Review Articles

Managing Contaminated Sediments

IV. Subaqueous Storage and Capping of Dredged Material

IV. Subaqueous Storage and Capping of Dredged Material	[JSS – J Soils & Sediments **1** (4) 205–212 (2001)]
III. *In-situ* Sediment Treatment (Spittelwasser Case Study)	[JSS – J Soils & Sediments **1** (3) 181–187 (2001)]
II. Integrated Process Studies	[JSS – J Soils & Sediments **1** (2) 111–116 (2001)]
I. Improving Chemical and Biological Criteria	[JSS – J Soils & Sediments **1** (1) 30–36 (2001)]

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Abstract. Remediation techniques on contaminated sediments are generally much more limited than for most other solid waste materials, except for mine wastes. The widely diverse contamination sources in larger catchment areas usually produce a complex mixture of contaminants that is more difficult to treat than an industrial waste.

In the first two chapters, additional information will be presented on *in-situ* treatment methods, which were the central topic in the Spittelwasser Case Study (JSS – Journal of Soils and Sediments, Vol. 1, No. 3, pp. 181–187), and on the development of ecologically sound dredging and processing techniques, where practical applicability had to be demonstrated as part of an integrated remediation chain. In the latter respect, mechanical separation of less strongly contaminated fractions may be a useful step prior to the final storage of the residues (chapter 2, Treatment of Strongly Contaminated Dredged Materials). For most sediments from maintenance dredging, there are more arguments in favor of 'disposal' rather than 'treatment' (chapter 3, Subaqueous Storage and Capping).

Consideration about the comparative assessment of the two basic management options of *in-situ* capping and dredging followed by sub-aqueous disposal are discussed on a legislative, economic and technical-environmental basis. The concept of capping of contaminated sediments *in-situ* has been developed in the last two decades as an ecologically sound and economic alternative to more costly remediation techniques. The main characteristics are related to the passive character of this concept, which minimizes labor and process costs. Mechanisms of contaminant retention in sediment caps is discussed with special regard to the chemical isolation component. From this consideration, the development of the active barrier concept is derived that denotes the use of reactive additives in capping layers to chemically bind one or more contaminants specifically.

Keywords: Calcite; clay cover; containment; disposal; final storage; fly ash; geochemical engineering; *in-situ*; mechanical separation; red mud; remediation measures; sediment treatment; sorption; zeolite

Introduction

On a worldwide scale, rivers transport eroded material to the coastal areas as suspended solids. Deltas, estuaries and their associated wetlands are natural sinks for this material. In the 1980s, the International Association of Ports and Harbors estimated about 350 million tons of maintenance dredging and 230 million tons of average annual dredging. In the harbors around the North Sea, approx. 100 million m^3 of sediment has to be dredged annually – about 10 times the average annual sediment discharge of the Rhine River.

Due to the economic implications, there is increasing worldwide interest in the development of dredging and disposal technologies. Among the authorities particularly dealing with the subject of contaminants in dredged materials, the U.S. Army Corps of Engineer Waterways Experiment Station at Vicksburg, Mississippi, has played a leading role. Further intensification of coordinated research was performed by the ARCS ('Assessment and Remediation of Contaminated Sediments') group of the U.S. Environmental Protection Agency, which was charged with assessing and demonstrating remedial options for contaminated sediment problems in the Great Lakes; laboratory tests were conducted utilizing 13 processes and a pilot-scale (field-based) demonstration of bioremediation. Particle size separation, solvent extraction and low temperature thermal desorption were also conducted (Anonymous 1994).

In Europe, the Dutch Development Program for Treatment Processes for Contaminated Sediments (POSW), starting up in 1989 and running until 1996, was aimed at the development of ecologically sound dredging and processing techniques, to be used in the remediation and reuse of polluted sediments (Anonymous 1997). Technical applicability had to be demonstrated in practice, as part of an integrated remediation chain. Attention was also paid to the economic and environmental consequences of the several types of techniques.

It becomes increasingly clear that remediation techniques on contaminated sediments are much more limited than for most other solid waste materials, except for mine wastes.

The widely diverse contamination sources in larger catchment areas usually produce a mixture of contaminants, which is more difficult to treat than an industrial waste. Often, traditional remediation techniques are economically unacceptable because of the large volume of contaminated materials to be treated. In such cases, the concept of 'geochemical engineering' (Salomons and Förstner 1988) can provide both cost-effective and durable solutions. Geochemical engineering applies geochemical principles (such as concentration, stabilization, solidification, and other forms of long term, self-containing barriers) to control the mobilization and biological availability of critical contaminants. This concept predominantly relates to *in-situ* aquatic sediment remediation and for the most relevant options, a provisional feasibility judgment has been presented by a recent investigation in the Netherlands (Joziasse and Van der Gun 2000).

Sediment remediation methods can be subdivided according to the mode of handling (e.g. *in-situ* or excavation), or to the technologies used (containment or treatment) (**Table 1**). In chapter 1, some additional information will be presented on *in-situ* treatment methods, which were the central aspect in our review and case study of this journal, third issue 2001. Dredged sediments can be chemically extracted or biologically treated to reduce concentrations of contaminants, or treated by additives to immobilize toxic metals. Mechanical separation of less strongly contaminated fractions may be a useful step prior to final storage of the residues (chapter 2). For most sediments from maintenance dredging, there are more arguments in favor of 'disposal' rather than 'treatment'. Important containment techniques include capping *in-situ* and confined disposal (chapter 3).

The goal of this review is thus to evaluate and compare innovative treatment and disposal options for contaminated dredged sediments with special regard to *in-situ* methods. The evaluation is based on economic and ecological aspects as well as on the general applicability of the respective techniques.

Table 1: Technology types for sediment remediation (Anonymous 1994)

	In-Place	**Excavated**
Containment	in-situ capping	confined aquatic disposal/capping
	contain/fill	land disposal
		beneficial use
Treatment	bioremediation	physical separation
	immobilization	chemical extraction
	chemical treatment	biological treatment
		immobilization
		thermal treatment

1 *In-Situ* Remediation

Similar to conventional waste management, handling of contaminated sediments follows the priority sequence of prevention – reuse – and safe disposal. Measures at the source may include an improvement of traditional wastewater purification, but also more approaches for *in-situ* treatment of highly contaminated effluents such as introducing active barriers (fly ash, red mud, tree bark, etc.) into ore mines to prevent heavy metal dispersion during flooding (Zoumis et al. 2000). Other techniques can be applied for the mechanical and chemical stabilization of interim depots of sediment in floodplains, polders and stormwater retention basins (Förstner et al. 2001). A big challenge is to deal with diffuse sources, e.g. from atmospheric deposition, agricultural runoff, etc., because adequate measures should go far beyond technical solutions and would involve a more detailed ecological balance between emission control and sediment remediation costs.

As shown from the examples of large-mass wastes in dredged material, mining residues and municipal solid waste, long-term immobilization of critical contaminants can be achieved by promoting less soluble chemical phases, i.e. by thermal and chemical treatment, or by providing respective milieu conditions. The selection of appropriate environmental conditions predominantly influences the geochemical gradients, whereas chemical additives are aimed to enhance capacity controlling properties in order to bind (or degrade!) micropollutants. In general, micro-scale methods, e.g. formation of mineral precipitates in the pore space of a sediment waste body, will be employed rather than using large-scale enclosure systems such as clay covers or wall constructions. A common feature of geochemically designed deposits, therefore, is their tendency to increase overall stability in time, due to the formation of more stable minerals and closure of pores, thereby reducing water permeation.

Recently a number of developments in remediation of terrestrial soil pollution, both with respect to policy aspects as to technical developments have led to a stimulation of *in-situ* remediation options: (i) remediation actions no longer have to be executed within a very short period of time, (ii) the result is not necessarily a 'multifunctional soil', and (iii) advantage is taken of natural processes (the self-cleaning capacity of the soil). In **Table 2** (selected from a review by Joziasse and van der Gun 2000) a number of potentially relevant options are summarized: It may be conceivable that the conditions for reductive dechlorination of chlorinated hydrocarbons are optimized. Also phytoremediation (for instance degradation of contaminants near plant roots) may be beneficial in certain cases (Ferro and Kennedy 1999). As to the immobilization of

Table 2: Selected options for *in-situ* sediment remediation (after Joziasse and van der Gun 2000)

Remediation type	**Scope (type of contaminants)**	**Technological concept**	**Technological implementation**
Stimulation of aerobic microbiological degradation	Organics (PAH, mineral oil, etc.)	Increase degradation rates by changing environmental conditions	Use enhanced degradation of contaminants in soil near plant
Fixation of contaminants (sorption or immobilization)	Metals	Precipitation of metals as hydroxides or insoluble complexes	Precipitation or adsorption near or at plant roots (phytostabilization)
Reduction of advective dispersion towards surface waters	All contaminants	Reduction of bank erosion/wash out	Introduction of plants
Reduction of advective dispersion towards ground water	All contaminants	Increased hydrological resistance	Application of a clay screen

contaminants by adsorption, one can think of applying clay screens, or clay layers (with or without additives). The advective dispersion of contaminants toward ground water or surface water can be reduced by capping the polluted sediment with a clay layer, with organic matter (humus) or other materials as possible additives.

Joziasse and Van der Gun (2000) emphasize, for every single case, that the effects of the actions (either dredging, or *in-situ*) on the aquatic ecosystem will have to be accounted for. In concrete cases, where a conventional approach encounters serious difficulties, an investigation dedicated to the prevailing conditions will have to give a decisive judgment on the feasibility of an alternative (*in-situ*) approach.

2 Treatment of Strongly Contaminated Dredged Materials

A general conceptual scheme related to dredged sediment material has first been proposed by the TNO, the Netherlands scientific technological organization (Van Gemert et al. 1988). 'A' and 'B' techniques are distinguished: 'A' is for large-scale concentration techniques like mechanical separation; these techniques are characterized by low costs per unit of residue, low sensitivity to variations, and they may be applied in mobile plants. 'B'-techniques are decontamination procedures, which are especially designed for relatively small scale operations. They involve higher operating costs per unit of residue, are more complicated, need specific experience of the operators and are usually constructed as stationary plants. 'B'-techniques include biological treatment, acid leaching, solvent extraction, etc.

Mechanical classification of dredged material from Hamburg is a typical example of an 'A'-technique (Detzner et al. 1993). Since 1993, the METHA (mechanical separation of harbor sediments) plant processes dredgings amounting to an annual quantity of approx. Two million m^3 combining a hydrocyclone and an elutriator as designed by Werther (1988). The advantage of the hydrocyclone is its simplicity and its ability to handle large throughputs; a disadvantage is a lack of sharpness in the separation. The elutriator, which follows in the classification scheme, provides a much better sharpness of separation. Contaminants such as heavy metals and organic compounds contained in the sediments are separated as fine fractions and dewatered to such an extent that they can be stored on a sealed land disposal site.

In the POSW, next to a critical review of the pre-dredging survey and the dredging technology, a study was conducted of the various principles of processing, and of several concrete processing methods based on them. Typical research issues of the POSW Stage II (1990–1996) program were (Anonymous 1997, Rulkens 2001):

- Thermal and chemical treatment methods (thermal desorption, incineration, wet oxidation, solvent extraction),
- Biological treatment (land farming, greenhouse farming, slurry treatment in bioreactors),
- Immobilization of contaminants in products (melting, sintering, practical experience in pilot remediation),
- Assessment of the environmental effects of processing chains (based on life cycle analysis, LCA).

This practice-oriented approach within POSW-II has succeeded in supplying a package of operational and environmentally sound methods for dredging and processing. However, similar to the experience made in soil remediation, the initial hope that physical-chemical treatment would find a considerable market has not been realized for these materials. The only wide-spread application is in the methods of grain-size separation, but in spite of the positive effects of processing – less dumping space needed, saving on the extraction of primary materials – the processing itself has negative side-effects (Rulkens 2001): The separation of sand consumes energy and requires water to dilute the input. The water is recycled during the process, but any surplus must be treated, either locally or in a purification plant elsewhere. Based on this experience, the Dutch government is preparing further steps to support the treatment of contaminated sediments in the Netherlands. An integrated approach is considered comprising fiscal and legislative measures as well as the installation of a new disposal facility.

3 Subaqueous Storage and Capping

International guidelines for managing dredged materials have been worked out during the last few decades to control and limit the contaminant input into the marine ecosystems. The London Convention (LC), the Oslo-Paris-Convention (OSPAR), and the Helsinki Convention, date back from the 1970s but are under permanent revision and development to account for the most recent state of knowledge. Two basic principles can be considered the heart of the LC and many regional conventions (Burt et al. 2000): The precautionary principle and the polluter-pays-principle. This means that, wherever a potential interference with the aquatic environment is apprehended, (1) precautionary safety measures are to be taken and (2) the costs for these measures are borne by the polluter.

3.1 Capping contaminated sediments *in-situ*

Wherever economic or technical implications counteract an excavation of a contaminated sediment, but remediation is required according to environmental implications, i.e. to prevent potential interference with the aquatic environment, *in-situ* technologies are considered. Subaqueous *in-situ* capping has become an attractive concept for isolating contaminated sediments. Subaqueous capping simply denotes the placement of a layer of clean material (i.e. material that is suitable for unrestricted open-water disposal) over contaminated sediments forming a permeable cap. A clear distinction, however, should be made between *in-situ* capping of contaminated autochthonous sediments on the one hand and dredged material capping that involves sediment removal by dredging, relocation, and the subsequent capping of the disposal area by a cap (Zeman 1994), a subject that will be discussed in the following chapter.

As depicted in Fig. 1, three main mechanisms inhibit the release of contaminants from the sediment through a cap into the water column (Palermo et al. 1998). Firstly, a stabilization of the sediments prevents sediment particles, that may transport solid phase bound contaminants, from being

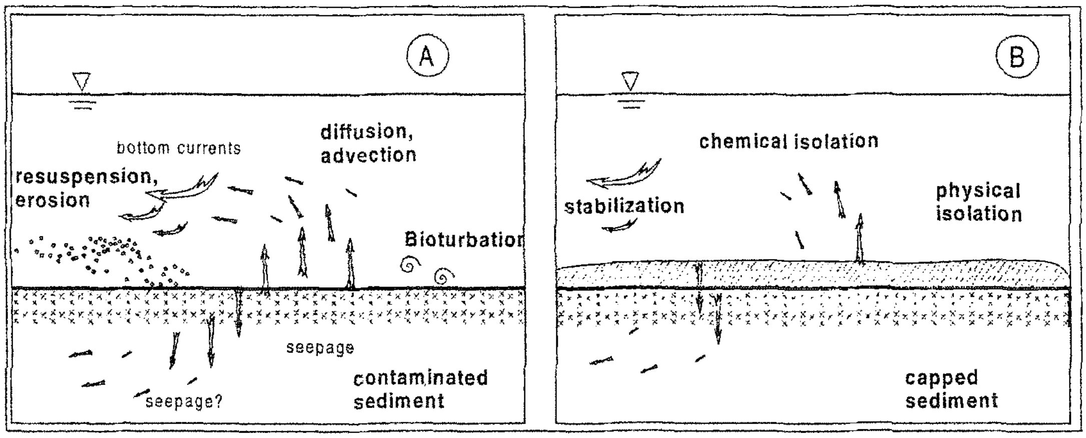

Fig. 1: (A) Remobilization mechanisms of contaminants from an aquatic sediment. (B) Stabilization and isolation of sediment by a capping layer

resuspended. Resuspension is considered a major path of release in waterways where strong bottom currents or ship traffic (anchoring, propeller wash) prevail. Secondly, a physical isolation of the sediment is achieved transferring the zone of active bioturbation from the contaminated sediment into the clean cap and thereby preventing the benthos from getting into contact with the contaminants. Consequently, a direct uptake into the food chain and possible bioaccumulation can be ruled out. For an effective isolation it is thus crucial to investigate the benthic community at the particular disposal site and, on that basis, determine the required minimum cap thickness. Thirdly, a chemical isolation prevents contaminants from being transferred from the sediment to the overlying water by dissolution, desorption, or ion exchange at the sediment to water interface by sheltering the interface with a diffusion barrier.

The interaction of these three mechanisms can result in an effective prevention of contaminant release into the surface water if the cap design is adapted to the conditions at the capping site. The design of a cap requires the proper application of (1) hydraulic principles, i.e. armor and filter equations, (2) chemical principles, i.e. advection-diffusion-retention equations, and (3) geo-engineering principles, i.e. settlement and stability equations (Mohan et al. 2000). Implementation of *in-situ* sediment capping, thus, is a typical example for collaborative projects involving strategic research, applied research and development, and technology sharing projects (Azcue et al. 1998). Major steps are (1) characterization of sediment materials (reactivity, mobility of contaminants), (2) suitability of capping techniques (currents, steep gradients, groundwater seepage), (3) provision of capping material (sand, granular materials, geotextile, additives; logistics; soft sediment/coarse, dense cover; impermeable materials, water flow); (4) thickness of capping material, (5) reactive additives; (6) monitoring of the sediment/cap system, early warning systems.

Capping materials in projects completed to date usually have been either sand, gravel, or clean sediments. An overview over a selection of full-scale capping projects is given in **Table 3**. The cap can either consist of a basic single-layer design, e.g. a layer of sand, or a more complex multi-layer design. After Mohan et al. (2000) such a multi-layer design can consist of the following components:

(1) A base stabilizing layer which provides local stability to the capped sediment to support the added weight of the cap
(2) A base isolation layer which provides the primary isolation of the contaminants from the environment
(3) A filter layer which provides hydraulic protection to the base isolation layer
(4) An armor layer which provides erosion protection of the cap

The capping concept has recently been extended by the concept of active barrier systems, ABS (Jacobs and Förstner 1999). To enhance the chemical isolation component, the ABS concept employs capping layers that consist at least partly of one or more reactive components. The addition of reactive matrix

Table 3: Overview over selected capping projects (after Palermo et al. 1998, modified)

Capping site	Contamination	Capped area	Cap design	Reference
Kihama Lake, Japan	Nutrients	3,700 m²	Fine sand, 0.05 und 0.2 m	
Akanoi Bay, Japan	Nutrients	20,000 m²	Fine sand, 0.2 m	
Denny Way, USA	PAH, PCB	12,000 m²	Sediment, 0.79 m	Sumeri (1995)
Simpson-Tacoma, USA	Creosote, PAK, dioxine	69,000 m²	Sediment, 1.2–6.1 m	Sumeri (1995)
Eagle Harbor, USA	Creosote	220,000 m²	Sediment, 0.9 m	Sumeri (1995)
Sheboygan River, USA	PCB		Sand	Eleder (1992)
Manistique River, USA	PCB	1858 m²	Geo-membrane	
Hamilton Harbor, Canada	Nutrients	10,000 m²	Sand, 0.5 m	
Eitrheim Bucht, Norway	PAH, metals, nutrients	100,000 m²	Geotextile, Armoring	Instanes (1994)
St.-Lawrence River, USA	PCB	6,989 m²	Sand, gravel, boulders	

Table 4: Examples for potential reactive materials for active barrier systems

	Material	Contaminant retention	Physical/ chemical suitability	Environmental acceptability	Availability / costs
industrial by– products	fly ash	metals	+/– (very fine grained)	– (high equilibrium pH in watery suspension, potential toxicity)	+
	red mud	metals	+/– (very fine grained, not stable under reducing conditions)	– (heavy metals)	+
natural minerals and rocks	calcite	metals, nutrients		+	+
	apatite	metals	+	+	–
	clays (e.g. bentonite)	metals	+/– (very fine grained)	+	+
	zeolites (e.g. clinoptilolite)	metals	+	+	+

components aims to actively demobilize the contaminants which are transported with percolating pore water. As a consequence, a long-term retention of dissolved contaminants may be achieved even under unfavorable conditions as a notable advective transport through the barrier. Advective transport, for example, can result from marine groundwater discharge or the squeezing of pore water during compression of the sediment due to the additional load of the cap. Under these conditions, the chemical isolation potential of chiefly inert sand or gravel barriers may be exceeded. Actually ongoing research work focuses particularly on the selection and characterization of reactive materials for active barrier systems. Potential materials have to meet a number of prerequisite properties: (1) They must have a good retention potential, (2) their chemical and physical properties (e.g. specific density, grain size distribution, chemical stability) must be suited for an underwater application, (3) they must be suited for unrestricted open water disposal (i.e. uncontaminated), and (4) they must be available at relatively low cost. Generally, industrial by-products and natural (rock-forming) minerals are the most promising materials, but often they do not meet all requirements listed above (**Table 4**). Some of the listed properties may be altered by appropriate treatment of the material. For example, surfaces of clays and zeolites can be modified for an enhanced sorption of organic and anionic contaminants. Fine-grained materials, such as clays or red mud, which would rather form a hydraulic barrier than a reactive, permeable one, may be granulated. However, this pre-treatment may apparently raise the capital costs. Fortunately, natural microporous materials, and in particular natural zeolites, show highly favorable chemical and physical properties with respect to their application in subaqueous capping projects along with a worldwide availability at relatively low cost (Jacobs 2000). Consequently, the actual research work focuses on these materials.

For the technical implementation of a cap, the same conventional dredging and construction equipment can be used as for the relocation of the dredged material. This is of particular advantage from the economic point of view. However, these practices must be precisely controlled. In general, the cap material must be placed so that it accumulates as an even and homogeneous layer covering the contaminated material. It must be prevented from displacing or mixing with the material due to the use of inappropriate placement methods or equipment (Anonymus 1994). Several methods of cap placement using land-based and sea-based equipment are discussed by Palermo et al. (1998).

As pointed out above, subaqueous capping is considered to be an economic management option. The capital costs of a capping project will be determined mainly by the cap materials, the equipment used for the placement and labor costs, and subsequently by the monitoring program. Where relocated dredged material is capped, as discussed in the following section, the costs are even decreased, as most of the equipment is generally easily available since it is used for the sediment dredging and relocation prior to the cap placement. However, not all costs are covered by the dredging and transportation components when such specialized equipment as submerged diffusers are needed for the cap placement. Generally, the cap positioning requires a greater level of precision and control than the disposal of the dredged material. The cap materials used are favorably low-cost materials, e.g. fresh sediment, sand, or natural mineral additives such as zeolites.

The ecological impact on the environment – compared to conventional remediation techniques – is minimized by avoiding transportation (and possible re-suspension), treatment, and upland disposal. Nevertheless, the impact on the benthic community by altering the habitat must be considered thoroughly (Collier and Meyer 1999). Due to differences in grain size and other characteristics between the capping material and the native sediment, capping may have substantially altered not only the contaminant concentrations but also the physical habitat characteristics of the remediated site. This effect may be of particular concern, e.g. where – different from clean sediment – clean sand or gravel with reactive additives or a cap design with an armoring top layer is used.

3.2 Disposal of dredged material

Currently, increasing efforts are being made to prefer the beneficial use of dredged material, i.e. the use in coastal defense and beach nourishment or habitat creation, or the

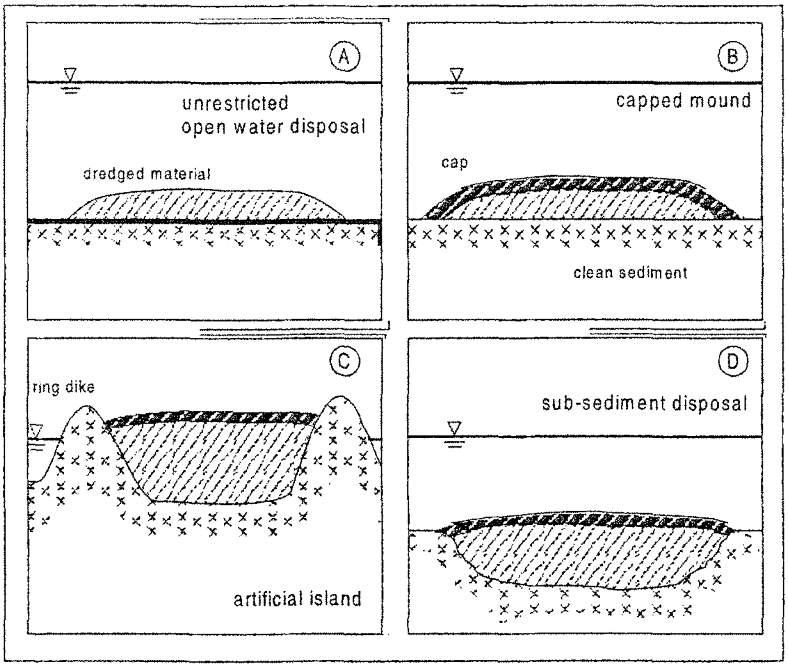

Fig. 2: Types of subaqueous disposal for dredged material

production of construction materials over disposal. However, beneficial use is not always a viable option, and it will not be compelled at unreasonable costs. Furthermore – according to national and regional stipulations as well as the above mentioned international conventions – it is only suited for uncontaminated material. Therefore, disposal remains an important option in managing dredged material. In its annexes, the LC provides detailed information for the disposal of dredged materials: (1) a 'black list' with materials prohibited from open water disposal, (2) a 'gray list' with materials that require safety measures when disposed of at sea, and (3) detailed suggestions on how to apply the convention in the countries having signed the convention. In addition to the chemical evaluation of the sediments, the effect-based evaluation using bio-assays will presumably play an increasing role in deciding whether disposal is to be restricted or not.

The most straightforward type of subaqueous disposal is the unrestricted open water disposal (**Fig. 2A**). This denotes a disposal without any previous treatment or following technical protective measures. Unrestricted open water disposal, however, is only suited for uncontaminated sediments or, more accurately, for sediments that do not exceed the legal threshold values of the relevant contaminants. Sediments that exceed relevant threshold values, consequently, may not be disposed of without further protective measures. In this case, three main options may be distinguished:

(1) The material is disposed of on land,
(2) treatment steps are applied to the sediment prior to the underwater disposal in order to meet the threshold values, or
(3) the underwater disposal site is safeguarded by technical means.

In the past– regarding the various containment strategies – it was argued that upland containment (e.g. on heap-like deposits) provide a more controlled management compared to containment in marine environments. However, contaminants released either gradually from an imperfect, impermeable barrier (also into the groundwater) or abruptly after a failure of the barrier could produce substantial damage (Kester et al. 1983). On the other hand, near-shore marine containment (e.g. in capped mound deposits), offers several advantages, particularly regarding the protection of groundwater resources, since the underlying water is saline and inherent chemical processes are favorable for the immobilization or degradation of priority contaminants.

Reviewing marine disposal options, Kester et al. (1983) suggested that the best strategy for the disposing of contaminated sediments is to isolate them in a permanently reducing environment. Under anoxic, strongly reducing, sub-sediment conditions, a great part of the metal content is present as sulfides compared to the respective carbonates, phosphates, and oxides due to microbially-mediated sulfate reduction. This process is particularly important in the marine environment, whereas in an anoxic freshwater milieu a tendency for enhancing metal mobility due to the formation of stable complexes with ligands from decomposing organic matter is observed. Marine sulfidic conditions, in addition, seem to repress the formation of mono-methyl mercury, that is one of the most toxic substances in the aquatic environment, by a process of disproportionation into volatile dimethyl mercury and insoluble mercury sulfide (Craig and Moreton 1984). Furthermore, Kersten (1988) reports the degradation of highly toxic chlorinated hydrocarbons being enhanced in the sulfidic environment. However, it has to be taken into consideration that changes in the redox-regime can be induced not only by diffusive transport of oxygen through the water-to-sediment interface, but also – and maybe more effectively – by bottom dwelling and burrowing organisms creating oxidizing micro environments. The risk of contaminant uptake by these organisms must thus be ruled out by appropriate cap designs.

Disposal in capped mound deposits above the prevailing seafloor, disposal in sub-aqueous depressions, and capping deposits in depressions provide procedures for contaminated sediment (Bokuniewicz 1983). In some instances it may be worthwhile to excavate a depression for the disposal site of contaminated sediment which can be capped with clean sediment. This type of waste deposition under stable anoxic conditions, where large masses of polluted materials are covered with inert sediment became known as 'subsediment-deposit'. Fig. 2 B–D differentiates three main disposal types. The first type, the capping of the disposal site (Fig. 2 B), represents a technically straightforward and economic measure to isolate the contaminated material from the environment. Due to its important role as an effective and economically passive technology, the capping concept is documented in the Dredged Material Assessment Framework (DMAF), the implementation guideline of the LC, as well as in the guidelines of the US Environmental Protection Agency (US EPA). The second type is the artificial island type, where the designated disposal area is excavated to a certain depth and the sediment material obtained is used to pile up a ring dike that encircles the disposal site. Within this ring dike the dredged material is disposed of and may finally be covered with an additional cap. The third option is to excavate an area of uncontaminated sediment, to dispose of the contaminated dredged material into the excavation and to cover the deposit with the clean, excavated material. This option is of particular economic interest as no capping material has to be transported to the disposal site.

In accordance with the precautionary principle, the choice of the appropriate disposal option has to be made by means of an effects-based assessment. That means that any potential long-term impact of the planned disposal on the aquatic environment has to be evaluated. Therefore, a chemical and biological characterization of the dredged material, in concert with an exact characterization of the disposal method and the disposal site, is crucial. During the disposal process, a short-term risk may be given due to suspension of contaminant-bearing sediment particles and desorption or dissolution of contaminants when passing through the water column. Another, possibly more serious, threat is posed to the ecosphere by the potential, continuous long-term release of contaminants. In analogy to the *in-situ* sediment caps (Fig. 1), underwater dredged material deposit without any further safeguard may be subject to (1) erosive forces resuspending contaminated sediment particles, (2) submarine groundwater discharge transporting dissolved contaminants into the water column or sea water intrusions into coastal ground water, as well as (3) benthic organism resuspending and feeding on the contaminated sediment. To prevent the contaminants, release measures are to be taken as described in Table 1.

4 Conclusions

As a conclusion of the remediation aspects discussed above, it can be stated that the concept of permeable reactive barriers as a general approach applies, as well as autochthonous sediment sites representative as disposal sites for dredged materials. This results, first of all, from the economic advantages which are characteristic of passive technologies: Due to the efficiency in isolating the contaminants from the environment along with the greatly reduced or zero process costs, these technologies always represent attractive remediation alternatives, where they are technically feasible and where they conform with the legislation. However, to achieve public acceptance as to the new technology, major efforts should be undertaken in respect to the development and application of monitoring systems for long-term prognosis of both mechanical and chemical stability in the new sediment deposits. At present, there are plans for two model sites in the tidal and non-tidal Elbe River, where different monitoring devices will be installed for the study of material fluxes between sediment and tidal water (subaqueous deposition only) and sediment/cap/soil cover, respectively.

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III. *In-situ* Sediment Treatment (Spittelwasser Case Study)

While remediation and storage of contaminated dredged materials is a key issue at harbour sites, there is another type of sediment pollution problem, which mainly originates from large-scale dispersion of contaminants in flood-plains, dike foreshores and polder areas. In recent years, catastrophic cases of sediment contaminations have occurred in connection with the failure of tailing dams from mines. Unlike problems related to conventional polluted sites, the risks here are primarily connected with the transporting and depositing of contaminated solids in a catchment area, especially in downstream regions.

A special example demonstrating the dispersion of highly contaminated sediments in a large catchment area will be shown from the so-called Chemistry Triangle of the upper Elbe River system, Germany. The Spittelwasser area, situated there, was chosen by the organisers of the international conference ConSoil 2000 for a case comparison and four expert teams from Denmark, Germany, the Netherlands and the UK were invited to participate in this Case Study. Evaluation of the plan was done by members of the networks of NICOLE (Network for Industrially Contaminated Land) and CLARINET (Contaminated Land Rehabilition Network).

In the study of the German team, five major groups of technical measures have been identified by the environmental authorities to be discussed in relation to the Spittelwasser case or for similar problem solutions in contaminated flood-plain areas. The team came to the conclusion that none of these techniques would be applicable as an individual measure. Instead, a stepwise approach combining different monitoring techniques and remediation measures was proposed. These would include point excavations of critical material, promotion of plant growth as an element for stabilising the soil and flood sediments, as well as the installation of sediment traps.

At the Spittelwasser site, investigations are planned on the effects of natural attenuation processes of organic and inorganic contaminants in flood-plain sediments and soils. In the practice of this concept, non-destructive, 'intrinsic' bonding mechanisms and their temporal development have thus far found much less recognition compared to destructive processes such as biological degradation. Yet these so-called 'diagenetic' effects, which apart from chemical processes involve an enhanced mechanical consolidation of soil and sediment components by compaction, loss of water, and mineral precipitations in the pore space, may induce a quite essential reduction of the reactivity of solid matrices [see Part I 'Improving Chemical and Biological Criteria' (JSS – Journal of Soils and Sediments, Vol 1, No 1, pp 30–36)].

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II. Integrated Process Studies

In the first part of our review, new insights into 'diagenetic' mechanisms on particles including ageing and their effects on biological interactions were presented. These findings clearly indicate the need to refine bioavailability models including equilibrium partitioning. A set of bioassays is a powerful supplement to assess sediment quality.

In the second part, an interdisciplinary process approach relating to the release of DOC, nutrients and pollutants into the open water is described, which has been derived from the evaluation of the international state-of-the-technology with three major themes: 'experimental techniques', 'processes and properties' and 'development and validation of models'. Special study targets are the formation of aggregates in turbulent water, flocs and biofilms from organic reactions, and formation of new surfaces for readsorption of dissolved pollutants. Of greatest importance is the degradation of organic matter, which affects both hydrodynamic processes and geochemical redox cycles, thus providing driving forces, e.g. for metal mobilization.

Models for predicting pollutant transport in rivers are still dominated by hydromechanical parameters. A first step for extending these models could involve typical milieu factors such as competing ions, complexing agents, redox conditions and pH-values. The next steps would include binding constants and other factors describing solid/solution interactions of critical chemicals in a multicomponent system.

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I. Improving Chemical and Biological Criteria

To understand bioavailability is the key issue for managing contaminated sediments. Therefore, scrutiny of the geochemical situation, toxicity, and biodegradability is needed. The first part of this review refers to the new insights into 'diagenetic' mechanisms on particles including ageing and their effects on biological interactions. Chemical and physical methods are described to quantify the retarded desorption behaviour of hydrophobic organic substances and toxic metals. Results of analyses on the extractability of particle-bound pollutants (e.g. solid phase micro-extraction) can be correlated with the bioavailability. Some techniques recently developed to mimic bioavailabilty are briefly summarised. As can be derived from this review, there is a clear need to refine bioavailability models including equilibrium partitioning.

A set of bioassays is a powerful supplement to assess sediment quality. Consequently, a paradigm shift should be initiated for the evaluation of biological data. All information of a survey have to be implemented in an assessment scheme. Multivariate statistics and fuzzy mathematics provide promising means to interpret multiple data pattern.