Management of Risk
Arising From Contaminated Sediments

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Introduction

Historically, initiatives to improve environmental protection in the United States have focused on imminent threats first; clean air and clean water have been paramount because we cannot live without them. Consequently, consideration of sediment and soil contamination has generally had a lower priority. Unfortunately, the media (soil, water and air) are inter related and cannot be effectively dealt with as separate independent environments; particularly when considering contaminated sediments.

Environmental protection initiatives implemented under the Clean Water Act over the last 30 years have made significant progress in cleaning surface waters of the U.S., the goal of swimmable water in lakes and rivers has largely been met. However, the goal of fishable waters in all lakes and streams may not be met without addressing the inventory of contaminants that lie within sediment deposits in surface water bodies. This challenge is complicated by the magnitude and cost of the undertaking. Sediment contamination has recently been recognized as a pervasive problem throughout the U.S. (NRC 1997). Contaminated sediments are present in over 70% of U.S. watersheds with the total estimated volume at over 1 billion cubic meters. Not all areas pose a significant environmental risk, but overall the scope is large and projected remedial costs are high (in the billions of U.S. $). Sediment restoration is additionally complicated by the realization that available management technologies are hindered by collateral adverse environmental impacts that, in some cases, may be worse than the primary concern. The key then is to make a balanced evaluation as to the benefits that may be gained by restoring sediments to a state that poses less risk and the cost (both in terms of economics and resource impacts) of the restorative measures.

The Potential Benefits

Sediments are an accumulation of Nature’s waste. They are the detritus of natural processes that get swept away and deposited in relatively low energy environments. Unfortunately, those same low energy environments have fostered the development of ecological communities that are now considered a significant link to overall ecological/environmental health. Life forms that live in or feed in sediments form an essential link in many food chains. As such, when sediments harbor chemicals that are detrimental to those life forms, the ramifications reverberate up the chain. The consequences can be particularly significant when the contaminants accumulate as they are passed up the food chain.

The risk to human health posed by contaminated sediments arises from direct contact or accumulation in the food chain. Pathways associated with direct contact include incidental ingestion or absorption through the skin. In either case, direct contact is only significant (typically) for sediments in shallow areas where wading and foraging for food (e.g., digging clams) are possible. The presence of water reduces particle adhesion to skin and thereby reduces the risk of subsequent absorption through the skin or direct ingestion. If the associated water with the sediments carries sufficient contaminant concentrations to pose an unacceptable risk in and of it's own right, then there is a contaminated surface water problem that is even greater than the contaminated sediment problem. As a consequence, the greatest threat to human health from contaminated sediment arises from food chain accumulation.

While food chain accumulation is the most significant pathway by which contaminated sediments may have an adverse effect on human health, it is primarily limited to a relatively small number of common contaminants: organo-metalic compounds, mercury, polychlorinated biphenyls, polyaromatic hydrocarbons, and chlorinated pesticides. These compounds are often extracted and stored in the tissue of the filter feeders that inhabit sediments such as mollusks and are subsequently concentrated when these species are harvested by higher predators including man. The lower the solubility of the contaminant and the higher its affinity for organic liquids, the greater the potential for bioaccumulation.

Bioaccumulation is generally predicted on the basis of modeling. Factors are available to predict concentration levels through the food chain. If the models indicate a high likelihood of reaching concentrations of concern, the model can be verified by sacrificing individual specimens from within a level of the food chain and determining tissue levels for the contaminant.

The most prevalent impact caused by contaminated sediments is direct toxic effects on aquatic life. It is difficult to estimate impacts from chemical data because of the complex chemistry of sediments and their heterogeneous composition, and the extremely diverse nature of potential receptors. This has led to observational/comparative methods (sometimes considered controversial) for setting criteria such as the Adverse Effects Threshold (AET) developed around Puget Sound. Given the low reliability of the methods, it is common to resort to direct sediment bioassays and elutriate water bioassays to measure the effects of a contaminated sediment on a selected receptor. Bioassays are also challenged because of the difficulty of reproducing in-situ conditions in the laboratory. Results can be compromised by allowing changes in oxidation-reduction state that convert common constituents into species toxic to the receptor (e.g., ammonia).

The Potential Costs

Currently, there are two standard methods for addressing contaminated sediments, capping and dredging with much more limited applications of natural attenuation. With the capping approach, clean fill or barrier materials are placed over the contaminated sediments; while with dredging, the bulk sediments are removed from the water body and disposed elsewhere. Both approaches are associated with negative impacts that change the cost-benefit balance in their application. Capping works by placing clean materials over the contaminated sediments such that the contamination no longer lies in the active zone. Most benthic organisms and environmental transport phenomena function in a very thin layer at the top of the sediments. By placing clean materials over that layer, the contaminants are sealed into a much less active zone and effectively contained. Unfortunately, by definition this restricts future maintenance dredging or other activities that would break the seal and allow contaminants to migrate back into the top layer. Moreover, the placement of capping media buries the benthic life present in the sediments and thus can sacrifice one of the resources that is intended for protection. Finally, this approach may not be effective in dynamic environments where sediment turnover and erosion continually expose new zones of contamination, unless it includes a layer of armoring.

Dredging suffers more immediate impacts than capping. The very act of dredging stirs the contaminated sediments. Because technology is not capable of capturing all the fines suspended in that stirring action, contaminants are mobilized and spread by dredging. Since contaminants have an affinity for the finer particles, it is the most contaminated sediments that are most likely to be mobilized and thus left in the environment. Dredging also exposes deeper layers that may be more contaminated than the surface layer, thus undoing nature's own attempts at capping. Finally, dredging removes all of the benthos present at the time, thus once again, sacrificing one of the resources it is intended to protect. Dredging is also difficult to implement if no suitable site can be found for disposal of the spoils. Open water disposal areas merely move the problem from one site to the next, while engineered disposal sites can be expensive. Upland disposal sites are particularly costly because of the need to dewater sediments for transport and burial.

Given both the economic and the resource loss implications of sediment restoration, the decision to move forward must be weighed carefully. The mere fact that contaminants are present above some concentration threshold does not provide sufficient assurance that restoration is warranted or will provide a net environmental benefit. The potential benefits must be balanced against the potential costs. Since neither can be estimated directly from sediment quality data alone, a number of lines of evidence must be collected and weighed to better calculate the probable benefit and cost. This so-called Weight of Evidence (WOE) approach is emerging as a preferred method of evaluating sites with contaminated sediments.

Weight of Evidence Application in Horseshoe Bay

A weight of evidence approach was applied to contaminated sediments in Horseshoe Bay located just north of San Francisco. Sediments in this small embayment were discovered to contain a variety of contaminants including:

- Lead from paint removed from the nearby Golden Gate Bridge;
- Tributyl tin from marina operations;
- Chlorinated pesticides from runoff;
- Heavy metals from marine paints; and
- Polyaromatic hydrocarbons from petroleum fuels and creosote-treated pilings.

Concentrations were above screening criteria developed for San Francisco Bay. However, the ramifications of restoration were complex. The Bay is home port to the local Coast Guard contingent and channel depths must be maintained to accommodate their vessels. Hence, capping was ruled out as an option. The Bay also harbors a healthy eel grass community that fosters valuable marine life forms. Eel grass beds are extremely sensitive to disruption and not easily restored. In addition, the need to leave a buffer zone around marina dock pilings would reduce the overall fraction of contaminated sediments that could be dredged without incurring economic damage. Sediments around the pilings contained some of the highest concentrations of contaminants observed. As a consequence, there was significant reluctance to dredge areas outside the navigation channel. At the same time, it was recognized that partial dredging would have limited benefits, since restored areas would be recontaminated by mobilization of sediments from areas left unaddressed.

In order to make the required decision as to whether the sediments would be dredged, the problem was formulated as follows:

"Does sediment quality pose a sufficient risk to ecological and human health to warrant sustaining the cost and resource damage implications of dredging?"

This formulation avoided the pitfalls of the more common "Are sediments contaminated?" and allowed the risk managers to depart from existing criteria formulated for other parts of San Francisco Bay that may not be appropriate given the unique aspects of this particular site.

Four lines of evidence were selected for use in the evaluation:

1. Whole sediment bioassays;
2. Elutriate bioassays;
3. Contaminant concentration in sediments; and
4. Food chain bioaccumulation potential.

A scoring system was devised to assign numerical values to different potential outcomes for each of these lines of evidence (Table 1). The scores were then summed across all the lines of evidence and a threshold score selected as the determinant of when an evaluation of dredging would be warranted.

Application of the approach resulted in a finding of low levels of impact whose overall score lay below the threshold at which dredging would be considered. As a consequence, no remedial action was implemented in Horseshoe Bay.

While no action was the right choice at Horseshoe Bay, it does not mean that there are no impacts. It means that the impacts are too small to justify the damages associated with dredging. An entirely different decision may have resulted had there been available remediation technologies that would have fewer collateral impacts. Recent work suggests that such approaches may now be available.

Table 1 Weight of Evidence Approach for Horseshoe Bay

Test	Result	Score
Whole sediment bioassay	Less than statistically significant	0
	Survival greater than half reference threshold value for biologically significant toxicity	3
	Survival less than half reference threshold value for biologically significant toxicity	5
Elutriate bioassay	Less than statistically significant	0
	Survival greater than half reference threshold value for biologically significant toxicity	3
	Survival less than half reference threshold value for biologically significant toxicity	5
Non-bioaccumulative contaminant content	Concentration of all analytes less than ER-L	0
	For each analyte with concentration greater than ER-L, but less than ER-M	3
	For each analyte with concentration greater than ER-M	5
	Nickel, mercury and contaminants without ER-L or ER-M values observed at level in excess of ambient for San Francisco Bay	2
Bioaccumulative contaminant content	Concentration below trigger level for shorebird food chain	0
	Concentration above trigger level for shorebird food chain	9
SCORE REQUIRED TO CONSIDER DREDGING		**9**

Innovative Approaches for Contaminated Sediments

Newer in-situ treatment approaches should be considered when a Weight of Evidence evaluation has indicated that the collateral impacts associated with dredging or capping options have significant adverse impacts.

Site characteristics that may support an in situ response include:
- a) Large area or volume of sediment affected by relatively low levels of contamination
- b) Contaminated sediment located in an area with sensitive/valuable habitat
- c) Low re-suspension and erosion potential
- d) Insurmountable public (or other) resistance to a removal remedy
- e) Presence of structures that could be damaged by dredging equipment

Site characteristics that may support a removal response include:
- a) Limitations cannot be placed on the future use of the site
- b) Institutional controls (e.g., fishing advisories) are not feasible, or deemed to be ineffective
- c) Human health or ecological risk is immediate or substantial and capping is not feasible
- d) Contaminated sediments are located in a dynamic environment with high re-suspension and erosion potential
- e) Insurmountable public or regulatory resistance to an in situ remedy

Recent research and development projects have demonstrated the efficacy of adding of sorption media (e.g., activated carbon) to sediments to immobilize contaminants. Work completed at Stanford University (Ghosh et. al. 2000) has demonstrated that carbon addition to contaminated sediments has several effects to minimize risk/exposure potential. Experimental results from Ghosh et al 2000 are shown in Figures 1 and 2. These experimental data demonstrate that carbon addition has the effect of binding the contaminants (PAHs, and PCBs) in a form that is much less soluble (dissolved concentrations of PCBs decreased by 90%, from 37 ng/L to 3 ng/L). The experimental data also demonstrate a significantly reduced bioavailability with the uptake by clams reduced by 98% for PCBs and 96% for PAHs. These data demonstrate that it is possible to reduce the thickness of a cap by adding materials that chemically bind toxics rather than physically entrap them. The existing data demonstrate the feasibility of chemically binding specific compounds but are not sufficient to determine what happens if the sorbent media are subsequently ingested by benthic life. The benthic organisms may potentially extract toxics from the adsorbent media in their digestive tract. If this is the case, then an additional design consideration is the ability to retrieve the sorbents after they have removed the toxics from the sediments matrix

One approach to sediment restoration focuses on retrieval of targeted contaminants with more limited disruption of the host sediments, in lieu of immobilizing the contaminants in place. One embodiment of this approach, a design suited for thinner sediment layers, has been tested on a limited basis at the bench and field scales. This thin layer (several feet thick) design extracts the targeted contaminants by means of retrievable media. The concept behind this technology is preferential adsorption of the contaminants on a tailored media that can be left in place for a period of time and then selectively removed. In its simplest form, the approach utilizes porous bags or a quilted fabric containing ion exchange media or adsorbents such as activated carbon.

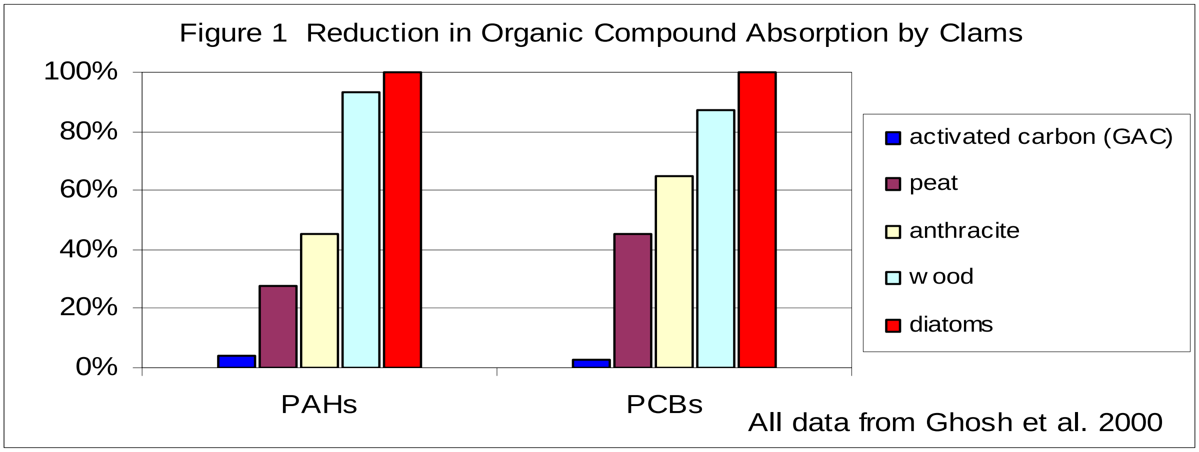
Figure 1 Reduction in Organic Compound Absorption by Clams

All data from Ghosh et al. 2000

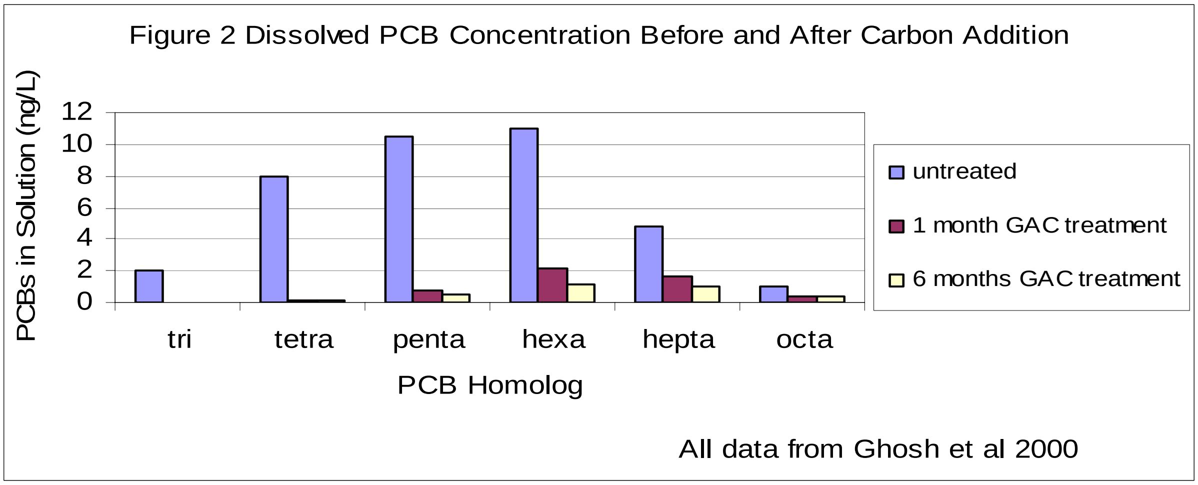
Figure 2 Dissolved PCB Concentration Before and After Carbon Addition

All data from Ghosh et al 2000

The adsorbent pads/bags can be placed on or in the sediment deposit and allowed to stay there for a period of weeks to months. As the media's affinity for the target contaminant causes contaminant to be adsorbed or exchanged, a concentration gradient is formed in the sediments. Contaminants continue to migrate to the media in the bags until equilibrium is reached. Periodically, the bags are pulled and regenerated to remove the concentrated contaminant and return the bags to service. In this way, contaminant only is removed. The use of pads/bags trades off ease of retrieval for less intimate contact between sediments and media and thereby extends the contact time required to achieve a given level of removal.

In a more sophisticated embodiment, the media itself is retrievable and used without the porous bag. In this configuration, the media may be produced with magnetite insertions so that each individual particle is susceptible to magnetic attraction. The media is distributed across the surface of the sediments much as seeds would be scattered across a field. The spent media is retrieved with an electromagnet. The latter configuration provides for more intimate contact with the contaminated sediments and hence reduced residence times because of the smaller distances over which contaminants must diffuse until captured. In addition, the loose media can be deployed in areas with vegetative growth. On the other hand, the loose particles suffer a greater loss rate in terms of the fraction that is not retrieved for regeneration. Moreover, magnetically retrievable media are not currently available on a commercial scale. Venders will produce batches at a higher unit cost in response to order. However, they will need a large market before they will produce such a product on any but an experimental scale.

Recent manufacturing technology developments have made an intermediate approach available. Carbon adsorption filters have been produced from activated carbon fibers that retain the adsorption properties generated with activation. Similarly, resins can be spun in fiber form and activated for use in ion exchange. These fibers can be woven into mats that can be anchored to the bottom sediments and retrieved periodically much the same as the previously described tea bags. The mats would be in closer contact with the sediments, but may not be as rugged with respect to their ability to withstand physical forces in the water body. In addition, manufacturers are also offering quilt like fabrics in which activated carbon or other media such as ion exchange resins have been imbedded.

Bench-scale tests were first run on the loose media approach to retrieve the chlorinated pesticide Kepone from river sediments. The aquarium tests revealed that contaminants could be removed selectively and that removal increased with residence time in the sediments. Vendors were identified who were capable of producing retrievable media on a commercial scale. The logistics of retrieval have not been demonstrated on a field scale. More recently, field trials have been initiated with carbon fabric

Ghosh, U., A. S. Weber, J. N. Jensen, and J. R. Smith. 2000. Relationship between PCB desorption equilibrium, kinetics, and availability during land biotreatment. Environ. Sci. Technol. 34:2542-2548.

National Research Council (NRC), 1997. Contaminated Sediments in Ports and Waterways, National Academy Press, Washington, D.C.