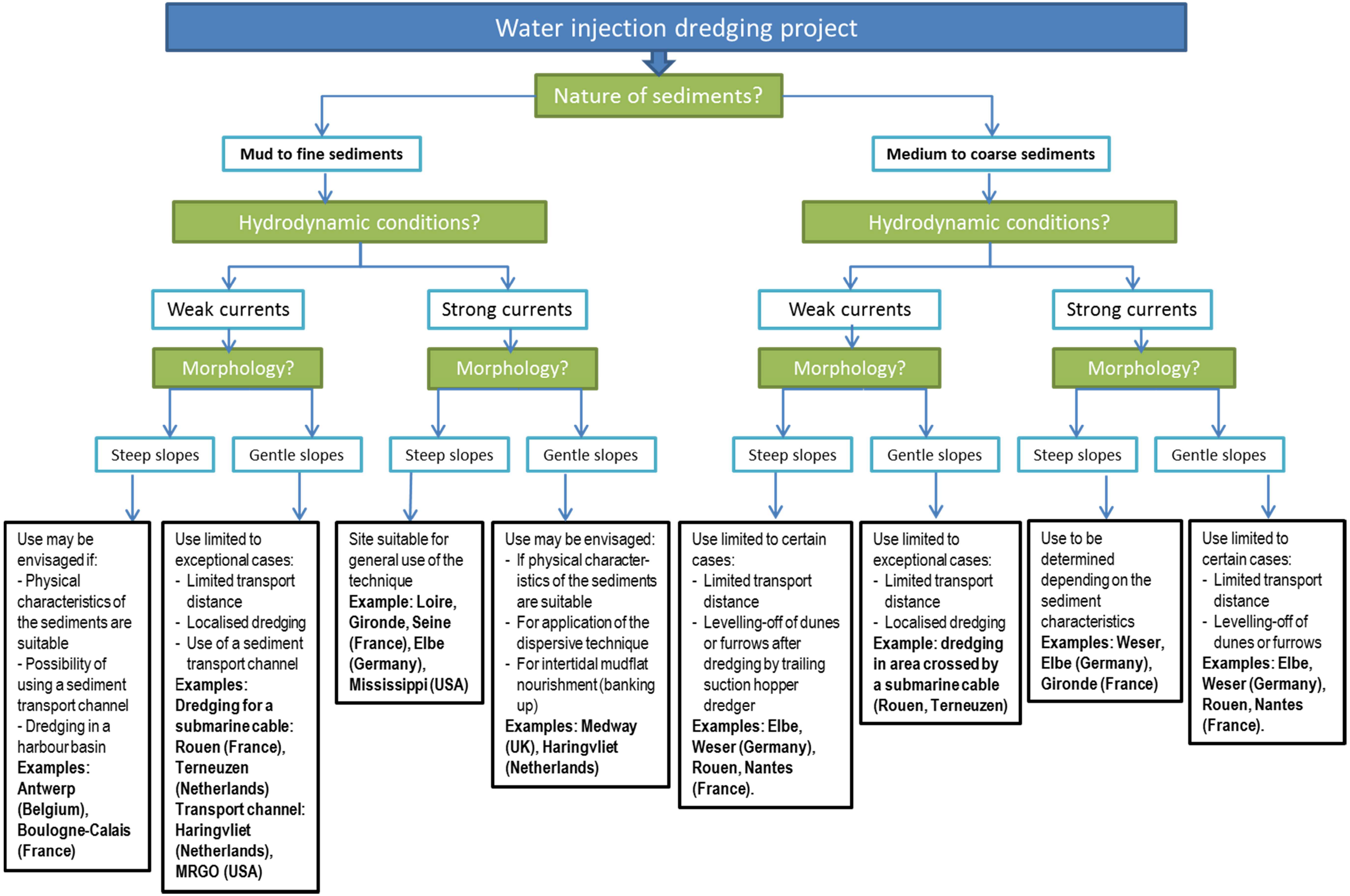
- the site morphology (slope, bathymetry), allowing the density current to be displaced by gravity,
- the hydrodynamics (river discharges, tides) that may accelerate or, on the contrary, slow down the density current.

Maintenance and propagation of the density current are therefore greatly facilitated by the following factors:

- presence of a transport channel that canalises the flows,
- substantial slopes down-gradient to the destination site (although some WID projects have been carried out with very gentle gradients, as low as 1:1000, in a channel or where there is otherwise a strong natural transport phenomenon, Borst 1994, Wilson 2008),
- local currents (river flow or tidal) in the same direction as the density current (generally a maximum of approx. one metre per second during dredging in the various projects researched).

3.3.2.3 - Check-list for a water injection dredging project

The following diagram summarises the essential technical factors to be taken into consideration in implementing a water injection dredging project.



Use may be envisaged if:
- Physical characteristics of the sediments are suitable
- Possibility of using a sediment transport channel
- Dredging in a harbour basin

Examples: Antwerp (Belgium), Boulogne-Calais (France)

Use limited to exceptional cases:
- Limited transport distance
- Localised dredging
- Use of a sediment transport channel

Examples: Dredging for a submarine cable: Rouen (France), Terneuzen (Netherlands) Transport channel: Haringvliet (Netherlands), MRGO (USA)

Site suitable for general use of the technique

Example: Loire, Gironde, Seine (France), Elbe (Germany), Mississippi (USA)

Use may be envisaged:
- If physical characteristics of the sediments are suitable
- For application of the dispersive technique
- For intertidal mudflat nourishment (banking up)

Examples: Medway (UK), Haringvliet (Netherlands)

Use limited to certain cases:
- Limited transport distance
- Levelling-off of dunes or furrows after dredging by trailing suction hopper dredger

Examples: Elbe, Weser (Germany), Rouen, Nantes (France).

Use limited to exceptional cases:
- Limited transport distance
- Localised dredging

Example: dredging in area crossed by a submarine cable (Rouen, Terneuzen)

Use to be determined depending on the sediment characteristics

Examples: Weser, Elbe (Germany), Gironde (France)

Use limited to certain cases:
- Limited transport distance
- Levelling-off of dunes or furrows

Examples: Elbe, Weser (Germany), Rouen, Nantes (France).

Figure 3-8: Essential technical factors to be taken into consideration in implementing a water injection dredging operation

3.3.3 - Complementarity with other dredging techniques

Water injection dredging is principally used in river or estuary environments, where the conditions are most frequently favourable due to the strong currents generated by the tides and river flows combined. Where conditions allow (cf. preceding chapter), its deployment has often enabled a significant reduction in the use of other dredging techniques for the general maintenance of navigation channels, where the most commonly used plant to date was the trailing suction hopper dredger or the cutter suction dredger (Loire, Elbe, etc.). The efficiency of injection dredging is also unequalled for operations required to level off dunes or ridges in the bed, as demonstrated by the experiments conducted on the Elbe in Germany.

The specific characteristics of water injection make it a highly efficient technique to complement works performed with other dredging techniques (hydraulic or mechanical):

- WID can be used to complement a trailing suction hopper dredger in order to level off the furrows that may be left by the latter, as illustrated in the diagram below (Weser, Elbe, Loire, Gironde, etc.),
- WID can shift the materials to a zone that is accessible to other dredging techniques (displacing materials from quay edges towards the centre of a harbour basin, to be dredged there by a trailing suction hopper dredger, as done in Antwerp or Boulogne-Calais),
- preventative use of WID to maintain local hydraulic conditions. The natural erosion of recently deposited materials is stimulated, thus reducing the dredging work to be handled by the other techniques (Rouen).

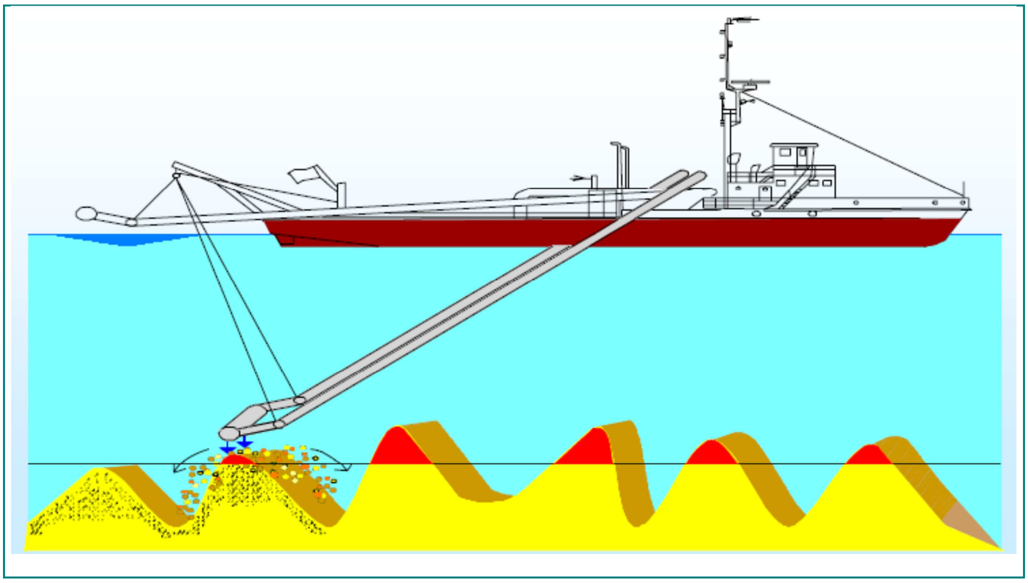


Figure 3-9: Levelling off dunes or furrows left by a trailing suction hopper dredger (STENGEL 2006)

This technique, which is generally simpler to implement, is thus to be considered a complement to or substitute for the so-called conventional methods (hydraulic or mechanical), on adapted sites.

4 - POTENTIAL IMPACTS OF WATER INJECTION DREDGING

This chapter aims to present in general terms the specific potential impacts of water injection dredging.

4.1 - General description of the potential impacts identified

Dredging activities in general impact the aquatic environment in a number of ways and have already been reviewed quite thoroughly (e.g. OSPAR 2008).

These environmental concerns are also of importance in WID, and broadly include (after SPENCER, 2012):

- loss or disturbance of benthic habitats and species including direct behavioural impacts on organisms due to e.g. suspended sediment blocking gills (Nightingale & Simenstad, 2001),
- alterations to bathymetry, benthic topography, hydrography and sedimentary regimes,
- loss in water quality due to increased turbidity, reduced dissolved oxygen concentrations (DO), release of sediment-bound contaminants or those present in sediment pore water (e.g. metals, organic contaminants, nutrients, pathogens) and dispersal of contaminated sediment.

The environmental impacts specifically associated with hydrodynamic techniques including WID have not been studied in detail in the scientific literature.

It is therefore appropriate to consider how the operating conditions of WID compare with conventional dredging techniques and how this might affect the environmental impacts.

These factors are detailed in the following paragraphs.

As a reminder, the principle of injection dredging is based on three fundamental phenomena, from which all the potential impacts are derived:

- modification of the dredged depths (being the *aim* of dredging),
- generation of a density current (being the basic principle of this technique),
- remobilisation of the sediments, generating high concentrations of suspended sediments, mainly in the lower layers of the water column (near the bed).

These three direct effects of water injection dredging may generate a potential impact on water quality (turbidity, contaminants, etc.), the physical environment (nature of the bed, hydrosedimentary equilibrium) or the habitat (spawning and feeding areas). These direct or indirect impacts may then have effects on the living environment or on human activities.

The following outline diagram illustrates the principal components of the environment that may be affected.

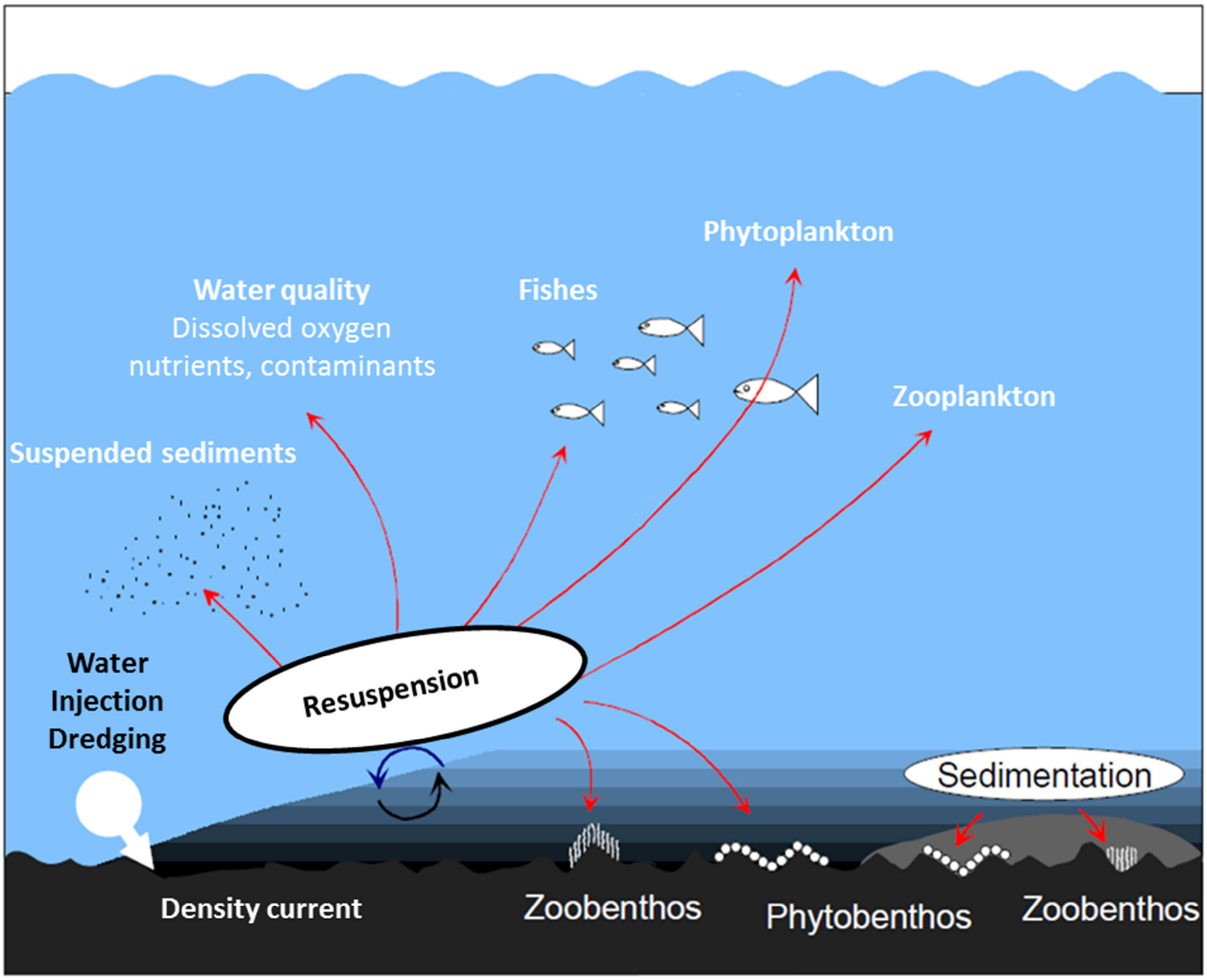


Figure 4-1: Potential impacts of injection dredging
(*after MEYER, 2000*)

The principal difference between WID and the other techniques is that with WID, the horizontal sediment transport is maintained within the water column, whilst the highest concentrations of suspended sediment remain at or near the sediment-water interface (PIANC, 2012 – in press).

In order to list and assess precisely all the possible impacts of water injection dredging, a matrix of potential impacts has been produced. This matrix, setting out the various direct or indirect impacts of this technique, is presented in graphic form on the next page (figure 4-2).

Each item is then covered in detail in the following paragraphs, while the impacts are compared in particular with those generated by the other so-called ‘conventional’ dredging techniques.

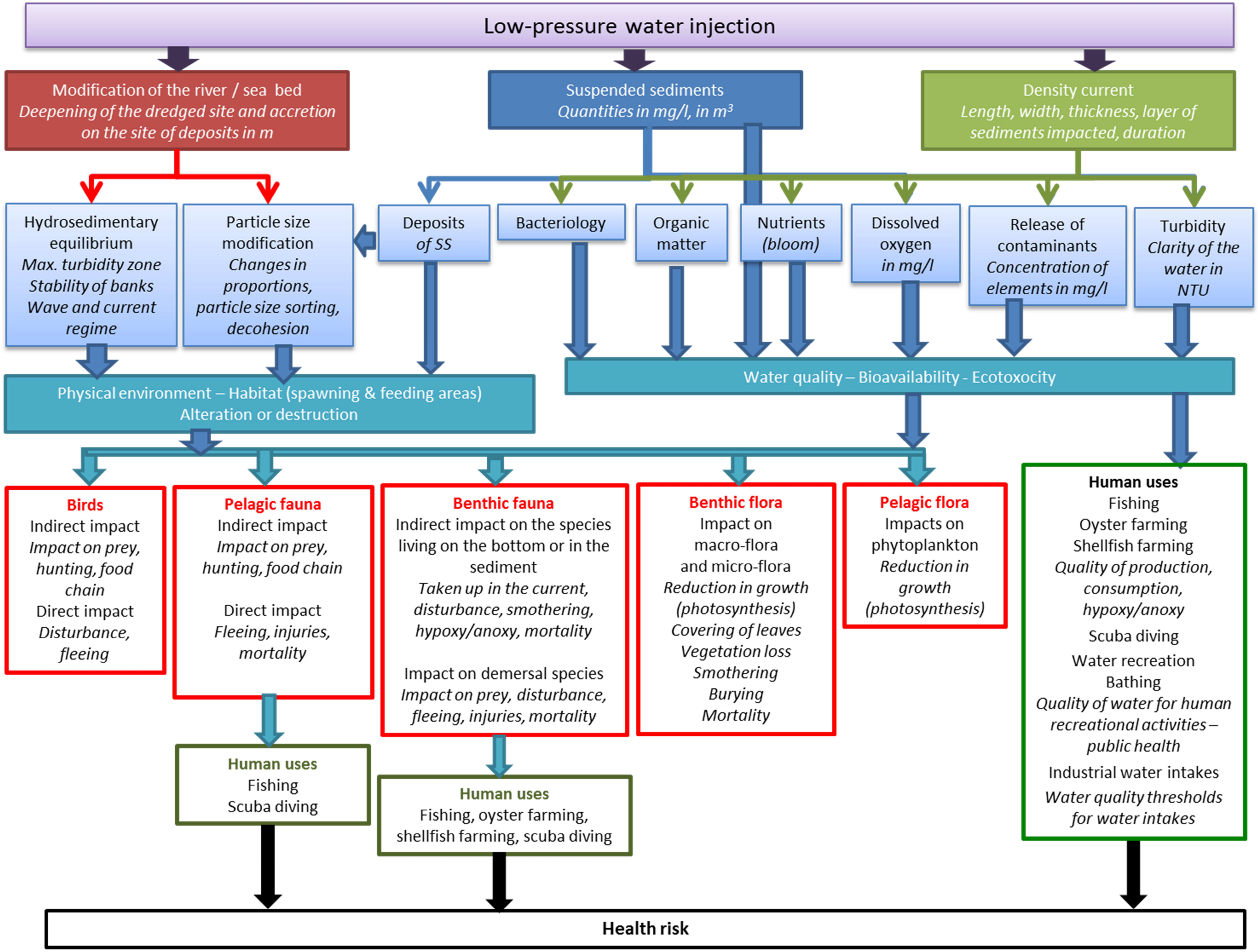


Figure 4-2: Matrix of the potential impacts of injection dredging

4.2 - Impacts on the physical environment

This section describes the overall impacts that may be generated by water injection on the physical environment.

4.2.1 - Modification of sea or river bed

4.2.1.1 - Bathymetry

Water injection dredging involves relocating the dredged materials. Some sectors close to the project may thus experience increased sedimentation if the sediments are not rapidly dispersed:

- downstream of the dredged area, if the density current is directed towards a sector of greater depth (river Don, UK),
- in the furrows between dunes, in the case of levelling operations (Weser, Germany),
- on the foreshore, if the technique is used to nourish the intertidal zone (Medway Estuary, UK).

The use of water injection dredging involves breaking inter-particle forces and reducing their density. Bathymetric surveys are highly sensitive to variations in density. Their precision may therefore be temporarily affected by this variation, and determination of the volume relocated during the operation may also be affected.

4.2.1.2 - Quality of sediments

4.2.1.2.1 - Particle size characteristics

➢ **Dredged area**

The density current remobilises the sediments and may therefore cause a modification in the nature of the materials in situ. The effect on particle size varies according to the homogeneous or heterogeneous character of the sediments:

- with heterogeneous sediments, the density current generally has the effect of sorting the sediment by particle size: the dredged zone loses the greater part of its fines,
- with homogeneous sediments, moving the sediment has no impact on the particle size distribution.

➢ **Disposal area**

The ‘destination’ zone receives the finer materials that have been moved from the dredged zone. Depending on the nature of the sediments in place, its own proportion of fines may tend to increase.

4.2.1.2.2 - Chemical properties

The injection dredging technique does not cause any modification in the chemical properties of the sediments. The density current may, however, locally mix the materials present (with other sediments or the surrounding waters, see 4.2.3.), thus altering the overall quality of certain zones, positively or negatively.

4.2.2 - Hydrosedimentary equilibrium

4.2.2.1 - Currents and sedimentary dynamics

Currents and sediment transport are modified very locally over the area of the density current. Its limited thickness means that it generally has no direct influence on the overall currents at the site.

The density current is formed temporarily, and solely during the period in which the dredger is operating (see 3.1.1 - for more details).

4.2.2.2 - Maximum turbidity zone

Several experiments have been performed with the maximum turbidity zone situated at the level of the dredged areas (Loire and Elbe estuaries). Although the maximum turbidity zone may affect the dredging operations (with naturally high suspended sediment concentrations and sedimentation rates), the impact of dredging on the zone itself is not always measurable:

- difficulty in establishing a measurement protocol (complexity of measurements, values close to the measuring range limits of instruments),
- difficulty in isolating the specific potential impacts of the dredging from the natural variations of the local environment,
- probable negligible effect of the dredging compared to the natural phenomena taking place on the site.

Experts are currently debating the possible short- or long-term impact of water injection dredging on the maximum turbidity zone:

- in the short term, it is considered to be plausible that WID may increase the mass of ‘liquid’ mud remobilised by the maximum turbidity zone. This volume could therefore be augmented by the materials that have previously been loosened and fluidised by the WID,
- in the long term, on an annual scale, it may be assumed that the potential impact of WID is offset by the permanent renewal of the maximum turbidity zone: when this is expelled into the estuary, as for example during a heavy flood, the stocks of remobilisable materials are reduced to zero. The impact of WID may then be considered nil in the longer term, from one hydrological season to the next.

4.2.3 - Water quality

Many studies have shown that the parameters of in situ water quality are modified during and/or after conventional dredging works (Van den Berg et al, 2001; Lohrer & Wetz, 2003; Semmes et al, 2003; Sturve et al, 2005; Nayer et al, 2007; Sundberg et al, 2007; Knott et al, 2009; Urban et al, 2010). There are few studies, however, that relate specifically to WID, and the impacts that have been identified depend on local biogeochemical conditions such as the sediment contamination level.

The parameters relating to water quality are those that are most commonly monitored in the papers analysing past experiences. They concern:

- turbidity and suspended sediments (SS),
- dissolved oxygen,
- chemical contaminants, nutrients and micro-organisms where there is a risk or where specific issues are at stake on the site.

4.2.3.1 - Suspended sediments – turbidity

Increased levels of suspended material in the water column can have a detrimental effect on water quality by reducing aesthetics, reducing light penetration and having direct behavioural impacts on fish and benthic organisms (Nightingale and Simenstad, 2001)

Remobilising the materials causes them to be resuspended. These SS remain concentrated principally close to the bottom or in the immediate vicinity of the density current. They may in certain cases by dispersed, albeit in lesser concentrations, throughout the water column.

The following table presents examples of the increase in SS measured during the various injection dredging projects identified. From these results the following phenomena may be distinguished in particular:

- increases in suspended sediments within the density current, of the order of a few grams per litre,
- increases in suspended sediments within water column, generally close to the natural values, but potentially reaching a few hundred milligrams per litre in certain cases.

Generally speaking, the impact of water injection dredging may be considered to be concentrated near the river/sea bed, in and close to the density current. The impacts on the rest of the water column remain limited.

Moreover, the various monitoring operations conducted show that it is very difficult to distinguish the density current in estuary zones with a high natural turbidity, on account of the very high natural variations in SS observed in the environment.

Table 4-1: Examples of resuspension during injection dredging

Site	Nature of sediments	Measurement depth	Distance from dredger	Background intensity	Suspended sediments	Source
Elbe Estuary	Sand (Rhinplatte)	/	/	25 mg/l	No measured increase	Meyer (2000)
	Mud (Köhlfleet)	Water column	Average in the dredging zone	25 mg/l	100 mg/l max	
		Bottom			3 g/l max	
Loire Estuary	Mud	Surface Mid-depth	100 m 1 km 2 km	1-4 g/l	No measured increase	CREOCEAN (2006-2009) HOCER (2010-2011)
Bayonne	Sand and mud	Surface	Average in the dredging zone	32-47 mg/l	28-200 mg/l	Ginger (2011)
		Mid-depth		38-58 mg/l	32-190 mg/l	
		Bottom		38-65 mg/l	32-580 mg/l	
Gironde Estuary	Mud	Water column	< 70 m	1-2 g/l	4 g/l	Ginger (2011)
		Bottom	Between 70 and 300 m		4 g/l	
		Water column and bottom	> 300 m		No measured increase	
Weser Estuary	Sand	/	/	50 to 200 NTU (winter-summer)	No measured increase	Stengel (2006)
Ems Estuary	Mud and fines	Surface	Downstream limit of dredged zone	50 mg/l	300 mg/l	BFG (2011)
		2.50 m above the bottom		100 mg/l	500 mg/l	
		At the bottom		150 mg/l	800 mg/l	
Antwerp (Scheldt)	Mud	-10 m	5 m	25 mg/l	60 mg/l	Port of Antwerp 2011
		-16 m (bottom)	5 m	50 mg/l	1 500 mg/l	
		-10 m	40 m	5 mg/l	30 mg/l	
		-16 m (bottom)	40 m	50 mg/l	200 mg/l	

4.2.3.2 - Dissolved oxygen

The dissolved oxygen (DO) content in the water is determined by the respiration of aquatic organisms, the oxidation and degradation of pollutants, photosynthesis in flora and exchanges with the atmosphere.

The dissolved oxygen in the water is in fact the net result of production activity (photosynthesis and re-aeration) and consumption activity (biodegradation and respiration).

There is an oxygen deficit when consumption exceeds production. This phenomenon is essentially caused by oxidation of organic matter. Sediments being resuspended may be the cause of this oxidation (Spencer, 2012).

There are specific processes that act on the dissolved oxygen in the estuarine environment:

- salt water intrusion, which contributes significantly to deoxygenation of water in the upstream estuary on each flood tide (since the water originating from the downstream maximum turbidity zone is less oxygenated),
- competition between tidal amplitude and river flow, which determines the extent of saline intrusion,
- variations in water temperature and salinity, limiting the dissolution of oxygen in the water,
- primary production in the estuary, which increases with the inflow of nutrients from the river during peak flows, stimulated by sunny conditions, low turbidity and water column stability,
- degradation by bacteria of organic matter generated in the estuary following these periods of production, which will locally increase the consumption of oxygen, thus possibly giving rise to anoxic episodes.

All these processes combine, making it difficult to isolate the effects attributable to dredging operations.

A number of studies have examined the impacts of conventional dredging on DO concentrations and have found that levels in the overlying water column decrease during dredging, but that this deterioration is brief with DO levels returning to natural levels as rapidly as within 15 minutes (e.g. Lohrer and Wetz 2003, Semmes et al. 2003, Jones-Lee and Lee, 2005)

In the case of water injection dredging, this drop in dissolved oxygen concentration is also a temporary phenomenon, observable for the duration of the dredging operation (principally in estuarine environments):

- the reductions measured during the various recorded injection dredging projects remain very slight or are non-existent (the drop very rarely exceeds 30%, see following table (Meyer, 2000, Creocean, 2006-2009, BFG, 2011)),
- the return to normal values for the site is very rapid (Meyer, 2000, Port of Antwerp, 2011),
- the effects are principally concentrated on the bottom. The drop in oxygen potentially induced by this technique therefore applies only in the deepest section (over a thickness of 1 to 3 m) of the water concerned (Port of Antwerp, 2011, Ginger, 2011).

Table 4-2: Examples of dissolved oxygen variations during injection dredging

Site	Nature of sediments	Measurement depth	Distance from the dredger	Background intensity	Dissolved oxygen	Source
Elbe Estuary	Mud Cuxhaven	Surface	/	84% saturation	50%	Meyer (2000)
		3.5m from the bottom			42%	
	Mud (Köhlfleet)	1 m from the bottom	Average over the dredging zone	82% saturation	70%	
Loire Estuary	Mud	/	/	3-9 mg/l	No reduction	Creocean (2006-2009)
Gironde Estuary	Mud	Water column	/	6 – 9.6 mg/l	No reduction	Ginger (2011)
Weser Estuary	Sand	/	/	5.5 to 12.5 mg/l	No reduction	BFG (2011)
Ems Estuary	Mud and fines	Surface	Downstream limit of dredged zone	12 mg/l	7 mg/l	BFG (2011)
Antwerp (Scheldt)	Mud	-10 m	5 m	87%	84%	Port of Antwerp 2011
		-16 m (bottom)	5 m	87%	60%	

4.2.3.3 - Release of contaminants and nutrients

4.2.3.3.1 - Impacts generally observed on water quality

Contaminants and nutrients generally tend to bind to finer sediments. In the substrate, where free oxygen concentrations are low, these sediments rapidly become anoxic. Any contaminants and nutrients present in the sediments could therefore be released into the water column if these materials were disturbed.

Chemicals are found in sediments in a particulate form (associated with the SS by colloid adsorption) and may, depending on the physico-chemical conditions of the environment (in particular salinity, pH, oxidation-reduction potential) change into the dissolved state. This form of contamination is the most bioavailable in the marine environment.

This is confirmed at the point of transition from fresh water to salt water in estuaries (with variable salinity depending on the site); the sediments here encounter modifications in the physico-chemical conditions of the environment (salinity, pH, etc.) that could solubilise the bound metals. Particles in suspension have thus already naturally released most of the available fraction of the metals adsorbed as they pass through the saline front, before they settle in the estuary.

This phenomenon of solubilisation, especially of particulate metals, is very frequent in the estuarine environment. It is due in particular to salinity, but also to mineralisation of particulate organic matter within the maximum turbidity zone, and to sediment inflows due to erosion of the upper layers of sediment induced by tidal currents and wave disturbance (the case of mud flat erosion).

Few studies have been carried out to assess the release of sediment-bound contaminants to the overlying water column during dredging operations. This is probably because other processes for disposing of the materials are envisaged wherever there are found to be significant risks of contaminant release.

However, in general, where studies exist for conventional dredging they have found that levels of dissolved contaminants, nutrients and ammonia in the water column have increased during dredging activity. However, this deterioration in water quality has been brief, localised and frequently within the natural variability observed in the environment (e.g. Lohrer and Wetz 2003; Semmes et al. 2003; Urban et al. 2010). Where increases in metal concentrations in the water column have not been observed, this has been attributed to the strong binding capacity of the sediments (Van den Berg et al. 2001). The mechanisms through which contaminants bind to sediment are detailed in the next paragraph.

First of all, it is widely accepted that injection dredging should not be used to dredge contaminated sediments. There are however some exceptional cases in the scientific literature (Don, Limehouse Basin, Haringvliet, etc.).

Contaminants are usually not monitored where the dredged area is deemed to be non-polluted.

In certain cases however, water quality has been subject to detailed monitoring for contaminant levels that are well below the limits imposed by regulations in force (for example the GEODE thresholds in France). No impact on water quality was detected.

4.2.3.3.2 - Analysis of the mechanisms specific to water injection dredging

Although few monitoring data exist for examining in situ release of contaminants during WID, laboratory elutriate tests and monitoring of other dredge activities suggest that contaminants will be released to the water column.

By its very nature, injection dredging means that the advective flow (and hence the dilution) of sediments and contaminants released to the overlying water column is limited (since the materials are concentrated on the bed). Therefore (see the following overview diagrams), the concentrations of soluble contaminants in the near-bed zone (i.e.: the sediments suspended in the density current) may be significantly higher than those observed during conventional dredging operations.

Fine-grained and organic rich sediments are important sinks for organic and inorganic contaminants and nutrients in estuarine and fluvial environments (e.g. Bianchi 2007). A number of particulate species or ‘binding sites’ are important for the removal of dissolved trace metals from the aquatic environment including particulate organic matter, carbonates, hydrous oxides (Turner et al., 2004) and of greatest importance in anoxic environments, sulphides (Simpson et al., 2000). Many organic contaminants such as PCBs and PAHs are hydrophobic and bind strongly to organic matter and are chemically stable and therefore persistent in the environment. .

The heavy concentration of suspended sediments in this density current provides many supporting elements for readsorption of the released contaminants. The contaminants are therefore less dispersed in soluble form since they are rapidly readsorbed by the density current.

It should be recalled, however, that these mechanisms are generated naturally in estuaries, at the boundary between fresh water and salt water. The potential impact of injection dredging on the balance between desorption and absorption of contaminants in the sediments is thus low compared to the natural phenomena taking place on these sites.

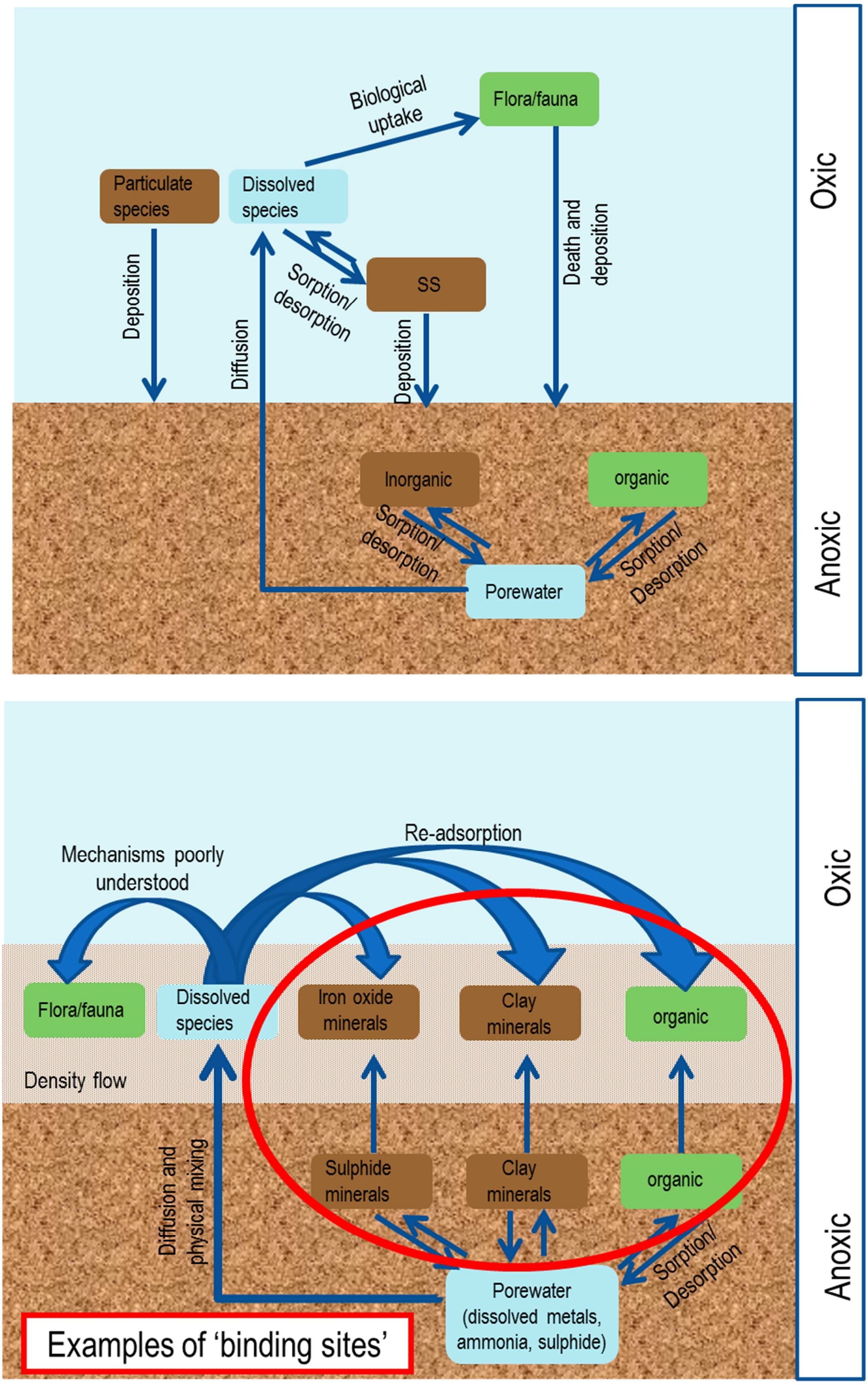


Figure 4-3: Assumptions regarding the chemical balances of contaminants in the natural state (above) and in the density current (below), Spencer (2012), Queen Mary University

4.2.3.4 - Bacteriology

Few bacteriological measurements have been taken during water injection dredging projects.

The dispersal of bacteria (Escherichia Coli or intestinal Enterococci) generally follows the pattern of suspended sediments during dredging operations. In the case of WID, the SS are concentrated principally in the density current. The potential impacts associated with bacteriology are therefore principally located close to the bottom.

4.2.4 - Evaluation of impacts on the physical environment

The following table summarises the potential impacts of water injection dredging on the physical environment.

Table 4-3: Summary of potential impacts of water injection dredging on the physical environment

Type of impact	Potential impacts	Characteristics specific to injection dredging
Modification of bed	Bathymetry	Rise in bed level at the destination site
	Density	Impact of fluidification: drop in liquid mud density
Hydro-sedimentary equilibrium	Currents	Localised density current
	Sedimentary dynamics	No measurable impact
	Maximum turbidity zone	No measurable impact
Water quality	SS/turbidity	Suspended sediments within the density current of the order of one g/l
	Dissolved oxygen	More substantial drops close to the bed Rapid return to the normal situation
	Release of contaminants	Expert appraisals indicating the existence of specific contaminant re-adsorption mechanisms in the density current (Spencer, 2012) Impacts concentrated on the bottom
	Bacteriology	Depending on SS dispersal
	Nutrients	Specific nutrient desorption or re-adsorption mechanisms in principle generated by the density current

4.3 - Impacts on the marine life

The biological impacts of hydraulic and mechanical dredging have often been the subject of detailed studies. Most of these studies focus on the impact on benthic communities and diversity by using the BACI[2] approach.

However, there are few ‘real-time’ evaluations of ecological impacts during resuspension operations (Knott et al., 2009) and even fewer on impacts during WID operations (Field 2009).

4.3.1 - Quality of habitat

The impact of dredging on the physical environment may alter the nature or the quality of habitats present in the zone:

- modifying the particle size distribution may affect species that live and lay their eggs in sediment. For example, the quality of a habitat formed by coarse or gravelly sediments could potentially be altered if it is covered with a layer of fines following injection dredging,
- deepening a zone may alter the regime of currents to which the habitat is exposed (an impact that is common to all dredging techniques), and thus the habitat quality.

Overall, the impact of injection dredging on the habitat remains a variable that has been rarely measured in the various projects undertaken.

4.3.2 - Benthic species

Benthic species are generally directly impacted by any dredging operation. Extracting materials leads to the destruction – which may be temporary – of the majority of benthic species found within the dredged zone. Injection dredging is no exception, and produces the following effects throughout the area dredged and crossed by the density current (depending on the thickness and frequency of the deposits):

- local loss of bottom fauna,
- destruction or alteration of the benthic macroflora.

The impact of water injection dredging on benthic species varies depending on the sites where it has been monitored and on the disposal zones used. It is to be weighted to reflect the relative wealth of such species in the zone (navigation channels are generally poor in benthic species), recolonisation processes that may be occurring locally and the natural variations of the populations involved.

The impact on benthic species (fauna and flora) is no different from that generated by the other dredging techniques. In the case of WID, the potentially impacted area is more extensive, however, since it includes the extent of the density current.

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[2] BACI: Before-After-Control-Impact = verification of impacts by assessing baseline conditions and performing monitoring after the works.

4.3.3 - Demersal species

Demersal fish, which are highly mobile, are not generally impacted by dredging operations (no mortality). On the other hand, since this compartment of the food chain feeds on macrobenthic species, the demersal species will temporarily leave the most impacted zone.

There is little monitoring data on demersal species during water injection dredging operations.

Instances have been recorded of individuals being destroyed or injured by the mechanical action of dredgers.

Since water injection dredging does not involve suction, the mechanical effects of dredging by this technique are less harmful in this respect.

4.3.4 - Pelagic species

There is no specific data on the impact of water injection dredging on pelagic flora in the scientific literature. The approach generally adopted corresponds to the one preferred for other dredging techniques (temporary drop in photosynthesis due to the increase in turbidity in the density current zone).

Injection dredging has relatively little impact on pelagic fauna:

- the density current is maintained close to the bed, in other words in a sector that is not specific to pelagic species; these can easily move away from the potential danger, without being subject to any harmful effects,
- sediment resuspended in the water column, while in a lesser concentration than in the density current, may disturb fish (visibility, respiration, etc.). However, since fish are highly mobile and the plume is localised (in open waters), they can easily swim away from the potentially dangerous zone and return after the plume has dispersed.

The sampling protocols and techniques are not sufficient to give a precise assessment of the population present in a given zone. Results of measurements must therefore be interpreted and analysed with caution. It is difficult to measure in concrete terms the impacts potentially induced on pelagic species by dredging in general, including water injection dredging.

The eggs and larvae of fish, being static, are naturally more vulnerable to dredging operations and their impacts. Eggs and larvae are generally less tolerant of variations in turbidity than the adults. Knowledge of the areas and periods where eggs and larvae are likely to be developing is therefore desirable, to adapt the works as necessary and limit these impacts.

4.3.5 - Birds

There is no specific data on the impact of water injection dredging on birds in the scientific literature. In general terms, the principal impacts of dredging on seabirds are of two types:

- modification of the birds’ food resources:
    - the potential impact is indirect since it is generated through the food chain,
    - It is very difficult to quantify the impact (methods for monitoring birds and interpreting observations),
- disturbance of individuals, for example close to a resting point or a feeding area:
    - the potential impact is direct since the dredger has a direct impact on the birds’ living conditions,
    - it may be observed during the works but is difficult to quantify.

Water injection dredging has no specific impact on the food chain, by comparison with the other hydraulic or mechanical dredging techniques (cf. paragraphs 4.3.1 to 4.3.4). Its presence over a long period in an area that is important for birds could potentially cause a nuisance, in the same way as with the other types of dredging plant.

4.3.6 - Evaluation of impacts on the living environment

The impacts of injection dredging on the living environment are summarised below.

Table 4-4: Evaluation of potential impacts of water injection dredging on the marine life

Type of impact	Potential impacts	Characteristics specific to injection dredging
Habitat quality	Alteration of habitat quality	No specific approach in the literature. Reduction in the proportion of fines in the dredged zone
Ecotoxicity	Bioaccumulation of contaminants in living organisms	Mechanisms of bioaccumulation associated with desorption/reabsorption phenomena during injection dredging are still little known. Expert's finding suggesting the existence of specific contaminant reabsorption mechanisms in the density current (Spencer, 2012) Potential impacts concentrated on the bottom
Benthic species	Total or partial fauna loss	Rarely measured; in principle, no impact specific to this technique.
	Alteration or destruction of flora	No specific measurements, generally little or no benthic flora in the dredged zones
Demersal species	Escape or injury, impact on prey	No specific studies on demersal species
Pelagic species	Escape or injury, impact on prey	Rarely measured, no specific approach in the literature. Potential impacts concentrated on the bottom
	Reduction of photosynthesis	No specific studies on the pelagic flora. Potential impacts concentrated on the bottom
Birds	Escape or disturbance, impact on prey	No specific studies on birds. In principle, no impact specific to this technique.

4.4 - Impacts on human activities

4.4.1 - Health risks

Generally speaking, the health risks in the marine environment concern:

- the quality of water in bathing areas,
- the quality of fish and seafood farming areas (oyster farming),
- the quality of fishing zones.

The approach adopted in the various studies conducted for water injection dredging projects is along the same lines as the analyses performed for the other dredging techniques, the impact being directly related to suspended sediments dispersal and environment quality.

As with the other dredging techniques, the health risk associated with injection dredging therefore depends on the destination of the dredged materials, their position in relation to potentially sensitive zones, control of the density current, as well as the general environment quality.

A 'Guide to health risk assessments related to dredging operations and disposal of maritime and estuarine materials at sea' has been produced by the GEODE group (2012 – IN PRESS[3]) and gives details on all these aspects.

4.4.2 - Navigation

During dredging operations, the dredgers operate in the same space as regular shipping. They must therefore respect the regular practices in maritime navigation to ensure harmonious coexistence with the other vessels in the channel or the harbour zones concerned. The water injection dredging technique does not generate specific impacts on fishing or navigation.

The potential impact on navigation and the progress of fishing vessels is often presented as being reduced by the fact that injection dredgers are generally smaller than the other types of dredging plant and work more rapidly.

4.4.3 - Fishing

Quite apart from the hindrance to navigation, the potential impact of injection dredging on fishing relates to the effects that this technique may have on fishery resources.

Considering that injection dredging will only cause adult fish to flee the dredged area temporarily, it has no impact on resources in this respect. The potential impact of the density current on eggs or larvae nevertheless remains to be examined on a case-by-case basis depending on the particular characteristics of the sites.

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[3] Published in 2014

4.4.4 - Industrial water intakes

Certain factories or electrical installations may have a water intake to meet certain production requirements or for a cooling system. These installations are generally sized to be capable of using water that has the highest possible sediment load, for example by filtering the water through settlement basins.

In the context of water injection dredging operations, it is important to ensure that the density current does not adversely impact these installations.

4.4.5 - Summary of impacts on human activities

The impacts of injection dredging on human activities are summarised below.

Table 4-5: Evaluation of impacts on human activities

Type of impact	Characteristics specific to injection dredging
Health risk **(bathing, fish farming, etc.)**	No specific approach in the literature. Depends on the distance and trajectory of the density current.
Navigation	No specific approach in the literature. Plant less cumbersome than with the other techniques.
Fishing	No specific approach in the literature. No specific impact on fishery resources.
Industrial water intakes	Depends on the length and trajectory of the density current.

5 - PRELIMINARY ASSESSMENT AND MONITORING METHODS

5.1 - General approach

For general considerations on the monitoring of dredging operations, the *Guide méthodologique relatif aux suivis environmentaux des opérations de dragage et d'immersion*, 2012, Egis Eau, GEODE and its appendices may be consulted.

The objective of this section is to provide indicators that are specific to water injection dredging, and which may thus be used as decision aid tools for project owners or their project managers involved in a water injection dredging project; this is in order to gear and adapt the monitoring or related studies to be carried out more closely to the characteristics of the project.

As specified in the above-mentioned guide, these monitoring operations must be:

- established case by case in relation to the specific site and project characteristics,
- efficient and relevant in relation to the results of impact assessment, the identified issues and the objectives assigned to the project,
- adaptable and modular, to be able to take into account the results of the experimental operations conducted during the first campaigns on the site,
- proportional to the issues involved.

5.2 - Assessment of density current impacts

5.2.1 - Preliminary analysis of density current trajectory

5.2.1.1 - Expert appraisal

The forces exerted on the density current and influencing its trajectory are principally:

- the action of the water injection itself,
- the action of local currents,
- the action of the bottom (friction),
- gravity (gradients),

With precise knowledge of the site morphology and local currents it is possible to anticipate the overall behaviour of the density current, depending on the strategy for deployment of the water injection dredger. The density current has little chance, for example, of being propagated towards shallower areas.

In the case of the Thames, where injection dredging is used locally on several sites, the trajectory of the density current is anticipated up to the point where it reaches zones that are sufficiently exposed to the energy of wave action for it to disperse.

This expert appraisal is based on precise knowledge of the morphological data (bathymetry, gradient, particle size characteristics) and hydrodynamic data (resultant currents, discharges) of the zone considered for the operations.

5.2.1.2 - Numerical modelling

In general, numerical models offer a useful complement to an expert appraisal of dredging and immersion operations, since they provide more precise data on the conditions of turbid plume dispersal and the trajectory of the particles.

In the case of water injection dredging, the exercise is much more complex.

The construction of numerical models for water injection dredging is still at the experimental and research phase, and the results need to be used with all due caution (PIANC, 2012, in press).

Two numerical modelling processes are currently used in combination:

- the density current and the sea water are considered as two distinct fluids, interacting through shear stress or erosive forces (Winterwerp et al., 2008). The reliability of this type of model is limited, however, in environments that are subjected to high energy levels, where exchanges in the water column are greater and the density current is therefore more difficult to maintain (PIANC, 2012, in press). It is not applicable to complex environments with stratification, such as estuaries,
- modelling of sediment dispersal (based on a 3D current model), based on an estimation of the volumes put back into suspension by dredging. This technique is used principally in zones that are exposed to high energy levels, where the action of local currents will have a preponderant influence on sediment dispersal, as for example in the Medway estuary (HR Wallingford, 2002). It does not take into account the notion of density current.

Modelling of these complex phenomena in an estuarine environment remains to be developed. It is not, to date, in a position to correctly represent the different processes at play and their interactions in environments that are already quite complex in their natural state (haline stratification, turbidity and density gradients of the mud deposited on the bed, liquid mud, maximum turbidity zone).

5.2.1.3 - Physical modelling

Construction of a physical model may offer a means of reconstituting the elements that have a bearing on the density current at a smaller scale:

- friction forces, sediment cohesion,
- gravity forces, bed gradient,
- local currents.

The behaviour of the density current may be reproduced in a test channel, thus enabling its characteristics and the quantities dredged to be evaluated (see following figure).

Figure 5-1: Physical modelling of a density current (BORST 1994)

Here too, although physical modelling indeed has the advantage of more accurately reproducing the processes involved in the density current, it does not allow this density current to be ‘re-situated’ within its natural environment.

5.3 - In situ monitoring on sites where water injection dredging has been carried out – experimental monitoring

5.3.1 - Overall strategy of the monitoring operations researched

A large number of the available documents on injection dredging refer to monitoring operations of a ‘scientific’ nature. These operations are conducted exceptionally in the course of a project or an experiment conducted specifically to improve general knowledge of injection dredging and its impacts. The different organisations that have conducted these tests have also defined monitoring strategies that are specifically adapted to regular operations.

The objectives of scientific or experimental monitoring are:

- to study in detail the impacts of injection dredging on the site concerned and to check the validity of the preliminary evaluation,
- to define the context of future regular use of injection dredging,
- to allow the deployment of a ‘lighter’ (so-called routine) monitoring for these future uses of the technique.

There is no ‘standard’ monitoring to be put in place for an injection dredging project. In the same way as with the other dredging techniques, the monitoring is to be set up:

- at the discretion of the owner or his representative (consulting engineers, project managers), based on knowledge of the project characteristics, the issues involved, and the history of the study area (possible pollution by certain particular types of contaminants),
- or by a steering group formed for this purpose,
- or by decree (published by the national or local authorities)

The table presented on the following page sets out the types of monitoring put in place on sites that have been subject to operational or experimental water injection dredging (and where the available data is sufficiently detailed to be exploited).

Generally speaking, as shown in the following diagram, the various parameters are monitored to very different levels in the literature:

- physical monitoring (SS, bathymetry, currents, particle size) is the most extensively researched in most of the projects,
- the most commonly practised chemical monitoring focuses on dissolved oxygen or nutrients,
- microbiological monitoring is very rarely practised,
- ecological monitoring is not generally considered to be relevant under experimental projects.

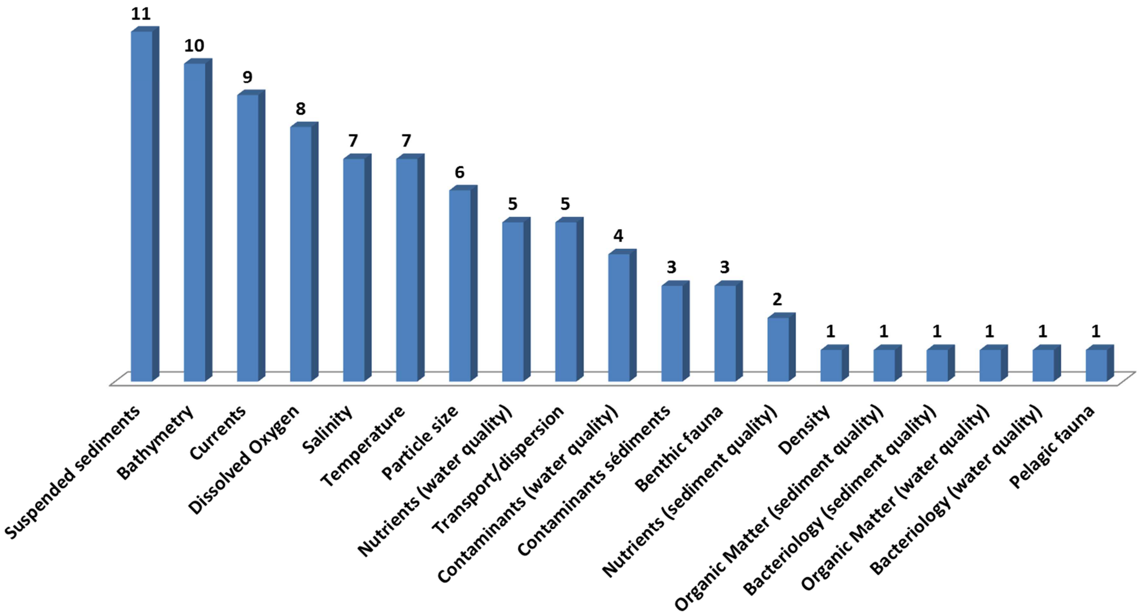

Figure 5-2: Monitoring conducted on the sites researched

5.3.2 - Scientific or experimental monitoring

5.3.2.1 - Types of monitoring put in place

5.3.2.1.1 - Physical environment monitoring

Physical environment monitoring is the principal focus in all the water injection dredging operations recorded (see previous table):

- a substantial proportion of the investigations were aimed at evaluating the physical efficiency of injection dredging,
- monitoring the density current means installing substantial, complex instrumentation (fixed and on-board ADCP).

Generally speaking, the aspects presented in the following table were measured using the various instruments in the course of the measurement campaigns that have been identified:

Table 5-1 Measurement methods in relation to the physical variables measured

Measured variable	Measurement method	Example	Observations
Suspended sediments/turbidity	Turbidimeter, multi-parameter probe	Bayonne	These instruments supply information on turbidity units in NTU (≠ g/l)
	Measurements by ADCP (fixed station or on board a ship)	Loire, Gironde (on-board ADCP)	The fixed station ‘verifies’ the presence or absence of the density current at a given point. The on-board ADCP enables more precise visualisation of its actual extent. N.B. measurements become difficult close to the bottom (1-2 m)
	Water samples	Antwerp	The various measurements are generally complementary: calibration, frequency of sampling, simplicity of operation, costs, etc.
Hydrosedimentary/ deposits equilibrium	Bathymetry immediately before, immediately after, and a few weeks after dredging	UK	Pay attention to the frequency used (density of the layer of materials detected) Pay attention to the definition of the zone to be surveyed
	Sediment trap, fluorescent tracers	UK, Elbe, Haringvliet	Limited efficiency in the experiments conducted
	In-situ density measurements	Crouch River, Elbe	Useful for the particular concerns of navigation
Modification of the sedimentary facies	Grab sampling and analysis	Gironde	For precise measurements of the particle size distribution
	Acoustic sounder	Weser	Gives a better overview of the whole area
Current measurements	ADCP	Loire, Elbe, Thames, etc.	/

5.3.2.1.2 - *Water quality monitoring*

By comparison with physical environment monitoring, water quality monitoring (or chemical monitoring) is more marginal in the operations that have been recorded.

In most cases, water injection dredging is carried out in a non-contaminated environment. Chemical water quality monitoring is thus generally kept to the minimum requirement (straightforward measurement of SS).

Table 5-2 Measuring equipment installed in relation to the measured variables

Measured parameter	Measurement method	Example
Contaminants	Niskin bottle	Gironde
Temperature/Salinity/O2	Multiparameter probe	Bayonne
Turbidity/SS	Turbidimeter	Boulogne - Calais
	ADCP	Loire

5.3.2.1.3 - *Marine life monitoring*

Ecological monitoring encounters difficulties relating to the implementation of reliable protocols, guaranteeing measurement results that are exploitable. The resulting analysis depends to a large extent on the baseline knowledge of the environment and the measurement processes already in place before the project is implemented.

Moreover, marine organisms are subject to substantial natural fluctuations in terms of density or diversity, that may be both seasonal and interannual, which makes it difficult to interpret the measurements made during a dredging campaign.

The protocols are similar to those followed during conventional dredging operations (cf. *Guide méthodologique GEODE sur les suivis de dragages et immersions, 2012*).

5.3.2.2 - Spatial and time scales

Using all the variables that can be measured to determine the environmental impact, it has been shown that there are significant natural variations in terms of both spatial extent and time scale. Thus the monitoring strategy has to take into account this heterogeneous character of the environment and ensure that the long-term variability has effectively been taken into account when acquiring the baseline data.

For example, turbidity may vary according to the tide cycles and seasons, while the structure, diversity and abundance of the benthic community may be influenced by the growth period.

5.3.2.2.1 - Spatial scale examined

There are three different spatial scales regarding the monitoring of WID:

- in the immediate vicinity of the dredger:
  - sampling at several distances from the dredger while operating,
  - vertical profiles measured by ADCP or by a multifunctional sounder,
- dredged zone, possibly extended depending on the suspected impacts:
  - fixed measurement stations distributed over the zone following the dredging scheme,
  - measurements on transects,
- overall environment:
  - estuary-type monitoring, as on the Loire, Gironde, Weser or Elbe,
  - water samples are generally taken from three depths: at the surface, at mid-depth, and at the bottom.

These three approaches are complementary in the context of injection dredging monitoring. The first two may effectively measure the impacts on the near field, while the third will measure the potential impacts on a large scale, and above all will provide reference values and enable an understanding of the natural processes at play.

The density of measurements is to be established case by case, depending on the nature of the operations envisaged and the sensitivity of the environment.

5.3.2.2.2 - Time scale

In order to obtain results that can be exploited to analyse the impacts of dredging, the monitoring must be performed before, during and after the operations, taking into account the characteristics of the site and of the dredging operation itself:

- monitoring before dredging:
  - serves as a benchmark for the dredged zone,
  - is generally carried out a few days or a few weeks before the start of operations,
  - may be performed over a long period before the operations in order to provide a better understanding of local natural variations (if there is no large-scale monitoring already in place in the study area), or could be coupled with a long-term monitoring system (MAREL in the Seine estuary, SYVEL in the Loire estuary, etc.),
  - must be defined according to the site characteristics, taking into account:
    - tides,
    - river discharges,
    - maximum turbidity zone,
- monitoring during dredging operations:
  - serves to measure the impacts of injection dredging,
  - must be defined according to the site characteristics, taking into account:
    - tides,
    - river discharges,
    - maximum turbidity zone,
- monitoring after dredging:
  - serves to measure the environment recovery/recolonisation processes,
  - is performed over a period that depends on the parameters to be examined (physical or biological).

5.4 - Proposed themes to be covered by operational monitoring

The “*Guide méthodologique sur les suivis de dragages et des immersions*” (Geode 2012) suggests a range of methodological tools for implementing monitoring geared to dredging operations in general, depending on the specific characteristics of the sites and the projects.

In the case of water injection dredging, there is no real ‘routine’ operational monitoring procedure, whether in the bibliography or on the sites examined. On the other hand, the initials monitoring, on first using the technique on a site, are set out in some detail.

Operational monitoring is to be established case by case, depending on the project site, in the same way as with the other dredging techniques.

In this context, the following table presents the general interest or relevance of each type of monitoring potentially put in place. The monitoring implemented must serve a technical purpose, or meet a mandatory requirement, or must address a specific issue on the site concerned. It is to be defined by asking the right questions:

- what is the nature of the density current generated?
- how this density current controlled?
- what is the quality of the dredged environment?
- what issues are there on or close to the site?

We may therefore distinguish monitoring that is put in place at a site on first use of the injection dredging technique. These monitoring operations, which are closer to scientific or experimental-type monitoring, are aimed at determining the general zones potentially affected by the density current and the sensitivity of the environment. Since each site has its specific characteristics, a full understanding of the phenomena observed on first use of injection dredging would then enable less systematic, routine-type monitoring to be put in place for future operations at the same site; these would be simply aimed at checking the previously identified parameters.

For example, at sites where it has proved impossible to distinguish the density current on account of the very high concentrations of SS and highly variable natural environment characteristics, it appears illusory to attempt to programme any monitoring of the density current.

These general principles may be applied in different ways, depending on whether the site is in an open or closed environment (harbour basin), or in a river or estuary (see following chapters). On this basis, monitoring proposals are made for a number of standard cases in Chapter 6.

Table 5-3: Objectives of routine monitoring that could potentially be put in place

		Dredging zone		Potentially impacted area		Zone with particular issues[4]	
		Initial evaluation	Operational phase	Initial evaluation	Operational phase	Initial evaluation	Operational phase
Hydro-sedimentary regime	Currents	Data on local efficiency: speed of the density current	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
	Transport /dispersal	Data on local efficiency of the process	Not relevant	Helps to define extent of the potentially impacted area	Not relevant	Helps to define the potentially exposed zones with particular issues	Not relevant
Seabed	Bathymetry	Informs on the volumes extracted and on the efficiency of the operations	Informs on the volumes extracted and on the efficiency of the operations	Helps to define extent of the potentially impacted area (sedimentation or erosion)	Not relevant	Helps to define the potentially exposed zones with particular issues	Verification of impact after event (erosion or sedimentation)
Sediment quality	Density	Relevant solely if the notion of navigation depth represents a specific issue for the zone or the project					
	Particle size	Data on local efficiency of the technique: dispersal of fines	Not relevant	Helps to define extent of the potentially impacted area (increase in the proportion of fines)	Not relevant	Helps to define the potentially exposed zones with particular issues	Allows verification (if necessary) of the impact on completion of the works (fines)
	Contaminants	Mandatory checks before the works	Mandatory checks before the works	Mandatory checks before the works	Mandatory checks before the works	Mandatory checks before the works	Mandatory checks before the works
	Nutrients	Relevant if there is an issue related to the presence of nutrients in the zone					
	Organic matter	Relevant in case of a particular issue with the living environment and organic matter (eutrophication, etc.)					
	Bacteriology	Verification of the micro-biological quality of the materials					
Water quality	Suspended sediments	Data on the extent of the density current and its dispersal (if necessary, monitoring of the plume by ADCP)	Verification of water quality during operations (point tests) or use of existing monitoring network	Helps to define extent of the potentially impacted area (if necessary, monitoring of the plume by ADCP)	Verification of water quality during operations (point tests)	Helps to define extent of the potentially impacted area (if necessary, monitoring of the plume by ADCP)	Verification of water quality during operations (point tests)
	Temperature /salinity	Verification of presence of a thermocline/halocline in the zone	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
	Dissolved oxygen	Data on the overall quality of the water column	Relevant if issues detected when first used	Data on overall quality of the water column	Relevant if issues detected when first used	Data on overall quality of the water column	Relevant if issues detected when first used
	Contaminants	Verification of absence of impacts	Relevant if issues detected when first used	Verification of absence of impacts	Relevant if issues detected when first used	Verification of absence of impacts	Relevant if issues detected when first used
	Nutrients	Verification of absence of impacts	Relevant if issues detected when first used	Verification of absence of impacts	Relevant if issues detected when first used	Verification of absence of impacts	Relevant if issues detected when first used
	Organic matter	Relevant in case of particular issues in the living environment and organic matter (eutrophication, etc.)					
	Bacteriology	Verification of absence of impacts	Relevant if issues detected when first used	Verification of absence of impacts	Relevant if issues detected when first used	Verification of absence of impacts	Relevant if issues detected when first used
Living environment	Benthic species	Baseline conditions	Baseline conditions possibly updated	Baseline conditions	Baseline conditions possibly updated	Verification of absence of impacts (depending on water and sediment quality issues), use of existing monitoring system	Relevant if issues detected when first used
	Pelagic species	Not relevant	Not relevant	Not relevant	Not relevant	Long-term monitoring depending on the issues	Long-term monitoring depending on the issues

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[4] Examples of areas with specific sensitivities (depending on site characteristics): oyster farming area, natural conservation area, area with sensitive industrial activity, bathing areas, etc.

6 - CASE STUDIES

6.1 - Introduction

The purpose of this chapter is to propose concrete cases of water injection dredging application and appropriate monitoring methodologies, respecting the general methodological principles set out previously. Three 'standard cases' of application of WID are thus proposed:

- case study No.1: maintenance dredging by water injection in an estuary port,
- case study No.2: maintenance dredging by water injection in an inland port,
- case study No.3: maintenance dredging in harbour basins.

6.2 - Case study No.1: dredging in an estuarine port

6.2.1 - Context

The present case study corresponds to the configuration of an estuary port. The maintenance dredging volumes may range from several hundred thousand to several million cubic metres per year, in an extremely dynamic environment, characterised by the strong currents caused by the flood and ebb tides and the river discharge.

Estuaries are generally characterised by the presence of a maximum turbidity zone, the position of which varies according to the river discharge. The site may also be affected by a substantial drop in the concentration of dissolved oxygen during low flow periods.

Implementation of water injection dredging in an estuarine environment must also take into consideration the following factors:

- complex currents: successful implementation of the project requires in-depth knowledge of the local currents,
- stratification: the thermoclines or haloclines may have a significant effect on the density current; knowledge of these is an important technical variable for the dredging project,
- the problems of resuspension, sedimentation and calculation of dredged volumes are made more complex by the possible presence of a maximum turbidity zone (high natural turbidity values and their variability over time make it impossible to distinguish between the effects of the water injection dredging operations and the natural phenomena),
- the sediments must carry little or no contamination,
- contaminant desorption and hence the monitoring of this variable of water quality is a less critical issue than in the river environment: the effects of injection dredging are negligible compared to the desorption phenomena that occur at the point of transition from the freshwater to the saltwater environment.

Estuaries are generally the subject of large-scale environmental monitoring.

6.2.2 - Dredged zones

In the case of an estuarine port, the dredged zones generally correspond to:

- the channels,
- the berths,
- levelling-off of dunes or furrows,
- areas crossed by cables or pipelines.

6.2.3 - Implementation of water injection dredging

The dynamism of the estuarine environment requires a specifically adapted strategy for using injection dredging. The remobilised sediments are rapidly picked up and diluted in the local currents. They again become part of the local natural sediment transport, and are not therefore intended to reach a specific disposal zone.

The potential impacts of this application of injection dredging are often limited because the system imitates the natural processes that exist in the estuary, so that the increases in suspended sediments or the reductions in dissolved oxygen in the water column generally remain within the ranges of natural variations; they are therefore hard to detect. The increase in suspended sediments is more significant, however, and is concentrated towards the bottom.

During low-flow periods, dissolved oxygen contents are lower (risk of hypoxic or anoxic conditions) and therefore potentially vulnerable to a further decrease. Where the experiments performed show that water injection dredging does not adversely impact these situations, then monitoring and alert processes may be established so as to effectively manage water injection dredging practices during sensitive periods.

6.2.4 - Objectives of monitoring

The complexity of the estuarine environment requires the implementation of a suitable monitoring system - which is often complex and requires considerable means - when water injection dredging is first used, in order to correctly identify the potential local impacts of the technique and its efficiency. Depending on the observed results, the routine monitoring put in place for subsequent campaigns may be considerably reduced.

Thus, on first use or on an experimental basis, the monitoring will be aimed at acquiring the following data, if it is not already available:

- the physical data necessary to use the water injection dredging technique effectively: currents, local morphology, nature of sediments,
- the environment quality data necessary to determine the impacts (or absence thereof) of the technique (SS, dissolved oxygen, contaminants),
- knowledge of the habitats present on the site (definition of high-sensitivity zones).

For regular application, the monitoring will be aimed at checking the overall coherence over time of the conclusions reached by the first experimental monitoring.

It is advisable to use any estuary monitoring networks that are already in operation, possibly adapting them locally depending on the particular sensitivities.

6.3 - Case study No.2: dredging in an inland port

6.3.1 - Context

This case study corresponds to the configuration of an inland port. The volumes of maintenance dredging are generally lower than in an estuary, and in an environment that is characterised by regular strong currents (river flows).

The river environment has the following specific characteristics:

- the problems of haline stratification are less present than in estuaries,
- the dissolution of contaminants is potentially greater since these have not yet been subject to massive desorption on reaching the saline environment,
- the characteristics of the currents are relatively constant compared to estuarine currents,
- the natural turbidity values are generally lower (outside the maximum turbidity zones).

6.3.2 - Dredged areas

In the case of an inland port, the dredged areas are similar to those in an estuary.

- channels,
- the berths,
- levelling-off of dunes or furrows,
- areas crossed by cables or pipes.

6.3.3 - Implementation of water injection dredging

The strong currents in the river environment require a dispersive use of injection dredging: the remobilised sediments are rapidly diluted in the river transit.

Since the currents are one-directional, the density current trajectory is easier to anticipate.

6.3.4 - Objectives of monitoring

The fluvial environment is often less complex than an estuary, so the objectives of monitoring are therefore in principle easier to attain. The issues of environment quality are more important, however:

- the turbidity values are lower, which therefore implies a greater sensitivity to an increase in SS in the surrounding environment,
- increased sensitivity to desorption.

Thus, on first use or on an experimental basis, the monitoring will be aimed at acquiring the following data, if it is not already available:

- the physical data necessary to use the water injection dredging technique effectively: currents, local morphology, nature of sediments,
- the environment quality data necessary to determine the impacts (or absence thereof) of the technique (SS, dissolved oxygen, contaminants),
- knowledge of the habitats present on the site (definition of high-sensitivity zones).

For regular application, the monitoring will be aimed at checking the overall coherence over time of the conclusions reached by the first experimental monitoring.

6.4 - Case study No.3: dredging in a harbour basin

6.4.1 - Context

The present case study corresponds to a seaport with harbour basins, which may be tidal or enclosed wet docks. The volumes to be dredged are generally lower in an enclosed environment than in open waters. The natural local currents are non-existent or very slight. However, the morphology is often favourable: sedimentation close to the quays generating gradients towards the centre of the basin, accumulation close to the entrance lock (if applicable), etc. The objectives in terms of transport distance are modest since they are related to the dimensions of the basin.

The sediment consists of mud of a potentially poor quality, depending on the local history and the frequency of maintenance dredging operations.

6.4.2 - Dredged areas

The dredged zones generally correspond to:

- the wet dock entrance lock,
- along the quays,
- areas crossed by sub-marine cables and pipes.

6.4.3 - Implementation of injection dredging

Water injection dredging enables the sediments accumulated along the quays to be shifted towards the deeper zones in the centre of the basin. The injection dredger will therefore operate between the centre of the basin and the quaysides.

In a wet dock, the notion of a potentially impacted area or an area with particular issues is obviously affected by the fact that the impacts are circumscribed within the enclosed basin. The environmental issues are also much less present in an environment strongly influenced by man.

6.4.4 - Objectives of monitoring

The limited environmental issues and the relative control of the density current makes it feasible to apply reduced in situ monitoring. Moreover, the action of the injection dredger is relatively homogeneous: no particular morphological structure or local currents are likely to influence the density current in an unforeseen manner.

The in situ monitoring therefore needs to focus simply on the efficiency of the technique and avoiding conflict with the various users present on the site.

7 - SUMMARY OF THE REGULATORY CONTEXT

7.1 - Context

In France, the water injection dredging technique was authorised for the first experimental dredging operations, although these still represent only a minority of dredging projects. Considering that the objective is not to extract materials from the marine environment to dispose of them elsewhere, as with the other dredging techniques, the question arises of whether the conditions laid down by the existing regulations are appropriate.

This section sets out to describe in detail the legal regime applicable to this technique, in regard to the various aspects analysed in this guide and the existing regulations in the European countries that have been using injection dredging on a regular basis for several years.

7.2 - Examples of existing regulations in Europe

7.2.1 - Germany

The German regulations consider water injection dredging, widely used on the Elbe, Ems and the Weser since the 1980s and 1990s, to be a dredging technique on a par with the others.

The German authorities use the reference levels RW1 and RW2 that are assessed on a similar basis to the reference levels N1 and N2 in France: assessment of the harmlessness of the sample, but leaving the option of carrying out complementary studies on a case-by-case basis with a view to expanding the supporting arguments. This approach applies directly to water injection dredging, where the level of detail of the requisite environmental studies depends on these criteria.

7.2.2 - UK

In the UK, all dredging projects are subject to obtaining a licence. In the same way as the Germans and the French, the British use reference thresholds, interpreted in a broadly similar way. This procedure is used in the context of dredging operations and immersion, which cover more than 98% of cases in the UK.

Until recently, hydrodynamic dredging, including water injection dredging, was not subject to any specific procedure. Since 2011, however, WID projects have been brought under the same licensing procedure. A methodological guide to the criteria to be taken into account in assessing projects and issuing licences is currently under preparation by the CEFAS.

7.3 - Recommendations on criteria to be taken into consideration

In regard to the existing regulations in those countries where injection dredging has been used for several decades, it appears that water injection dredging should be considered to be a dredging technique on a par with the others, applying the same criteria concerning contamination levels.

However, the actual volume (as prescribed by French law, clause R.214-1 of the *Code de l'Environnement*) is more difficult to assess on account of the uncertainty surrounding the measurement of the volumes dredged by WID in certain natural environments. Three methods may nevertheless be envisaged:

- the volume may be calculated by the difference in cubic metres between a bathymetric survey performed before the operation and a second survey performed at least one week after completion of the operation, accepting the uncertainties and difficulties related to this type of measurement in an estuary (cf. paragraph 3.1.2 -),
- the volume may be calculated by difference between the natural bed level and the target dredged level, which may be different from the volume actually dredged on account of the discrepancies related to natural bottom variations on the site and the variations intrinsic to implementation of the technique,
- the volume may be estimated by considering a mean yield of the dredger for the duration of its use, which may be determined statistically after WID has been used on the site for a substantial period of time.

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APPENDIX 1:
WATER INJECTION DREDGING PLANT IDENTIFIED
(2012)

Dredger	*Owner*	*Year*	*Length (m)*	*Beam (m)*	*Air draught (m)*	*Draught (m)*	*Propulsion (kW)*	*Pump (kW)*	*Dredging depth (m)*
Norma	Boskalis	1981/2008	27	9.5	3	2.15	625	–	19
Arca	Boskalis	–	–	–	–	–	–	–	–
Hol Blank	Bremenports	2006	–	–	–	–	–	–	–
Hol Deep	Bremenports	–	–	–	–	–	–	–	–
Dhamra	Deme	–	31	10	–	–	–	–	22
Parakeet	Deme	–	31	11.75	3.75	3.07	–	2*184	25.7
Deltaqueen	Dutch Dredging	–	43.2	12.15	2.21	1.09	2*405	–	20
Airset	Dutch Dredging	–	31.8	10.12	2	1.2	2*185	2*220	20
Milouin	GPMNSN	1997/2011	36.8	14.02	–	2.20	2*486	2*545	20
Brotonne	GPMR	1985/2001	48.5	16.7	8.1	2.5	1193	2*382	5 à 20
Inai Terasek	Inai Kiara	2008	35.2	12	4	–	–	–	–
International Seaport Dredging Limited (ISD)	International Seaport Dredging Limited (ISD)	2009	31	10	4.8	3.4	2*1350	1200	4.5 à 22
MS Akke	Meger & van der Kamp	–	46	11.8	–	1.2	2*221 PS	2*240	23
Maasmond	Meger & van der Kamp	–	47.2	12	–	2.25	882	1250	21
Steubenhöft	Niedersächsisches Hafenamt	2009	–	–	–	–	–	–	–
Draga Tocantins	Van Oord	2009	35.72	8.25	2.57	1.7	2*261	447	20
Draga Rio Madeira	Van Oord	2009	35.72	8.25	2.57	1.7	2*261	447	20
Antareja	Van Oord	1995	47.17	11.22	4	2.84	2*447	2*350	20
Odin	Van Oord	2007	17.5	4.5	1.8	1.45	2*89	220	10

Dredger	*Owner*	*Year*	*Length (m)*	*Beam (m)*	*Air draught (m)*	*Draught (m)*	*Propulsion (kW)*	*Pump (kW)*	*Dredging depth (m)*
Wodan	Van Oord	2007	32.85	12.15	1.84	1.39	Tug	2*459	20
HAM 922	Van Oord	1992	29.8	6.06	2.4	1.8	17	502	20
Norham Camorim	Van Oord	1982/1995	46.28	15	3.5	2.96	3*223	1007	25
Iguazu	Van Oord	1999	43.8	12.5	4.2	2.9	2*746	2*285	26.85
Jetsed	Van Oord	1987/2003	37.34	13.85	2.2	1.4	645	452+400	24.9
Baldur	Van Oord	–	8.2	–	–	0.6	–	–	6.5
Njord	Van Oord	1994/2009	34.7	11.67	2.48	1.8	2*261	716	19
Sagar Manthan	Van Oord	–	–	–	–	–	–	–	–
BT 208	Weeks Marine Dredging Inc (USA)	–	–	–	–	–	–	–	–

APPENDIX 2:
USE OF WATER INJECTION DREDGING IN COUNTRIES OUTSIDE FRANCE

Use of water injection dredging in countries outside France (according to MEYER 2000, WILSON 2008 and PIANC 2012 – in press, completed by ARTELIA 2012)

–: no data available X: monitoring performed 0: no monitoring performed NR: not recorded

Country	Site	Regime	Date	Duration (days or hours)	Displaced volume (m^3)	Sediments	Contaminants	Monitoring			Model
								Phy	Chem	Bio	
UK	Broads	Fluvial	2006	16	7 900	D50=12-30µm / 60-80% fines	0	X	0	0	X
	Crouch	Estuary	January 1996	7	6 200	Clay mud D50=4µm	NR	X	0	0	X
	Don	Fluvial	1997	NR	Maintenance	Fine to coarse	PAH	X	X	X	0
	Port of Tilbury Bellmouth (Thames)	Estuary / Tide lock	1990-2011	NR	Maintenance 85 000 m^3/ year	Mud	TBT on lower layers	X	X	0	0
	Channel (Thames)	Estuary	Maintenance	NR	Maintenance 6 000 m^3/ year	Fine sand, mud, rarely coarse	NR	NR	NR	NR	NR
	Shell Bravo (Thames)	Estuary	NR	20h	60 000m^3/ year	Fine sand, mud	NR	X	X	NR	NR
	Custom House Jetty (Thames)	Estuary	1990-2011	NR	NR	NR	NR	NR	X	NR	NR

Country	Site	Regime	Date	Duration (days or hours)	Displaced volume (m^3)	Sediments	Contaminants	Monitoring			Model
								Phy	Chem	Bio	
	Robbins Wharf (Thames)	Estuary	1990-2011	NR	1000m^3/ year	Mud	0	0	0	0	0
	Oikos Terminal (Thames)	Estuary	NR	15h	60 000m^3/ year	Fine sand, mud	0	NR	NR	NR	NR
	Trenches for Petroplus Coryton	Estuary	NR	50h	105 000 m^3/year	Medium sand, mud, fines	NR	NR	NR	NR	0
	Limehouse (Thames)	Wet dock	Nov 2002 - Jan 2003	NR	NR	Fines	Nutrients	0	X	0	0
	Medway	Estuary	2001	NR	Deepening + 8 000 m^3/year maintenance	NR	NR	X	0	0	X
	Portsmouth	Ria	NR	NR	NR	NR	NR	X	X	0	0
	River Severn (Gloucester)	Fluvial - Estuary - Wet dock	2002-2012	NR	Maintenance	Sand/ gravel + fines	Ammonia	X	X	0	0

Country	Site	Regime	Date	Duration (days or hours)	Displaced volume (m^3)	Sediments	Contaminants	Monitoring			Model
								Phy	Chem	Bio	
	Port Hedgar (Scotland)	NR	1993	NR	NR	NR	NR	NR	NR	NR	NR
	Swansea Marina (Wales)		2007								
Germany	Elbe (Hamburg, Cuxhaven)	Estuary	Operation 1988-2011 Experiments 1997-1999	NR	Maintenance 400 000m^3/ year at the level of the port of Hamburg, NR on the estuary	Fine sand and mud	NR	X	X	0	0
	Weser (Bremenport, Bremerhaven)	Estuary	Operation 2003-2011 Experiments summer 2008	NR	NR several spot interventions 300-1 000m^3	Medium sand	0	X	X	X	0
	Ems (Herbum, Papenburg)	Estuary	Experimental, March 2010	8 days	NR	NR	0	X	X	0	0
	Eider (Tönning)	Estuary	1995	NR	NR	NR	NR	NR	NR	NR	NR

Country	Site	Regime	Date	Duration (days or hours)	Displaced volume (m³)	Sediments	Contaminants	Monitoring			Model
								Phy	Chem	Bio	
Nether-lands	Haringvliet	Estuary	1994	14 days	121 000	Mud	Contaminated by PCB, PAH, heavy metals	X	X	0	0
	Rotterdam	Estuary	1990s	NR	NR	NR	NR	NR	NR	NR	NR
	Groningen	Estuary	2011	NR	NR	NR	NR	NR	NR	NR	NR
	Outer harbour Terneuzen	Estuary	1988-1989	NR	NR	NR	NR	NR	NR	NR	NR
	Epon Harbor Groningen/ Delfzijl (Waddenzee)	Estuary	1989 1991	NR	NR	Fine sand	NR	NR	NR	NR	NR
	Channels - Waddenzee	Wadden-zee	NR	NR	NR	Mud	NR	NR	NR	NR	NR
	Texel (Waddenzee)	NR	NR	NR	NR	Mud	NR	NR	NR	NR	NR
	Scheldt	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR

Country	Site	Regime	Date	Duration (days or hours)	Displaced volume (m^3)	Sediments	Contaminants	Monitoring			Model
								Phy	Chem	Bio	
	Wet dock at Hanswert	NR	1992-1993	NR	NR	Mud and sand	NR	NR	NR	NR	NR
Ireland	Waterford	NR	1992-1993	NR	NR	Loam and sand	NR	NR	NR	NR	NR
Italy	Venice	Lagoon	NR	NR	NR	NR	NR	NR	NR	NR	NR
USA	Atchafalaya river	Estuary	2009	161h	33 440	NR	NR	NR	NR	NR	NR
	Galveston district (Houston Ship Channel)	Estuary	2001 (July-September)	13 days	272 331	NR	NR	NR	NR	NR	NR
			2004 (July-November)	89 days	435 775						
	Hudson Estuary	Estuary	June 2005	7 days	38 000	Mud	NR	X	NR	NR	X
	Upper Mississippi	Fluvial	July-August 1992	4 days	6 154	Fine sand 0.3-0.4mm	NR	X	0	0	0
	Mississippi	Estuary / Fluvial	2009	565h	264 700	NR	NR	NR	NR	NR	NR
	Mississippi NR Port of New Orleans	Estuary	1998, (January-March)	57 days	500 371	NR	NR	NR	NR	NR	NR
			2001 (February-March/Aug.)	46 days	257 331	NR	NR	NR	NR	NR	NR

Country	Site	Regime	Date	Duration (days or hours)	Displaced volume (m^3)	Sediments	Contaminants	Monitoring			Model
								Phy	Chem	Bio	
			2002 (June-July)	40 days	683 389	NR	NR	NR	NR	NR	NR
			2005 (March)	28 days	408 497	NR	NR	NR	NR	NR	NR
			2009	NR	NR	NR	NR	NR	NR	NR	NR
	Fernandina Harbor Marina	Estuary	2012	Project	Project	Project	Project	Project	Project	Project	Project
	Calcasieu river	Estuary	2009	86h	5 490	NR	NR	NR	NR	NR	NR
	Mobile district	Estuary	2005	5,5 days	NR	NR	NR	NR	NR	NR	NR
	Calumet	Estuary	1994	1 days	12 034	Mud	NR	NR	NR	NR	NR
		Tide lock	2009	22 h	17 245	NR	NR	NR	NR	NR	NR
Brazil	Sao Luis / Sao Marcos	NR	NR	NR	750 000/ year	Mud and sand	NR	NR	NR	NR	NR
	Itajai	Estuary	1999-2009	NR	Maintenance	NR	NR	X	X	0	X
Tanzania	Dar es Salam	NR	1997	NR	NR	NR	NR	NR	NR	NR	NR
New Zealand	NR	NR	1985	NR	NR	NR	NR	NR	NR	NR	NR
China	Hong-Kong	NR	1992-1994	NR	NR	NR	NR	NR	NR	NR	NR
India	Mumbai	NR	NR	NR	NR	Loam	NR	NR	NR	NR	NR
	Bombay	NR	1994	NR	NR	Loam	NR	NR	NR	NR	NR
	Kakinda	NR	NR	NR	1 980 000	Mud	NR	NR	NR	NR	NR
	Mangalore	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR

Country	Site	Regime	Date	Duration (days or hours)	Displaced volume (m^3)	Sediments	Contaminants	Monitoring			Model
								Phy	Chem	Bio	
	Hazira	NR	NR	45 days	NR	NR	NR	NR	NR	NR	NR
Belgium	Antwerp	Tide lock	2001	NR	Maintenance	Mud	NR	NR	NR	NR	NR
		Wet dock	February 2011	1 day	NR	NR	Heavy metals, PCB, TBT, etc.	X	X	0	0
Bangladesh	River Jamuna	NR	NR	2 years	Maintenance	NR	NR	NR	NR	NR	NR
Yemen	Ash Shihr harbour	NR	NR	45 days	NR	NR	NR	NR	NR	NR	NR
Argentina	Canal del Dique	Canal	NR	NR	NR	NR	NR	NR	NR	NR	NR
	Estuario de Bahía Blanca	Estuary	NR	NR	NR	NR	NR	NR	NR	NR	NR

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