Sustainable remediation of contaminated sediments

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ABSTRACT
The geoenvironment provides the base for life support and is a significant resource. The combination of these two factors, with their direct link to human population, makes it an integral part of the considerations on the sustainability of the geoenvironment and its natural resources. In this paper, we will discuss the impacts observed as a result of these discharges of hazardous materials and of eutrophication, the remediation techniques developed to restore the health of the sediments and how to evaluate the remediation technologies using indicators. Cost effective integrated technologies are required to ensure the full restoration of the sediments and its benthic community.

RÉSUMÉ
Le géoenvironnement soutiens la vie et est une résource importante. La combinaison de ces deux facteurs avec le liasson avec la population humaine est une facteur intégrale dans la considération du développement durable du géoenvironnement et les résources naturelles. Dans cet article, nous discuterons les impacts observés resultant des décharges des matériaux dangéreuses et l'eutrophication, les techniques de restauration dévelopés pour restaurer la santé des sédiments et comment on peut évaluer les technologies en utilisant les indicateurs. Les technologies intégrées et économiques sont requis pour assurer la restauration complete des sédiments et la communauté benthique.

1 INTRODUCTION

Contaminated sediments are a risk to fish, humans, and animals that eat the fish. Although part of the geoenvironment, sediments have received much less attention from researchers, policy-makers, and other professionals than other components. Sediments are an essential and valuable resource in river basins and other aqueous environments. A large biodiversity live in the sediments. It is thus a source of life and resources for humans as construction materials, sand for beaches, and farmland and wetland nutrients.

There is a need to develop a better understanding of the sediment-water environment and better management practices due to their potential impact on human health and the environment. In particular, they need to be considered during efforts to meet sustainability requirements. Sediments can be exposed to multiple sources of contaminants and are located at the bottom of water columns. This makes risk assessment and management more difficult for soils. The benthic community cannot be isolated from the contaminated sediments. This community is at the base of the aquatic food chain but can be highly tolerant to the contaminants. Sediment quality criteria thus are much lower than for soils as the sediments can have a significant influence on the aquatic food chain.

Approximately 0.9 billion m^3 of sediment in the United States are contaminated according to the United States Environmental Protection Agency (USEPA, 1998). The rate of survival, immunity to diseases and growth of fish such as salmon may be affected by exposure to contaminated sediments early in life (Varanasi et al., 1993).

The close contact of sediments with the water environment ensures that the sediments are both a source and a sink for contaminants. To develop a better understanding of the sediment-water environment better management practices are needed due to their potential impact on human health and the environment. In particular, they need to be considered during efforts to meet sustainability requirements. Some impacts resulting from the increasing population include:

- Loss of biodiversity and living resources
- Increased production of wastes and pollutants
- Depletion of non-renewable natural resources
- Decreased soil, water and air quality
- Increased discharges of greenhouse gases.

Although some of these issues have been examined previously in regards to the geoenvironment (Yong et al., 2006), here we will focus on the stresses and how to mitigate the impacts of these factors in relation to sediments, as they are a highly important resource and basis for life. This environment will be defined as the aquatic geoenvironment and some of the sources of contaminants are shown in Figure 1. They form an integral part of a functioning ecosystem and partake in various types of physical, chemical and biological activities. Some of these as detailed by Trevors (2003) include partaking in various cycles such as the carbon, nitrogen, phosphorus and sulfur, in addition to the hydrologic, and natural processes for the control of the biodegradation of pollutants in the sediment and water.

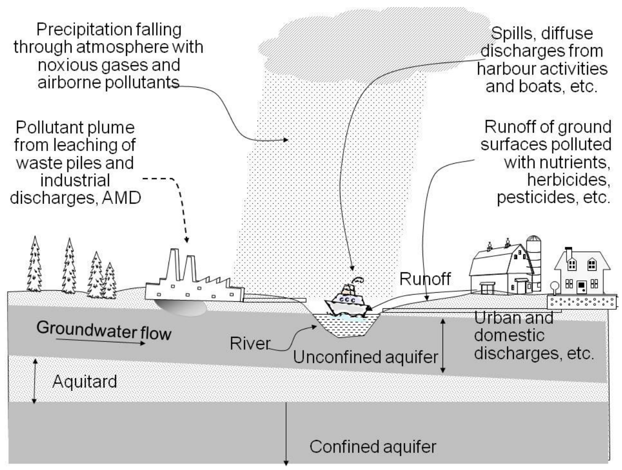

Figure 1. Sources of contaminants entering the aquatic geoenvironment

Sediments have been removed by dredging for many years to maintain navigation. The binding of the contaminants to the sediments, their bioavailability, mobility and degradability are all important aspects that must be taken into account. Sediments are found in lakes, rivers, streams, harbors and estuaries after traveling downstream from their origin. Sources of effluents containing the solids include urban, agricultural and industrial lands.

Technologies for environmental management for remediation and impact avoidance would reduce the degradation of sediment quality. Protocols and procedures to monitor and manage changes in the environment will also be required and will be discussed.

Remediation of the sediment in a sustainable manner requires: (a) source control of contaminants (b) natural processes within the surface sediment layer that maintains the remediated state of the sediment, and (c) restoration of habitat and re-establishment of biodiversity. Human intervention in providing the necessary elements for restoration of habitat and re-establishment of biodiversity, after or during remediation of the contaminated sediment, will provide for sustainable remediated sediment. However, it must be done in a cost-effective manner.

2 SEDIMENT COMPONENTS

Sediment components include inorganic and organic solid materials and are often classified by size, as gravel, sand, silt and clay. The term "sediments" is used for soils deposited in water. Thus, sediments are in contact with inorganic, organic and other human-discharged materials, through the influence of the pore water. Therefore, the properties of the pore water are an important factor regarding the quality of the sediments.

The interactions of the pore water with the contaminants and the solids are complex and will be discussed. It is important to understand the physical and physico-chemical interactions of the contaminants with the sediment solids to understand the capacity of retention of the sediments and potential parameters for contaminant release. Sediment composition, properties and characteristics will influence the interactions at the sediment-pore water interface. The reactions between pollutants and sediment will determine their transport through the sediments, and fate.

Sediment quality is related to the quality of surface water. It is due to the mechanisms of the dissolution of organic matter and the exclusion of contaminants due to the consolidation of sediments or the leaching of contaminants. Therefore, in order to make an appropriate assessment of sediments, the physical, chemical and biological mechanisms have to be understood well. Some are shown in Figure 2. Since the mechanisms are complex, there is the possibility that non-predictable results can be obtained. Therefore, it is required for engineers to modify or take measures suited to the occasion.

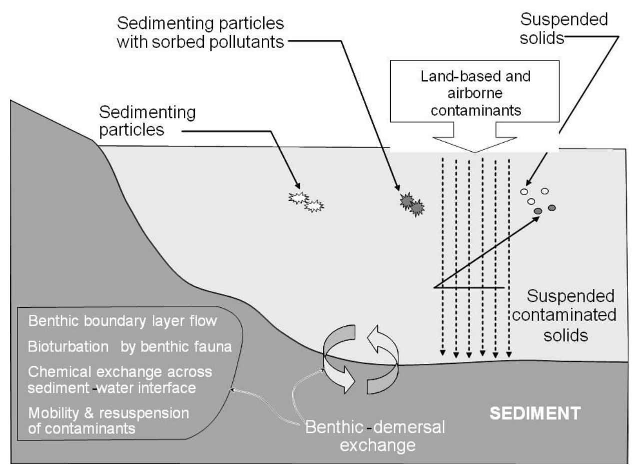

Figure 2. In situ contaminant fate and transport processes

To develop an understanding, information including sampling and physical, chemical and biological test procedures to determine the state and extent of contamination needs to be examined. Sampling can be also used to predict future trends or to evaluate the progress of the remediation work. The scale for sampling and monitoring will be site-dependent. Since most of the physical and chemical properties of sediments have to be determined by the laboratory tests, sampling is almost always needed. Therefore, monitoring of sediment properties can be achieved by tests on samples obtained from the sites. Thus, much effort and planning is required for the monitoring of sediments. A summary of some of the tests required can be seen in Figure 3.

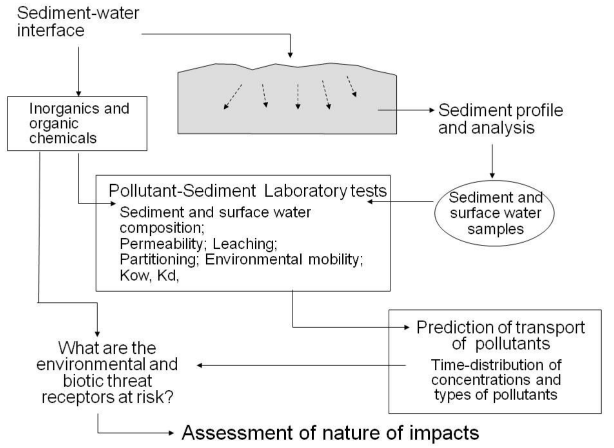

Figure 3. Information required for evaluation of contaminant risks.

3 COMPARISON AND SELECTION OF STRATEGIES

Conceptual model development is a vital part of the evaluation of technology processes and must be site specific. Therefore, human and ecological exposure to contaminants must be reduced and risks of the technology implementation during remediation must be low. Reduction of the bioavailability or bioaccessibiltyof the contaminants can be achieved by reducing the exposure potential via burial or isolation of the contaminants, destruction of the contaminants or removal from the site.

Various in situ and ex situ sediment management options are available. The most frequently considered alternatives are monitored natural recovery (MNR), in situ capping and dredging to remove the sediment from the site. Other approaches include combined techniques and innovative technologies.

More recently, the assimilative capacity of sediment materials has been exploited as a means to attenuate the contaminants in the contaminated sediments. The term natural recovery (NR) has been used to identify the results of contamination attenuation in the sediments through natural processes. The processes involved are in almost all respects similar to those available in the corresponding natural attenuation (NA) treatment processes used in the solid land environment and have been described in Yong and Mulligan (2004). For MNR, exposure to contaminants by the organisms at the sediment surface and within the sediment can continue until the contaminants are degraded. Sediment stability is another issue for long term risks. Low sedimentation rates and other changes can reduce the rate of MNR. Erosion or human disturbance (such as boat wash) may disperse the contaminants.

For in situ capping, contaminant releases may continue until capping is completed. During this period, workers, organisms and the community are exposed to the contaminants. The contaminants outside the main contaminant area may be left untouched and are subject to disturbance. The placement of the cap can disrupt the public and the benthic community. For dredging and excavation, many of the risks are similar to capping. Additional risks to the workers and to the community may occur due to sediment handling during subsequent disposal if no treatment is performed. Further risks can occur due to generation of side-streams during treatment.

Therefore, overall a net environmental benefit should be obtained. Short and long term environmental effects must be balanced. Combined approaches may be more appropriate than single ones, especially for large sites as shown in Fig. 4. Dredging (for high level contamination) can be combined with thin capping (for medium contamination) and then MNR (for low level) if not all of the material can be removed.

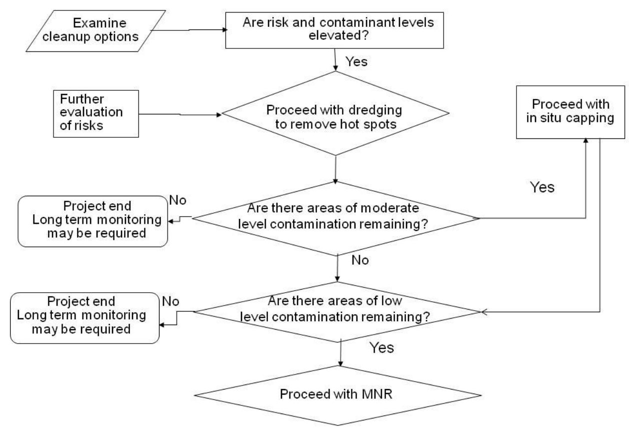

Figure 4. Combined approach for sediment remediation

3.1 Management plan

To determine the best approach for a site, a conceptual model should be developed for evaluation of the various approaches and risk identification. Both short term and long term objectives must be fulfilled. Source control is essential to decrease contaminant inputs (US EPA, 2002). A continuous input of contaminants can defeat remediation effectiveness and recontaminate the area. A combination of approaches may be appropriate if the site is highly heterogeneous. Estimates of residuals and contaminant releases from in situ and ex situ approaches must be realistic to enable comparisons. Sediment stability and contaminant transport are issues of concern. Models are used to determine these differences and should incorporate the transport pathways or evaluation of these phenomena.

Monitoring during and after the remediation period is highly important. This should be planned and initiated at contaminated sites. It can also be used to document short and long term impact and for comparison with the impacts predicted in an Environmental Impact Assessment (EIA). Monitoring will indicate the risk during the remediation, if the cleanup objectives have been achieved and if recontamination is a possibility. Recovery of biota including fish and benthic organisms is essential both on the short and long term. Five year assessments are often required and will assist in the determination of the long-term effectiveness of the remediation and to reduce uncertainties.

Chemical, physical and biological data should be collected at appropriate times and places. Baseline data is usually collected during the initial site characterization phase. The nature and extent of contamination is determined to evaluate remediation feasibility and risk. Predictions by modeling should be compared to long term monitoring data and thus the monitoring plan should be appropriate. Background data from related uncontaminated areas is required to enable establishment of background levels and to determine changes to indicate sources of contamination.

Monitoring at sediment sites can be complicated by the multiple media including surface water, biota, groundwater (if applicable), floodplain soils, and of course, sediment. Sources of contamination can be diverse and thus a wide variety of contaminants is often found. Sites can also be very large and heterogeneous. Goals for remediation are risk-based and the relationship between sediment, contaminants and biota is complex. The frequency and extent of the monitoring should be established from the beginning. Electronic databases may be desirable for sharing results. Statistical or other quantitative methods for analysis of the data should be identified.

Six steps (Figure 5) have been developed as a monitoring plan by the EPA’s Monitoring Guidance (USEPA, 2004). To develop a monitoring plan, the objectives must be clear and specific, particularly due to the limited funding for monitoring. Useful data needs to be collected and often in consultation with the public, local agencies and other parties. Often funding agencies such as the World Bank require Environmental Management Plans which are integrated into EIA before permits can be issued. Physical, chemical and biological objectives should be identified. However, biological endpoints may be more difficult. Toxicity or bioassessment tests may be superior for examination of the effects on organisms. Short-term acute toxicity tests on an organism or measurement of a specific contaminant such as PCBs may be used, whereas in the long term, species diversity or fish tissue contaminant measurements may be more appropriate. Often a combination of physical, chemical and biological approaches is needed to determine risk reduction.

Once the goals are established, the rules should be established to enable the choice of the various actions. The contaminants of interest, the remediation action, the goals of the remediation and various alternatives to achieve the goal should all be included. The time frame should also be considered as a particular action may not be proceeding quickly enough (such as natural recovery) and thus an alternative must be employed (such as in situ capping).

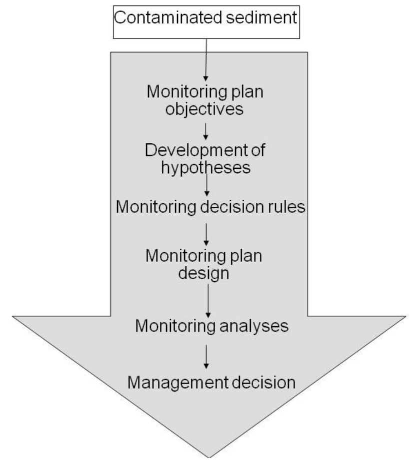

Figure 5. Development of a monitoring plan.

Methods for analysis and sampling methods are continually being improved. Modelling can complement the monitoring to evaluate local variations of stochastic nature. If no modeling is performed, then the affected area needs to be completely monitored. Physical measurements are needed to evaluate erosion and/or deposition of sediments, depth of the sea or riverbed, suspended solid concentration, groundwater flow, particle size, water flow rates and sediment homo- or heterogeneity. Acoustic Doppler Current Profilers (ADCP), satellite images and aerial photography are now being developed to provide indications of suspended sediment content (Bray, 2008). Chemical data is needed for information on the sediment chemistry, and to evaluate biodegradation and partitioning of the contaminant and total organic carbon content. Biological testing can include tests for toxicity, bioaccumulation, biodiversity and food chain effects. Sonar and radar are useful for studying fish and bird behavior, respectively. Beneficial use of dredged sediments should be encouraged.

3.2 Beneficial use of dredged residuals

Prior to disposal of residuals, the following scheme should be undertaken (Figure 6). Beneficial use should be evaluated based on economics and feasibility. If this is not possible, then disposal will have to be performed. Treatment of residuals at a disposal facility will also need to be evaluated to ensure contaminants are not released. The toxicity characteristic leaching procedure (TCLP) test can be used on the residuals to determine if there is the potential for contaminant leaching. The facility itself needs to be monitored to ensure that the structure, leachate collection systems, liners, and treatment facilities are not compromised. Storage capacity must not be exceeded and consolidation/compactions, gas production and organic matter decomposition must be monitored. Leakage of the contaminants from the confined disposal facility (CDF) or landfill to groundwater or surface water needs to be identified through monitoring. Runoff control from the facility is also needed. Noise, dust and odor are other considerations. If there is a cap in the disposal area, revegetation by plants or recolonization by animals needs to be monitored.

Overall, monitoring must be well planned and executed to ensure that the requirements are met. Sampling, analysis, quality control and reporting must be performed professionally. Often analytical laboratories are used to ensure that the procedures are timely and at the lowest cost. The benefit of the remediation work must outweigh any impact caused. Therefore, advantages versus disadvantages must be compared, in particular, to ensure that the remediation method is sustainable and long term risk reduction has occurred.

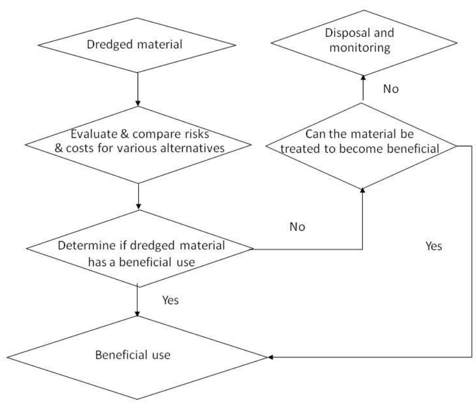

Figure 6. Evaluation of beneficial use of dredged materials

3.3 Sustainable remediation

When treated successfully, sediments can be considered without risk to humans and the environment. However, other aspects must also be considered such as if the remediated sediment be maintained over a long period of time and can habitat restoration, species preservation and biodiversity regeneration. By definition, sustainability means the ability to sustain, maintain or preserve the system in its initial uncontaminated condition or state. Sustainability of remediated sediments is thus the ability of the remediated sediments to be restored and maintained in a remediated state. The key to sustainability assessment is identification of the basic objective of remediation. As previously discussed, the intent of remediation is to minimize and/or eliminate health risk to humans. The remedial solutions must ensure that contaminants in the sediment must not resuspend or resolubilize so that they either bioaccumulate or become bioavailable.

For a remediated sediment treatment to become sustainable, the sediment must: not require retreatment to preserve its remediated state, and must re-establish its original uncontaminated benthic ecosystem. Given the various sources and inputs of contaminants and the various natural processes in the benthic zone, sustainable remediated sediment preservation may not be easily achieved. The fundamental problem is that strategies and technologies must be developed for the preservation of sustainable remediated sediment. Maintaining the state of remediated sediments will avoid threats to human health. Re-treatment of contaminated sediments is costly and needs to be avoided and may also pose further threats to the ecosystem.

A sustainability assessment of remediated sediments is a procedure designed to determine if the remediated state of the sediment can be preserved. The results of the assessment can evaluate if re-contamination of the remediated sediment can occur, if measures are needed to enhance the remediation, or if further remediation of the re-contaminated sediment is required. If habitat restoration and species preservation or biodiversity regeneration are the final objectives, at least four interacting components must be acquired and include: The characteristics of the sediments, the characteristics of the contaminants, the treatments used and the requirements for sustainability. Resuspension and remobilization of contaminants of the contaminated sediments must be avoided. The information obtained will also allow one to determine the best or most technically and cost effective means for treatment.

The various strategies (Figure 7), for remediation of contaminated sediments vary according to how the contaminants in the sediments are neutralized or eliminated. The nature of the remediated sediment will have a direct influence on the strategies and capabilities for sustainability of the remediated sediment to be achieved. The requirements for remediated sediment sustainability assessment will include short and long-term human health risks, regulatory attitudes and goals, economics, and various site specific parameters.

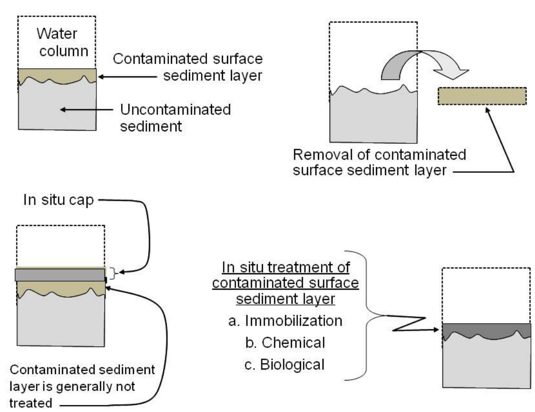

Figure 7. Various remediation strategies

Unless further actions are undertaken, the problems causes by human activities will continue and may escalate. The main challenges are related to land management, energy utilization, consumption of resources, waste management, reduction of pollution and water resource management. Evaluation of the alternative should include a life cycle assessment of the remediation alternative. Some of these factors are indicated in Figure

8. To do this, the overall process must be considered including the assessment, remedial process, disposal of materials (if applicable) and monitoring. Energy consumption, emissions, material use and wastes are major components of this assessment.

3.4 Strategy for remediated sediment sustainability

Remediated sediments must not pose indirect or direct threats to human health. The sustainability goal for remediated sediment is the long term preservation of its remediated state. For this to occur, it is necessary that the treatment technology used in remediation be effective, and that the inputs of contaminants into the ecosystem (including suspended solids, noxious airborne gases and particulates) is eliminated or substantially eliminated.

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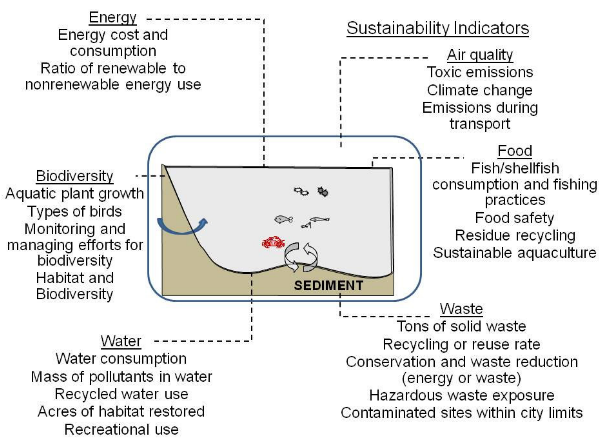

Figure 8. Indicators for evaluating the sustainability of the sediment management option

Figure 9 indicates a five-part strategy that can be implemented to obtain sustainability of the remediated sediment. To reduce the suspended solids above the sediment, clean-up of the water would be required. If the source of contaminants is controlled then this would be a one-time event. The suspension of the solids may also be due to the treatment action itself such as dredging of hot spots or storm events or extensive bioturbation that breach an in situ cap . In areas that are not technically or economically feasible to remediate, natural recovery processes can be exploited or enhanced, if necessary. These natural processes, which have been previously discussed, must be able to neutralize, decontaminate, and/or reduce the bioavailability of contaminants for the benthic animals. Finally, ultimate remediation encompasses the restoration of habitat and re-establishment of benthic species and biodiversity similar to the precontamination state of the zone. Monitoring must play an essential role in ensuring the short and long term remediation of the site.

Sustainability indicators used for monitoring the remediated state of contaminated sediments can be very simple or complex. The choice of indicators to establish sustainability could include the level of bioturbation and bioirrigation, distribution of partitioned contaminants, nature and concentration of contaminants in the interstitial water, and the biological diversity, etc.

Figure 10 provides a protocol leading to the sustainability assessment of remediated sediments based on the distribution of concentrations in the remediated sediment. Several criteria can be employed to declare when sustainability of the remediated sediment has been achieved. As shown in Fig. 10, the presence of contaminants or soil quality guidelines (SQGs) in the remediated sediment will be frequently evaluated to determine sustainability. The indicators may also refer to the distributions and concentrations of target species of contaminants in the surface sediment layer at the top of an in situ cap, the MNR layer, or the treated layers by other remediation processes.

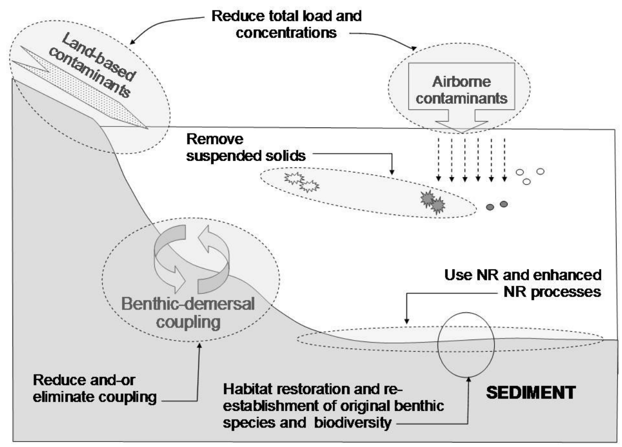

Figure 9. Five-part strategy for contaminant remediation

To determine the nature and distribution of contaminants attached to sediment solids and in the pore water, laboratory tests and studies for partitioning of the kinds of contaminants found in the sediment are needed along with studies on the intermediate products of the organic chemical pollutants found in the sediment. Potential resuspension and remobilization of contaminants in the turbulent layer must be predicted. To accomplish this, fate and transport models must be developed and implemented to predict the distribution of contaminants found in the remediated sediment over time. Although the required activities can be considerable and that many of the detailed activities are unnecessary, the risk to human health and the ecosystem must be minimized. The risk of re-contamination of the remediated sediments is a central issue in the sustainability assessment and thus the control of the input of contaminants is vital.

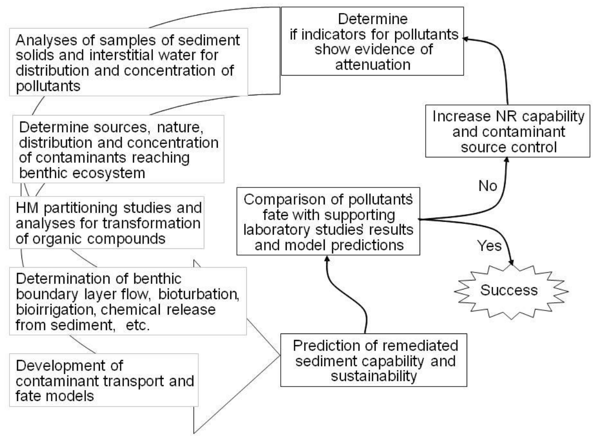

Figure 10. Complete cycle for sustainability analysis

Remediation of contaminated sediments includes contaminant removal, isolation, or reduction of the toxicity. Remediation goals are mainly focused on the contaminant levels. Restoration of the habitat and biodiversity is gaining more attention as this is the ultimate goal for the benthic ecosystem. Specification of the indicators requires baseline information. Species diversity, natural communities and other related biomarkers need to be included as sustainability indicators.

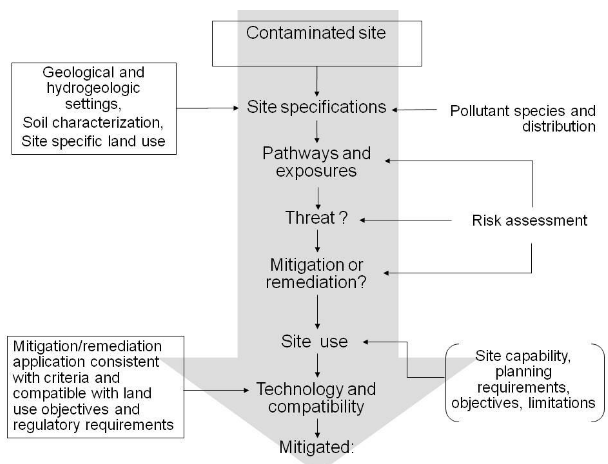

Figure 11. Steps in the remediation process

4 CONCLUSIONS

Remediated sediments do not necessarily mean that contaminated sediments have been remediated to the extent that all the contaminants in the sediments have been removed, or the sediments are devoid of contaminants. Based on site specific characteristics, the most appropriate remediation technology can be chosen. The important lesson to be learnt is that remediated sediments mean that the threats posed by the contaminants in the sediments have been neutralized or eliminated. Except for physical removal of all contaminated sediment layers (which even in the case of dredging is often not obtained), there will be contaminants remaining, in one form or another, in the sediments remediated with currently used technologies. Successful application of treatments involves reducing the bioaccessibility and bioavailability, in addition to the resuspension and remobilization of the contaminants.

Sustainable remediation practices preservation requires:

(a) source control of contaminants entering the ecosystem,

(b) utilization of the natural processes in the ecosystem to maintain the remediated state of the sediment,

(c) restoration of habitat and re-establishment of biodiversity.

Contaminants accumulate both in the sediment and the food chain. Global warming will put further stresses on the fresh and salt water environments. Eutrophication in addition to accumulation of contaminants is also a major concern. Figure 11 shows an illustration of a simple strategy for rehabilitation of the aquatic geoenvironment. Nutrient levels must be balanced so that limitations and excesses are avoided. To avoid obtaining a sterile sediment bed, a natural purification system needs to be established so that habitat restoration can occur. Human intervention in providing the necessary elements for restoration of habitat and re-establishment of biodiversity, after or during remediation of the contaminated sediment, will provide for sustainable remediated sediment preservation.

Environmental dredging requires evaluation of the risks of dredging, determination of disposal methods and/or potential beneficial use. Depending on site conditions, in situ management may be preferable and may pose less risk to human health, fisheries and the environment. Both short term and long-term risks must be evaluated for the in situ and ex situ options. To work towards sustainability, waste must be minimized, natural resources must be conserved, landfill deposition should be minimized, benthic habitats and wetlands must not be lost and must be protected. Innovative integrated decontamination technologies must be utilized. The fate and transport of contaminants must be understood more thoroughly to develop appropriate strategies. Sediment quality standards and guidelines and conventions are detailed in the appendices.

A long term vision is needed. Otherwise, natural resources will continue to be depleted, landfills will continue to be filled with contaminated sediments, and biodiversity in the aquatic geoenvironment will be diminished. Integrated innovative management practices need to be developed and applied.

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