LABORATORY SCALE INVESTIGATIONS IN ARTIFICIAL ARMORING AS A REMEDIATION MEASURE FOR CONTAMINATED RIVERBED SEDIMENT

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ABSTRACT: Contaminated sediments are a serious threat to Great Lakes ecosystems. Numerous efforts currently under examination for sediment remediation are focused on expensive, recently developed destruction and extraction technologies. A simple alternative to these technologies may be artificial armoring. Several flume tests were designed to evaluate the capability of gravel armoring to isolate contaminated Buffalo River sediment from the water column. The sediment was placed in a sediment pocket of a recirculating flume and subjected to velocities up to 32 cm s^{-1}. Measurements of bedload and suspended load were recorded. In subsequent runs, the sediment was armored with limestone gravel. Various factors such as the size of the gravel, the thickness of the armoring layer and the duration of the run were changed. Armored runs typically showed a 98% reduction in the mass of bedload transported and a greater than 99% reduction in suspended solids when compared to the unarmored runs. Suspended sediment and bedload data from the armored and unarmored runs show logarithmic relations as predicted by theory. Several chemical tests were conducted to evaluate the ability of gravel armoring to reduce the transfer of metals to the water column above. On average, levels of Fe were 84% lower and levels of Cr were 93% lower in the water column for armored runs as compared to unarmored runs.

INTRODUCTION

The International Joint Commission Water Quality Board has identified 43 Areas of Concern (AOCs) in the Great Lakes basin. The AOCs are so designated because they exhibit some level of environmental impairment. A major threat to water quality in most AOCs is contaminated sediment. The 1978 Great Lakes Water Quality Agreement emphasized the remediation and eventual elimination of pollution in the Great Lakes. To help accomplish this goal, the Environmental Protection Agency (EPA) established the Assessment and Remediation of Contaminated Sediments (ARCS) program in 1987. The primary focus of the ARCS program is the development, testing and evaluation of new remediation technologies for contaminated sediment (IJC, 1988).

The ARCS program has approached the sediment remediation problem through a variety of options. The first option is the destruction of contaminants by thermal or chemical means. Methods include Wet Air Oxidation, Low Temperature Thermal Stripping, Vitrification, Nucleophyllic Substitution and various sophisticated forms of incineration (Averett et al., 1990). The second option is the extraction of contaminants from the sediment through the addition of various solvents. The three major forms of extraction technologies are Basic Extractive Sludge Treatment, Critical Fluids Systems and Low Energy Extraction (Averett et al., 1990). A third option is the consumption or digestion of contaminants by microorganisms. Bioremediation has been applied successfully in the sewage treatment and petroleum industries for years (Atlas, 1981). It is now being tested for broader applications like contaminated sediment. The fourth option involves immobilization or containment of contaminants. Immobilization refers to various processes where cement, lime, activated carbon or silica gels are mixed with the sediment to create a solidified mass that is resistant to leaching. Containment technologies involve the construction of a physical barrier (typically clay caps or more recently geotextile liners) to limit the transport of sediment and contaminants (Averett et al., 1990). Sediment particles may be a major transport mechanism for contaminants. If sediment is resuspended from the bed, contaminants can desorb from the particles and become integrated into the water column (Allen, 1986). The amount of contaminants released into the water column should be reduced if the amount of sediment released to the water column is reduced.

Another method of containment involves the addition of coarse material like sand or gravel to cover the contaminated sediment. Subaqueous sand caps are a relatively new concept presently being evaluated in the Hamilton Harbor, Ontario, Canada AOC (Zeman, 1992) and in Seattle, Washington (Randall and Palermo, 1990). However, the use of gravel armoring has not been sufficiently researched. The objective of this study is to evaluate the use of gravel as an artificial armoring for contaminated riverbed sediment. This is a flume scale investigation on the effectiveness of limestone gravel armoring to contain Buffalo River (Buffalo, New York; an AOC and a locally accessible waterway)(Figure 1) sediment and its contaminants.

METHODOLOGY

Buffalo River sediment primarily is composed of silt sized particles and shows a decrease in grain size in the downstream direction (Torok, 1993). Since differences in sediment texture can affect erodibility, no one sample of Buffalo River sediment can be considered typical of the river. Therefore, sediment was collected from four sites along the river (Figure 1) using a ponar grab sampler. Sediment from each of these samples was placed into a sediment pocket in the floor of a 6.5 meter long plexiglass recirculating flume. The flume was filled with water to a depth of 20 cm and the sediment was then subjected to various flow conditions. Each flume experiment was run at successively increasing velocities of 5, 12 and 32 cm s^{-1} for 6 hours each. A flow of 5 cm s^{-1} represents typical low flow conditions in the Buffalo River. Flows of 12 and 32 cm s^{-1} represent a range of event velocities. The highest velocity obtainable in the flume is 32 cm s^{-1}.

Water samples (from the flume) were collected using a Sigma Streamline automated pump sampler model 700. These water samples were then passed through 0.45 micron filters to calculate the suspended sediment load in milligrams per liter. Bedload samples also were taken using a collection tray system attached to the floor of the flume, downstream from the sediment pocket (Torok, 1993). The total mass of material on the trays was determined to quantify the amount of bedload transported in grams. The suspended sediment and bedload samples were collected after each 6 hour flow (3 samples per run). The suspended sediment and bedload samples provided a measure of erodibility of the sediment samples.

In subsequent runs, fresh sediment was placed in the flume and armored with limestone gravel. Limestone was chosen as an armoring material because 1.) it is readily available in the Buffalo area, 2.) it is the natural base for most waterways in western New York and should not cause any adverse effects on the aquatic environment, and 3.) limestone raises the pH of water which effectively immobilizes some soluble metals. The armored sediment was subjected to the same flow conditions and samples of suspended sediment and bedload again were collected. In all, 17 flume runs were conducted, 4 runs with each sediment (Table 1). Each sediment sample was evaluated in an unarmored run, an armored run with fine gravel, an armored run with coarse gravel and a fourth run with various adjustments in armoring design or flow conditions (Torok, 1993).

A series of water chemistry experiments was incorporated into some of the flume runs to determine the effect that gravel armoring might have on limiting contaminant release rates. The runs with sediment from site #2 (runs 5, 6, 7, 8 and 17) were used for the chemistry experiments because the sediment in this reach typically contains the highest concentrations of contaminants in the river. A blank run with tap water in the empty flume also was done for comparison purposes. Water samples were extracted from the flume at the end of each of flume run and analyzed for concentrations of iron (Fe), chromium (Cr) and lead (Pb). Colormetric Spectrophotometry was used to measure the concentration of total Fe in water. Atomic Absorption Spectroscopy was used to measure the total concentrations of Cr and Pb. Analytical methodologies are discussed in more detail by Torok (1993).

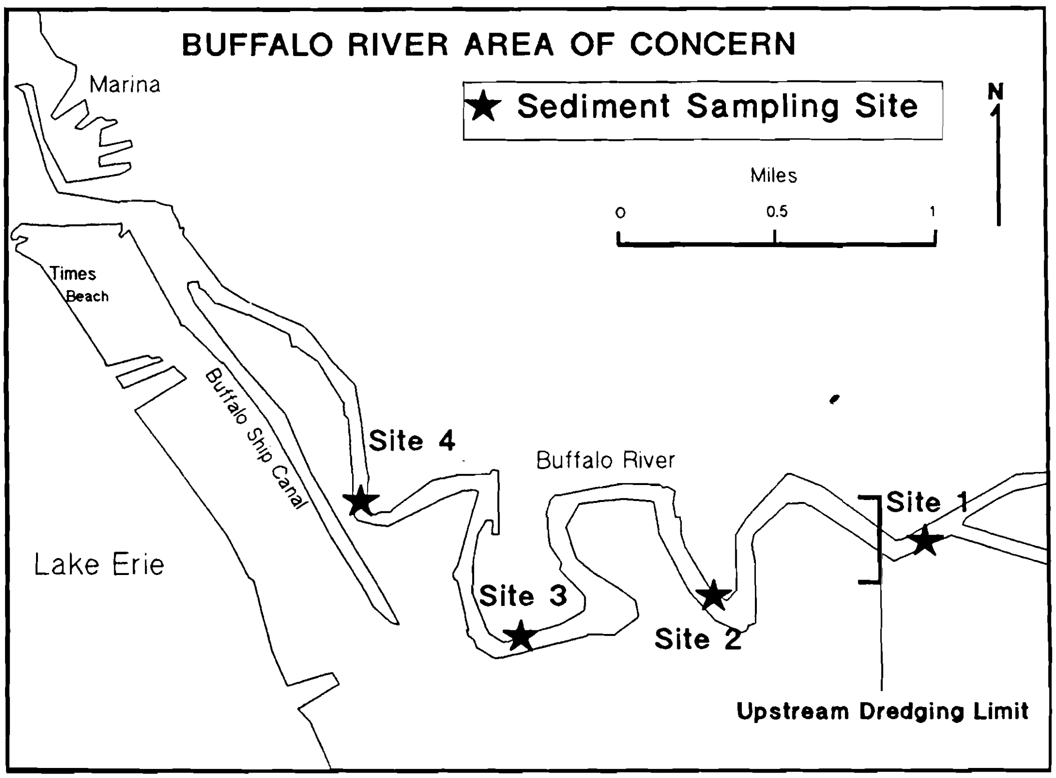

Figure 1. A map of the Buffalo River AOC showing the four sediment sampling sites.

Table 1
Description of the Flume Runs

Run	Sediment Sample*	Description
1	1	18 hours, unarmored
2	1	18 hours, fine gravel armoring, 4 cm thick
3	1	18 hours, coarse gravel armoring, 4 cm thick
4	1	18 hours, mixed gravel armoring, 4 cm thick
5	2	18 hours, unarmored
6	2	18 hours, fine gravel armoring, 4 cm thick
7	2	18 hours, coarse gravel armoring, 4 cm thick
8	2	36 hours, fine gravel armoring, 4 cm thick
9	3	18 hours, unarmored
10	3	18 hours, fine gravel armoring, 4 cm thick
11	3	18 hours, coarse gravel armoring, 4 cm thick
12	3	18 hours, coarse gravel armoring, 8 cm thick
13	4	18 hours, unarmored
14	4	18 hours, fine gravel armoring, 4 cm thick
15	4	18 hours, coarse gravel armoring, 4 cm thick
16	4	18 hours, stratified armor, 5 cm thick
17	2	duplicate of run #7

* numbers correspond to sample locations in Figure 1.

RESULTS

The difference between various armoring configurations were small (Torok, 1993). Basically, if the bed was armored, a drastic reduction was recorded in the amount of sediment that could escape. It did not matter (in this scale experiment) if the armoring was fine gravel or coarse gravel, or if the armoring layer was 4 cm or 8 cm thick. The mean values for eroded sediment and the corresponding standard deviations are presented in Table 2. On average, the gravel armoring contributed to a 50% reduction in suspended sediment concentrations after the 5 cm s^{-1} flow, an 83% reduction at 12 cm s^{-1} and a 99% reduction at 32 cm s^{-1}. A 98% reduction in bedload was observed at 12 cm s^{-1} and at 32 cm s^{-1}. The results of the chemical tests show that gravel armoring has some positive effect on the reduction of metals released to the water column (Figure 2).

Table 2
Mean Eroded Sediment Values and Standard Deviations for all Flume Runs

		5 cm s^{-1}		12 cm s^{-1}		32 cm s^{-1}	
		Mean	S.D.	Mean	S.D.	Mean	S.D.
Armored *	Suspended mg l^{-1}	0.9	.185	2.8	.197	88.9	.835
	Bedload grams	**	**	0.0184	.0053	0.3290	.0435
Unarmored	Suspended mg l^{-1}	1.8	.156	16.5	.982	991	170.6
	Bedload grams	**	**	0.89	.171	16.36	3.512

* Armored runs, suspended sediment, n = 38
Armored runs, bedload, n = 25
Unarmored runs, suspended sediment, n = 11
Unarmored runs, bedload, n = 7

** No bedload movement was observed at this velocity.

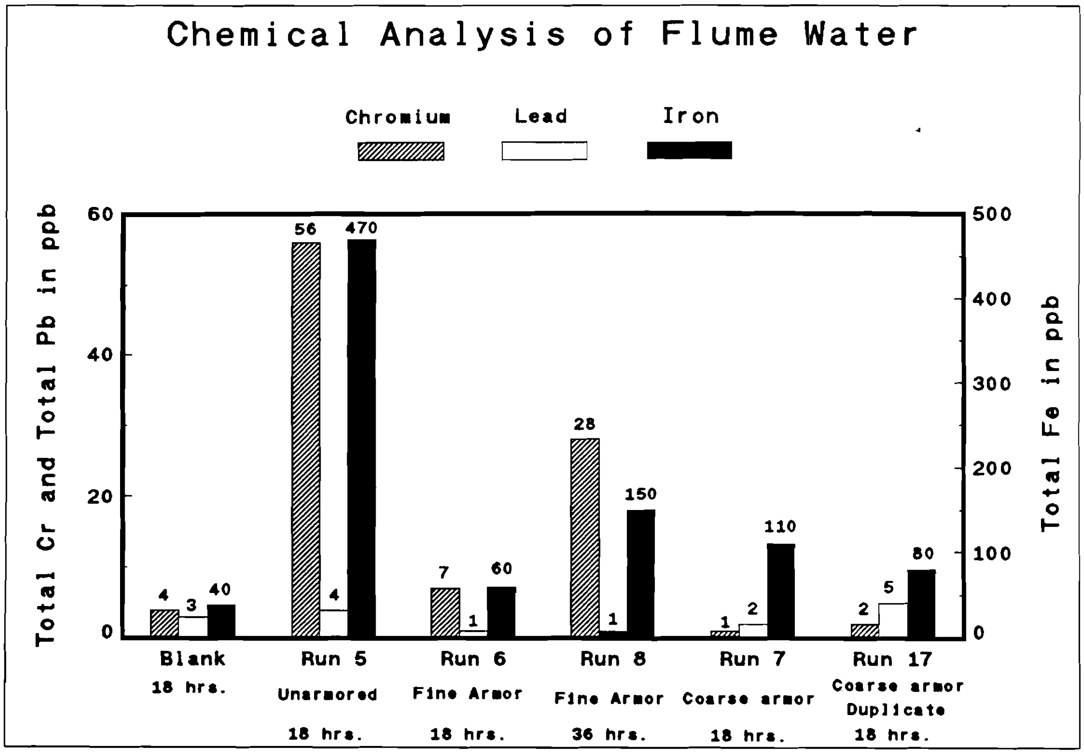

Figure 2. The Concentration of Metals in the Flume Water After Various Runs.

DISCUSSION

Least squares analysis plots summarize the sediment data for armored and unarmored runs in regards to suspended sediment (Figure 3) and bedload (Figure 4). It is unclear why the suspended sediment slopes in Figure 3 intersect. The intersection at approximately 4.2 cm s^{-1} could be an artifact of the least squares method, or it could be that armored beds are more erodible at low velocities, or that with more data at low velocities the unarmored line becomes asymptotic with the armored line. A final possible explanation is the recycling of gravel for flume runs (the gravel was washed between runs, but some mud stayed attached to the gravel and probably detached during the next run). Regardless, the first graph shows that the concentration of suspended sediment increases substantially with an increase in velocity and that the rate of increase is greater for unarmored runs. The armoring becomes more effective as velocity increases (probably to a critical point where velocity becomes so great that the armor is disturbed).

The bedload graph (Figure 4) is interesting because the lines are parallel. The ratio of the percent change in bedload divided by the percent change in velocity is constant. This means that the absolute measures of sediment eroded are different, but the relation of release to velocity is the same.

Once the sediment is armored, only pore water is in contact with the contaminated sediment particles. Although some diffusion can occur, metal transfer is reduced. The concentrations of Fe and Cr are much lower during the armored runs. The results for Pb are inconclusive. It should be noted that all of the recorded values for Pb were close to detection limits, thereby increasing uncertainty in data interpretation.

The concentrations of Fe and Cr in water increased as the exposure time increased (run #8, double duration 36 hours). This raises a question about the effectiveness of gravel armoring to suppress chemical transfer over time. However, the recirculating flume uses the same water for the entire experiment and contact time with the contaminated sediment therefore is longer than it would be in many naturally flowing rivers.

The sediment and chemical data from this study suggest that gravel armoring could be a successful remediation tool for contaminated sediment. Some design considerations should be discussed. The two main design considerations for armoring are the durability and the permeability of the armor. The durability is easily determined based on engineering studies of riprap (Brown and Clyde, 1989). The two main factors for durability are stone size and the thickness of the armoring layer. Both of these can be calculated using standard equations given hydraulic conditions of the site to be armored. The permeability of the armoring layer is more difficult to design. The armoring needs to be impermeable to block the migration of sediment and contaminants to the water column. It also needs to be somewhat permeable to relieve pore pressure and control subsidence of the underlying riverbed. This is usually achieved with a filter layer. A filter usually is used to evenly distribute the weight of an overlying cap and relieves pore pressure from the bed. Optimal design might be a stratified armoring which includes a filter layer of coarse sand and/or fine gravel to seal the contaminated bed. This filter layer should be composed of mixed sizes to reduce the permeability, but not enough to render the filter impermeable. The top covering of coarse gravel should be composed of uniform sizes to increase the durability of the armoring during large scale events (Worman, 1989).

Sediment stability is one factor that must be considered when designing a gravel armoring. The water content of Buffalo River sediment was thought to be too high (typically water contents range between 52% and 60%) to support a layer of gravel armoring although recent laboratory tests suggest that Buffalo River sediment may indeed be stable enough to support a heavy load of gravel (Torok, 1993). If the sediment is unstable, it could be solidified inexpensively or design adjustments in stone size and shape could be made to compensate. Regardless, unstable sediment in the Buffalo River does not eliminate the use of gravel armoring in other AOCs where sediment characteristics could be much different.

Several other factors concerning gravel armoring should be considered. Incoming fines (silt) deposited on top of the armor would fill the pore spaces in the coarse top layer which may strengthen the resistance to erosion by cementation of grains and the elimination of protruding grains. This not only would make the armor stronger, but also would serve as a double protective measure against the release of bed material. Also, the increased capacity of floodwaters may consume more energy by transporting additional fines, causing a reduction in the stream's competence to entrain coarse material. In effect, this would make the armoring layer less vulnerable to erosion.

Armoring could be a simple, inexpensive alternative to other remediation technologies. If site conditions are ideal, then armoring could be simply a matter of dumping rock material onto the riverbed. This would be analogous to dredging in reverse. The same equipment and labor would be involved. Instead of scooping sediment from the bed and placing it on a barge, armoring would consist of scooping gravel from a barge and placing it on the riverbed. Based on this concept of armoring, total cost would be approximately $31 (1992 US dollars) per cubic meter ($14 per cubic meter of gravel, $8 for transportation, and $9 per cubic meter "in place" measure of dredging costs) to armor a section of river (Torok, 1993). An average cost for destruction and extraction technologies is between $250 and $400 (1992 US dollars) per cubic meter of sediment (Averett et al., 1990). If site conditions were less than ideal, additional measures such as solidification of bed material, adjustments in stone size and shape, or more elaborate installation like hand placed rock may be needed and the cost of armoring would increase accordingly.

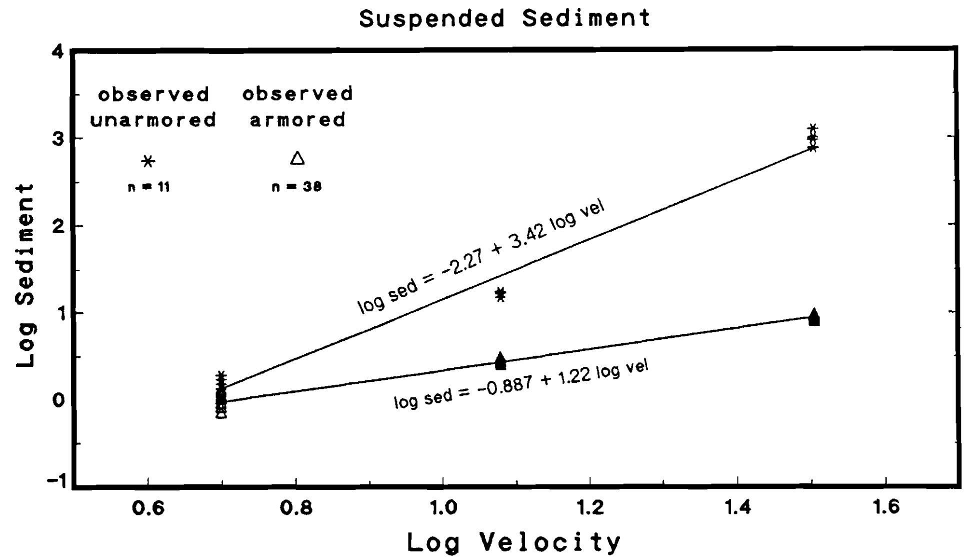

Figure 3. Least Squares Analysis of Suspended Sediment Data from all Runs.

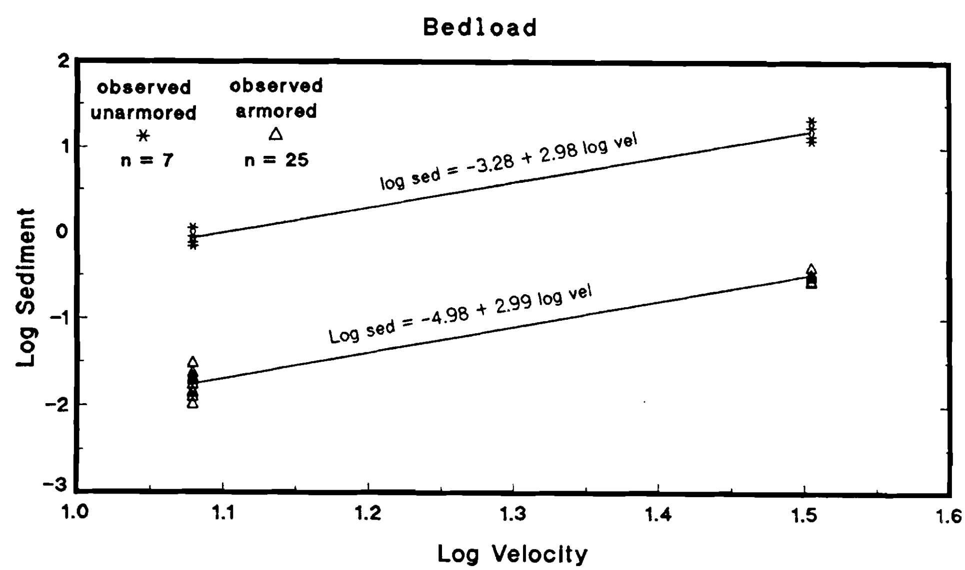

Figure 4. Least Squares Analysis of Bedload Data from all Runs.

CONCLUSIONS

Despite some of the uncertainties, artificial armoring still offers some advantages over other remediation options. First, armoring applies to virtually all contaminants, whereas other remediation technologies are contaminant specific. Second, if design and installation of armoring can be kept simple, armoring would provide a much less expensive alternative. Third, the depth of contamination is insignificant because armoring is applied to a given area (if a river section of 100 m^2 is contaminated to a depth of 5 m, 500 m^3 of sediment would need to be treated with destruction or extraction technologies, whereas armoring the same section would only require covering 100 m^2).

There also are a number of disadvantages to armoring. First, complete destruction of contaminants is more desirable than merely covering them up. Second, the presence of a gravel bed could disrupt the habitat of some aquatic organisms. Third, if an armoring system is installed in a navigable waterway, then future dredging of the channel needs to be considered.

Additional research is recommended before any pilot scale operation is made. The effectiveness and durability of gravel armoring needs to be tested under more adverse conditions than could be applied in the flume used. Also, some flume runs of longer duration need to be performed to see if equilibrium conditions can be attained. Finally, additional chemical tests with more metals and some organic compounds should be considered.

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