SedNet SSM Guidance Document

Treatment Methodologies at the River Basin Scale

Prof. Dr. Ulrich Förstner, Technical University of Hamburg-Harburg (u.foerstner@tu-harburg.de)

Introduction

Remediation techniques on contaminated sediments generally 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 produces a mixture of pollutants, which is more difficult to treat than an industrial waste (section 1). For most sediments from maintenance dredging, there are more arguments in favour of “disposal“ rather than „treatment“ (section 2). In the future, remediation methodology will be seen in the context of sustainable sediment management. This will include development of “soft” techniques applying principles of long-term, self-containing barriers which control the mobilization and biological availability of critical pollutants in soils and sediments (section 3). In the following overview, special emphasis is given to the utilization of innovative techniques for sediment treatment, which can be applied in different parts of a river basin; the examples presented here are mostly from the Elbe River catchment area (section 4).

1 Conventional Treatment Techniques

Sediment remediation methods can be subdivided according to the mode of handling (e.g. in-place or excavation), or to the technologies used (containment or treatment) (Table 1).

Table 1 Technology types for sediment remediation (Anonymous 1994)

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

A general conceptual scheme related to excavated sediment material was 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 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, need specific experience of the operators and are usually constructed as stationary plants. "B"-techniques include, for example, biological treatment, acid leaching and solvent extraction.

Separation of Dredged Material Fractions. An example of "A"-techniques is the classification of harbor sludge from Hamburg by the METHA (mechanical separation of harbor sediments) plant (Detzner et al. 1993). The core of this technique is the combination of hydrocyclonage and elutriator as designed by Werther (1988). In the hydrocyclone the separation of the coarse fraction from the polluted fines is effected by the action of centrifugal forces. The coarse fraction leaves the cyclone in the underflow, while the fines are contained in the overflow. The advantage of the hydrocyclone is its simplicity and its ability to handle large throughputs; disadvantage is the fairly low sharpness of the separation. The elutriator, which follows in the classification scheme, allows a much better sharpness of separation.

Solidification/Stabilization. The aim of solidification/stabilization techniques is a stronger fixation of contaminants to reduce the emission rate to the biosphere and to retard exchange processes. Most of the stabilization techniques aimed for the immobilization of metal-containing wastes are based on additions of cement, water glass (alkali silicate), coal fly ash, lime or gypsum (Goumans et al. 1991). Generally, maintenance of a pH of neutrality or slightly beyond favors adsorption or precipitation of soluble metals. Best results are attained with calcium carbonate, since the pH-conditions are not changed significantly (Calmano et al. 1986). Several factor negatively interfere with the objective to solidify or stabilize: Organic compounds, oil and grease, inorganic salts such as nitrates, sulfates and chlorides, small particles sizes, volatile organic compounds, and low solids content.

Solvent Extraction. The primary application of solvent extraction is to remove organic contaminants such as halogenated compounds and petroleum hydrocarbons (Anonymous 1988). Extraction processes may also be used to extract metals, but these applications which usually involve acid extraction, have not proven to be cost effective for contaminated sediments. Fine grained materials are more difficult to extract, and presence of detergents adversely impacts oil/water separation. The procedure is less effective for high molecular weight compounds and very hydrophobic substances. In any case, careful selection of reagents and laboratory testing is required.

Biodegradation and Biorestoration. Biological treatment has been used for decades to treat domestic and industrial wastewater, and in recent years has been demonstrated as a technology for destroying some organic compounds in contaminated soils. Bioremediation or biorestoration may be applied in certain cases to organically contaminated sediments. However, since in large catchment areas contamination with only organic compounds is rare, the expectations in this technique of remediation seem to be overestimated. Even in optimal cases, there are many limitations to biodegration processes: Temperature, nutrients, oxygen, are the most important ones.

Likelyhood of Success, Costs of Conventional Treatment Methodologies. Similar to the experience 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 are the methods of separation according to grain size, but even with 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 is energy-consuming and requires water to dilute the input. The water is recycled during the process, but any surplus will have to be treated, either locally or in a purification plant elsewhere. Cost estimations for decontamination techniques cover wide range for individual examples from the fields of bioremediation, chemical dechlorination, soil washing, solvent extraction, thermal desorption and vitrification (Anonymous 1994, 1997). Typical cost factors for sediments include water quantity, moisture contents, physical and chemical characteristics, for example, grain size and organic material content.

2 Subaquatic Depots and Capping of Dredged Material

Since the late 70s there is a controversy regarding the various containment strategies. Some experts have argued that upland containment could provide a more controlled management than, for example, containment in the marine environment; others have inferred, that contaminants released either gradually from an imperfect impermeable barrier or catastrophically from failure of the barrier could produce substantial damage. In an early review of various marine disposal options, Kester et al. (1983) suggested that the best strategy for disposing off contaminated sediments is to isolate them in a permanently reducing environment. Additional safety measures include capping procedures, both of deposits above the prevailing sea-floor and of subaquatic depresssions (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.

Preference for Subaquatic Depots. In the centre of today's sediment management there is a science-based technology for the final storage of sediments – called 'subaquatic depot'. The EU Landfill Directive does not refer to waste disposal below the groundwater level (Anonymous 1999), and here the two most promising conditions for a sediment depot can be found: (i) a permanent anoxic milieu to guarantee extremely low solubility of metals, (ii) base layers of compacted fine-grained sediments which prevent the advective transport of contaminants to the groundwater (Anonymous 1998, 2002). Together with advanced geochemical and transport modelling, such deposits offer the most cost-effective and sustainable problem solutions for dredged sediments. In the convoy of this technology – flagship is the Dutch 'De Slufter' depot – innovative sediment-specific applications are developing, for example, techniques for active capping to safeguarde both depot and in-situ contamination against pollutant release into the surface water.

Table 2 Advantages and disadvantages of subaquatic depots (after Anonymous 2002)

Type of depot	Advantages	Disadvantages
Excavation (pit) type of depot	• *reduced conditions* • not visible • simple fill up • less maintenance	• cost intensive dig off • superfluous sand (?) • contamination of surface waters • special filling equipment • no regulation of water level
Dike (ring wall) type of depot	• *reduced conditions* • less cost-intensive dig off • less contamination of surface waters • easy regulation of water levels • easy management and control of emissions	• *visible* • obstacles for navigation and fisheries • more difficult fill up (compared with pit depot)

Development of Subaquatic Depots. Two types of subaquatic depots can be distinguished (table 2): Excavation (pit) type of depot and dike (ring wall) type of depot. Both are characterized by reducing conditions, but from the Dutch experience one of the major advantages of the former type, at least for smaller depots in flat areas is that these are no more visible after the filling period. Actually there are 16 sites of depots for harbor sediment in The Netherlands, most of them at near coast sites. The preparation work before construction is between 4 and 7 years. Filling for the smaller depots will take place within 5 years, for the larger ones within 20 year. Cost estimations for construction, operation and aftercare are between 5 and 10 Euro per m³ (Anonymous 2002). Only the process of relocation within the water body, favorite option, e.g., of German authorities for sediment treatment, is cheaper (Anonymous 2003).

Sediment Capping Techniques. Further precautionary measures should be considered, e.g. an armoring layer which provides erosion protection of the depot. New developments relate to reactive cap additives to reduce pollutant transfer from sediment through pore water into the open water. Cap additives have to meet a number of prerequisites such as good retention potential, chemical and physical properties suited for an underwater application (Jacobs and Förstner 2001).

3 In-Situ Treatment Methodologies

As shown from the examples of large-mass wastes like mining residues and municipal solid waste, long-term immobilization of critical pollutants can be achieved by promoting less soluble chemical phases, i.e., by chemical treatment, or by providing respective milieu conditions. Selection of appropriate environmental conditions predominantly influence the geochemical gradients, whereas chemical additives are aimed to enhance capacity controlling properties in order to bind (or degrade!) micropollutants. A common feature of such deposits 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.

Risk Reduction by Ageing Processes. Part of these effects may be related to specific geosorbents such as combustion residue particulate carbon (e.g., chars, soot, and ashes), where typical hysteretic sorption behavior has been observed for organic and inorganic substances (Luthy et al. 1997). For inorganic pollutants, mainly heavy metals and arsenic, the effect of ageing mainly comprises enhanced retention via processes such as sorption, precipitation, co-precipitation, occlusion, and incorporation in reservoir minerals (Salomons 1980). In practice, "intrinsic" bonding mechanisms which also involve mechanical consolidation of soil and sediment components by compaction, and mineral precipitations in the pore space, may induce a quite essential reduction of the reactivity of solid matrices (Table 3).

Table 3 Demobilization of Pollutants in Solid Matrices by Natural Factors (Förstner 2003)

Cause (Example)	Effect
Compaction	Reduction of Matrix...
Consolidation	*Erodibility*
Phytostabilization (Plant Roots)	*Permeability*
Penetration into Dead-End-Pores	*Reactivity*
Interlayer Collapse of Clay Minerals	Reduced Pollutant...
Co-precipitation (High-Energy-Sites)	*Mobility*
Occlusion and Over-coating	*Availability*
Absorption/Diffusion	*Toxicity*
"Diagenesis"	"Natural Attenuation"

Example: Natural attenuation and ageing effects will characteristically influence the use of equilibrium partitioning models in developing sediment quality criteria (SQC) from final chronic value (FCV) water quality criteria. The example in Fig. 1 (Chen et al. 2000) indicates that the SQC of 1,4-dichlorobenzene would be nearly 2 orders of magnitude less strict when the process of irreversible adsorption on the resistant fraction in sediment is taken into account.

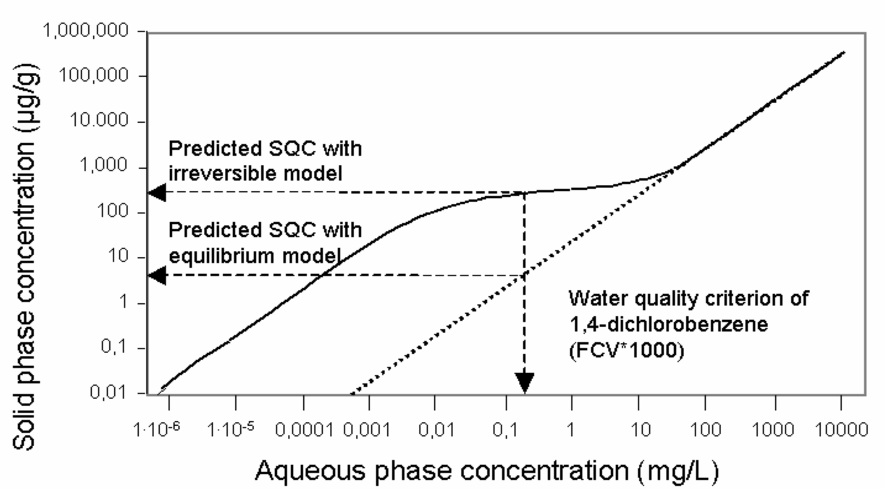

Figure 1 Implication of irreversible adsorption on sediment quality criteria (after Chen et al. 2000)

Enhanced In-Situ Stabilization based on Natural Processes. Recent developments in the Netherlands in “soft” (geochemical and biological) techniques on contaminated soils and sediments, both with respect to policy aspects as to technical developments have led to a stimulation of in-situ remediation options. In Table 4 a number of potentially relevant options for metals are summarized: Phytoremediation, for instance degradation of contaminants near plant roots, may be beneficial in certain cases. As to the immobilization of 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. These problem solution strategies, which consider both the chemical demobilization and the reduction of mechanical erodibility, can be applied in situations, where traditional remediation procedures become economically unacceptable.

Table 4 Selected options for in-situ sediment remediation (after Joziasse and Van der Gun 2000; the original version comprises more than 20 technological concepts)

Remediation type	Scope (type of contaminants)	Technological concept	Technological implementation
Fixation of contaminants (sorption/immobilisation)	metals	precipitation of metals as hydroxides or insoluble complexes	precipitation or adsorption at plant roots (phytostabilisation)
Reduction of dispersion towards surface waters	all contaminants	reduction of bank erosion/-wash out	introduction of plants
Reduction of dispersion towards ground water	all contaminants	increased hydrological resistance	application of a clay screen

4 Treatment Methodologies at the Catchment Scale – Examples from the Elbe Basin

Many sources contribute to sediment contamination in a river catchment area (Figure 2 from Shea 1988): Wet and dry fallout from air emissions, agricultural runoff from farms, solid and dissolved inputs from mines, discharges from landfills, industrial plants and sewage treatment plants and direct dumps into rivers, lakes and coastal seas. The biggest “sediment trap” can oftenly be found at the end of the river, but substantial amounts of polluted sediments are also trapped upstream at flood plains, locks, dams, and smaller ports and at channels connected to the river.

Limited financial resources require a direction of investments to those sites with the highest efficiencies in risk reduction. Establishing a rough sediment dynamic model, building on tributary/main river dilution factors, sedimentation data, suspended particulate matter monitoring data, integrating a higher number of data on critical erosion thresholds than exist today, and calculating long-term costs and benefits based on a basin-wide risk assessment, it should be possible to achieve a site prioritization with detailed answers about the preferred treatment technique for a specific location. Figure 2 presents a number of treatment methodologies under the aspect of sustainable sediment management, i.e., predominantly geochemically-based techniques, which could be applied for specific problem solutions in the Elbe River catchment area:

I. In-situ treatment of mine effluents. Predominantly in the upper and middle course of river systems, sediments are affected by contamination sources like wastewater, mine water from flooded mines and atmospheric deposition. Measures at the source are particularly important and may include 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).

II. In-situ stabilization of floodplain soils and sediments. From an initial example of the Spittelwasser case comparison (Anonynmous 2000) in a 60 km² flood plain of the upper Elbe River it has been shown that problem solutions for such areas deserve thorough consideration of legal and socio-economic aspects. The German group presented a stepwide approach combining different monitoring techniques and remediation measures; in the 2nd step, comprising the “regulation project”, measures such as the installation of efficient sediment traps, a point withdrawal of sediments rich in pollutants, yet also the utilization of the processes of natural attenuation (see section 3) in the floodplain area and promotion of plant growth may be investigated.

III. Storage in reservoirs. In the course of the river and its tributaries, natural or man-made depressions can be used for the storage of contaminated sediments on the mode of “subaquatic depots”. A typical example is the Mulde reservoir (~ 6 km²) in the Elbe River system, which was created in 1975, when a 10 km section of the river was displaced in order to get access to a lignite coal area. Retention is approx. 50 % of the sediment-bound cadmium discharge of the Elbe River and it has been predicted that this type of sediment trap could last for 500 to 1000 years (Zerling et al. 2001).

IV. Subaquatic depot and capping. Application of this technology can be considered for small yachting harbors. For the Hitzacker/Elbe harbour site, a draft approval has been made which involves the excavation of approx. 10.000 m³ fine grained, polluted sediments from the harbor area and their deposition close to the site, in a communication channel between the Elbe River and the harbor (Förstner 2003). Active capping of the sediment depot will include natural zeolite additives and monitoring of the site will be performed using dialysis sampler and diffusional gradient technique probes (Jacobs 2003).

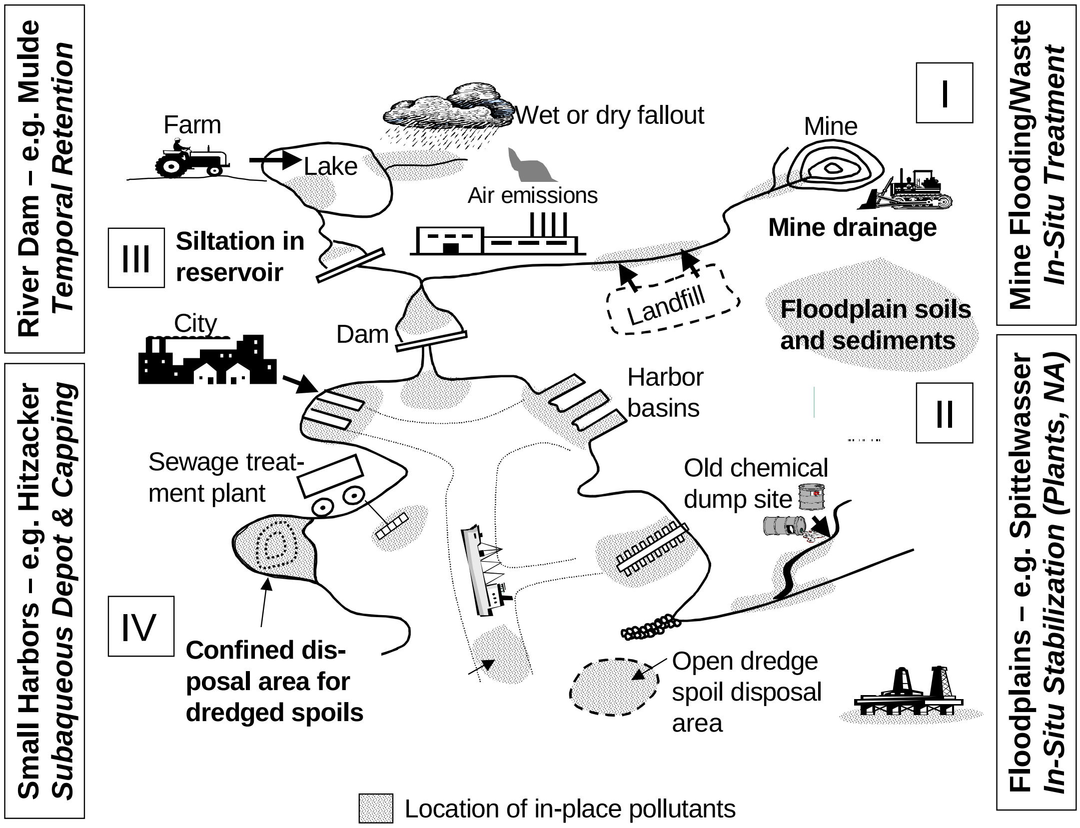

Figure 2 Sediment contamination in a river catchment area (after Shea 1988) and proposals for treatment methodologies in the Elbe River basin

From the examples presented above, it becomes clear that the handling of sediment problems at a catchment scale is a complex task which cannot be tackled by science and engineering alone. It deserves thorough consideration of legal and socio-economic aspects including public relations. The experience from the Spittelwasser case comparison (see III) has shown, that the measures in the framework of sustainable sediment management have to be so flexible that an adaptation to changing basic conditions will be possible (Anonymous 2000). In particular, a close coordination between project management, planners, technicians and authorities will be of decisive importance.

References

Anonymous (1988) Technology Screening Guide for Treatment of CERCLA Soils and Sludges. EPA/540/2-88/004, U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response and Office of Emergency and Remedial Response, Cincinnati, OH

Anonymous (1994) Assessment and Remediation of Contaminated Sediments (ARCS) Program – Remediation Guidance Document, US-EPA 905-R94-003. Chicago, IL

Anonymous (1997) Development programme for treatment processes for contaminated sediments (POSW), Stage II (1992-1996). Final Report, RIZA Rep 97.051. Rijkswaterstaat Lelystad, 58 p.

Anonymous (1998) Prognose gebruiksduur Slufterdepot 1997-1998. GWR Report No. 97-124/C, Dec. 1998, cit. Anonymous 2002

Anonymous (1999) Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste. Brussels

Anonymous (2000) Contaminated Soil 2000 – Case Study "Comparison of Solutions for a Large Contamination Based on Different National Policies". ConSoil 2000, 7th Intern. FZK/TNO Conference on Contaminated Soil. Leipzig, 165 p.

Anonymous (2002) Die subaquatische Unterbringung von Baggergut in den Niederlanden (Subaquatic Depots of Dredged Material in The Netherlands). DEPOTEC, Amersfoort, and Strom- & Hafenbau, Hamburg. Report, January 2002, Hamburg

Anonymous (2003) Dutch-German Exchange on Dredged Material. Part 1. Dredged Material and Legislation. 2nd ed. April 2003

Bokuniewicz HJ (1983) Submarine borrow pits as containment sites for dredged sediments. In: Kester DR, Ketchum BH, Duedall IW, Park PK (Eds) Dredged-Material Disposal in the Ocean (Waste in the Ocean, Vol. 2), pp. 215-227. Wiley, New York

Calmano W, Förstner U, Kersten M, Krause D (1986) Behaviour of dredged mud after stabilization with different additives. In: Assink JW, Van Den Brink WJ (Eds) Contaminated Soil. pp. 737-746. Martinus Nijhoff, Dordrecht

Chen W, Kan AT, Tomson MB (2000) Irreversible adsorption of chlorinated benzenes to natural sediments: Implications for sediment quality criteria. Environ Sci Technol 34: 385-392

Detzner D, Kitschen L, Weimerskirch W (1993) METHA – The first large-scale plant for treatment of harbour sediments. Aufbereitungs-Technik 34: 235-242

Förstner U (2003) Geochemical techniques on contaminated sediments – river basin view. Environ Sci Pollut Res 10: 58-68

Goumans JJJM, Van der Sloot HA, Aaalbers ThG (Eds): Waste Materials in Construction. Studies in Environmental Science 48. Elsevier, Amsterdam

Jacobs PH (2003) Monitoring of subaqueous depots with active barrier systems for contaminated dredged material using dialysis sampler and DGT probes. J Soils Sediments 3: 100-107

Jacobs PH, Förstner U (2001) Managing contaminated sediments. IV: Subaqueous storage and capping of dredged material. J Soils Sediments 1: 205-212

Joziasse J, Van der Gun J (2000) In-situ remediation of contaminated sediments : Conceivable and feasible?! In: Contaminiated Soil 2000, Vol 1: 516-522. Thomas Telford London

Kester DR, Ketchum BH, Duedall IW, Park PK (Eds)(1983): Wastes in the Ocean, Vol. 2: Dredged-Material Disposal in the Ocean, 299 pp. Wiley, New York

Luthy RG, Aiken GR, Brusseau ML, Cunningham SD, Gschwend PM, Pignatello JJ, Reinhard M, Traina SJ, Weber WJ jr, Westall JC (1997): Sequestration of hydrophobic organic contaminants by geosorbents. Environ Sci Technol 31: 3341-3347

Rulkens WH (2001) An overview of soil and sediment treatment research in the Netherlands. In: Stegmann R, Brunner G, Calmano W, Matz G (Eds.), Treatment of Contaminated Soil – Fundamentals, Analysis, Application; pp. 21-34. Springer Berlin

Salomons W (1980) Adsorption processes and hydrodynamic conditions in estuaries. Environ Technol Lett 1: 356-365

Shea D (1988) Developing national sediment quality criteria. Environ Sci Technol 22: 1256-1260

Van Gemert WJTh, Quakernaat J, Van Veen HJ (1988) Methods for the treatment of contaminated dredged sediments. In: Salomons W, Förstner U (Eds) Environmental Management of Solid Waste - Dredged Material and Mine Tailings, pp. 44-64. Springer, Berlin

Werther J (1988) Classification and dewatering of sludges. In: Salomons W, Förstner U (Eds) Environmental Management of Solid Waste - Dredged Material and Mine Tailings, pp. 65-79. Springer, Berlin

Zerling L, Müller A, Jendryschik K, Hanisch Ch, Arnold A (2001) Der Bitterfelder Muldestausee als Schadstoffsenke. Abh Sächsische Akad Wiss Vol 59, No 4, 69 p. Leipzig

Zoumis T, Calmano W, Förstner U (2000) Demobilization of heavy metals from mine waters. Acta hydrochim hydrobiol 28: 212-218