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Framework for Research Leading to Improved Assessment of Dredge Generated Plumes

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Abstract

At a meeting held in Washington DC in January 2003 a number of organisations in the USA, including US Army Corps of Engineers (USACE) and Environmental Protection Agency (EPA), and Europe recognised the need for a more structured approach to conducting research into the generation and impact of sediment released by dredging. The authors were commissioned to produce a framework for research and presented some of the preliminary findings at WEDA XXIII.

The aim of the research was to produce a framework of the steps and knowledge needed to properly assess dredge-generated plumes. This begins with improving knowledge of the source term and finishes with real impact assessment. For each item identified, the state of knowledge that already exists is being reviewed and this is leading to identifying what further research (if any) is needed. An attempt will eventually be made to prioritise what research is most needed and will achieve the greatest initial contribution to the assessment procedure. In this way it is to be hoped that future research funding may be well-targeted and that it will be possible to better protect the environment without the need to invoke the precautionary approach quite so often, which sometimes results in possibly unnecessary expense or restriction on development.

The research presented here is still in progress and is to some extent an invitation to contact the authors with information that will help in setting priorities for research. The scope of the article has been focused primarily on the *physical* processes involved and their impacts. The research will also include contaminant release and impacts and it is hoped to present this in the future. The paper was presented at the WEDA XXIV in July 2004, Orlando, Florida and published in the *Proceedings*. It is reprinted here in a slightly revised form with permission.

Figure 1. The draft protocol has been used in Europe to monitor the trailing suction hopper dredger Cornelia (foreground) in Rotterdam in 2003. Left, the Cygnus, the Dutch Rijkwaterstaat's survey vessel that was used for the observations.

Introduction

There are two types of driving force that urge us to assess the effects of dredge-generated plumes, a genuine concern for the environment and the regulations that forbid us to dredge unless we can demonstrate that harm will not be caused to the environment. Ideally the two will work hand-in-hand but sadly this is not always the case. A brief summary of the latter pertaining to the USA and Europe is given first. The remainder of the article is then devoted to the research.

Regulations

London Convention 1972

The London Convention is a global convention with about 90 member countries. Members agree to introduce legislation in their own countries in order to implement the Convention. The aim of the Convention is to protect the marine environment. Its application is limited to non-territorial waters although many countries choose to apply it to their territorial waters, including estuaries. Impact assessment is supposed to include potential effects on human health, living resources, amenities and other legitimate uses of the sea. It has to define the nature, temporal and spatial scales and duration of expected impacts based on reasonably conservative assumptions.

At present the Convention covers only deliberate placement of dredged material in the sea. Some parties would like to see the scope of the convention increased to include regulation of the dredging process and the geographical boundaries extended. A paper presented by The Netherlands (LC 72, 2003) put forward a number of options about this but there was not much enthusiasm from most other parties for a major change in the scope. OSPAR is going through the same discussion.

OSPAR Convention

OSPAR functions in a similar way to the London Convention but only applies to countries bordering the North Sea and North East Atlantic. It too has dredged material guidelines that are very similar to the LC guidelines for dredged material and there is little value in repeating the above discussion.

More significant is that OSPAR is more enthusiastic about moving towards regulating dredging operations. A working group is in the process of preparing papers covering the effects of capital works, maintenance works and aggregate dredging. This is at an early stage so it is not possible to be precise about what new regulatory processes may emerge. However, it would be wise to take into account in any research the possible need to monitor dredging operations in addition to disposal. Most, perhaps all member countries apply OSPAR to their territorial waters.

EC Water Framework Directive
The European Community's Water Framework Directive (EC-WFD) came into force on December 22 2000 and now has to be incorporated into national legislation in the Member States. Its aim is to bring about co-ordinated management of water systems, extending beyond national and state boundaries. It is expected that the Directive will stimulate an all-embracing approach to water protection with a stronger ecological focus and that, in addition, economic considerations will increase in importance. The Directive will affect the way that dredged sediments are handled.

The EC-WFD mentions themes of dredging and dredged material only indirectly, in Appendix VIII, in the sense that "suspended solids are some of the most important harmful substances". Those who are experts in dredging and dredged material know that suspended solids are an essential part of the biological system of a river and will naturally become sediment in the river at some later stage further down stream. Eventually, this sediment will appear to dredging operators downstream as "material to be dredged".

In future, bodies of water are to be managed according to standardised principles and objectives in relation to river basins, i.e. all the way through from tributaries to coastal waters. Administrative and state boundaries will no longer be relevant.

A good ecological and chemical status is to be achieved within 15 years in the case of surface waters, and a good ecological potential and good chemical status is to be achieved in 15 years in the case of heavily modified or artificial water bodies. In addition, the ban on deterioration will apply. In Annex X, the Directive contains a list of 32 priority substances, 20 of which accumulate in the material in suspension or in the sediment. Apart from known parameters such as mercury and cadmium, the list also includes new, previously less well-known groups of substances.

Environmental Windows
The US National Academy of Sciences (NAS) held a workshop in Washington DC in March 2001, resulting in "A Process for Setting, Managing and Monitoring Environmental Windows for Dredging Projects" (NAS 2002). On behalf of CEDA Neville Burt carried out a review of the windows concept as it is being considered or applied in Europe. The following is based on extracts from the resulting paper (Burt 2002).

One factor is common in the comments of those consulted, that there are inherent problems in the concept which may not only unreasonably restrict dredging operations (with consequences for social and economic costs) but may actually increase the risk of environmental harm.

In the USA the concept of Environmental Windows was introduced about 30 years ago and now about 90% of civil and maintenance dredging works are confined to specific periods of the year. In Europe, until recently the majority of dredging operations have been allowed to proceed all year round. However since the introduction of the EU Directives for the conservation of Natural Habitats and protection of birds (Habitats Directive and Birds Directive) the effects of dredging operations have and are being considered in more detail leading to the idea of introducing the concept Environmental Windows.

Whilst Environmental Windows appears to be a simple tool to limit the environmental impacts, people directly involved in environmental dredging issues in Europe are concerned at the severity with which it is being applied in the US and would seek to avoid such problems in Europe. The concept places a great deal of pressure on those promoting a dredging operation to prove that it will not cause harm to the environment. Scientifically this is a very difficult thing to do. All of this results in critical standards or windows being set based on something that is not yet capable of being measured or predicted and the actual environmental impact of which is hardly known.

In the face of these things the only solution would seem to be research to gain a better understanding of the real effects of dredging as opposed to the perceived effects, and further investigation into ways of mitigating those impacts. It will also be essential to communicate the results of the research in an effective way so that policymakers, decision makers and stakeholders understand and accept them.

Review of Mechanisms of Sediment Release

The mechanisms of sediment release by dredging operations have been presented previously (Burt and Land 2003) and to those involved they have become fairly familiar. However, quantifying them is another matter. Models of source terms have been produced (e.g. TASS, (Burt *et al.* 2000)) but remain largely uncalibrated. The problems are:

– the lack of a consistent definition of sediment release,
– the practical difficulty of taking measurements,
– identifying suitable opportunities, and
– the cost of obtaining the measurements.

To try to gain international co-operation in obtaining calibration data two initiatives have been taken, the production of a protocol for taking measurements (HR Wallingford and DRL, 2003) and the setting up of a co-operation group called ACCORD (Advice and Consultation Committee on Re-suspension by Dredging).

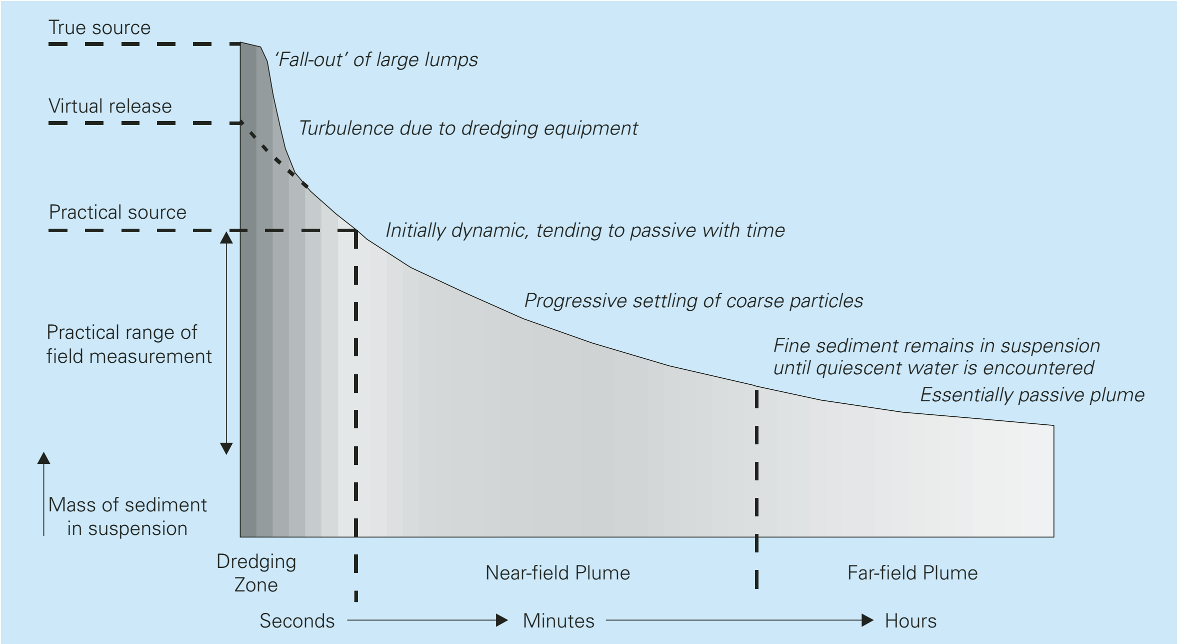

Figure 2. Definition of sediment release.

Development of the protocols was commissioned by a consortium of Dutch dredging contractors (VBKO) together with the Dutch Rijkswaterstaat. The draft protocol was circulated to selected experts worldwide and the comments received were taken into account in the version released in June 2003. It is seen as a living document and will be updated regularly in the light of practical experience. So far it has been used in Europe to monitor a trailing suction hopper dredger in Rotterdam in 2003 (Figure 1) and a grab dredger working on the River Tees in 2000 (a brief account was given of the Tees measuring exercise at WEDA XX and an account of the Rotterdam experiment was given at WODCON XVII in September 2004). It has also been used on the Providence River in the US in 2003.

The protocols include a definition of sediment release as illustrated in Figure 2. The protocols are available for general use and may be obtained from the authors. Protocols in summary form are available on the ERDC Vicksburg (Mississippi) website, http://el.erdc.usace.army.mil/dots/accord/index.html.

ACCORD was initiated following a meeting in Washington DC in January 2003, organised by the US Army Engineer Research and Development Center (ERDC) (Clausner 2003). The purpose of the Washington meeting was to bring together those involved in research on sediment and contaminant resuspension. It was attended by representatives of the Environment Protection Agency, the Minerals Management Service, ERDC, other Corps of Engineers offices, academia from the USA and number of researchers from Europe. ACCORD held its first meeting in London in November 2003 and its second meeting took place at the ERDC in Vicksburg in May 2004. At present it is simply a group of people with a common interest. It is thought that to be effective it needs to be more formally constituted. The main aim is to identify opportunities for measurement of sediment release using the internationally reviewed protocol and to share the knowledge gained from the results, though it may be extended as a forum for other areas of related research.

The sediment released or re-suspended by dredging operations should properly be seen in the context of natural variability due to river flow, wave action, etc. and the framework for research should take this into account (Figure 3).

Finally it should be noted that dredgers are not the only anthropogenic sources of sediment release. Shipping operations, particularly when large vessels are manoeuvring onto or off berths can cause bed sediment to be brought into suspension. This remains largely unquantified but is likely in most situations to be a much more frequent occurrence than a dredging operation (Figure 4).

Review of Mechanisms of Contaminant Release

Although many contaminants are associated with sediment they do not necessarily move or behave in the same way when disturbed by dredging.

Principally, the physicochemical environment controls the processes involved with the immobilisation and

Figure 3. Released or re-suspended sediment should be seen in the context of natural variability such as river flows and wave action.

mobilisation of sediment-associated contaminants. The main sediment properties affecting the reaction of the sediment with contaminants are clay type and content, organic matter content, cation exchange capacity, reactive iron and manganese, oxidation-reduction potential (redox), pH and salinity. Of these properties, it is the clay, organic matter, pH change and redox conditions that predominantly influence the mobilisation of contaminants from the sediment.

Contaminant mobilisation occurs owing to a dredging induced change in physicochemical sediment conditions. Where dredging causes a sediment plume to arise, the physicochemical environment changes considerably and substantial contaminant release can occur. This reaction is not always the case and a change in the physicochemical environment can release contaminants from the sediment yet favour other immobilising reactions.

There are various contaminants that pose a risk to the marine environment. The main contaminant groups include heavy metals, hydrocarbons and organochlorine compounds. In addition, there are other specific contaminants of environmental concern such as tributyl tin (TBT), the biocide agent used in anti-fouling paint formulations. The environmental effect of each contaminant differs, depending upon the receiving environment, but contaminants are often discussed in terms of their toxicity, ability to bioaccumulate and environmental persistence.

Heavy metals

Metals enter the aquatic environment from both natural and anthropogenic sources. Trace amounts of metals arise from the weathering of rocks and soils. Natural contributions can be high in areas of metal ore bearing strata. Large quantities of metals enter the environment through diffuse sources such as run-off and atmospheric deposition in addition to point sources such as domestic and industrial wastewater discharges. Metals are used in many industries including manufacturing processes and as chemical catalysts.

Metals discharged into the naturally turbid estuarine water can be rapidly bound onto the surface of fine suspended sediment particles, by various adsorption processes. As the suspended sediment settles to the bed, the associated metals are gradually buried and become immobilised in anoxic sediment conditions.

Metals (and other contaminants) are of concern because of their toxicity, persistence and tendency to bioaccumulate in living organisms. In addition to the amount of a metal present, toxicity depends upon the degree of its oxidation and the form(s) in which it occurs. The ionic form of a metal is generally the most toxic (eg. cadmium 2+). Toxicity can be increased if the metal is complexed with natural organic matter. Metallo-organic compounds such as methyl-mercury form under certain natural conditions and exhibit greater toxicity than inorganic elements alone.

A metal's ability to remain in the environment is known as its persistence. Unlike some organic substances (ie. hydrocarbon and organochlorine compounds), metals tend not to decay at any appreciable rate and

Figure 4. Other anthropogenic sources of sediment release such as shipping operations, ferries and other vessels can be seen in this aerial view of Hong Kong.

therefore can remain indefinitely within the aquatic environment.

Aquatic organisms may bioaccumulate metals, depending upon the organism's physiology and the degree of metal bioavailability. Bioaccumulation is the ability of an organism to accumulate contaminants in body tissues. Depending on the degree of bio-accumulation and the sensitivity of the particular organism, accumulated contaminants can cause toxic effects such as tumours, bodily deformation and even death.

Hydrocarbon and organochlorine compounds

There are many types of hydrocarbon compounds and organochlorine (OCl) compounds that can adversely affect the marine environment. The compounds most commonly occurring in dredged material are poly-nuclear aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs) and OCl pesticides.

In the aquatic environment, PAHs are found at low concentrations in water due to poor aqueous solubility. However, they are easily adsorbed to organic matter and inorganic particles in the water column and, should local sources exist, are likely to arise in deposited river silt.

In the aquatic environment, PCBs tend to be adsorbed quickly by organic matter because of their hydrophobic nature.

Unlike many other contaminants, OCl pesticides are designed by manufacturers to be distributed in the environment, supposedly targeting a particular pest.

Other contaminants

Tributyl tin (TBT) is often of concern during dredging projects. Since the discovery of its biocidal properties in the 1950s, the industrial application of TBT includes its use as the biocide agent in anti-fouling paints and coatings, molluscicides and agricultural fungicides. TBT enters estuaries from a limited number of point sources including dry docks and marinas, and many diffuse sources such as vessel hulls.

Because of its hydrophobic nature, once in the water column TBT readily comes out of solution and adsorbs to particulate matter and sediment. TBT also binds with phytoplankton, thereby introducing it to one of the lowest levels of the food chain.

Contaminant mobilisation between sediment and water

The risk of contaminant mobilisation affecting water quality and having subsequent environmental effects on aquatic life needs to be put into context with regard to the partitioning behaviour of individual contaminants. Contaminants have different degrees of solubility. Metals, such as lead, are quite insoluble and their partitioning from sediment is largely controlled by changes in pH. The potential for contaminant partition-ing from the sediment to water can be measured through laboratory research. For example, sediment-water partition coefficients for TBT vary considerably, but are mainly are in the order of 103-104 (Waldock *et al.* 1990). It should, therefore, be recognised that many of the contaminants mobilised by dredging actually remain bound to re-suspended sediment rather than become dissolved into the surrounding water (limiting their potential impact). The environmental impact of mobilised contaminants is more of a concern after sediment plumes have settled on the seabed.

Impacts

In the research here described the environmental effects have been related, as far as possible, to different types of dredging project, sediment types, plume types and dredgers. Short-term and long-term effects have been identified, highlighting how sediment plumes affect the water column and seabed in different ways and the influence of natural variability on this.

The baseline dataset must cover natural variations and seasonal patterns in order to provide the context within which to determine if a *change* constitutes an *impact*. A variety of factors need to be investigated in order to make predictions regarding the effects of dredging, including knowledge of existing water quality, biological communities, substratum, fisheries and shellfisheries resources.

It is important to determine the thresholds of acceptability in any particular environment, in terms of the tolerance of the species present, and to relate this, for example, to the environmental change caused by the re-suspension and movement of a sediment plume, particularly the concentration of re-suspended sediment that can be tolerated over the background concentration. Such thresholds will be site specific and species specific. Some fish species are tolerant of turbid water conditions and so dredging-induced increases in turbidity might not cause a significant long-term effect.

In essence, therefore, in order to determine whether an *effect* constitutes an *impact*, information is firstly needed on the plume's concentration and its footprint, secondly on the duration of the plume, and thirdly how this compares to background levels and the tolerances of the species present.

The environmental effects associated with sediment plumes tend to occur as a result of two types of direct physical environmental change. Chemical changes can also occur if the sediment in the plume changes physicochemical conditions by reducing dissolved oxygen levels or introducing toxic contaminants to the marine environment.

The first physical change is associated with the presence of the sediment plume in the water column, which increases the concentration of suspended sediment in the affected water. In the context of marine biological resources, the effect of a sediment plume in the water column depends greatly on background suspended sediment concentrations and the ability of marine life to either cope with or adapt to a change in conditions.

The second change occurs when the sediment plume settles out of suspension, thereby changing the environmental conditions of the seabed. Denser, deeper sedimentation might occur when a dynamic plume reaches the seabed compared to shallower, dispersed sedimentation from a passive plume. In the context of marine biological resources, the effect of sedimentation on the seabed depends greatly on the existing substratum and the ability of benthic life to either cope with or adapt to changed conditions.

Research Framework

Since the aim of the research framework is to identify and prioritise areas where research is needed to be better able to assess the effects of dredge resuspension it seems logical that the framework should be based on an assessment framework. This will help to identify what we need to know to improve confidence in our decision making. Prioritisation can then be based on a more "joined up" approach than simply choosing things that we would like to study because they are interesting.

The assessment framework does not need to be complicated. In broad outline it consists of a number of basic questions. Of course this may lead to many more in-depth questions that can be difficult to answer.

A general assessment framework is given in Figure 5 and a draft research framework is given in Figure 6. It is a logical breakdown of the questions that need to be answered in making an assessment, the mechanisms (in very simple form) that we believe have the potential to bring about an impact and the tools that are either available or need to be developed to give quantitative predictions of impacts.

Priorities

It is not possible in the context of this paper to give a full priority assessment, partly because the information needs to be presented in a much more detailed way and partly because the review process is still underway. However, it is appropriate for the authors to make a few comments.

How much sediment is released?
Many of the measurements made over the last 20 years have been made in still water situations. This means that any sediment falling relatively quickly to the bed is not measured and the suspended solids concentrations that are measured are those due

primarily to diffusion out of the dredging area rather than advection. This suggests that release rates will be underestimated in the case of flowing water.

Measurements have also generally been made either with bottle or pumped water samplers or with turbidity meters. The main difficulty with water sampling techniques is the limited number of samples that it is possible to take in a plume that is transient, constantly changing in both dimension and sediment concentration. Calibration of optical systems is very poor when there is sand present in the suspension, again tending to give underestimates for any sediment coarser than silt. ADCP techniques show promise but still require a lot of effort and skill in calibration and interpretation.

Referring to the diagram of sediment release (Figure 2) it is clear that it will remain impossible to measure what happens in the "dredging zone". The fact that material settles back into the area being dredged is not of great concern since it is already accepted that the bed in this area is being greatly disturbed. It is of more importance to know how much sediment may travel out of the dredging zone and thereby affect the aquatic environment. The definition postulates a "virtual release rate" which, although virtual is very important to know because all other aspects of the assessment process depend on it. It does require measurements to be made at several sections downstream of the dredger.

Dredging process
To study this aspect process models are needed. As stated previously some models exist but lack field calibration. This has to be regarded as a high priority because until it is known how much sediment is released and at what rate, the impact assessments are based on guesswork. Additional models are needed for specialist dredgers that are used in environmental clean-up projects (Superfund projects in the USA) and calibration data are needed for all of them.

Related to this is the determination of how much sediment is released by the action of the draghead in the case of a trailing suction hopper dredger. The re-suspension process is a combination of hydraulic erosion caused by turbulent kinetic energy and a bulldozing effect. The hydraulic erosion lends itself to computational fluid dynamics modelling (CFD) combined with classic bed erosion theory. A literature search has not revealed any formulations for the bulldozing effect. It does not lend itself to a purely theoretical approach and will probably require physical modelling to observe the processes taking place.

Mitigation
It is also important to know if the rate of sediment release can be controlled by operating the plant in a special way or selecting special plant (always with a cost penalty).

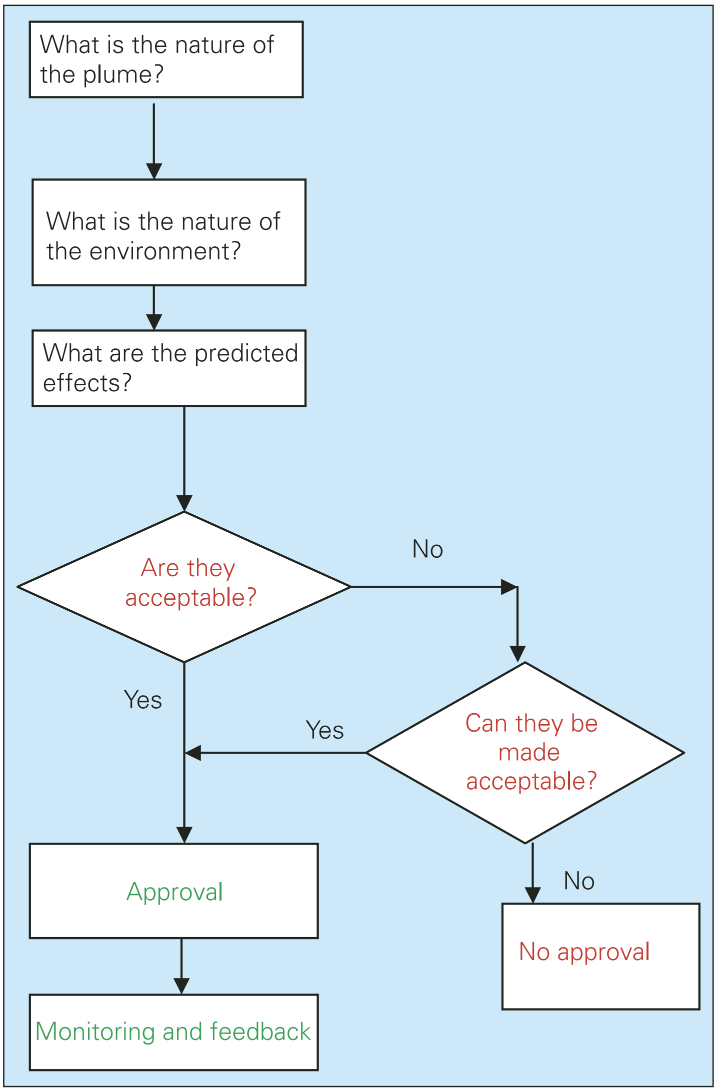

Figure 5. A simple assessment framework.

Perhaps not directly relevant to the release of sediment but relevant to some projects is the use of silt screens to restrict the release of sediment from the dredging area. In the authors' experience these are often specified in dredging contracts without any real knowledge of their practicality or effectiveness. Research is needed to provide guidelines for their use. Past experience on use of silt screens in almost all navigation dredging projects has shown them to be of essentially no practical value beyond aesthetics, while increasing costs and operational complexity.

Soil properties
As part of the modelling process we need to understand the way that various soils behave when subjected to dredging processes. In most cases the forces acting on the sediment are a combination of mechanical and hydraulic forces. Existing formulations tend to use the percentage fine material present assuming it all to become available for re-suspension. This does not account for properties of cohesion which, in the case of

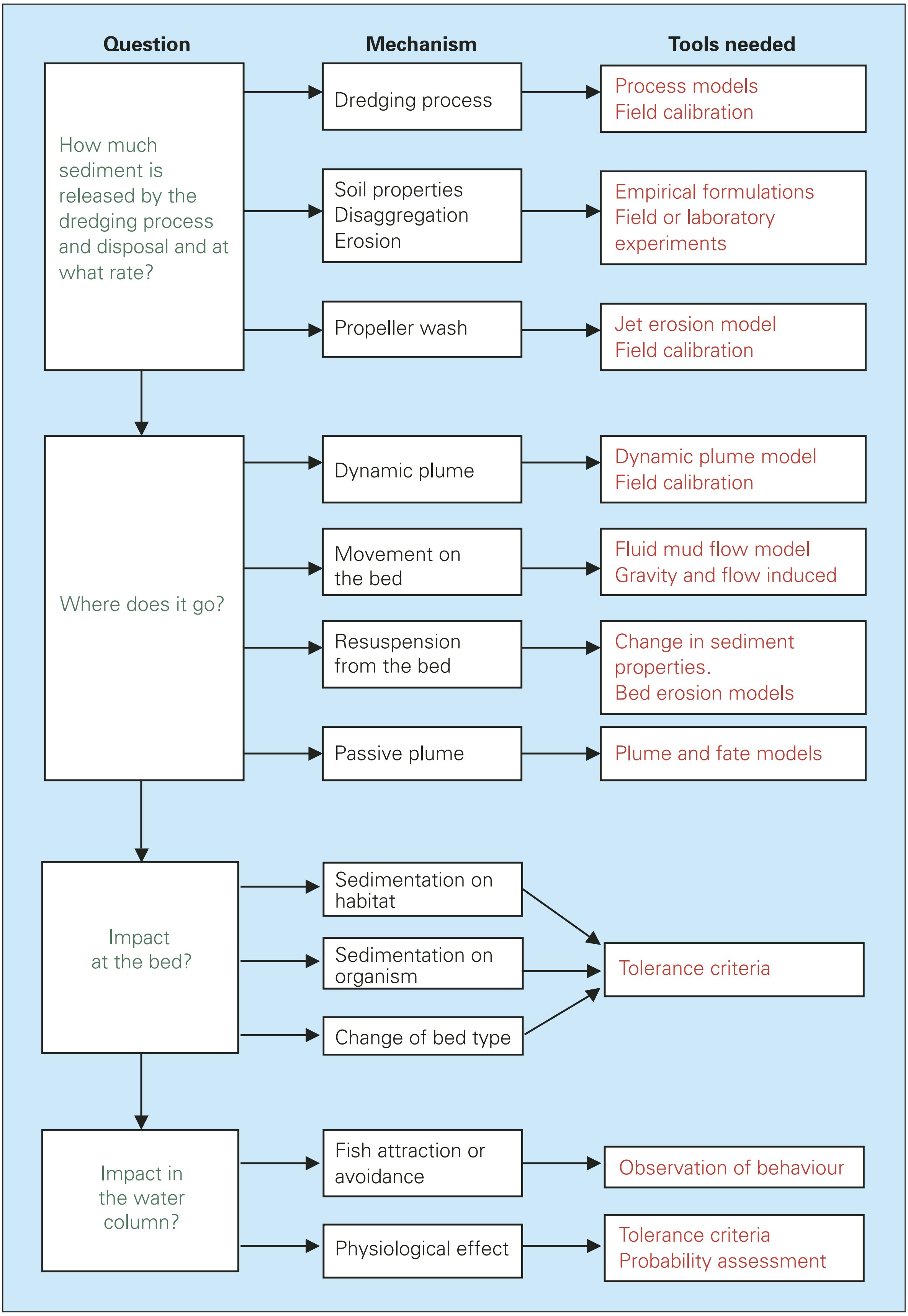

Figure 6. Research Framework A – Physical Impact.

clay-size particles, is very strong. In that particular case the dredging process often results in the formation of clay balls rather than release of the very fine material. There is a need for research to identify and correlate the relevant soil properties and perhaps a new soil disaggregation test to be developed.

Propeller wash
The trailing suction hopper dredger may re-suspend sediment by the turbulence caused its propeller. Models exist for jet induced erosion but recent studies by Maynard (pers. com. 2004) have shown that the pressure wave caused by a passing vessel may actually re-suspend more material than the propeller.

The importance of both draghead and propeller re-suspension can be questioned on the grounds that in most muddy situations overflow is not efficient and often not allowed. In sandy areas where overflow improves the dredging efficiency the losses are orders of magnitude higher than those created by either the draghead or the propeller. The only relevant application is thus when dredging in sandy material in an area thought to be very sensitive to turbidity, for example in the case of coral.

Of course it is not only dredgers that resuspend sediment by propeller action or by towing equipment along the aquatic bed. Perhaps in making impact assessments the effects of dredging should be examined in the context of the effects of shipping and fish trawling.

Where does it go?
This is probably the question that has been given most attention in research, both pure and applied, to date.

Dynamic plume
The density-driven dynamic plume phase is complex but has been well researched and modelled. In the case of stationary dredgers the dynamic plume, if one exists at all, descends into the dredging zone so for reasons already discussed is probably not very important. For the overflowing trailing suction hopper dredger and especially in the case of aggregate dredgers, which also screen the material, the material may be released over a large area and could be important depending on the circumstances.

Another case where a dynamic plume forms is disposal either through pipe discharge into the aquatic environment or, more commonly, disposal on the aquatic bed by bottom dumping from a hopper.

An important factor regarding the dynamic plume is the extent to which it acts a secondary source causing a passive plume. Recent dynamic plume models include this element. However, the great lack is in calibration data to ensure that predictions are reasonably accurate.

Figure 7. A dynamic plume is most likely to spread out like a pancake, and the affected area is small and predictable.

Movement on the bed
Material spilled or placed on the bed is often in a quasi-fluid form. The dynamic plume is likely in most cases to spread out like a pancake. Models of this part of the process have been in existence for many years.
The extent of the area affected is generally quite small and the impact reasonably predictable (Figure 7). Because the impact is obviously significant in terms of quantity and depth of material on the bed it would be most unusual for a dynamic plume to be permitted to occur in a sensitive area. The spread of the pancake is thus not considered to be a high priority for research, except perhaps for placement of contaminated sediment in a pit.

Resuspension from the bed
Material that has settled on the bed and whose properties have been changed by the dredging and/or disposal process may be re-suspended by hydrodynamic forces, i.e. currents and waves. Computer models exist that describe bed erosion by these processes, but what is not well known is how the properties of the material are changed between their in situ condition and in their new location. Some research has been carried out on this in the UK and in the USA using various types of field erosion devices, but more field work is needed to be able to predict the properties in advance of a project with any confidence.
The research should be linked to the research recommended earlier on disaggregation. Differential settling processes are also very relevant to this aspect.

Passive plume
Many passive plume models exist, mostly in the form of “add-ons” to hydrodynamic models. It is relatively easy to build a tracking function into a hydrodynamic model and add factors of settling and dispersion to determine the fate of the material. Whilst the models themselves are generally good they depend on the physical properties assigned to the material in suspension and once again this is probably the greatest area of weakness with them. The processes of flocculation

greatly affect settling velocities. In the authors' own experience of measuring settling velocities in the field an order of magnitude of difference can exist naturally between similar materials from different locations, without the added complication of the impact of dredging plant on the sediment (Burt 1986). Again the greatest need is for good quality field measurements of passive plumes to improve knowledge of this parameter.

It is noted that while some models do include re-suspension from the bed, others, such as SSFATE (Johnson 2000), currently do not. This is particularly relevant in some tidal situations where the only time during the tidal cycle when the turbulent kinetic energy is sufficiently low to allow settlement is at slack high or low water. The deposited material can in many cases be easily and quickly re-suspended by the accelerating flow in the next phase of the tide. Thus it is important, as in the previous section, to have a good knowledge of the relevant properties of the material (temporarily) deposited on the bed in order to predict how it will re-erode.

Impact at the bed?

Sedimentation on habitat

Should significant deposition of sand occur in areas that have a similar sediment type, the impacts on benthic communities are likely to be small. The benthic community in such an environment is likely to be adapted morphologically and behaviourally to a dynamic environment. It is, therefore, likely to be able to cope with the disturbance caused by sedimentation and this combination is not considered a high priority for research.

In gravel seabed environments, sedimentation is most likely to affect sessile species because they are unable to burrow or vertically migrate in response to an increased sedimentation rate. Sessile species include delicate organisms such as bryozoans and hydrozoans.

Sedimentation also affects filter-feeding epifauna, for example sponges. Coral and kelp forest communities are also susceptible to increased sedimentation rates (Selby and Ooms 1996).

The loss of key species in communities can lead to the collapse of the entire biologically-accommodated community even though individual species within the community may be apparently tolerant of environmental disturbance (Newell *et al.* 1998).

As shown in Figure 6 the main area of research needed is into the tolerance criteria. This applies to individual species and communities as a whole. "Tolerance" includes the ability of the species and/or community to recover because the temporary loss may have a lasting impact on species that rely on the habitat for spawning or feeding. Some research on recovery of seabed benthic communities is taking place in the UK at the present time but is still at an early stage.

Sedimentation on species

This includes direct smothering of susceptible organism life stages, such as negatively buoyant or adhesive fish eggs or larval shellfish that attach to the substrate. Most shellfish are able to cope with limited covering by sediment. Again the need is to establish reliable criteria for tolerance, including the ability to recover.

Change of bed type

This particularly applies to aggregate dredging where, for example, a gravel bed is dredged and the fine material is screened out and discharged back into the water. The benthic species that are adapted to gravel may not be tolerant of the new finer bed material. Again the need is to establish tolerance and recovery criteria.

Impact in the water column?

The physical, chemical and biological processes that take place in the water column are highly complex and it is beyond the scope of this paper to attempt to list them. With regard to the potential impact of additional sediment in the water column caused by dredging the effects are not well understood and there is much speculation about the impact on fish migration (Palermo *et al.* (1990), and Environment Canada (1994)). It seems obvious that fish have, in most practical cases, the ability to avoid a plume. Some have argued that far from avoiding a plume certain fish species are attracted to it because of the organic matter that is stirred up. This clearly requires research to clarify the issue because it has major implications on the application of Environmental Windows.

As with benthic impact the impact on the water column requires research into the tolerance of relevant species to temporarily increased sediment concentrations. This topic was recently reviewed by Wilbur and Clarke (2001). Additional research should include observation of the ability of species to tolerate natural variations such as during times of flood or storm, and other temporary elevations caused by shipping and fishing (trawling and shrimping).

Conclusions

The research presented here is still in progress and is to some extent an invitation to contact the authors with information that will help in setting research priorities.

It seems clear that there is much speculation about the impacts of sediment resuspended by dredging that is not backed by research. From the point of view of the authors it would appear that the greatest priority is to be able to measure and predict how much sediment is actually released by dredging and at what rate. Without this basic information it is not possible to produce meaningful correlations with environmental impacts. The development, verification and calibration of models is therefore an essential stage in the development of assessment tools. Furthermore, such models are needed to determine the effect of mitigative measures such as operating existing plant in a special way or using specialist environmental dredging plant.

It is also the authors' view that research on impacts should be carried out in the context of the ability of individual species and communities to tolerate (and perhaps even require) natural variations in suspended solids concentration caused by normal variations in rainfall and tides as well as more extreme variations caused by floods and storms.

Finally, it will also be essential to communicate the results of the research in an effective way so that policymakers, decision makers and stakeholders understand and accept them. One possible mechanism for assisting in this process may be the ACCORD group that has already been referred to.

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