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An Evaluation of the Behaviour of Pollutants During Dredging Activities

Abstract

The growing environmental concern in the world is also noticeable in the dredging world, especially in relation to dredging polluted sediments. The knowledge obtained during the last decades of the behaviour of pollutants in aquatic systems has been used to manage the environmental quality of aquatic systems. The situation during dredging differs from the regular situation, due to processes with short time scales and very heterogeneous environmental conditions. In this article the risks of dredging polluted sediments are shown to depend on the risk of dispersion and on the mode of occurrence of the pollutants. During dredging, shifts in mode of occurrence may occur which affect the availability for uptake by organisms (the bioavailability) and consequently the toxicity of the pollutant. The toxicity is highest in the free mode of occurrence, i.e. when the pollutant occurs as single molecules dissolved in water.

General descriptions are given of the behaviour of the two main classes of pollutants: heavy metals and organic micropollutants. Evaluating the processes occurring during dredging revealed the conditions and activities causing environmental risks.

As a conclusion, the risks of dredging polluted sediments are related to the uncontrolled dispersion of pollutants, both in dissolved state and in particulate state, and to the incomplete removal of polluted sediment. Shifts in environmental conditions may cause substantial release of pollutants to the water column. Complete removal of the polluted sediment is very important. When the new top layer of the sediment has higher concentrations than the top sediment prior to dredging both heavy metals and organic micropollutants may be mobilised. The liberation mechanisms, however, are different for both classes of pollutants. For heavy metals, iron chemistry may provide a temporary, partial safety belt preventing the dispersion of dissolved heavy metals during the dredging process. On the longer time scale of the after-dredging situation, however, substantial release of heavy metals into the water is expected. Consequently, for heavy metals,

temporary mixing with the water column on the short time scale (hours) can be allowable, whereas complete removal of the polluted sediment is important.

For organic micropollutants a substantial amount of Dissolved Organic Matter bound pollutants may enter the water column during dredging. Therefore, mixing with the water column should be avoided as much as possible. The mobilisation of organic micropollutants from resuspended sediment depends on the pollution level of the suspended solids in the water column prior to dredging. When the layer coming to top in the after dredging situation has a higher pollution level than the old top layer, substantial release of pollutants will occur. In that case complete removal of the polluted layer is important.

There is an urgent need for proper data collection during dredging projects to support the results of this evaluation. Based on the available knowledge and the data to be collected, sensible control options and measures can be designed for specific dredging projects in polluted sediments.

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Introduction

Over the last years the dredging world has faced growing public awareness of environmental issues and in many dredging projects "the environment" requires explicit considerations in the design phase as well as in the operational phase. The point of environmental awareness is very clear when dredging polluted sediments. Projects with the single, dedicated goal of removing pollution, are rare and the market for these projects, though promising, is only at its beginning. Nevertheless, many dredging projects are carried out in

polluted sediments, simply because dredging projects and pollution both have a strong link to populated, industrially developed areas. The problem of dealing with polluted sediments is thus very common. In the more general context of pollution in the aquatic environment, an overwhelming amount of data on the behaviour of pollutants in aquatic systems has been collected over the last decades. From the 1960s on, the problem of pollution has been recognised and, progressively, measures are being taken to reduce the loads on the waterways, especially in the western world. A substantial reduction of pollution level has been achieved in some cases. These measures have been founded by scientific research on the behaviour of pollutants in aquatic systems. The knowledge obtained has been formalised in numerous computer models, with which rather reliable predictions can be made of the effect of measures and management options on the pollution level of a specific system.

Surprisingly little, however, is known of the behaviour of pollutants *during dredging* (some relevant information can be found in: Calmano *et al.*, 1989; Kersten *et al.*, 1985; Hafferty *et al.*, 1977; Rice and White, 1987). Obviously, this is because environmental conditions during the dredging process are very complex and show a high variability in space and time. Dredging-related turbidity often occurs in "clouds", indicating steep gradients in suspended sediment concentrations. Steep gradients are also apparent from the relatively small zone of impact around dredging vessels in quiet water (50-100 m, Pennekamp and Quaak, 1990). The water movements in a dredging area are also very complicated as a result of density currents caused by the different densities in the turbidity clouds in combination with the currents caused by vessel propellers. In addition, the time scale of these processes is very short. Typically, the turbidity generated by the dredging process lasts only several hours (Pennekamp and Quaak, 1990).

This high variability and the short time scale differ substantially from the generalised conditions used in computer models for policy making and management of polluted water systems. These models are therefore not suited to the development of environmental control measures in dredging projects.

Nevertheless, the fundamental knowledge of the behaviour of pollutants in aquatic systems has developed enormously and could be utilised to improve the environmental quality of dredging operations. Recently, we performed an evaluation of the environmental aspects of the dredging process, based on fundamental, theoretical knowledge of the behaviour of pollutants. The aim of this evaluation was to provide better insight into the behaviour of the pollutants to be expected under dredging conditions. Although the evaluation was theoretical for the greater part, some

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important conclusions for the practice of dredging were derived. In addition, the insight obtained can help improving the environmental quality control of specific dredging operations on the basis of project-specific information.

In order to expand this knowledge to real dredging projects, there is an urgent need for proper data collection during dredging operations to support the conclusions. The combination of knowledge and collected data will provide a solid basis to design sensible control options of environmental aspects in specific dredging projects.

THE POLLUTANTS

Anthropogenic substances accumulating in aquatic systems can be distinguished into two groups:

- nutrients (Jones and Lee, 1975); and
- pollutants.

This study is confined to pollutants present in sediments which can be generally classified in two classes:

- heavy metals; and
- organic micropollutants.

This distinction is related to different (chemical) behaviour.

Understanding the potential risks of dredging polluted sediments requires some basic knowledge of the behaviour of both classes of pollutants. In addition, it is necessary to know how pollutants are present in the water and in the sediment (Table I).

Table I. The main forms of pollutants in the aquatic environment.

State	Dissolved (in pore water and water column)	Particulate (in sediment and suspended matter)
Mode of occurrence	– free – complexed	– adsorbed – precipitated

An important distinction is made between dissolved and particulate state. The state affects the potential for dispersion. The "particulate fraction" of a pollutant will be dispersed with particles. Any measure to control the dispersion of particles will also control the dispersion of this pollutant fraction. In the dissolved state, a pollutant is dispersed with the water. This type of dispersion is invisible to the human eye and difficult to control. Both dissolved and particulate states can be further specified into "modes of occurrence". Mode of occurrence is a general term for "speciation", which is the term chemists use for the different molecules in which a specific pollutant may occur.

The specification of the mode of occurrence is important for the chemical behaviour of the pollutants, especially for the heavy metals. The mode of occurrence is also an important factor in the "toxicity" of pollutants. A much higher toxicity is exerted in the free mode of occurrence than in a different mode as a result of increased "bioavailability", i.e. the availability for uptake by organisms.

Therefore, an evaluation of the risks of dredging polluted sediments should include a study of the possible shifts of states and modes of occurrence as a result of dredging activities, in addition to the possible dispersion of polluted sediment particles.

Heavy metals

Heavy metals occur in different modes in aquatic systems. Figure 1 shows the four basic modes of occurrence and the potential transfers of one mode to another. Central is the free mode of occurrence. In this mode, heavy metal molecules discussed in this paper (Cadmium (Cd), Copper (Cu), Mercury (Hg), Nickel (Ni), Lead (Pb) and Zinc (Zn)) occur as single, positively charged ions in the water. [The metals Arsenic (As) and Chromium (Cr) occur in negatively charged forms; these metals are not discussed here].

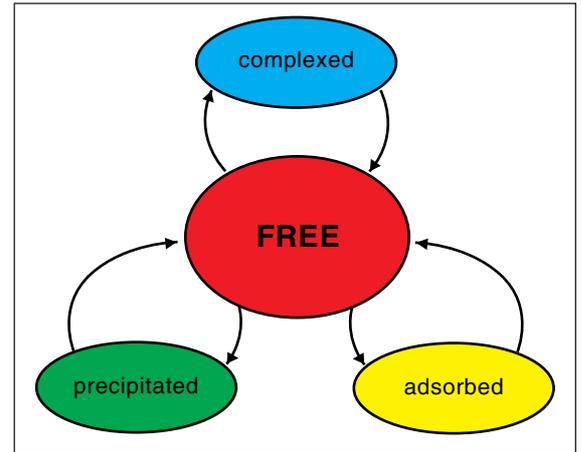


Figure 1. Description of the different forms of presence of pollutants and a schematised view on the possible shifts between modes of occurrence of heavy metals.

In the free mode, metals are transported with the water, are easily taken up by organisms and, generally, exert their highest toxicity.

From the free mode heavy metal molecules can shift to three other modes which differ fundamentally.

The complexed mode indicates a combination of the metal molecule with another molecule. Complexation occurs with so-called Dissolved Organic Matter (DOM), i.e. organic material which is too small to be particulate (i.e. < 0.45 µm) and with negatively charged molecules, e.g. metal-carbonate or metal-chloride. Both in the free mode and in the complexed mode the metal is in dissolved state.

In the particulate state, heavy metals may occur in an adsorbed or a precipitated mode. In the adsorbed mode, the metal molecules are adsorbed to the surface of particles. The bond of the metal to the surface is often the result of opposite electrical charges of the metal molecule (positive) and the surface of the particle (negative). This bond is very susceptible to changes in electrical charge of the surface, e.g. as a result of changes in pH (acidity) of the water.

The precipitated mode of metal ions is the result of precipitation from the water through formation of an insoluble salt with a counter-ion (mostly sulfide, see hereafter). The sulfide form is chemically stable as long as anoxic conditions are preserved.

In the particulate state the metals cannot be taken up directly by organisms (unless by ingestion of particles) and thus the toxicity is reduced as long as the particulate state is preserved.

In sediments only a small fraction of the total amount of heavy metals is dissolved because of a high ratio of sediment to pore water and the tendency of the metals to be bound to the particles. In anoxic pore waters the dissolved part is reduced further by precipitation with sulphide.

Measurements in the sediment of the Western Scheldt, The Netherlands, indicated that <1% of the amount of heavy metal (Cadmium, Copper and Zinc) in the sediment was in the dissolved state (Zwolsman and van Eck, 1993). This is a general phenomenon in anoxic sediments, caused by the very low solubility of heavy metal sulfides (Davies-Colley *et al.*, 1985; Moore *et al.*, 1988).

Figure 2 indicates how heavy metals can behave during dredging, i.e. through possible shifts in mode of occurrence. Clearly, all shifts proceed via the free mode of occurrence. The processes causing the shifts are under control of the environmental conditions. Changes in the redox conditions are very important, because oxidation causes a shift from the precipitated mode (metal-sulfides) to the free mode. The reverse, precipitation from the free mode to the insoluble precipitated mode, occurs under anoxic conditions.

Another important environmental parameter is the pH (acidity). The exchange between the adsorbed and the free mode strongly depends on the pH. A pH decrease may cause a very rapid transfer of a substantial fraction of the adsorbed amount to the free mode.

Organic Micropollutants

The class of organic micropollutants includes an enormous number of compounds. For the dredging world it is relevant that a common characteristic of many of these compounds is that they tend to stick to particles, preferentially to Organic Matter (OM). This behaviour is caused by their "oily" nature, i.e. their inability to dissolve in water.

A second common characteristic is that they are persistent (Poly Aromatic Hydrocarbons, PAHs) (Delaune *et al.*, 1981; Mille *et al.*, 1988) or are degraded very slowly (Poly Chloro Biphenyls, PCBs) in the sediment under natural, i.e. anoxic conditions (Brown *et al.* 1987). Due to the slow degradation rate, only the "exchange process" between water and particles (Organic Matter) is relevant for dredging. The class of organic micropollutants thus differs from the heavy metals, which cannot be degraded at all and show shifts in mode of occurrence mainly as a result of "chemical reactions", driven by redox conditions.

Organic micropollutants occur in only three modes:

- free,
- complexed or
- adsorbed.

The free mode and the adsorbed mode belong to the dissolved and particulate state, respectively. The complexed mode represents pollutants bound to Dissolved Organic Matter (DOM). Substantial amounts of organic micropollutants may adsorb to DOM, forming a complexed fraction which is included in the operationally defined dissolved state (particles <0.45 µm, Table I), although the micropollutants occur in bound form (Figure 3).

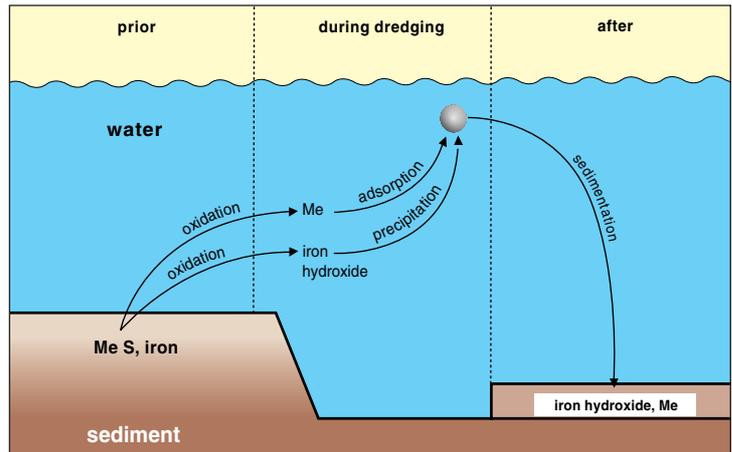


Figure 2. Schematised view on the shifts in mode of occurrence of heavy metals before, during and after dredging activities (Me: heavy metal; S: sulphide).

When looking more closely, there are also important variations in the particulate fraction, as can be concluded from the pollutant exchange characteristics. It is argued that penetration of pollutants into particles is important. Exchange processes are very slow as a result of slow diffusion of a pollutant from the inner side of the particle to the surface where the exchange processes take place (Brusseau *et al.*, 1991). Penetration of pollutants into particles may be caused by diffusion or by coverage of the outside of the particle by (organic) coatings (e.g. iron precipitation, see below).

These considerations are important when exchange processes (mobilisation and immobilisation) have to be quantified. To understand the behaviour of organic micropollutants qualitatively, however, a distinction between dissolved and particulate state is sufficient. The process of exchange between free and adsorbed mode is driven by a compounds potential to dissolve in water, which is determined by its molecular structure. A given total amount of a specific compound shows a distribution over free and adsorbed mode which is determined by its solubility. The distribution reflects a free concentration (in µg/l) in equilibrium with the concentration in the organic matter part of the particles (in µg/g). It is generally assumed that the ratio of these two concentrations is constant for a specific compound. This theory of the distribution is called the partition theory and is widely accepted. It has important consequences for the dredging case, as shown later.

Measuring the truly dissolved fraction of organic micropollutants is very difficult due to the low dissolved concentrations and the adsorption of organic micropollutants to Dissolved Organic Matter (DOM). Some calculations were performed which indicate that the truly dissolved fraction in the pore water is very low and reaches only about 2% of the total present amount for the best solving pollutants (e.g. lindane). The DOM-

bound fraction, however, deserves attention because this fraction may contain substantial amounts of pollutants. This fraction will be dispersed with the pore water when entering the water column during dredging operations and behaves independently from the particle fraction.

The description of the behaviour of organic micropollutants during dredging can be limited to the exchange of pollutant between dissolved and particulate states which is described below. Changes in environmental conditions have relatively little influence on this exchange and can be omitted in the analysis.

THE SEDIMENT

For the present evaluation two fractions of the sediment should be distinguished:

- the pore water and
- the solid part.

The pore water might be important because pollutants present in the pore water can mix directly with the overlying water column, thus escaping measures to control particle dispersion.

For the solid part the distribution of particle dimensions could be relevant because these classes might be different, e.g. with respect to concentrations of pollutants, dispersive properties, etc.. There is a general agreement that the greater part of the pollutants is bound to the "fine" fraction (< 63 µm). However, data of pollutants on that level are almost completely lacking. For the present evaluation the solid part is considered homogeneous.

MOBILISATION OF POLLUTANTS DURING DREDGING

The Dredging Process

During dredging, sediment is transferred from its original position to somewhere outside the system (via barges or transport pipe). This transfer has at least two side effects:

- part of the sediment is lost to the water column. This sediment, which is contaminated, can be dispersed into the adjacent environment forming the new top layer (after sedimentation).
- after removal of the dredging layer, the new sediment top layer is exposed to environmental conditions which differ from the situation prior to dredging (e.g. a shift from anoxic to oxic conditions, etc.).

Of course, many more side effects can be identified but, basically, the risks of dredging polluted sediments can be evaluated by considering these two side effects.

The Risks of Dredging Polluted Sediments

To evaluate the ecological risks of dredging polluted sediments both the amounts of pollutants dispersed into the surrounding environment and the toxicity of the pollutants are important.

As shown above, the direct contribution to the amount of dissolved heavy metals from the pore water is negligible while the direct contribution to the amount of dissolved organic micropollutants is low, unless there is a substantial contribution of DOM-bound organic micropollutants (e.g. in case of high DOM concentrations). When risks would be based on the amounts of the pollutants only, the amount of particulate polluted material entering the water column would be most important. With respect to toxicity, however, the increase in bioavailability which results from a shift from particulate to the free mode, is also very important. The risks of dredging polluted sediments are primarily related to activities or conditions promoting the shift of pollutants from the particulate state into the dissolved state.

Dispersion of pollutants with the suspended solids

Dispersion of pollutants may occur in both the dissolved and the particulate state. The latter form of dispersion is obvious and is recognised in the dredging world. The measures taken in "environmental dredging" projects are, in general, directed towards minimal dispersion of particles:

- The generation of turbidity can be minimised by using special dredging equipment.
- The dispersion of generated turbidity to the surroundings can be minimised by the utilisation of silt screens.

Measures to reduce the dispersion of particles will also reduce the dispersion of pollutants. However, this is not always sufficient, due to the potential dispersion of pollutants in the dissolved state.

Dispersion of pollutants in the dissolved state

The dispersion of pollutants in the dissolved state is less obvious because this process is invisible for the human eye. Nevertheless, it is clear that pollutants, once desorbed from particles into the dissolved state, will be dispersed with the water and thus escape control by silt screens or by other measures taken to prevent dispersion of particles. The risks of dredging polluted sediments thus include risks of creating situations which provoke desorption.

The dissolved amount of a pollutant in a sediment to be dredged is determined by the pore-water content of the sediment and the concentration of the pollutant in the pore water. Only a (unknown) part of this pore water will be lost into the water column. Depending on the thickness of the layer to be dredged, the porosity of the sediment, the loss percentage of pore water (depending on dredging equipment and operation) and

the depth of the water column, a substantial dilution of the concentration in the pore water occurs upon mixing with the water column.

Simple calculations indicate that the direct pore-water contribution of heavy metals to the water column concentration is (almost) negligible compared to the contribution by particles. This may hold also for organic micropollutants, but depends on the contribution of DOM adsorbed pollutants.

Since sediment particles contribute by far the greatest amount of pollutants to the water column during dredging, desorption from particles is the most important potential source of dissolved pollutants in the water column. Establishing the risk of desorption of pollutants from particles requires an analysis of the behaviour of the pollutants in those circumstances. Due to the different processes causing mobilisation, the behaviour of heavy metals and organic micropollutants is discussed separately.

Heavy metals show complex behaviour related to the complicated chemistry of Sulfide, Oxygen and Iron. Generally, polluted sediments are anoxic. The sulfide forming heavy metals are then precipitated as sulfides.

The free concentrations of heavy metals in the pore water are very low because of the very low solubility of these precipitates (Davies-Colley *et al.*, 1985; Moore *et al.*, 1988). Simultaneously, there is a substantial concentration of dissolved iron (Fe^{2+}) in anoxic pore-water, especially in fresh water sediments. Generally, the iron concentration in sediments is in the percentage range, i.e. ca. 100 times the heavy metal concentration in polluted sediments.

When sedimentary material is mixed with column water, it is transferred from anoxic into oxic conditions. Then, two reactions will take place: oxidation of heavy metal sulfides and oxidation of the dissolved iron (to Fe^{3+}). These two processes have counteractive consequences:

- The oxidation of sulfides liberates the heavy metals because the precipitates are degraded;
- The oxidation of iron causes precipitation of iron-(oxo)hydroxides which form a very strong adsorptive surface.

This precipitation process will cover any particle available with a layer of iron-(oxo)hydroxide. As a result, the heavy metals, mobilised by the oxidation of sulfides, will adsorb to the freshly created adsorption surface. The net outcome of these two counteractive processes thus depends on how fast the processes proceed. If oxidation of sulfides would proceed more rapidly than the oxidation of iron, then the adsorption onto precipitated iron cannot compensate entirely the mobilisation of heavy metals. If, however, the oxidation of iron is faster, then there is ample adsorption surface for heavy

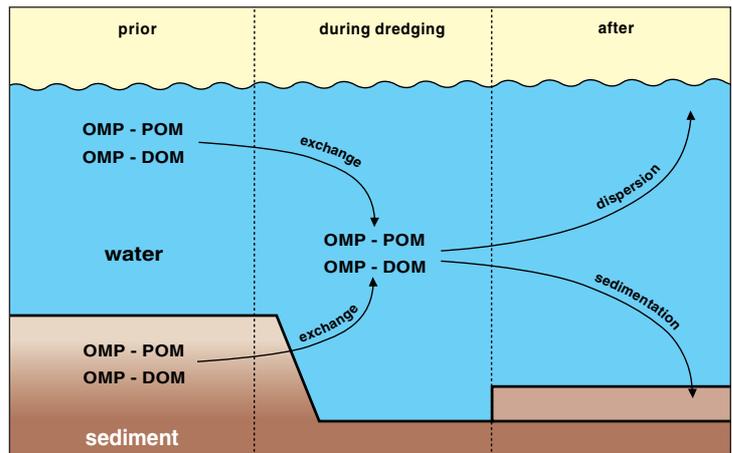


Figure 3. Schematised view on the shifts in mode of occurrence of organic micropollutants before, during and after dredging activities (OMP: Organic Micro Pollutant; POM: Particulate Organic Matter; DOM: Dissolved Organic Matter).

metals and the oxidation of sulfides is slowed down because particles get covered by a layer of iron-hydroxide and the penetration of oxygen into the particles is hampered.

Available measurements of the rate of oxidation of iron and sulfide suggest that the oxidation of iron is faster than sulfide oxidation (Pugh *et al.*, 1984; Millero *et al.*, 1987; Ahmad and Nye, 1990). Some preliminary measurements of the change in concentration of dissolved metals in the vicinity of a dumping site during dumping confirm the expected decrease of dissolved heavy metal concentrations (Hegeman *et al.*, 1991).

In summary, the present amount of heavy metals will probably show a shift from precipitated mode to the adsorbed mode, during dredging. Both modes are particulate, but adsorbed heavy metals can be released very quickly following a pH decrease in the water. In the "after dredging" situation problems may arise when sedimentation yields a top layer polluted with heavy metals.

Frequent resuspension (wind, navigation) promotes continuous desorption of heavy metals, under control of the prevalent environmental conditions. Once the material is transferred to anoxic conditions (e.g. after burial by sedimentation), the heavy metals will be transferred back to their stable sulfide precipitates.

The possible mobilisation of organic micropollutants during dredging is hardly dependent on the chemical conditions. Here, the distribution over different fractions is determined by the continuous equilibration exchanges of pollutants between particles and surrounding water. When the environmental conditions are more or less constant, an equilibrium will be reached, dependent on the characteristics of pollutant and adsorbent.

During dredging, several changes occur when sedimentary material is dispersed into the water column:

1. the particle concentration in the water increases
2. DOM-bound pollutant concentration in the water column increases
3. the total concentration of pollutant in the water increases
4. particles with different pollutant concentrations are mixed.

According to the partition theory, a new equilibrium will be established. The concentrations in this newly equilibrated situation can be estimated using the theory which says that, for a given compound, the ratio of the concentration on the particles ($\mu\text{g/g}$) and the dissolved concentration in the water (in $\mu\text{g/l}$) is a constant, characteristic for that compound.

What will happen when polluted material enters the water column?

The dissolved concentration in the water column will increase due to the mixing of pore water bearing a higher concentration. However, the amount of pore water will be very small, generally, compared to the volume of the receiving watercolumn and the resulting increase of concentration will be small, unless mixing is substantial. Substantial mixing may occur when using silt screens.

Since most of the pollutant enters the water column in particulate (adsorbed) state, the dissolved concentration is determined primarily by desorption and adsorption processes. The change in the adsorbed concentration depends on whether the particulate matter in the water column and in the sediment have different concentrations.

When both concentrations are the same, no desorption or adsorption will occur when sedimentary material enters the water column.

It is important to realise that in the first instance the number of particles present in the water column is irrelevant. It is the difference in concentration of the particles which determines whether or not desorption occurs. When the sedimentary particles have a lower concentration than the water particles, the dissolved concentration in the water will even get lower, due to adsorption.

Finally, in cases where the particulate concentration in the sediment to be dredged is lower than the concentration in the suspended matter, it is sufficient to control the dispersion of the particles. Only when the pollution concentration on the sediment particles is greater, does the particle concentration also become important, because this determines the total amount which can be liberated.

In many cases the concentration on the sediment particles can be expected to be higher than the suspended matter concentration, because dredging of polluted

sediments will often take place in systems where measures are taken to reduce the loads to the water system. In that case, mixing of sediment particles will cause desorption, according to the partition theory, to restore the equilibrium. It is not very clear how much time this desorption process will take, but desorption seems to be slow (Coates and Elzerman, 1986; Shorten *et al.*, 1990). It is difficult to estimate how much time is spent in the water column by a sediment particle brought into the water during dredging. The water movements, as well the natural movements as those resulting from the dredging equipment, are very important. In quiet conditions and salt water, the settling time for the generated turbidity is about hours. In fresh water sedimentation may take some more time. However, in less quiet conditions (rivers, tidal waters) the residence time in the water column can be much higher for "fine" particles, which generally carry the highest pollutant concentrations, than for "coarse" particles. For the fine particles the water residence time will be much longer and a substantial mobilisation (and dispersion) of pollutants might be the result.

THE CONSEQUENCES

What can be done to reduce the risks of dredging polluted sediments? In the first place, dispersion of pollutants to the surroundings, either in dissolved or in particulate state, should be prevented as much as possible. In the second place, care should be taken that the pollution level of the new top layer is much lower than that of the existing top layer, because release of pollutants may be high due to exposition to the environmental conditions in the water column.

Preventive actions are different for heavy metals and organic micropollutants.

For heavy metals the precipitation of iron-(oxo)hydroxides provides a certain safety belt. This safety belt is present in the turbidity cloud, and offers protection against dispersion in dissolved state on the very short term. In those circumstances, the mode of occurrence of the metals changes from precipitated to adsorbed. When the adsorbed metals are quickly transferred back to anoxic conditions, the original precipitated mode of occurrence is restored.

However, frequent resuspension of sediment containing adsorbed heavy metals might cause continuous desorption of pollutants to the water column.

The removal of heavy metal polluted material must therefore be as complete as possible. As long as there is good control of the dispersion of the water which comes into contact with the sediment material (e.g. properly functioning silt screens, isolated dredging location), the generation of turbidity is less important. However, the control of dispersion of the most riskful fine material and of the water itself, may offer as yet unresolved technical problems.



Figure 4. The Willem Bever at work with auger in a box. Specially designed and constructed dredger heads may reduce the turbidity generation substantially. Turbidity clouds seen here in the lower righthand corner are caused by a multicat and the traffic of a working vessel, not by the dredger.

For organic micropollutants, any mixing of sedimentary material and the water column should be avoided as much as possible. The amount of pollutants adsorbed to the DOM in the pore water may cause an increase of the dissolved pollutant concentration in the water column. In addition, the amount of pollutant released depends on the concentration difference between sediment and suspended matter. When the concentration in the dredging layer is higher than the concentration of the suspended matter, mixing within a volume of water isolated by silt screens may cause a substantial release of organic micropollutant into the dissolved state. This amount will escape control because of its dissolved nature.

Therefore, isolation of the sediment and process water from the water column should be achieved (e.g. by proper dredger head design, construction and operation (e.g. Figure 4).

The desorption from polluted particulate matter depends on the actual rate of release. It is as yet not clear whether the rate of desorption under dredging conditions is high enough to cause a substantial increase of the concentration in the water column.

A proper evaluation of the potential impact of dredging operations requires a reliable assessment of the background concentrations in the water column prior to dredging (i.e. suspended matter concentrations), because mobilisation is primarily determined by the difference in concentration between sediment and suspended matter. Due to the low concentrations in the water column and the analytical detection limits, this requirement deserves special attention.

Conclusions

1. The risks of dredging polluted sediments depend heavily on the local situation. Measures to reduce the risk can only be designed properly after a detailed analysis, using site specific data.
2. There is an urgent need for proper data collection during dredging activities to verify the results of this general, theoretical evaluation.
3. The environmental risks of dredging polluted sediments are primarily uncontrolled dispersion of pollutants and shifts in mode of occurrence towards dissolved forms, which have a higher bioavailability.
4. To reduce the risk of dredging polluted sediments, the dispersion of pollutants, either in dissolved or in particulate state, should be prevented as much as possible.
5. For heavy metals, a complete removal of the polluted sediment is more important than a temporary mixing of sedimentary matter with the water column, as long as dispersion from this mixing zone is prevented. Iron chemistry provides a temporary safety belt against dispersion in the dissolved state.
6. For organic micropollutants, mixing of sedimentary matter with the water column may result in a substantial, lasting increase in water column concentration due to the transfer of pollutants bound to Dissolved Organic Matter to the water column and to the desorption of pollutants from particles (see also 7).

7. For organic micropollutants the risks of dredging depend on the difference between the pollutant concentrations of the sediment and of the suspended matter. When the suspended matter concentration is lower than the sediment concentration, any mixing of sedimentary matter might cause a substantial release of pollutants to the water column.
8. The role of desorption kinetics in the mobilisation process in relation to the residence time of particles in the water column is as yet not very clear.

Further investigations will be directed towards the confirmation of the results of this evaluation in practical situations. These include performing monitoring programmes during dredging projects, evaluation of the kinetics of sulfide oxidation and desorption processes in relation to sedimentation rates, and the development of measuring equipment to monitor the dispersion of pollutants and (fine) particles.

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