Greenhouse Experimental Methods Towards in-situ Burial and Restoration of Contaminated Sites in Submerged Wetlands

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Abstract As a result of commercial and industrial activities conducted in the absence of environmental regulations and enforcement in the past, sediments contaminated by organic compounds, heavy metals, and other potentially toxic chemicals have accumulated in many of the world’s deepwater and wetland environments. These sediment-borne contaminants can eventually become incorporated into aquatic food webs and adversely affect ecological receptors like benthic organisms and fish, and ultimately pose a risk to human health. This laboratory research tested a commercial product AquaBlok™ (patented, composite-aggregate technology comprised of a solid core, an outer layer of clay material, and polymers) as an in-situ capping technology that could be used to remediate and/or manage contaminated sediments in the New Jersey Hackensack Meadowlands, a superfund site. In a greenhouse setting, tubs containing representative Meadowland marsh soil and water were capped with AquaBlok. This research not only examined the potential use of this product as an in-situ capping material and possible substrate for flora colonization, but also examined the improvements of the same patented, clay mineral-based composite aggregate technology (SubmerSeed™) as an alternative to traditional means of wetland plant propagation. At the end of a two-year period, both the sediment/cap and vegetation plant tissues were examined for metallic contaminants (including Cd, Cr, Cu, Pb, Hg, and Zn). Overall, capping provided a less contaminated substrate. Results indicated that AquaBlok cap alone did not allow contaminants in the sediment below to breakthrough. Nevertheless, vegetation colonization was restricted to a limited number of plant species. Furthermore, plants growing in AquaBlok were less robust with lower dry weight and smaller root system than plants growing in uncapped sediments despite the fact that their tissue contained smaller amounts of metallic contaminants. The improvements of the clay mineral-based composite aggregate technology (SubmerSeeds) as an alternative to traditional means of plant propagation worked very well in successfully delivering aquatic plant seeds into permanently inundated conditions.

Keywords Heavy Metals Contamination, In Situ Capping Material, Aquablok, Wetland Vegetation

1. Introduction

As a result of commercial and industrial activities conducted in the absence of environmental regulations and enforcement in the past, sediments contaminated by organic compounds, heavy metals, and other potentially toxic chemicals have accumulated in large quantities in the New Jersey Hackensack Meadowlands[1]. The contamination of marine and freshwater sediments with organic and inorganic pollutants has become a worldwide problem with implications for human and ecological health[2]. The need for remediation or management of contaminated sediments has become increasingly evident. Contaminated sediments can be managed in various ways: They can be removed by dredging and treated ex-situ, as appropriate, prior to disposal. The sediments can also be managed in-situ by capping, or treatment by biological or chemical means. Among these techniques, treatment of contaminated sediment sites with in-situ caps has become an established practice that can provide advantages over other alternative methods [3].

Advantages of in-situ capping relative to sediment removal include minimal environmental and habitat disturbance, minimal sediment exposure and handling, minimal release of volatile organics and elimination of the need for disposal facilities, resulting in lower remediation costs. In addition, in-situ sediment caps are relatively easy to construct, repair or replace as part of ongoing operation and maintenance.

Clean sand has traditionally been employed as capping material and remains a large component of many field-scale capping applications. Sand-based caps have the potential to delay contaminant breakthrough when diffusive transport dominates[4-5], but eventual contaminant breakthrough...
remains a source of concern. Additionally, traditional sand caps are less effective at sites where groundwater seepage or mobile contaminants are present[4].

Recent research studies have focused on in-situ sequestration[6-7], in-situ transformation[8-9] and the development of active caps that incorporate reactive and/or absorptive constituents designed to reduce contaminant bioavailability[6],[10-14]. Ideally, active caps eliminate the risk of contaminant breakthrough into the overlying water column, and can potentially be implemented as alternative sediment.

The objectives of this laboratory research were to:

1) Test the ability of a patented “active cap” i.e. AquaBloc (AB) to serve as physical barrier between contaminated sediments and overlying biological receptors. 2) Evaluate the ability of plants to colonize AB as an alternative to sediment. 3) Determine if adding organic matter (2% peat) improved AB’s suitability as a substrate. 4) Evaluate the effectiveness of AB pellet (Subm eSeeds) as an alternative tool for plant propagation in permanently inundated waters.

1.1. Why AquaBlot™

AquaBloc (AB)[15] is a commercial patented, clay mineral-based composite aggregate technology comprised of a solid core (typically stone aggregate), an outer layer of clay material (bentonite) and polymers. Bentonite, which is well known and widely used throughout the environmental industry, comprises the primary clay material for typical freshwater product formulations, however, other clay or quasi clay-sized materials such as organic matter or plant seeds (Composite Seeding Technology “Subm eSeeds™”) can also be incorporated into product formulations as needed. Empirical and preliminary laboratory data from the manufacturing industry indicate that AB[16] not only serves as a physical barrier between sediments and overlying biological receptors but it can also serve as a benthic substrate for flora and fauna colonization[17].

Based on a series of EPA reports[18-19], AB has distinct advantages over sand for sediment capping with respect to meeting targeted remedial capping functions. It offers physical and chemical blocking of contaminant pathways to overlying receptor organisms and minimizes adverse impacts to wetland hydrology. Granular materials (e.g., sand) can serve as appropriate and adequate capping materials at many sediment remediation sites[20]. Granular materials are typically inexpensive, often locally available, relatively easy to place and can provide substrate for marsh biota. However, typical granular materials are also relatively easily eroded and permeable to the diffusive and advective movement of dissolved sediment-borne contaminants[21]. Additionally, sand-based remedial caps are often relatively thick (i.e. on the order of feet rather than inches) in order to adequately overcome these performance limitations. Relatively thick caps may adversely affect waterway navigation at some deepwater sites or adversely impact the hydrology and vegetative communities in wetland ecosystems[22-23]. Finer-grained materials (e.g., clays) are typically more cohesive, less permeable, and more reactive than sands. A relatively thin clay-based cap (i.e. on the order of inches rather than feet) can provide a better capping remedy that is less disruptive of wetland quality and function. Additionally, clay has a higher cation exchange capacity than sand making it more effective in trapping contaminants such as heavy metals.

The addition of plants seeds into their formulation - Composite Seeding Technology “Subm eSeeds™” creates an attractive alternative to traditional means of plant propagation in wetland/aquatic settings, especially when confronted with the challenges of establishing a favourable vegetative community in permanently inundated conditions.

2. Experimental Design

To study the effectiveness of AquaBloc (AB) and AquaBloc amended with 2% peat moss (ABPM) as in-situ “active” capping material and benthic substrate for wetland biota in a greenhouse setting, a total of six 100 gallon tubs containing Hackensack Meadowlands soil and water were used during a two year period. Wetland vegetation seeds of 28 common regional species (Table 1) were incorporated into the AquaBloc formulation to produce Subm eSeed™.

| Table 1. Subm eSeed composition |
|--------------------------------|
| Botanical Name   | Oz. | Botanical Name   | Oz. |
| Carex comosa    | 2.5 | Decodon verticillatus | 1.25 |
| Carex lacustris  | 0.2 | Eupatorium maculatum | 0.50 |
| Carex lurida    | 4.0 | Hibiscus spp.     | 3.00 |
| Carex vulpinoidea | 6.0 | Iris virginica  | 6.00 |
| Eleocharis ovata | 1.0 | Lobelia cardinalis | 0.25 |
| Juncus effusus  | 1.0 | Lobelia siphilitica | 1.50 |
| Leersia oryzoides | 3.0 | Ludwigia alternifolia | 0.25 |
| Scirpus acutus  | 2.5 | Mimulus ringens   | 1.00 |
| Scirpus pungens | 4.0 | Cephalanthus spp. | 1.00 |
| Scirpus validus  | 6.0 | Pelantina virginica | 16.0 |
| Acorus calamus  | 1.0 | Pontederia cordata | 10.0 |
| Asclepias incarnata | 1.5 | Sagittaria latifolia | 2.00 |
| Alisma subcordatum. | 3.0 | Thypa angustifolia | 2.00 |
| Zizania aquatica | 8.0 | Sparganium spp. | 4.00 |

Replica sediment samples from different areas representing the marsh were collected from the New Jersey Hackensack Meadowlands Marsh. Pre-capping sediments were characterized by measuring % moisture and % total organic carbon (TOC) (ASTM-D2974[24]), grain size (ASTM-D422[25]) and heavy metals of concern (HMOC) (SW 846 Method 7000A[26]). Each experimental tubs received one of three treatments in duplicate: Treatment 1 (Soil) consisting of Hackensack Meadowlands Marsh sediment (sufficient to fill the tub to the 22” mark). Treatment 2 (AB) consisting of Hackensack Meadowlands Marsh sediment (sufficient to fill the tub to the...
13” mark) and 150 lb of AB (8” hydrated). Treatment 3 (ABPM) consisting of Hackensack Meadowlands Marsh sediment (sufficient to fill the tub to the 13” mark) and 150 lb of ABPM (8” hydrated). All tubs were filled with Hackensack Meadowlands Marsh water to the rim mark. Marsh sediments and water were allowed to settle on the tubs for two weeks before capping. Once the cap had completely hydrated to 8”-9”, approximately one week, wetland plant species were sown into the tubes in the form of 1 ½ lb of SubmerSeeds as per the manufacture recommendations.

At the end of each growing season, plants were harvested and characterized based on their numbers, size, dry weight, and root system. Plant tissues as well as sediments in the tubs were monitored for HMOC using the SW 846 Method 7000A[26].

3. Initial pre-capping analysis

Tables 2 and 3 represent the Meadowlands sediments characterizations including percent moisture, ash content (Ash), total organic matter (TOC) and grain sizes. The average percentage moisture of the sediment was 91.1%, ash content varied from 11.9 % to 15.2%, and the average total organic matter content was 86.31% (Table 2).

### Table 2. Characterization of Meadowlands marsh sediments based on ASTM-D2974[24]: percent moisture, ash content (Ash) and total organic matter (TOC)

| Sample | % moisture | % Ash | % TOC |
|--------|------------|-------|-------|
| 1      | 92.8       | 11.9  | 88.1  |
| 2      | 91.3       | 15.1  | 84.9  |
| 3      | 90.8       | 13.6  | 86.4  |
| 4      | 90.1       | 13.1  | 86.9  |
| 5      | 90.5       | 13.2  | 86.8  |
| 6      | 91.1       | 15.2  | 84.8  |
| Average| 91.1       | 13.68 | 86.31 |

The grain size distribution included 50.59% of sand (coarse, medium, fine and very fine), 33.48% silt, 13.92% clay and 2.19% of pebbles and granules (Table 3). Heavy metals of concern present in sediment during the initial collection are presented on Table 4. Based on the Ontario Aquatic Sediment Criterion[27] concentrations for all initial HMOC were above LEL (Lowest Effects Limit) with Cu (281.66 mg/Kg) and Pb (392.86 mg/Kg) concentrations being above SEL (Severe Effects Limit).

### Table 3. Meadowlands marsh sediment samples grain sizes characterization based on ASTM-D422[25]

|Sample| Pebble| Granule| Coarse Sand| Medium Sand| Fine Sand| Very Fine Sand| Silt| Clay |
|------|-------|--------|------------|------------|----------|----------------|-----|------|
|1     | 0.10% | 0.44%  | 11.73%     | 17.56%     | 18.23%   | 11.37%         | 25.92%| 14.64%|
|2     | 0.23% | 3.29%  | 11.86%     | 8.44%      | 11.32%   | 10.00%         | 40.21%| 14.66%|
|3     | 1.64% | 2.20%  | 16.40%     | 11.69%     | 12.98%   | 9.63%          | 33.00%| 13.54%|
|4     | 0.22% | 2.38%  | 13.84%     | 13.71%     | 14.40%   | 8.10%          | 34.79%| 12.55%|
|5     | 0.29% | 1.41%  | 11.11%     | 15.23%     | 15.97%   | 9.48%          | 30.65%| 15.87%|
|6     | 0.06% | 0.88%  | 11.49%     | 14.87%     | 14.05%   | 10.09%         | 36.31%| 12.24%|
|Average|0.42%|1.77% |12.74%|13.58%|14.49%|9.78%|33.48%|13.92%|

### Table 4. Meadowlands marsh sediment analyses of Heavy metals of concern in (mg/Kg) based on SW 846 Method 7000A[26]

| Site | Cd   | Cr   | Cu   | Hg   | Ni   | Pb   | Zn   |
|------|------|------|------|------|------|------|------|
| 1    | 3.19 | 80.6 | 237  | 1.07 | 58.1 | 459  | 534  |
| 2    | 4.69 | 74.7 | 261  | 2.47 | 56.3 | 416  | 589  |
| 3    | 3.75 | 116  | 329  | 1.03 | 76   | 473  | 606  |
| 4    | 4.84 | 88.4 | 342  | 1.98 | 69.4 | 478  | 810  |
| 5    | 4.86 | 87.4 | 329  | 2.13 | 70.6 | 449  | 712  |
| 6    | 4.22 | 43.8 | 192  | 1.62 | 62.6 | 78.6 | 757  |
| Average|4.25|81.81|281.66|1.72|65.5|392.26|668|
| LEL  | 0.6  | 26   | 16   | 0.2  | 16   | 31   | 120  |
| SEL  | 10   | 110  | 110  | 2    | 75   | 250  | 820  |

**LEL** = Lowest Effects Limit based on Ontario Aquatic Sediment Criterion[27].

**SEL** = Severe Effects Limit based on Ontario Aquatic Sediment Criterion[27]
4. Post-capping analysis

4.1. Plant Growth

A limited number of species of marsh vegetation were able to germinate in the test substrate; only six of the original 28 species prepared as SubmerSeeds: Zizania aquatica, Alisma subcordatum, Typha angustifolia, Peltandra virginica, Scirpus validus and Scirpus spp. Large numbers of seedlings of Peltandra virginica, Scirpus validus and Scirpus spp. germinated but were not able to reach full maturity. Due to the low numbers of established mature representatives of these species, they were not fully considered under this study.

During the first growing season, wetland vegetation grew better in uncapped sediments when compared to AquaBlok capped sediments. Zizania aquatica, Alisma subcordatum and Typha angustifolia germinated and developed better in ABPM when compared to AB alone. In addition to the above-mentioned species, Phragmites australis from the local seed/rhizome banks equally colonized both capped and uncapped sediments (Figure 1).

Observations of wetland vegetation during the second growing season revealed that plant germination and growth rates in ABPM declined considerably when compared to the AB and Soil treatments (Figure 1).

Plants growing in AquaBlok (AB and ABPM) as alternative sediment source were less robust than plants growing in Soil (uncapped sediment control) (Figure 2 and Table 5).

The average plant dry weight growing in soil, (control) was 3.8g/plant for Zizania aquatica, 5.4g/plant for Alisma subcordatum, 12.9g/plant for Typha angustifolia and 158.5g/plant for Phragmites australis. Plants growing in AquaBlok (AB and ABPM) have produced smaller plants with lower dry weight when compared to those growing in soil (Figure 2 and Table 5); 1.2g/plant and 1.33g/plant for Zizania aquatica, 2.1g/plant and 1.7g/plant for Alisma subcordatum, and 10.1g/plant for Typha angustifolia.

![Figure 1](image1.png)

**Figure 1.** Average number of plants that germinated and reached maturity at the different treatments; Soil, AB and ABPM. Y1=first growing season, Y2=second growing season.

![Figure 2](image2.png)

**Figure 2.** Average size and dry weight of two plant species representatives growing in different treatments. Soil, AB and ABPM.

When further examining the vegetation growth patterns, a dramatic decrease in leaf sizes (Figure 3) and root development (Figure 4) were observed in plants growing in AquaBlok (AB and ABPM) capped sediments tubs when compared to the same vegetation growing in uncapped marsh sediment (soil).

| Plant Species           | SOIL          |          |          |          |          |          |          |
|-------------------------|---------------|----------|----------|----------|----------|----------|----------|
|                         | Average size  | Average dry weight | Average size  | Average dry weight | Average size  | Average dry weight |
| Zizania aquatica Y1     | 52.6 cm      | 3.8 g    | 43.6 cm  | 1.2 g    | 43.7 cm  | 1.33 g   |
| Alisma subcordatum Y1   | 59.3 cm      | 5.8 g    | 58.7 cm  | 5.8 g    | 44.9 cm  | 5.6 g    |
| Alisma subcordatum Y2   | 58.9 cm      | 5.4 g    | 59.8 cm  | 2.1 g    | 42.2 cm  | 1.7 g    |
| Typha angustifolia Y2   | 92.2 cm      | 12.9 g   | NG       | NG       | 74.4 cm  | 10.1 g   |
| Phragmites australis Y2 | 158.5 cm     | 14.7 g   | 162.7 cm | 27.9 g   | NG       | NG       |

**Table 5.** Average size and dry weight of dominant plants growing at different treatments. Soil, AB and ABPM. NG= no growth. Y1=first Growing season, Y2=second growing season.
While growing within the AquaBlok, roots appeared attached to the aggregate core of the SubmerSeeds and continued to be heavily covered by the clay; this being more noticeable in the AB than in ABPM (Figure 4).

Heavy metal of concern concentrations in sediment shows treatment related effects (Figure 5). Total metal concentrations in AquaBlok (AB and ABPM) treated tubs declined significantly after capping from 1496.83 mg/Kg to 330.70 mg/Kg in AB and 315.18 mg/Kg in ABPM. In uncapped tubs (soil), sediment concentrations of Cu (450.67 mg/Kg) and Pb (460.63 mg/Kg) were consistently above their SEL and Hg (1.21 mg/Kg) and N (45.72 mg/Kg) were above LEL when compared to capped sediment tubs. Cd and Hg was above LEL in all tubes, uncapped soil had twice as much Cd and five times more Hg than capped ones. Uncapped sediments had 5 to 6 times more Cr and Cu than capped sediments. Ni quantities above ELE in uncapped sediments were five and one half times higher than capped sediments. Pb levels above SEL in uncapped sediments were also five and one half times higher than capped sediments.

Table 6 summarizes the amount of heavy metals of concern concentrated in sediments and plant material grown within each of the treatments during two growing seasons.

4.2. Heavy Metals of Concern

Vegetation growing at the different sediment treatments (soil, AB and ABPM) showed great variation in the amounts of HMOC in their tissues (Figure 6).
| Species                      | Treatment | Description | C | Cr  | Cu  | Hg  | Ni  | Pb  | Zn  | Total |
|-----------------------------|-----------|-------------|---|-----|-----|-----|-----|-----|------|-------|
| Zizania aquatica            | SOIL      | End substrate | 4.258 | 81.81 | 281.66 | 4640.76 | 3.322 | 65.5 | 392.26 | 668 | 1496.8 |
| After Planting              | SOIL      | Initial substrate | 2.56 | 51.885 | 450.671 | 23235.41 | 1.21 | 45.728 | 460.638 | 382.219 | 1394.9 |
| Phragmites sp (Y2)          | SOIL      | Stems/leaf  | 0.47 | 3.01 | 4.47 | 209.17 | 0.67 | 0.86 | 5.97  | 87.84  | 103.29  |
| Alisma subcordatum          | SOIL      | Leaves      | 1.775 | 20.345 | 119.631 | 21219.4 | 0.297 | 17.34 | 13728.3 | 253826 | 550.45  |
| After Planting              | SOIL      | Roots       | 2.245 | 23.355 | 124.101 | 21428.6 | 0.967 | 18.2 | 143208 | 341666 | 653.74  |
| Typha angustifolia (Y2)     | SOIL      | Stems       | 0.97 | 3.772 | 26.66 | 1188.24 | 0.184 | 3.371 | 16.98 | 202138 | 254.07  |
| Alisma subcordatum          | SOIL      | Stems       | 0.57 | 1.47 | 14.13 | 232.58 | 0.14 | 1.15 | 5.19  | 50.28  | 72.93   |
| Phragmites sp (Y2)          | SOIL      | Roots       | 5.543 | 21.53 | 150.15 | 36200.7 | 0.255 | 25.262 | 223539 | 47697 | 903.24  |
| After Planting              | SOIL      | Total       | 7.084 | 26.772 | 190.94 | 37621.6 | 0.579 | 29.783 | 245709 | 729388 | 1230.2 |
| Zizania aquatica            | AB        | End substrate | 1.069 | 14.984 | 65.956 | 16291.4 | 4.31 | 15.494 | 94006 | 229343 | 425.16  |
| Phragmites sp (Y2)          | AB        | Initial substrate | 0.169 | 0.92 | 6.266 | 161.899 | 0.191 | 2.259 | 1.603 | 22813 | 34.219  |
| Alisma subcordatum          | AB        | Leaves      | 1.93 | 18.88 | 137.091 | 29549.4 | 0.33 | 23.031 | 238692 | 347383 | 767.33  |
| After Planting              | AB        | Stems       | 3.167 | 34.784 | 209.312 | 46002.8 | 4.831 | 40.784 | 334301 | 599539 | 1226.7 |
| Alisma subcordatum          | AB        | Stems       | 0.128 | 10.25 | 6.956 | 450.645 | 0.068 | 4.512 | 4.862 | 35.692 | 62.469  |
| Typha angustifolia (Y2)     | AB        | Stems       | 0.482 | 1.343 | 15.495 | 399.782 | 0.121 | 1.784 | 7.052 | 95167 | 120.54  |
| Phragmites sp (Y2)          | AB        | Roots       | 3.21 | 11.644 | 84.694 | 17567.4 | 0.194 | 10.263 | 177706 | 369354 | 657.06  |
| After Planting              | AB        | Total       | 3.821 | 23.237 | 126.045 | 19015.4 | 0.384 | 16.559 | 189621 | 500213 | 840.08  |
| Alisma subcordatum          | AB        | Leaves      | 0.065 | 2.806 | 8.205 | 461.13 | 0.03 | 2.584 | 5.471 | 48391 | 67.552  |
| Phragmites sp (Y2)          | AB        | Stems       | 0.271 | 8.924 | 9.881 | 731.774 | 0.023 | 4.275 | 9.05 | 49666 | 82.092  |
| After Planting              | AB        | Roots       | 1.852 | 5.691 | 54.098 | 17838.9 | 1.86 | 7.406 | 119.14 | 170995 | 361.04  |
| Phragmites sp (Y2)          | AB        | Total       | 2.187 | 17.422 | 72.184 | 19031.8 | 1.913 | 14.265 | 136662 | 269052 | 510.68  |

| Species                      | Treatment | SOIL | SOIL | ABPM  | ABPM  | ABPM  | ABPM  |
|-----------------------------|-----------|-----|-----|-------|-------|-------|-------|
| Substrate before Planting   | SOIL      |     |     |       |       |       |       |
| Zizania aquatica            | SOIL      | Stems/leaf |     |     |       |       |       |
| After Planting              | SOIL      | End substrate |     |     |       |       |       |
| Alisma subcordatum          | SOIL      | Leaves |     |     |       |       |       |
| After Planting              | SOIL      | Stems |     |     |       |       |       |
| Typha angustifolia (Y2)     | SOIL      | Leaves |     |     |       |       |       |
| After Planting              | SOIL      | Stems |     |     |       |       |       |
| Alisma subcordatum          | SOIL      | Roots |     |     |       |       |       |
| After Planting              | SOIL      | Total |     |     |       |       |       |

Table 6. Heavy metals concentrations (mg/kg) in substrate and plants. Soil= control (no cap), AB= AquaBlok, ABPM= 2% peat moss amendment, Y1= first growing season, Y2=second growing season. Total= sum of metals without Fe.
Most HMOC tended to accumulate in higher amounts in plants’ underground structures (Figure 6). When growing in the control marsh soil *Zizania aquatic* accumulated 653.7 mg/kg of heavy metals excluding Fe, were 84% of that amount was found in their root tissues with exception of Hg, which was found to be concentrated twice as much in the leaves and stems than the roots. While growing in AB and ABPM, the total accumulation of HMOC were 542.76 mg/kg and 447.77 mg/kg respectively excluding Fe, were 74% in AB and 69% in ABPM were found in the underground root tissue with exception of Hg which was not detected on roots growing in AB. *Alisma Subcordatum* when growing in marsh soil has a total excluding Fe of 1230.31 mg/kg of heavy metals in their tissues were 68% was found in their roots with exception of Hg where more than 80% of its total amount was found in the aboveground (leaves and stems) portion of the plants. When growing in AB and ABPM, the total accumulation of HMOC was 343.43 mg/kg and 372.56 mg/kg and 58% of these metals were found in the belowground structures of the plant. As in the plants growing in marsh soil, Hg concentrates mostly in the aboveground portion of the plants.

*Typha angustifolia* has accumulated 840.08 mg/kg of heavy metals excluding Fe while growing in marsh soil. From this total, more than 78% was found in their belowground structures. Most heavy metals were found in higher quantities approximately 4 times more in the roots than the leaves with exception of Hg and Cr, which had similar amounts throughout the plant. When growing in AB and ABPM, very similar results were observed.

*Phragmites australis* like the other plants accumulated higher quantities (5 times more) of heavy metals in their underground portions (rhizomes and roots). From its 510.6 mg/kg of total heavy metals excluding Fe, 84% was found in tissues below the substrate surface with exception of Hg.

### 5. Conclusions

Overall, capping provided a less contaminated substrate, 1496.83 mg/Kg total contaminant of concern versus 330.70 mg/Kg in AB and 315.18 mg/Kg in ABPM. The concentrations of metals in the cap itself were much lower than in the sediments they covered. Comparison of collection dates showed no significant increase in heavy metals in the cap over a two-year period indicated that the heavy metals below the cap were not breaking through it. Amending the AquaBloks with peat moss (ABPM) did not significantly affect metal concentrations or plant growth. The initial germination and growth of plants in ABPM was better when compared to AB alone, but it quickly declined after the first growing season. In general, plants growing in AB and ABPM as an alternative sediment source were less robust than plants growing in uncapped sediments control (soil) despite the fact that they have smaller amounts of heavy metals in their tissues.

Most of the plants growing in the experimental tubs (soil, AB and ABPM) concentrated higher amounts of heavy metals into their roots and/or underground portion of their stems, between 2.5 and 5 times more than the amounts concentrated in their aerial stems and leaves. This is consistent with other research findings such as the works of Raskin et al.[28], Sawidis et al.[29], Bennett et al.[30], and Reboreda and Caçador[31]. In all, the reduction of heavy metals provided by the capping material did not increase the...
growth or the health of vegetation in contaminated environment.

AquaBlok has proven to be an active barrier between contaminants and the biota. Nevertheless, it is not a good substrate for plant colonization despite the addition of organic matter (2% peat moss) to its formulation. Plants growing in AquaBlok capped sediments were less robust with lower dry weight and smaller root systems. The improvements of the clay mineral-based composite aggregate technology (SubmerSeeds) as an alternative to traditional means of plant propagation worked very well in successfully delivering aquatic plant seeds into permanently inundated conditions.

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