

OPERABLE UNIT V

PECONIC RIVER

**Determination of Phytoextraction and Harvesting
Efficiency of Several Dominant Emergent Wetland
Plants – Contaminated Sediment in the Peconic River,
Brookhaven National Laboratory, Upton, New York**

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1 Introduction

The Peconic River is a coastal plain stream that originates in the Manorville drainage basin on Long Island. Brookhaven National Laboratory (BNL) forms part of the upper drainage area or headwaters of the Peconic River. The surface drainage is poor in the drainage basin and this accounts for much of the land near the river being swampy. East of the BNL property, the Peconic River valley widens and forms the Riverhead basin (ERDA, 1977). The Peconic River drains in an easterly direction and then flows into Flanders Bay, an arm of the Great Peconic Bay. The marshy areas in the northern and eastern sections of BNL have the potential to be a principal tributary of the Peconic River. However, this tributary often undergoes dry periods. Another significant tributary to the Peconic River enters the system from the north in the off-site portion west of Schultz Road. This tributary does not experience the frequent dry conditions that the southern branch does.

Recent investigations regarding BNL have reported the presence of contaminants in the sediments of the Peconic River on the BNL site that likely originated from the sewage treatment plant (STP) discharge on-site. Fourteen inorganic contaminants were detected at concentrations greater than the sediment screening levels. Of these, the metals mercury, silver, and copper were detected most often, and at the highest concentrations above the screening levels. Another contaminant of concern was polychlorinated biphenyls (PCB) measured as Aroclor-1254 and Aroclor-1260. Contamination was highest in surface sediment and was most prominent in depositional areas approximately 1 mile and 1.5 miles downstream of the STP. Although radionuclides are present at levels not requiring cleanup, radionuclides (particularly cesium-137) are present at elevated concentrations in the sediment. Cesium-137 has been found in the flesh of both fish and deer within the vicinity of BNL, and cesium-137 has also been identified as a contaminant of concern.

The on-site portion of the Peconic River is primarily an emergent wetland. It is dominated by cattails, common reed, and sedges. Concerns regarding the remediation of these wetlands and the impact of remediation on the wetlands, have led to the evaluation of less intrusive remediation techniques. One potential remedial technique that has been suggested makes use of the natural phytoextraction (the uptake of contaminants from the sediment and into plants) of the common plants already present coupled with harvesting of the above-ground portion of these plants.

This report only addresses the use of the natural phytoextraction of the common plants already present coupled with harvesting of the above-ground portion of these plants. It does not address the use of introduced plants, induced hyperaccumulation, phytostabilization, or whole plant harvesting. These phytoremediation methods were addressed in a previous assessment conducted by Argonne National Laboratory for BNL (Hayse et al., 2002). A workshop held in December 2000 involving national and international environmental restoration companies, and attended by regulatory agency staff, BNL and DOE project staff, and community members, focused on the identification

of alternative technologies that might be capable of reducing wetland damage while achieving the necessary cleanup objectives. The Argonne National Laboratory report (Hayse et al., 2002) and the work reported herein were conducted to address the interests and concerns regarding the use of phytoremediation for the Peconic River sediments.

The Peconic River area under consideration for remediation has a variety of hydrological characteristics. Water depth, flow, intermittency, and other characteristics vary widely. The use of introduced plants would necessitate the control of these factors throughout the remediation period. The less than optimal growing conditions (such as excess moisture because of an elevated water table or the inability to effectively drain the site for a sufficient period of time) may severely limit the growth of phytoextracting plants. This phytoremediation would require clearing the existing vegetation and treating the areas to be remediated like cultivated fields. The negatives associated with such disruption of the wetlands due to standard excavation techniques is the reason that phytoremediation is being considered.

Hyperaccumulation is conducted by growing select plants in the contaminated sediment. Typically, natural hyperaccumulators are small in size, have a small and shallow root system, a relatively slow growth rate, and are quite sensitive to adverse growing conditions, such as excess moisture. A number are copper hyperaccumulators, but none have been used for remedial applications and most are native to Africa (Reeves and Baker, 2000). No natural hyperaccumulators have been identified for mercury or silver. Hyperaccumulation may be induced through the addition of soil treatments to increase the availability of metals. This technology has focused primarily on lead contamination. Copper may respond to induced hyperaccumulation techniques but may also result in phytotoxic effects to the plants, thus actually decreasing removal rates (Phytotech, 1999). No examples of induced hyperaccumulation for copper, mercury, or silver were available. Additionally, the use of soil treatments for induced hyperaccumulation can increase the potential for contaminants to leach into groundwater due to the increased bioavailability or to increase the potential for increased partitioning into the water column whereby they would be more readily available for uptake by aquatic organisms or for transport further downstream.

Whole plant harvesting is conducted by growing selected plants (introduced or native) with standard farming techniques. Plants are harvested in their entirety (i.e., roots and stalks, etc.) with modified farming equipment. This method may be effective which the plants naturally tend to accumulate nonessential and toxic elements in their roots. Tests conducted at Argonne National Laboratory-West reported removal rates on the order of 4% for cesium-137 and 2% for silver and mercury in greenhouse tests (Negri et al., 1998). Whole plant harvesting is only feasible in relatively loose soils (those with higher sand content) where roots are easily removed, and it has a higher physical impact on the surrounding environment because of the disruption of the sediment surface caused by the harvesting activities.

This report presents the results of a study that was conducted of the dominant plants within the Peconic River on site and their ability to potentially reduce sediment

contaminant concentrations through the process of phytoextraction and harvesting. The study was conducted in two parts. First, several samples of above-ground and below-ground portions of four dominant plant species were collected. Samples of the sediment surrounding the below-ground portion were also collected. These samples were analyzed for the constituents of potential concern: mercury, copper, silver, lead, cesium-137, and the PCBs aroclor-1254 and aroclor-1260. Additionally, the samples were also analyzed for DDT, DDE, and DDD, which had been detected previously in some sediment and biota samples. Second, a model of the reduction of sediment contaminants via harvesting of the above-ground portions of the plants was developed. The analytical data from the plant and sediment samples was used to estimate species- and contaminant specific removal rates and estimates of the time necessary to reach proposed target levels. Based on the analysis and interpretation of the bioaccumulation data gathered for the dominant vegetation types on the site, phytoextraction and harvesting does not appear to be a viable solution for remediation at this site.

The work presented in this report was reviewed by Dr. Elly Best of the U.S. Army Corps of Engineers, Waterways Experiment Station in Vicksburg, Mississippi, as well as by a review panel established and conducted according to the American Society of Mechanical Engineers' peer review process (American Society of Mechanical Engineers [ASME], 2002). This report has subsequently been revised to address issues and concerns expressed during the review process.

2 Materials and Methods

The collection and analysis of plant and sediment samples was carried out under the conditions specified in a work plan that focused on further characterization of sediment contamination in the Peconic River sediments (IT, 2001). All plant and associated sediment samples were collected on September 19 and 20, 2001.

Plant and Sediment Sampling

Four species of emergent wetland plants were selected for this study based on dominance within all or significant portions of the on-site portion of the Peconic River where elevated levels have been reported to occur. The selected species were the cattail, *Typha latifolia*, common reed, *Phragmites communis*, sedge, *Carex* sp., and tussock sedge, *Carex stricta*.

Vegetation samples were collected with a spade and garden shears. First, the spade was driven into the sediment adjacent to the vegetation to be removed down to a depth of approximately 1 foot. The sample, including the sediment and vegetation was removed and placed into a large stainless steel bowl. The vegetation was separated into an above-ground and below-ground portion, and the vegetation was cut into manageable pieces with garden shears. The surrounding sediment was retained in a separate bowl. Sediment adhering to the below sediment portion was removed by shaking, scrubbing, or gently rinsing. This sediment was retained with the surrounding sediment samples and, together, represents the sediment sample associated with that vegetation sample. Vegetation samples were placed into large sealable plastic bags or into glass jars. Sediment samples were homogenized and placed into glass jars. Samples were placed on ice and shipped to the analytical laboratory for further processing.

All field sampling equipment was decontaminated prior to sampling and, as appropriate, in between samples. Gross contamination was removed through rinsing with site water and scrubbing with a brush, followed by application of paper towels. The equipment was then rinsed with potable water and scrubbed with a soap solution. The equipment was then rinsed again with potable water followed by a rinse with deionized water. All samples were collected by biologists and environmental technicians from IT Corporation of Somerset, New Jersey.

Chemical Analysis

All samples, both vegetation and sediment, were analyzed General Engineering Laboratory (GEL) of Charleston, South Carolina using the following methods: mercury by method 7471a “Mercury in solid or semisolid waste (Manual cold-vapor technique)”; copper, lead, and silver by method 6010b “Inductively coupled plasma-atomic emission spectrometry”; DDT, DDE, and DDD by method 8081a “Organochlorine pesticides by gas chromatography”; aroclor-1254 by method 8082 “Polychlorinated biphenyls (PCBs)

by gas chromatography”; and cesium-137 by method 901.1 “Gamma-emitting radionuclides in drinking water.” All sample data were reported in terms of sample dry weight.

Data Validation

An independent data validation was performed on all data generated for this study by Environmental Data Validation, Inc. of Pittsburgh, Pennsylvania. The analytical data validation process consisted of ensuring analytical data quality through the use of standard field sampling and analytical laboratory procedures; specific evaluation of data completeness; verification of instrument calibration; measurement of laboratory precision using duplicates; measurement of laboratory accuracy using spikes; examination of blanks for contamination; assessment of adherence to method specifications and QC limits; and evaluation of method performance in the sample matrix. All chemical data were validated using the procedures outlined in USEPA’s Contract Laboratory Program (CLP) Statement of Work (SOW). Only data deemed useable through the data validation process were used in this study. Results of the data validation are presented in later with the results of the analyses.

Data Analysis

Sample specific bioaccumulation factors (BAF) were calculated for each vegetation-sediment pair for which useable data were available for detectable concentrations of contaminants in both vegetation and sediment samples. BAFs are simply the ratio of the contaminant concentration in the plant to the contaminant concentration in the sediment. Thus, the sample-specific BAFs were calculated using the following equation:

$$BAF = \frac{C_{veg}}{C_{sed}}$$

where

- BAF = Bioaccumulation factor (mg/kg dry weight vegetation per mg/kg dry weight sediment);
- C_{veg} = Dry weight concentration in vegetation (mg/kg); and
- C_{sed} = Dry weight concentration in sediment (mg/kg).

For each species-contaminant pair, a best estimate BAF was calculated as the average of the sample-specific BAFs:

$$BAF_{ij} = \frac{1}{n} \sum_{k=1}^n BAF_{ijk}$$

where

- BAF_{ij} = Average BAF for the i^{th} species and j^{th} contaminant (mg/kg per mg/kg);
- N = The number of valid sample-specific BAFs for the i^{th} species and j^{th} contaminant (unitless); and

$BAF_{ijk} =$ Sample-specific BAF for the n th sample of the i^{th} species for the j^{th} contaminant (mg/kg per mg/kg).

A mathematical model was developed to predict the resulting concentration of contaminant in sediment following any number of successive periods of harvesting of the above-ground portion of the plant. Based on the mathematical models developed, the efficiency of phytoextraction and harvesting as a remedial technique for the Peconic River was evaluated.

3 Results and Discussion

Analytical Results

A total of five cattail samples, ten common reed samples, five sedge samples, and five tussock sedge samples were collected. For each vegetation sample collected, both the aboveground portion (identified in the results as a depth of 0 feet) and the below ground portion (identified in the results as a depth of 0.5 feet) were analyzed. For each vegetation sample, the surrounding sediment was collected as a sample. The results for the above-ground vegetation samples, below-ground vegetation samples, and vegetation-associated sediment samples are presented in Table 1, Table 2, and Table 3, respectively. A summary of the data is presented in Table 4. Table 4 presents the minimum and maximum detected concentration for each contaminant for the above-ground vegetation, below-ground vegetation, and sediment, the average of the detected values, and the frequency of detection.

As indicated in Table 3 and in Table 4, 15 of the copper sediment results and 12 of the 4,4'-DDD results were rejected by the data validator, and these were not used for the evaluations contained in this report. Based on the data validation, all 400 of the vegetation sample results were deemed useable. A total of 173 of the 200 sediment results (86.5%) were deemed useable. The overall rejection rate for the project was 4.5 percent.

Copper was detected in all vegetation samples. Concentrations were higher in the below-ground portions than the above-ground portions. The highest concentrations in the above-ground vegetation were found in sedge (32.4 mg/kg to 69.2 mg/kg) and tussock sedge (4.72 mg/kg to 46.9 mg/kg) and the lowest concentrations were found in cattails (0.96 mg/kg to 4.38 mg/kg) and common reed (2.24 mg/kg to 10.5 mg/kg). Most of the copper sediment results were rejected during data validation due to percent spike recovery outside the acceptable range, and, thus, were unusable. The percent recovery was higher than the acceptable limit, which would indicate a potential bias high in the analytical results for copper in sediment. Based on the model used to determine efficiency of this remedial process, use of sediment data that is biased high would result in BAFs that are biased low, which could result in rejecting the remedial technique due to lack of efficiency when it may actual be efficient. Therefore, these data were not used in the analysis for calculation of BAFs. For the usable data, copper was found to be higher in the sediments (74.8 mg/kg to 1000 mg/kg) than in the plants.

Lead was detected in all the above-ground portion of the tussock sedge (0.81 mg/kg to 5.46 mg/kg) and sedge samples (2.73 mg/kg to 10.6 mg/kg) but in only a few of the cattail and common reed samples, with detected concentrations of 1.48 mg/kg to 1.54 mg/kg and 0.59 mg/kg to 1.0 mg/kg, respectively. Lead was higher in the below-ground portions than in the above-ground portions. Lead was detected in all sediment samples at higher concentrations (7.6 mg/kg to 166 mg/kg).

Mercury was also detected in all the above-ground portion of the tussock sedge (0.168 mg/kg to 0.892 mg/kg) and sedge samples (0.23 mg/kg to 2.17 mg/kg) but also in only a few of the cattail and common reed samples, with detected concentrations of 0.73 mg/kg to 0.09 mg/kg and 0.011 mg/kg to 1.73 mg/kg, respectively. Mercury was higher in the below-ground portions than in the above-ground portions. Mercury was detected in all sediment samples with generally higher concentrations (0.029 mg/kg to 32.6 mg/kg) than in the vegetation.

Silver was detected in all the above-ground portions of tussock sedge (0.85 mg/kg to 7.24 mg/kg), sedge (2.2 mg/kg to 6.86 mg/kg), and cattail samples (1.17 mg/kg to 2.65 mg/kg). Silver was detected in just over half of the common reed samples with detected concentrations of 0.72 mg/kg to 1.97 mg/kg. Silver was higher in the below-ground portions than in the above-ground portions. Silver was generally detected in all sediment samples at higher concentrations (0.69 mg/kg to 194 mg/kg).

**Table 1
Analytical Results of Above-Ground Vegetation Samples**

| Sample Number | Site ID | Depth Ft. | Cesium-137 | | Copper | | Lead | | Mercury | | Silver | | 4,4"-DDD | | Aroclor 1254 | | Aroclor 1260 | |
|----------------------|---------|--------------|------------|------|--------|------|-------|------|---------|------|--------|------|----------|------|--------------|------|--------------|------|
| | | | pCi/g | Qual | mg/Kg | Qual | mg/Kg | Qual | mg/Kg | Qual | mg/Kg | Qual | ug/Kg | Qual | ug/Kg | Qual | ug/Kg | Qual |
| CATTAILS | | | | | | | | | | | | | | | | | | |
| B-V1 | 049-40 | 0 | 0.148 | UI | 3.27 | J-Q | 1.48 | J-Q | 0.09 | J-Q | 2.65 | J-Q | 35.5 | J-Q | 69.6 | UJ-Q | 69.6 | UJ-Q |
| B-V2 | 049-41 | 0 | 0.015 | DL | 2.12 | J-Q | 0.67 | UJ-Q | 0.013 | UJ-Q | 1.33 | J-Q | 25.2 | J-Q | 40.7 | UJ-Q | 40.7 | UJ-Q |
| B-V3 | 049-42 | 0 | 0.773 | UI | 0.96 | J-Q | 0.89 | UJ-Q | 0.018 | UJ-Q | 1.17 | J-Q | 17 | J-Q | 56.5 | UJ-Q | 26.5 | UJ-Q |
| B-V4 | 049-43 | 0 | 0.14 | UI | 2.23 | J-X1 | 1.54 | J-X1 | 0.073 | J-X1 | 1.98 | J-X1 | 5.9 | J-Q | 10 | UJ-Q | 10 | UJ-Q |
| B-V5 | 049-44 | 0 | 0.103 | | 4.38 | J-Q | 0.79 | UJ-Q | 0.015 | UJ-Q | 1.32 | J-Q | 1.2 | UJ-Q | 48.1 | UJ-Q | 48.1 | UJ-Q |
| COMMON REED | | | | | | | | | | | | | | | | | | |
| C-V1 | 049-45 | 0 | 0.354 | | 3.08 | J-Q | 0.59 | J-Q | 0.011 | J-Q | 1.04 | J-Q | 10.6 | UJ-Q | 15.3 | J-Q | 26.5 | UJ-Q |
| C-V2 | 049-49 | 0 | 0.467 | | 2.24 | J-Q | 1 | J-Q | 0.01 | UJ-Q | 0.72 | J-Q | 13.8 | UJ-Q | 34.4 | UJ-Q | 34.4 | UJ-Q |
| C-V3 | 050-31 | 0 | 0.3 | | 7.53 | J-Q | 0.52 | UJ-Q | 0.009 | UJ-Q | 0.53 | UJ-Q | 12.8 | UJ-Q | 31.9 | UJ-Q | 31.9 | UJ-Q |
| C-V4 | 050-32 | 0 | 0.527 | | 5.49 | | 0.65 | B | 0.007 | U | 1.1 | B | 9.8 | U | 24.6 | U | 24.6 | U |
| C-V5 | 050-33 | 0 | 0.204 | | 6.3 | | 0.45 | U | 1.73 | * | 0.72 | B | 11.1 | U | 27.9 | U | 27.9 | U |
| D-V1 | 061-67 | 0 | 0.826 | J-D | 7.98 | J-Q | 0.67 | UJ-Q | 0.013 | UJ-Q | 1.97 | J-Q | 4 | UJ-Q | 42.9 | UJ-Q | 42.9 | UJ-Q |
| D-V2 | 061-66 | 0 | 1.08 | J-D | 10.5 | J-Q | 0.51 | UJ-Q | 0.038 | J-Q | 1.14 | J-Q | 4 | UJ-Q | 31.6 | UJ-Q | 31.6 | UJ-Q |
| D-V3 | 061-63 | 0 | 0.752 | J-D | 3.68 | J-Q | 0.54 | UJ-Q | 0.01 | UJ-Q | 0.56 | UJ-Q | 4 | UJ-Q | 32.9 | UJ-Q | 32.9 | UJ-Q |
| D-V4 | 061-62 | 0 | 0.159 | J-D | 5.23 | J-Q | 0.42 | UJ-Q | 0.008 | UJ-Q | 0.43 | UJ-Q | 4 | UJ-Q | 26.1 | UJ-Q | 26.1 | UJ-Q |
| D-V5 | 061-68 | 0 | 1.46 | J-D | 4.66 | J-Q | 0.39 | UJ-Q | 0.008 | UJ-Q | 0.4 | UJ-Q | 4 | UJ-Q | 25.2 | UJ-Q | 25.2 | UJ-Q |
| TUSSOCK SEDGE | | | | | | | | | | | | | | | | | | |
| C-V11 | 049-46 | 0 | 1.55 | | 46.9 | | 5.46 | | 0.892 | | 7.24 | | 2.7 | JP | 50.1 | P | 33.8 | U |
| C-V12 | 049-47 | 0 | 0.42 | | 21.3 | | 2.05 | | 0.17 | | 2.76 | B | 13.4 | U | 33.5 | U | 33.5 | U |
| C-V13 | 049-48 | 0 | 0.531 | | 12.1 | | 1.11 | B | 0.184 | | 1.24 | B | 13.6 | U | 33.9 | U | 33.9 | U |
| D-V21 | 060-26 | 0 | 0.61 | | 11.8 | | 1.97 | | 0.168 | | 2.2 | B | 12.2 | U | 14.7 | J | 30.4 | U |
| D-V22 | 061-64 | 0 | 0.635 | | 4.72 | B | 0.81 | B | 0.67 | | 0.85 | B | 10.6 | U | 26.5 | U | 26.5 | U |
| SEDGE | | | | | | | | | | | | | | | | | | |
| D-V11 | 061-65 | 0 | 1.49 | J-D | 69.2 | J-X1 | 10.6 | J-X1 | 1.64 | J-X1 | 4.9 | J-X1 | 4 | J-X1 | 284 | J-X1 | 284 | J-X1 |
| D-V12 | 060-22 | 0 | 0.905 | J-D | 34 | J-X1 | 4.41 | J-X1 | 0.23 | J-X1 | 2.2 | J-X1 | 4 | J-X1 | 128 | J-X1 | 128 | J-X1 |
| D-V13 | 060-23 | 0 | 1.04 | J-D | 37.7 | J-X1 | 5.27 | J-X1 | 1 | J-X1 | 2.52 | J-X1 | 4 | J-X1 | 148 | J-X1 | 148 | J-X1 |
| D-V14 | 060-24 | 0 | 1.26 | J-D | 32.4 | J-Q | 4.84 | J-Q | 0.804 | J-Q | 2.53 | J-Q | 4 | UJ-Q | 72.3 | UJ-Q | 72.3 | UJ-Q |
| D-V15 | 060-25 | 0 | 0.329 | | 32.7 | | 2.73 | B | 2.17 | | 6.86 | B | 62.3 | U | 156 | U | 156 | U |

U – undetected, value presented is detection limit

J – value is estimated

* - Duplicate analysis was not within control limits

B – Reported value is below the contract required detection limit

DL – Qualified due to accuracy problems (Control Standards outside limits)

JP – Estimated value, differences between columns above limits

interference problems (Serial dilutions or poor spike recovery)

D – Qualified due to precision problems (duplicates outside limits)

Q – Qualified for other reasons

X1 – Does not meet general USEPA criterion meets project specific DQOs

R – Rejected, data unusable (compound may not be present)

N – Spiked sample recovery not within control limits

S – Qualified due to accuracy problems (spike recoveries outside limits) | – Qualified due to

Table 2
Analytical Results of Below-Ground Vegetation Samples

| Sample Number | Site ID | Depth | Cesium-137 | Copper | Lead | Mercury | Silver | 4,4"-DDD | Aroclor 1254 | Aroclor 1260 |
|----------------------|---------|-------|------------|------------|------------|------------|------------|------------|--------------|--------------|
| | | Ft. | pCi/g Qual | mg/Kg Qual | mg/Kg Qual | mg/Kg Qual | mg/Kg Qual | ug/Kg Qual | ug/Kg Qual | ug/Kg Qual |
| CATTAILS | | | | | | | | | | |
| B-V6 | 049-40 | 0.5 | 2.44 | 61.9 J-Q | 18.5 J-Q | 0.757 J-Q | 12.2 J-Q | 262 J-Q | 72 J-Q | 97.4 UJ-Q |
| B-V7 | 049-41 | 0.5 | 0.978 | 19.9 J-Q | 5.65 J-Q | 1.01 J-Q | 4.17 J-Q | 14.6 J-Q | 54 J-Q | 68.7 UJ-Q |
| B-V8 | 049-42 | 0.5 | 0.282 | 165 J-Q | 18.8 J-Q | 1.32 J-Q | 17.9 J-Q | 9.7 J-Q | 156 J-Q | 46.3 J-Q |
| B-V9 | 049-43 | 0.5 | 0.542 | 10.3 J-Q | 6.17 J-Q | 7.09 J-Q | 3.74 J-Q | 2.1 J-Q | 93.7 UJ-Q | 93.7 UJ-Q |
| B-V10 | 049-44 | 0.5 | 3.5 | 457 J-Q | 69.2 J-Q | 2.82 J-Q | 96.5 J-Q | 4.9 J-Q | 54.6 J-Q | 74.3 UJ-Q |
| COMMON REED | | | | | | | | | | |
| C-V6 | 049-45 | 0.5 | 1.54 | 147 J-Q | 24.9 J-Q | 0.999 J-Q | 13.8 J-Q | 5.7 J-Q | 82.6 J-Q | 34.2 J-Q |
| C-V7 | 049-49 | 0.5 | 0.876 | 78.2 J-Q | 8.84 J-Q | 2.26 J-Q | 12.3 J-Q | 4.8 J-Q | 116 J-Q | 55.9 UJ-Q |
| C-V8 | 050-31 | 0.5 | 0.407 | 18.7 J-Q | 2.74 J-Q | 1.31 J-Q | 2.52 J-Q | 3.4 J-Q | 209 J-Q | 56.2 UJ-Q |
| C-V9 | 050-32 | 0.5 | 1.88 | 117 | 14.1 | 0.873 | 14.8 | 17.1 U | 69.1 | 40.5 J |
| C-V10 | 050-33 | 0.5 | 0.885 | 86.1 | 6.92 | 0.63 | 11.9 | 20.2 U | 95.8 | 46.4 JP |
| D-V6 | 061-67 | 0.5 | 1.17 J-D | 28.3 J-Q | 5.49 J-Q | 0.808 J-Q | 6.29 J-Q | 4 UJ-Q | 39.2 J-Q | 76.9 UJ-Q |
| D-V7 | 061-66 | 0.5 | 0.881 J-D | 32.8 J-Q | 7.81 J-Q | 1.78 J-Q | 7.4 J-Q | 4 UJ-Q | 40.3 J-Q | 47.6 UJ-Q |
| D-V8 | 061-63 | 0 | 1.41 J-D | 26.7 J-Q | 2.8 J-Q | 1.84 J-Q | 1.15 UJ-Q | 4 UJ-Q | 73.6 UJ-Q | 73.6 UJ-Q |
| D-V9 | 061-62 | 0.5 | 0.711 J-D | 9.35 J-Q | 1.07 UJ-Q | 1.22 J-Q | 1.1 UJ-Q | 4 UJ-Q | 65.1 UJ-Q | 65.1 UJ-Q |
| D-V10 | 061-68 | 0.5 | 0.485 J-D | 13.8 J-Q | 1.01 UJ-Q | 2.02 J-Q | 1.04 UJ-Q | 4 UJ-Q | 47.8 J-Q | 61.5 UJ-Q |
| TUSSOCK SEDGE | | | | | | | | | | |
| C-V14 | 049-46 | 0.5 | 3.78 | 349 | 40.6 | 2.79 | 52.7 | 31.6 U | 471 P | 224 P |
| C-V15 | 049-47 | 0.5 | 2.34 | 485 | 62.1 | 2.5 | 53.7 | 10.2 JP | 121 | 56.2 J |
| C-V16 | 049-48 | 0.5 | 4.29 | 819 | 85.4 | 2.9 | 104 | 31.2 U | 275 | 124 |
| D-V23 | 060-26 | 0.5 | 3.12 | 195 | 49.2 | 1.29 | 23.4 | 4.8 J | 54.1 J | 78.4 U |
| D-V24 | 061-64 | 0.5 | 4.03 | 254 | 79.6 | 2.76 | 40 | 38 U | 94.9 U | 94.9 U |
| SEDGE | | | | | | | | | | |
| D-V16 | 061-65 | 0.5 | 2.51 J-D | 185 J-X1 | 26.9 J-X1 | 5.61 J-X1 | 31.9 J-X1 | 4 J-X1 | 238 J-X1 | 238 J-X1 |
| D-V17 | 060-22 | 0.5 | 4.26 J-D | 292 J-X1 | 76.6 J-X1 | 1.03 J-X1 | 39.8 J-X1 | 4 J-X1 | 84.6 J-X1 | 130 J-X1 |
| D-V18 | 060-23 | 0.5 | 2.9 J-D | 237 J-X1 | 54.3 J-X1 | 4.42 J-X1 | 36.8 J-X1 | 4 J-X1 | 89 J-X1 | 191 J-X1 |
| D-V19 | 060-24 | 0.5 | 2.18 J-D | 62.5 J-X1 | 10.5 J-X1 | 1.65 J-X1 | 7.29 J-X1 | 4 J-X1 | 63.5 J-X1 | 143 J-X1 |
| D-V20 | 060-25 | 0.5 | 2.86 | 238 | 48.7 | 1.46 | 51.3 | 76.9 U | 111 J | 192 U |

U – undetected, value presented is detection limit

J – value is estimated

* - Duplicate analysis was not within control limits

B – Reported value is below the contract required detection limit

DL – Qualified due to accuracy problems (Control Standards outside limits)

JP – Estimated value, differences between columns above limits

I – Qualified due to interference problems (Serial dilutions or poor spike recovery)

D – Qualified due to precision problems (duplicates outside limits)

Q – Qualified for other reasons

X1 – Does not meet general USEPA criteria meets project specific DQOs

R – Rejected, data unusable (compound may not be present)

N – Spiked sample recovery not within control limits

S – Qualified due to accuracy problems (spike recoveries outside limits)

Table 3
Analytical Results of Vegetation-Associated Sediment Samples

| Sample Number | Site ID | Depth Ft. | Cesium-137 | Copper | Lead | Mercury | Silver | 4,4"-DDD | Aroclor 1254 | Aroclor 1260 |
|---------------------|---------|--------------|------------|------------|------------|------------|------------|------------|--------------|--------------|
| | | | pCi/g Qual | mg/Kg Qual | mg/Kg Qual | mg/Kg Qual | mg/Kg Qual | ug/Kg Qual | ug/Kg Qual | ug/Kg Qual |
| CATTAILS | | | | | | | | | | |
| B-VS1 | 049-40 | 0.5 | 11.1 | 158 J-Q | 34.5 J-Q | 5.99 J-Q | 29 J-Q | 6 R-Q | 42.8 J-Q | 14.7 J-Q |
| B-VS2 | 049-41 | 0.5 | 11.9 | 105 J-Q | 51.1 J-Q | 12.3 J-Q | 28.1 J-Q | 3.7 J-Q | 27.2 J-Q | 5.3 J-Q |
| B-VS3 | 049-42 | 0.5 | 1.59 | 97.7 J-Q | 16.9 J-Q | 4.49 J-Q | 13.5 J-Q | 5.3 J-Q | 54.3 J-Q | 21.3 J-Q |
| B-VS4 | 049-43 | 0.5 | 7.94 | 376 J-Q | 61.7 J-Q | 13.1 J-Q | 67.2 J-Q | 5.5 R-Q | 59.5 J-Q | 32.4 J-Q |
| B-VS5 | 049-44 | 0.5 | 12.1 | 1170 J-X1 | 166 J-X1 | 25.7 J-X1 | 219 J-X1 | 16.4 J-X1 | 261 J-X1 | 140 J-X1 |
| COMMON REED | | | | | | | | | | |
| C-VS1 | 049-45 | 0.5 | 5.73 | 542 J-Q | 50 J-Q | 10.5 J-Q | 84.8 J-Q | 6.7 UJ-Q | 166 J-Q | 58.4 J-Q |
| C-VS2 | 049-49 | 0.5 | 12.3 | 1000 J-Q | 115 J-Q | 32.6 J-Q | 194 J-Q | 11.9 R-Q | 121 J-Q | 54.8 J-Q |
| C-VS3 | 050-31 | 0.5 | 9.45 | 967 J-Q | 92.9 J-Q | 19.9 J-Q | 158 J-Q | 12.4 R-Q | 129 J-Q | 44.6 J-Q |
| C-VS4 | 050-32 | 0.5 | 8.63 | 805 R-S | 98 J-Q | 15.8 J-Q | 145 J-Q | 10.3 UJ-Q | 21.4 J-Q | 25.7 UJ-Q |
| C-VS5 | 050-33 | 0.5 | 9.05 | 661 R-S | 84 J-Q | 21.3 J-Q | 176 J-Q | 8.7 R-Q | 22 J-Q | 18.7 UJ-Q |
| D-VS1 | 061-67 | 0.5 | 9.9 | 125 R-S | 40 J-Q | 4.38 J-Q | 16.6 J-Q | 4.1 R-Q | 13.7 J-Q | 5.1 J-Q |
| D-VS2 | 061-66 | 0.5 | 7.58 | 274 R-S | 63.9 J-Q | 11 J-Q | 88 J-Q | 7.5 J-Q | 7.5 J-Q | 9.7 UJ-Q |
| D-VS3 | 061-64 | 0.5 | 5.57 | 197 R-S | 61.4 J-Q | 4.91 J-Q | 38 J-Q | 6.2 J-Q | 7.6 J-Q | 9.4 UJ-Q |
| D-VS4 | 061-62 | 0.5 | 3.59 | 109 R-S | 38 *N | 3.68 * | 27.8 | 3.8 R-Q | 6 J | 6.6 U |
| D-VS5 | 061-68 | 0.5 | 3.94 | 193 R-S | 38.3 J-Q | 5.71 J-Q | 50.8 J-Q | 3.8 R-Q | 17.6 J-Q | 6.8 J-Q |
| TUSOCK SEDGE | | | | | | | | | | |
| C-VS11 | 049-46 | 0.5 | 10.6 | 146 R-S | 23.4 *N | 1.63 * | 18.3 | 2.6 U | 7.9 P | 3.7 JP |
| C-VS12 | 049-47 | 0.5 | 2.96 | 110 R-S | 27.5 *N | 0.811 * | 9.73 | 2.4 U | 4.9 J | 6.1 U |
| C-VS13 | 049-48 | 0.5 | 26.4 | 298 R-S | 72.8 J-Q | 5.48 J-Q | 55.3 J-Q | 3.5 UJ-Q | 16.8 J-Q | 6.4 J-Q |
| D-VS21 | 060-26 | 0.5 | 1.21 | 10.9 R-S | 7.6 *N | 0.139 * | 0.69 B | 1.8 U | 4.5 U | 4.5 U |
| D-VS22 | 061-64 | 0.5 | 4.85 | 51.7 R-S | 29.9 *N | 0.744 * | 6.64 | 2.2 R-Q | 4.6 J | 5 U |
| SEDGE | | | | | | | | | | |
| D-VS11 | 061-65 | 0.5 | 14.5 | 587 R-S | 93.9 J-Q | 18.4 J-Q | 152 J-Q | 8.5 R-Q | 39.5 J-Q | 14.1 J-Q |
| D-VS12 | 060-22 | 0.5 | 3.25 | 29.5 R-S | 18.3 *N | 0.029 * | 3.49 B | 2.6 R-Q | 3.2 J | 6.2 U |
| D-VS13 | 060-23 | 0.5 | 4.17 | 98.9 *N | 25.3 J-S | 2.7 * | 23.4 | 2.9 R-Q | 10.9 P | 3.8 JP |
| D-VS14 | 060-24 | 0.5 | 2.28 | 74.8 *N | 14.7 J-S | 1.79 * | 15 | 2.3 U | 7.2 | 3.2 JP |
| D-VS15 | 060-25 | 0.5 | 9.27 | 319 R-S | 53.6 J-Q | 10.1 J-Q | 70.1 J-Q | 5.8 UJ-Q | 13.7 J-Q | 14.4 UJ-Q |

U – undetected, value presented is detection limit

J – value is estimated

* - Duplicate analysis was not within control limits

B – Reported value is below the contract required detection limit

DL – Qualified due to accuracy problems (Control Standards outside limits)

JP – Estimated value, differences between columns above limits

I – Qualified due to interference problems (Serial dilutions or poor spike recovery)

D – Qualified due to precision problems (duplicates outside limits)

Q – Qualified for other reasons

X1 – Does not meet general USEPA criterion meets project specific DQOs

R – Rejected, data unusable (compound may not be present)

N – Spiked sample recovery not within control limits

S – Qualified due to accuracy problems (spike recoveries outside limits)

Table 4
Summary of Detected Concentrations

| | Minimum Detected Concentration | Maximum Detected Concentration | Average Detected Concentration | Frequency of Detection |
|--------------------------------|--------------------------------|--------------------------------|--------------------------------|------------------------|
| Above-Ground Vegetation | | | | |
| Cesium-137 (pCi/g) | 0.015 | 1.55 | 0.68 | 22 of 25 |
| Copper (mg/kg) | 0.96 | 69.2 | 14.9 | 25 of 25 |
| Lead (mg/kg) | 0.59 | 10.6 | 3.0 | 15 of 25 |
| Mercury (mg/kg) | 0.011 | 2.17 | 0.66 | 15 of 25 |
| Silver (mg/kg) | 0.72 | 72.4 | 2.31 | 21 of 25 |
| 4,4'-DDD (ug/kg) | 2.7 | 35.5 | 12.3 | 8 of 25 |
| Aroclor-1254 (ug/kg) | 14.7 | 284 | 107 | 6 of 25 |
| Aroclor-1260 (ug/kg) | 127 | 284 | 187 | 3 of 25 |
| Below-Ground Vegetation | | | | |
| Cesium-137 (pCi/g) | 0.282 | 4.29 | 2.01 | 25 of 25 |
| Copper (mg/kg) | 9.35 | 819 | 176 | 25 of 25 |
| Lead (mg/kg) | 2.74 | 85.4 | 31.6 | 23 of 25 |
| Mercury (mg/kg) | 0.63 | 7.09 | 2.13 | 25 of 25 |
| Silver (mg/kg) | 2.52 | 104 | 29 | 22 of 25 |
| 4,4'-DDD (ug/kg) | 2.1 | 262 | 24 | 14 of 25 |
| Aroclor-1254 (ug/kg) | 39.2 | 471 | 116 | 24 of 25 |
| Aroclor-1260 (ug/kg) | 34.2 | 238 | 116 | 11 of 25 |
| Sediment | | | | |
| Cesium-137 (pCi/g) | 1.21 | 26.4 | 8.0 | 25 of 25 |
| Copper (mg/kg) | 74.8 | 1170 | 459 | 10 of 10 ¹ |
| Lead (mg/kg) | 7.6 | 166 | 55 | 25 of 25 |
| Mercury (mg/kg) | 0.029 | 32.6 | 9.3 | 25 of 25 |
| Silver (mg/kg) | 0.69 | 219 | 68 | 25 of 25 |
| 4,4'-DDD (ug/kg) | 3.7 | 16.4 | 7.8 | 5 of 13 ¹ |
| Aroclor-1254 (ug/kg) | 3.2 | 261 | 44 | 24 of 25 |
| Aroclor-1260 (ug/kg) | 3.2 | 140 | 25 | 17 of 25 |

1 Total number of samples less than 25 due to data being rejected by validator.

Cesium-137 was detected in all the above-ground portions of tussock sedge (0.42 pCi/g to 1.55 pCi/g), sedge (0.329 pCi/g to 1.49 pCi/g), and common reed samples (0.159 pCi/g to 1.46 pCi/g). Cesium-137 was detected in only two of the five cattail samples with detected activities of 0.0154 pCi/g to 0.103 pCi/g. Cesium-137 was higher in the below-ground portions (0.282 pCi/g to 4.29 pCi/g) than in the above-ground portions. Cesium-137 was detected in all sediment samples at higher concentrations (1.21 pCi/g to 26.4 pCi/g). The average sediment background concentration of cesium-137 due to general anthropogenic sources has been reported as 1.05 pCi/g as measured in a nearby river (IT, 2000). All cesium-137 concentrations measured for this study were greater than this average concentration.

Organic contaminants (DDD, aroclor-1254, and aroclor-1260) were rarely detected in the above-ground vegetation samples, and only slightly more frequently in the below-ground vegetation samples. They were detected more frequently in the sediment samples. Much of the detected concentrations of DDD in the sediment samples were rejected during data validation. Rejection of the DDD was due to high differences between the results of the two analytical columns. This high difference was likely due to the relatively low concentrations present in the samples. The potential bias of the results could not be ascertained from a review of the analytical and validation procedures, and these rejected results were not used in the subsequent analyses.

Bioaccumulation Factors

A summary of the bioaccumulation factors (BAF) is presented in Table 5 for the above-ground vegetation samples only and a summary of the BAFs is presented in Table 6 for the below-ground vegetation samples only. Since the objective of this study is to determine the efficiency of harvesting vegetation as a less-destructive means of remediation than excavation, the harvesting of the below-ground portion is not considered and the BAFs for the below-ground portion are not incorporated in the contaminant removal kinetics considered in the subsequent sections. The above-ground vegetation BAFs represent the plant concentrations at the time of harvesting. Since sampling of vegetation was only conducted during one time period, in late summer/early fall, BAFs measured during other time periods may be different. The BAFs listed include both the minimum and maximum BAF measured for each chemical-species pair as well as the average BAF for that chemical-species pair. The analytical results for the organic contaminants, 4,4'-DDD, Aroclor-1254, and Aroclor-1248, provided very few usable pairs of data (i.e., useable and detected values for both above-ground vegetation and associated sediment samples) for calculating BAFs: only 2 useable pairs for 4,4'-DDD and aroclor-1260 and only 5 useable pairs for aroclor-1254. Due to the low reliability of the results based on the lack of useable data pairs, BAFs are not presented for these organic contaminants and the efficiency of phytoremediation and harvesting for organic contaminants is not further evaluated in this report.

Removal Kinetics

In order to determine the efficiency of harvesting above-ground vegetation as a remediation technique, the time-dependent removal kinetics need to be estimated based

on the measured BAFs. The following discussion presents the derivation of the removal kinetics model. It should be noted that the kinetics described below are the kinetics for the removal of contaminants from the sediment through the harvesting of the above-ground vegetation; they are not the kinetics of the physiological uptake of contaminants from the sediment into the plants.

During the process of phytoextraction (i.e., uptake of contaminants to the plant), a mass of the contaminant is removed from the sediment and transported to the above-ground biomass of the plant. This uptake (and release) of contaminants is a continuous process. Uptake rates may vary during the life of the plant. Uptake rates are expected to be greater during the growing season, though this does not necessarily indicate that concentrations in the plant are greater during the growing season. This model assumes that a certain mass of contaminant has been taken up into the plant since the beginning of its growth to the time of the first harvest. The total mass of the contaminant thus removed is determined by the following equation:

$$M_{biota} = C_{biota} \times BM$$

where

M_{biota} = Mass of contaminant in above-ground vegetation (mg);
 C_{biota} = Dry weight concentration in biota (mg/kg); and
 BM = Dry weight above ground biomass (kg).

A review of the literature found values of above-ground dry weight biomass for cattails from 1 kg/m² to 3.36 kg/m² (Beule, 1979). Common Reed was reported with maximum above-ground dry weight biomass from 1 kg/m² to 3.687 kg/m² (Lenssen et al., 2000). Sedge above-ground biomass was significantly less, with maximum values reported at 0.28 kg/m² (Kost and De Steven, 2000).

Table 5
Summary of Bioaccumulation Factors for Above Ground Portion of Plants

| | Frequency of Pairs with Detected Levels | Units | Minimum BAF | Maximum BAF | Mean BAF | Standard Deviation |
|----------------------|---|-------|-------------|-------------|----------|--------------------|
| CATTAILS | | | | | | |
| Mercury | 2 of 5 | mg/kg | 0.0056 | 0.015 | 0.010 | 0.0066 |
| Cesium-137 | 2 of 5 | pCi/g | 0.0013 | 0.0085 | 0.0049 | 0.0051 |
| Copper | 5 of 5 | mg/kg | 0.0037 | 0.0207 | 0.012 | 0.0079 |
| Silver | 5 of 5 | mg/kg | 0.006 | 0.0914 | 0.052 | 0.037 |
| Lead | 2 of 5 | mg/kg | 0.025 | 0.0429 | 0.034 | 0.013 |
| COMMON REED | | | | | | |
| Mercury | 3 of 10 | mg/kg | 0.0010 | 0.081 | 0.029 | 0.045 |
| Cesium-137 | 10 of 10 | pCi/g | 0.023 | 0.37 | 0.099 | 0.104 |
| Copper | 3 of 3 | mg/kg | 0.0022 | 0.0078 | 0.0052 | 0.0028 |
| Silver | 6 of 10 | mg/kg | 0.0041 | 0.12 | 0.027 | 0.125 |
| Lead | 3 of 10 | mg/kg | 0.0066 | 0.01 | 0.009 | 0.003 |
| TUSSOCK SEDGE | | | | | | |
| Mercury | 5 of 5 | mg/kg | 0.034 | 1.21 | 0.58 | 0.483 |
| Cesium-137 | 5 of 5 | pCi/g | 0.020 | 0.50 | 0.19 | 0.184 |
| Copper | 0 of 0 | mg/kg | NA | NA | NA | NA |
| Silver | 5 of 5 | mg/kg | 0.022 | 3.19 | 0.80 | 1.34 |
| Lead | 5 of 5 | mg/kg | 0.015 | 0.26 | 0.12 | 0.12 |
| SEDGE | | | | | | |
| Mercury | 5 of 5 | mg/kg | 0.089 | 7.93 | 1.81 | 3.42 |
| Cesium-137 | 5 of 5 | pCi/g | 0.035 | 0.55 | 0.24 | 0.2 |
| Copper | 2 of 2 | mg/kg | 0.38 | 0.43 | 0.405 | 0.35 |
| Silver | 5 of 5 | mg/kg | 0.032 | 0.63 | 0.21 | 0.24 |
| Lead | 5 of 5 | mg/kg | 0.051 | 0.33 | 0.19 | 0.11 |

Table 6
Summary of Bioaccumulation Factors for Below Ground Portion of Plants

| | Frequency of Pairs with Detected Levels | Units | Minimum BAF | Maximum BAF | Mean BAF | Standard Deviation |
|----------------------|---|-------|-------------|-------------|----------|--------------------|
| CATTAILS | | | | | | |
| Mercury | 5 of 5 | mg/kg | 0.082 | 0.54 | 0.23 | 0.192 |
| Cesium-137 | 5 of 5 | pCi/g | 0.068 | 0.29 | 0.17 | 0.093 |
| Copper | 5 of 5 | mg/kg | 0.027 | 1.69 | 0.54 | 0.661 |
| Silver | 5 of 5 | mg/kg | 0.056 | 1.33 | 0.48 | 0.503 |
| Lead | 5 of 5 | mg/kg | 0.100 | 1.11 | 0.46 | 0.414 |
| COMMON REED | | | | | | |
| Mercury | 10 of 10 | mg/kg | 0.030 | 0.37 | 0.172 | 0.134 |
| Cesium-137 | 10 of 10 | pCi/g | 0.043 | 0.27 | 0.151 | 0.078 |
| Copper | 3 of 3 | mg/kg | 0.019 | 0.27 | 0.123 | 0.132 |
| Silver | 7 of 10 | mg/kg | 0.016 | 0.38 | 0.125 | 0.120 |
| Lead | 8 of 10 | mg/kg | 0.029 | 0.50 | 0.142 | 0.150 |
| TUSSOCK SEDGE | | | | | | |
| Mercury | 5 of 5 | mg/kg | 0.53 | 9.3 | 3.66 | 3.37 |
| Cesium-137 | 5 of 5 | pCi/g | 0.16 | 2.6 | 0.94 | 0.96 |
| Copper | 0 of 0 | mg/kg | NA | NA | NA | NA |
| Silver | 5 of 5 | mg/kg | 1.88 | 33.9 | 10.04 | 13.46 |
| Lead | 5 of 5 | mg/kg | 1.17 | 6.5 | 2.86 | 2.10 |
| SEDGE | | | | | | |
| Mercury | 5 of 5 | mg/kg | 0.14 | 35.5 | 7.71 | 15.56 |
| Cesium-137 | 5 of 5 | pCi/g | 0.17 | 1.3 | 0.69 | 0.47 |
| Copper | 2 of 2 | mg/kg | 0.84 | 2.4 | 1.62 | 1.10 |
| Silver | 5 of 5 | mg/kg | 0.21 | 11.4 | 2.88 | 4.79 |
| Lead | 5 of 5 | mg/kg | 0.29 | 4.2 | 1.65 | 1.58 |

Since the mass of contaminant in the biota is removed from the underlying sediment, the mass of the contaminant in the sediment is reduced by this mass. The initial mass of the contaminant is given by the following equation:

$$M_{sed} = C_{sed} \times V_{sed} \times D_{sed}$$

where

- M_{sed} = Mass of contaminant in underlying sediment (mg);
 C_{sed} = Dry weight concentration in underlying sediment (mg/kg);
 V_{sed} = Volume of underlying sediment (152 L which is equal to a 6" deep square meter); and
 D_{sed} = Dry density of sediment (assumed to be 1.3 kg/L).

The concentration in the underlying sediment after uptake by the plant at the time of harvesting is given by the following equation:

$$C_{sed}(t+1) = C_{sed}(t) - \frac{BAF \times BM}{D_{sed} \times V_{sed}} C_{sed}(t)$$

where

- $C_{sed}(t+1)$ = Concentration in sediment after phytoextraction (mg/kg dry weight);
 BAF = Bioaccumulation factor (mg/kg dry weight biota per mg/kg dry weight sediment);
 BM = Dry weight above ground biomass (kg);
 V_{sed} = Volume of underlying sediment (152 L which is equal to a 6" deep square meter); and
 D_{sed} = Dry density of sediment (assumed to be 1.3 kg/L); and
 $C_{sed}(t)$ = Concentration in sediment before phytoextraction (mg/kg dry weight).

If the above-ground biomass were harvested each year, the following year's growth would again extract some of the contaminant from the sediment. The same would occur in each successive year. This can be written as the following difference equation:

$$C_{sed}(t+1) - C_{sed}(t) = - \frac{BAF \times BM}{D_{sed} \times V_{sed}} C_{sed}(t)$$

which can be written as a differential equation

$$\frac{dC_{sed}}{dt} = - \frac{BAF \times BM}{D_{sed} \times V_{sed}} C_{sed}(t)$$

and solved for the initial condition, $C_{sed}(0) = C_{initial}$, where $C_{initial}$ is the initial concentration of the contaminant in the sediment at time $t=0$.

The resulting equation,

$$C_t = C_{initial} \times e^{-\frac{BAF \times BM}{D_{sed} \times V_{sed}} t}$$

describes the change in sediment concentrations through phytoextraction and harvesting of above-ground biomass, and fits the form of a standard exponential regression model:

$$Y = a e^{bX}$$

Based on the parameters presented above and the average BAFs as presented in Table 5, predictive curves depicting the removal of contaminants from sediment through phytoextraction and harvesting of above-ground vegetation can be constructed. These are shown in Figure 1 through Figure 5.

Discussion

The efficiency of phytoextraction and harvesting can be determined in terms of the sediment half-life (i.e., the time necessary for the sediment concentration to be reduced to ½ the initial sediment concentration). The sediment half-life ($t_{1/2}$) due to phytoextraction and harvesting can be calculated by the following equation:

$$t_{1/2} = -\frac{\ln\left(\frac{1}{2}\right) \times D_{sed} \times V_{sed}}{BAF \times BM}$$

The following table presents the calculated half-lives based on the parameter values presented herein. The half-lives based on the average BAFs, as well as those based on the maximum and minimum BAFs, respectively, are presented in the table. Half-lives are not presented for organic contaminants due to the few useable data available for calculating the BAFs used to derive the half-lives.

Table 6
Calculated Phytoextraction and Harvesting Half-Lives (years)

| Parameter | Cattail | Common Reed | Sedge | Tussock Sedge |
|------------|-------------------------|-------------------------|-------------------------|-------------------------|
| Mercury | 3,958 (2,718-7,279) | 1,281 (459-37,148) | 271 (62-5,516) | 846 (406-14,439) |
| Cesium-137 | 8,319 (4,796-31,357) | 375 (100-1,615) | 2,045 (893-14,026) | 2,584 (982-24,546) |
| Copper | 3,369 (1,969-11,017) | 7,144 (4,763-16,886) | 1,212 (1,142-1,292) | NA |
| Lead | 1,202 (950-1,631) | 4,128 (5,629-3,715) | 2,584 (1,488-15,341) | 4,091 (1,888-37,728) |
| Silver | 781 (446-6,794) | 1,376 (9,061-310) | 2,338 (779-9,626) | 614 (154-22,314) |

The cesium-137 half-life listed in the table above does not include radioactive decay. The half-life of cesium-137 due to radioactive decay is 30 years, whereas the half-life based on phytoextraction alone is on the order of hundreds or thousands of years. Figure 6 compares the attenuation of cesium-137 based on radioactive decay alone or phytoextraction alone is attached. The attenuation of cesium-137 due to radioactive decay alone is essentially indistinguishable from that of radioactive decay along with phytoextraction, as can be seen in Figure 7.

Figure 1
Copper Attenuation through Phytoextraction

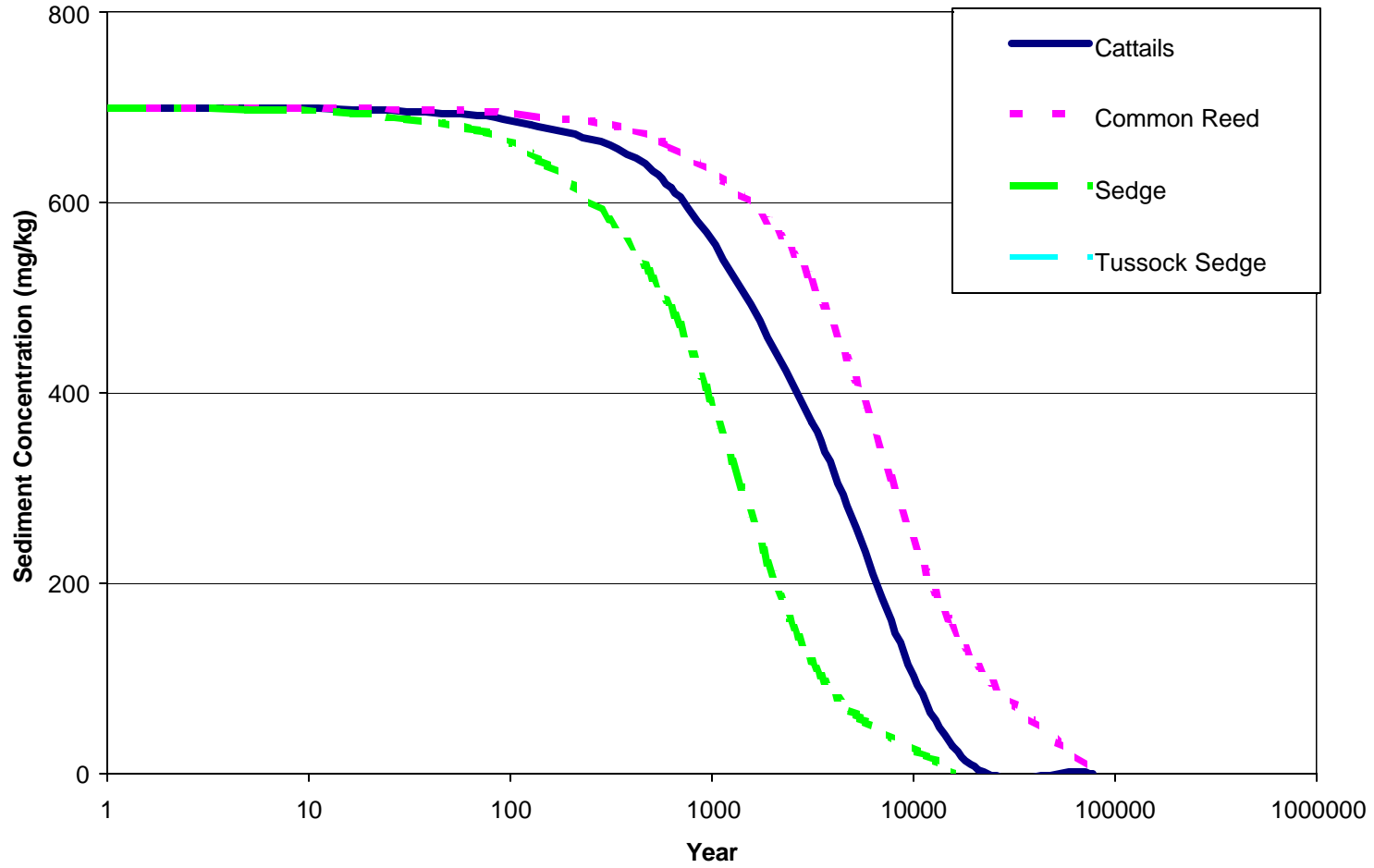


Figure 2
Lead Attenuation through Phytoextraction

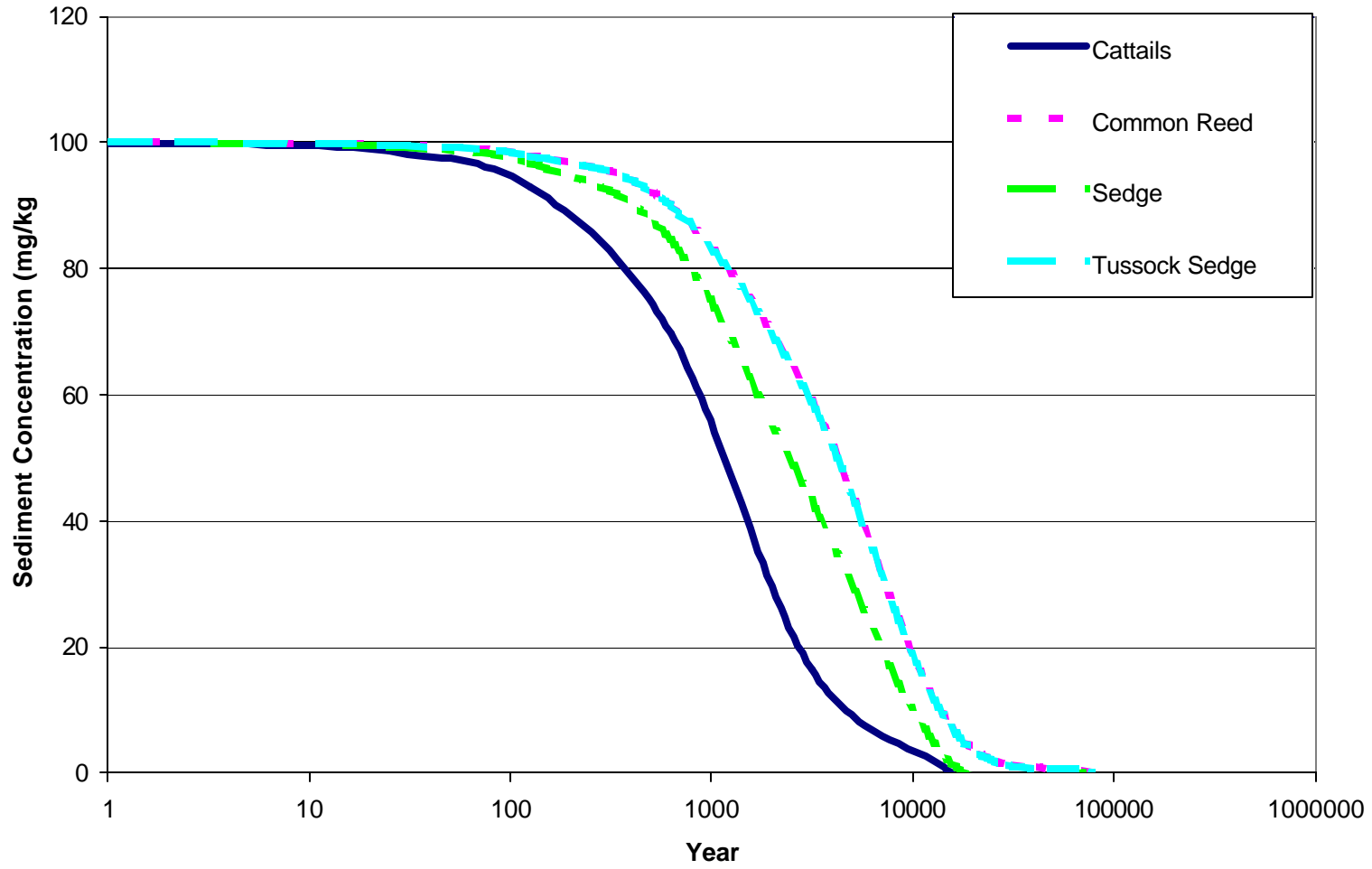


Figure 3
Mercury Attenuation through Phytoextraction

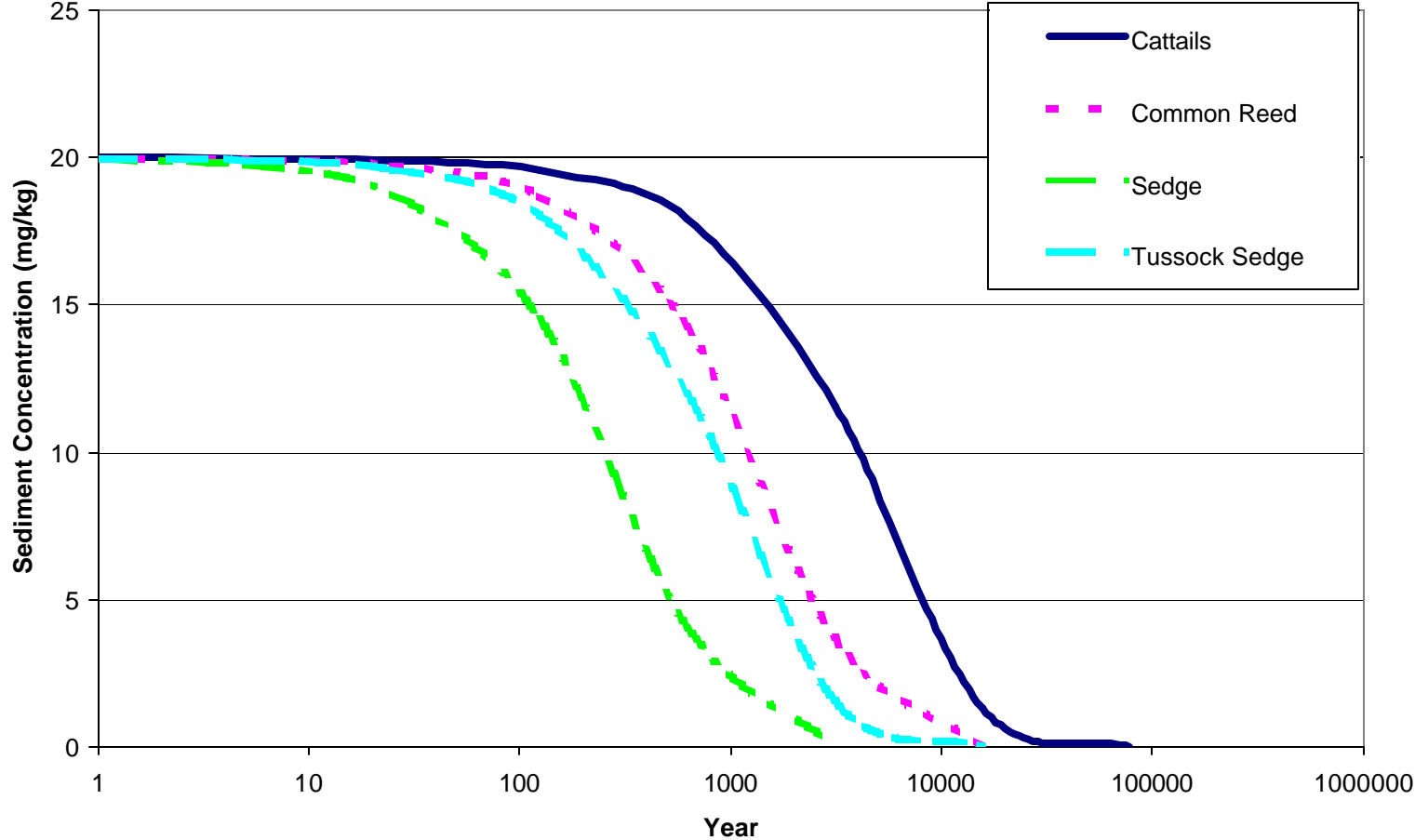


Figure 4
Silver Attenuation through Phytoextraction

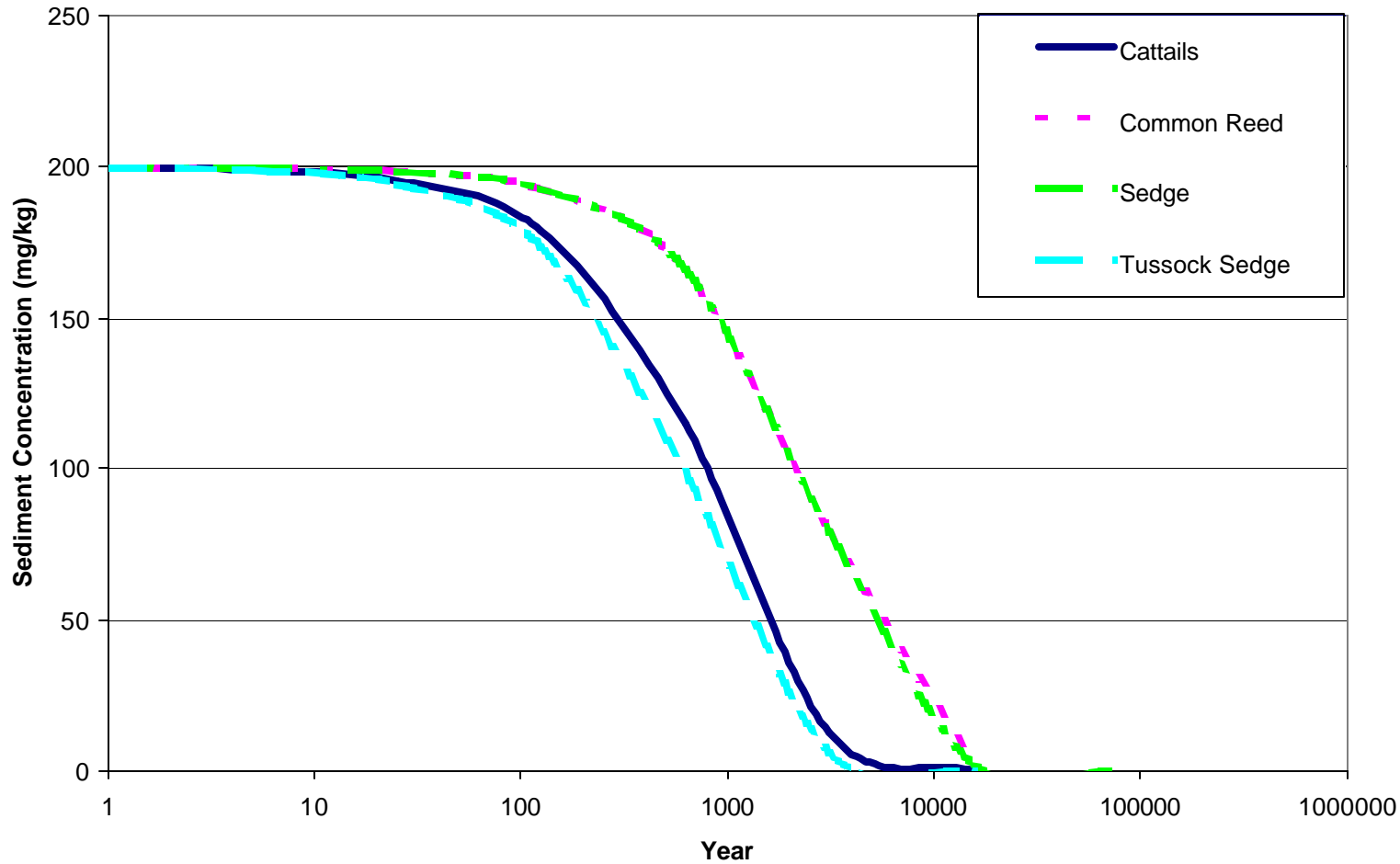


Figure 5
Cesium-137 Attenuation through Phytoextraction

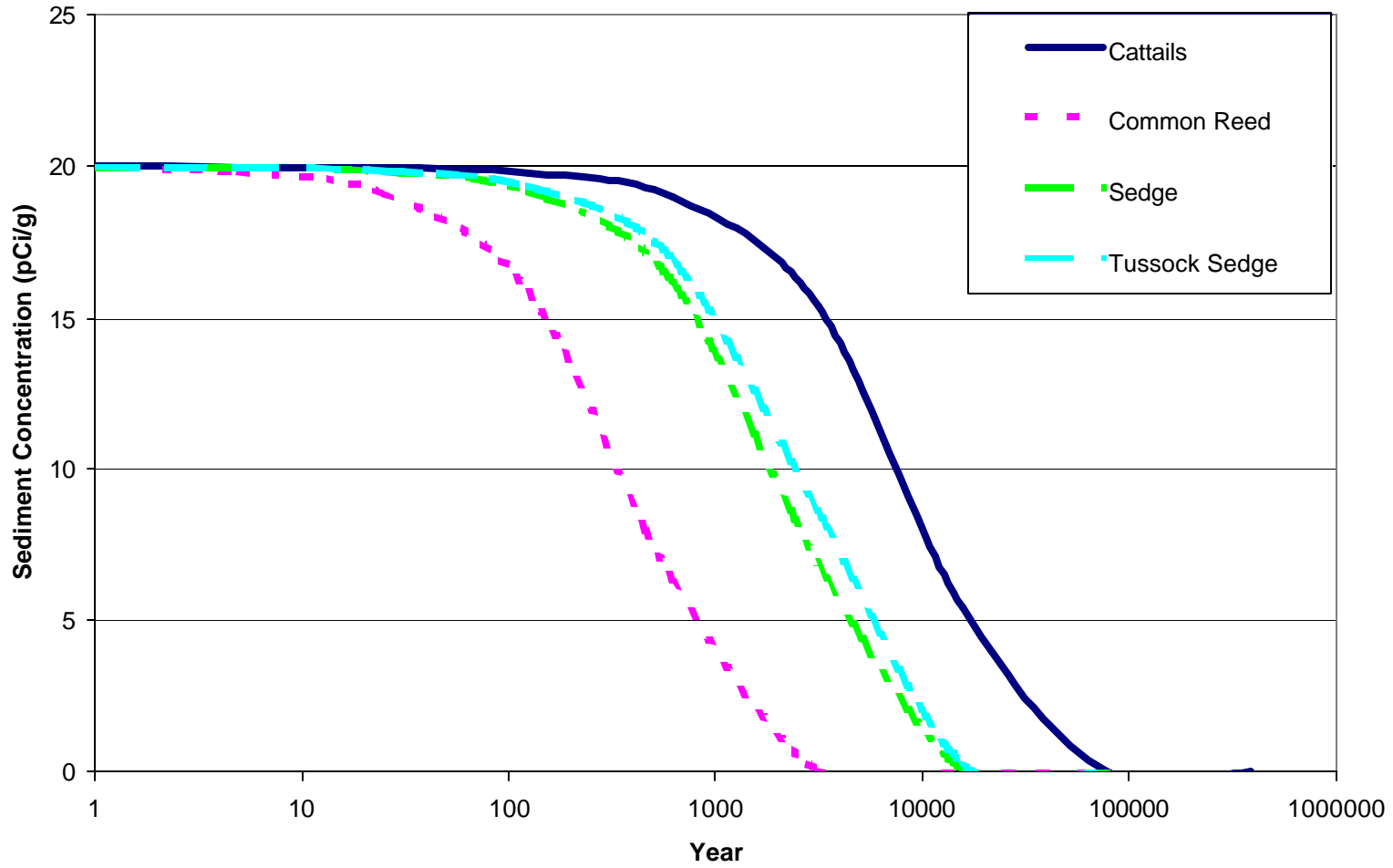


Figure 6
Cesium-137 Attenuation through Phytoextraction or through Radioactive Decay

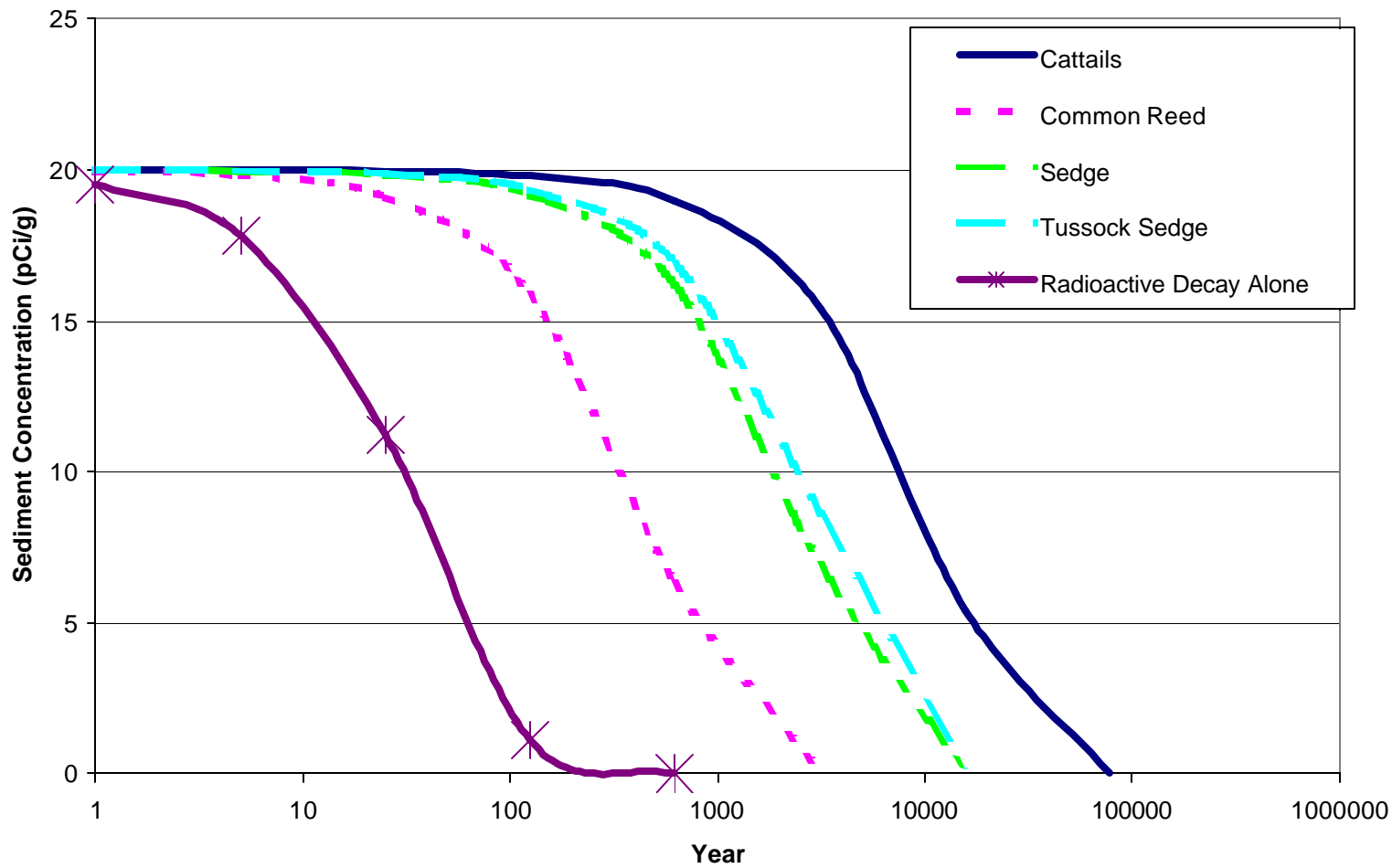
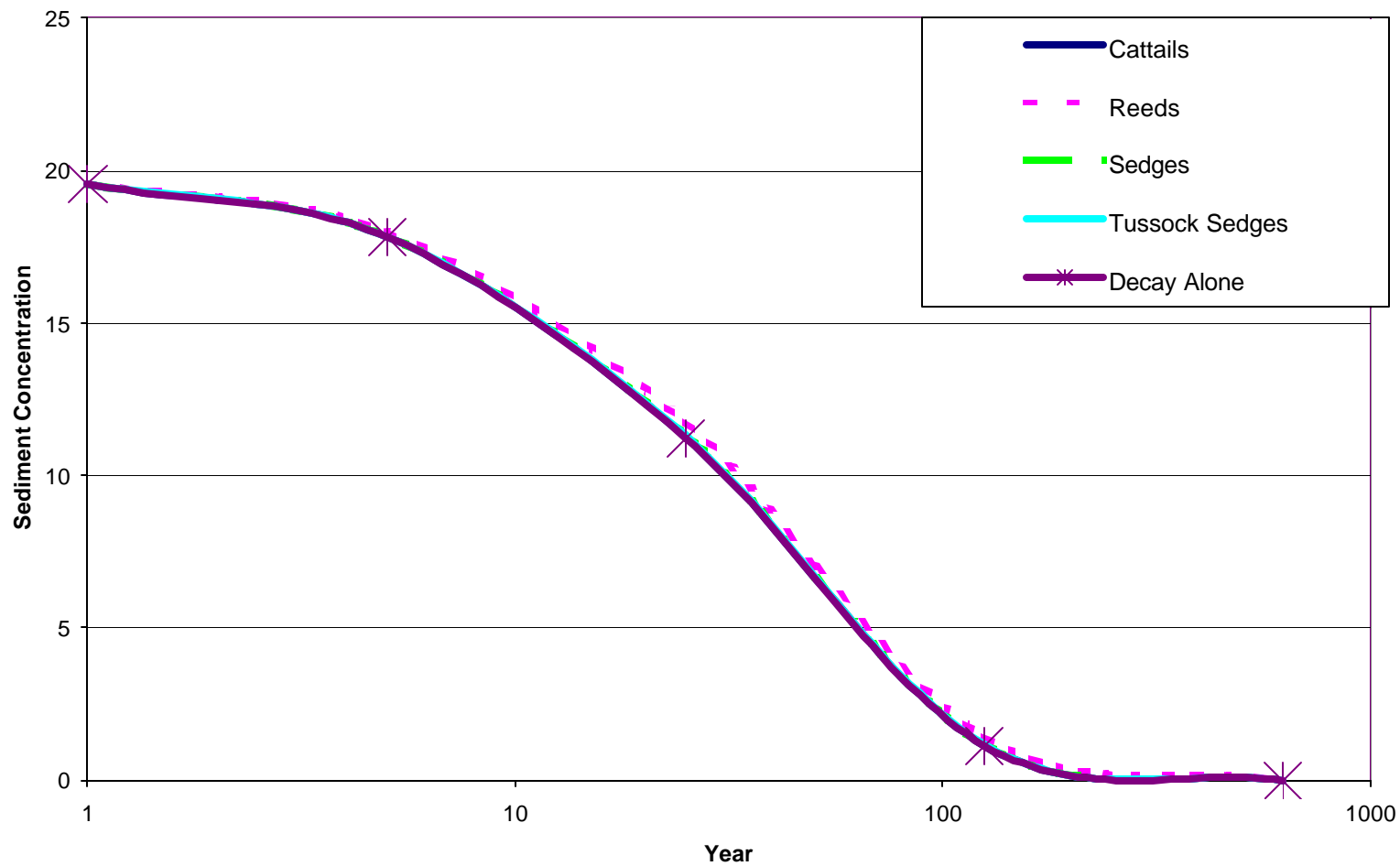


Figure 7
Cesium-137 Attenuation through Phytoextraction and Radioactive Decay or Radioactive Decay Alone



4 Conclusions

This paper presented an evaluation of the potential for phytoremediation to be used to clean up the Peconic River sediments using the present common plants and successive harvesting of the above-ground portions of those plants. There are sources of uncertainty related to the evaluation that are important to illuminate.

One source of significant uncertainty is the biomass of the above-ground portion of the plant that could be removed during each successive harvest. The literature was reviewed for references to the above-ground biomass per area that the evaluated plants produce. Actual site-specific biomass data was not gathered for this evaluation. Site-specific biomass may be greater (especially in areas of high density) or lower (there are open water areas where growth is low or non-existent). For the purposes of a conservative evaluation the biomass assumed in the calculations was an upper range of the literature values. The removal times based on the upper range biomass values were quite long; lower biomass would result in much longer remediation times.

The evaluation considered annual harvests. It is possible that multiple harvests could be achieved during each year. If one assumes that the biomass able to be removed with each harvest in multiple harvest years is this years or multiple harvests in the same year? Please clarify. If you did not include multiple harvests in the same year there should be some discussion of this. was the same as that in each annual harvest and that the BAF values were the same at each of the harvest periods, then the half-lives presented in this evaluation can be considered to be in units of harvests instead of units of years. For example, the half-life for mercury removal through harvesting of cattails is listed as 3,958 years. This could alternatively be considered to be a half-life of 3,958 harvests. If two harvests were conducted each year then it would be 1,979 years, and if three harvests were conducted each year then it would be 1,319 years. Though multiple harvests should certainly shorten remediation time, it is also possible that the biomass achieved in each harvest during each of the multiple harvests is not as great as the biomass at the time of only one annual harvest, since the maximum growth may not be achieved in these shorter periods. Thus, the projected half-lives for multiple harvest would not be achieved, though the half-lives would still likely be shorter than for only one harvest per year.

Another source of uncertainty is related to the collection of data during only one period of time. Total biomass is expected to change during the growing season, increasing with time until reaching its maximum where after the plants would eventually die back and lose biomass. Thus, the biomass obtainable during the optimal harvesting time may be greater or less than the assumed value. Also, BAFs are likely to be different during different time periods. BAFs may be higher or lower at other time periods. For example, during the active growth phase (e.g., spring), uptake may be more rapid. So, though the plants have not yet reached maximum biomass, the BAFs at that time may be higher.

The bioavailability of the contaminants in the Peconic River sediments may limit the potential for uptake by plants and, thereby, limit the efficiency of this remedial method.

The principal contaminants of concern at the Peconic River in relation to the BNL site are mercury, PCBs, cesium-137, as well as copper, mercury, silver, and DDD. An assessment of the potential bioavailability of inorganic contaminants (including copper, mercury, and silver) was conducted through chemical analysis using a process called the sequential extraction procedure (SEP). SEP analysis provides information about the sequestering of metals into immobilized fractions that reduce metal solubility and thus bioavailability, rather than simply providing a value for the total metal concentration. The SEP analysis separates the metal content of each sediment sample into the following target fractions: the exchangeable fraction that is generally water-soluble and/or ionically bound to the sediment matrix, the carbonate fraction that can be dissolved by weak acids and is considered mobile and bioavailable, the oxyhydroxide bound fraction, which may be complexed with oxidized iron or manganese, and is also considered mobile and bioavailable, and the organic bound fraction, sulfide bound fraction, and residual fraction that are considered inert and non-bioavailable (Tessier et al., 1979; Pardo et al, 1990). The following paragraphs discuss the principal contaminants of concern at the Peconic River and address the bioavailability as suggested by the SEP analysis.

Copper is a plant nutrient that is actively taken up by plants. However, because it is toxic at high concentrations, plants have systems that actively limit its uptake and plants may be adversely affected by elevated levels of copper in mobile, bioavailable forms. In sediment, copper is often associated with organic matter, iron and manganese oxides, and silicate clays. The amount of copper that is available to plants is usually limited, especially in organic environments. Analysis of sediments of the Peconic River using a sequential extraction procedure found that less than 10% of the copper is present in a potentially mobile or bioavailable form (i.e., in an ion exchangeable fraction or carbonate bound fraction). The majority of the copper was found to be present in either the organic bound fraction or the sulfide bound fraction, and is generally considered inert and not bioavailable (Tessier et al., 1979; Pardo et al, 1990).

Silver is typically mostly immobile and unavailable to plants (Negri et al., 1998; Fuhrmann, 2001). The sequential extraction procedure analysis conducted on Peconic River sediments showed again that less than 10% of the silver is present in a potentially mobile or bioavailable form and that the majority of the silver was organically bound and not bioavailable (Tessier et al., 1979; Pardo et al, 1990).

Mercury has a more complex behavior in sediments and can be volatilized by plants and microorganisms in different forms (e.g., methyl mercury). Bioaccumulation factors for mercury from soil to plants are usually low under natural conditions. Sequential extraction procedure analysis found that less than 1% of the mercury was in a potentially mobile or bioavailable fraction and that at most 0.3% was found as methyl mercury. The vast majority of the mercury was found as the essentially inert mercury sulfides (Tessier et al., 1979; Pardo et al, 1990).

Some plants naturally take up cesium-137 instead of potassium or ammonium, both of which are essential for plants. These uptake rates are dependent on the concentrations of

potassium, ammonium, and other competing cations, as well as the amounts of clays that have a high affinity for cesium-137.

Organic contaminants such as PCBs and DDD are not usually removed by phytoremediation. However, biodegradation of these contaminants have been shown to accelerate in rhizosphere soils as compared to soils without root surfaces, and in soils that undergo aerobic/anaerobic cycles.

Tests at Argonne National Laboratory-West had reported removal rates of about 4% for cesium-137 and 2% for mercury and silver under optimal greenhouse conditions for whole plant harvesting. Harvesting of above-ground portions would result in smaller removal rates. Estimates reported here are based on measured above-ground BAFs are less than 1%.

Several factors are important for effective phytoextraction and harvesting of the above-ground portion of plants as a sediment remediation process.

- The bioaccumulation factor representing the ratio of the concentration in biota to the concentration in sediment needs to be high. In general, measured BAFs were less than 1. Even with BAFs greater than 1, phytoextraction and harvesting is not predicted to be efficient, with half-lives in the hundreds to thousands of years. The minimum half-life predicted was 62 years and was for the removal of mercury by sedges based on the maximum measured BAF.
- The above-ground biomass needs to be high. The ratio of underlying sediment mass to above-ground biomass, based on the assumptions presented herein, is assumed to be in the ratio of 50 to 1000, with these ratios based on the upper range of reported vegetative biomass values. Actual natural biomass at the site may be quite less, thus requiring even more time for effective remediation.
- The vegetation cover also is important. Different vegetation types dominate different areas of the site. In fact, several areas (e.g. intermittent open water area near North Street) do not have sufficient natural vegetation cover for any phytoextraction.

Based on the analysis and interpretation of the bioaccumulation data gathered for the dominant vegetation types on the site, phytoextraction and harvesting does not appear to be a viable solution for remediation at this site.

5 References

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