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*Hopper Dredge "McFarland" (courtesy of USACE)*

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## AIMS & SCOPE OF THE JOURNAL

The *Journal of Dredging* is published by the Western Dredging Association (WEDA) to provide dissemination of technical and project information on dredging engineering topics. The peer-reviewed papers in this practice-oriented journal will present engineering solutions to dredging and placement problems, which are not normally available from traditional journals. Topics of interest include, but are not limited to, dredging techniques, hydrographic surveys, dredge automation, dredge safety, instrumentation, design aspects of dredging projects, dredged material placement, environmental and beneficial uses, contaminated sediments, litigation, economic aspects and case studies.

# HOPPER OVERFLOW CHARACTERISTICS FOR THE DELAWARE RIVER

Jerry L. Miller[1], Michael R. Palermo, Ph.D[1]., and Thomas W. Groff[2]

## ABSTRACT

Hopper Dredges are often loaded past the point of overflow for economic reasons. As the hopper is filled, dredged material is stored in the hopper until overflow begins. The density of the hopper contents is increased by allowing the low density supernatant to overflow back into the waterway. As the low-density supernatant overflows, the average density of the hopper contents increases. Thus, more material can be transported per trip to the disposal site or facility resulting in an economical loading.

There is normally a tradeoff between the potential economic benefits and potential environmental effects. Overflow results in increased water column turbidity, and supernatant solids may be re-deposited near the dredge site. Also, if sediments are contaminated, the overflow may result in some release of contaminants to the water column. Therefore, the relationship between dredge production, density of the hopper load, and the rate of material overflow are important variables in maximizing the efficiency of the dredging operation while minimizing harmful contaminant release.

A field study was conducted during hopper dredging operations in the Delaware River and Delaware Bay area to quantify the potential load gains realized by overflow, the degree of suspended solids and contaminant release generated by overflow, and the dispersion of the overflow plume. Monitoring was conducted at two sites, one of predominately fine-grained material in the Delaware River, and the other of predominately coarse-grained material in Delaware Bay. This report summarizes the results of the study and describes the potential economic and environmental considerations for overflow at these sites.

## INTRODUCTION

The U.S. Army Engineer District, Philadelphia, has an extensive navigation responsibility throughout the Delaware River Basin. Maintenance dredging averages about 3 million $m^3$ (4 million $yd^3$) of material annually of which about 191,000 $m^3$ (250,000 $yd^3$) is removed by the Hopper Dredge McFarland (Figure 1). The dredging provides a safe navigation channel, which supports the shipping of nearly 136 million metric tons (150 million short tons) of cargo per year.

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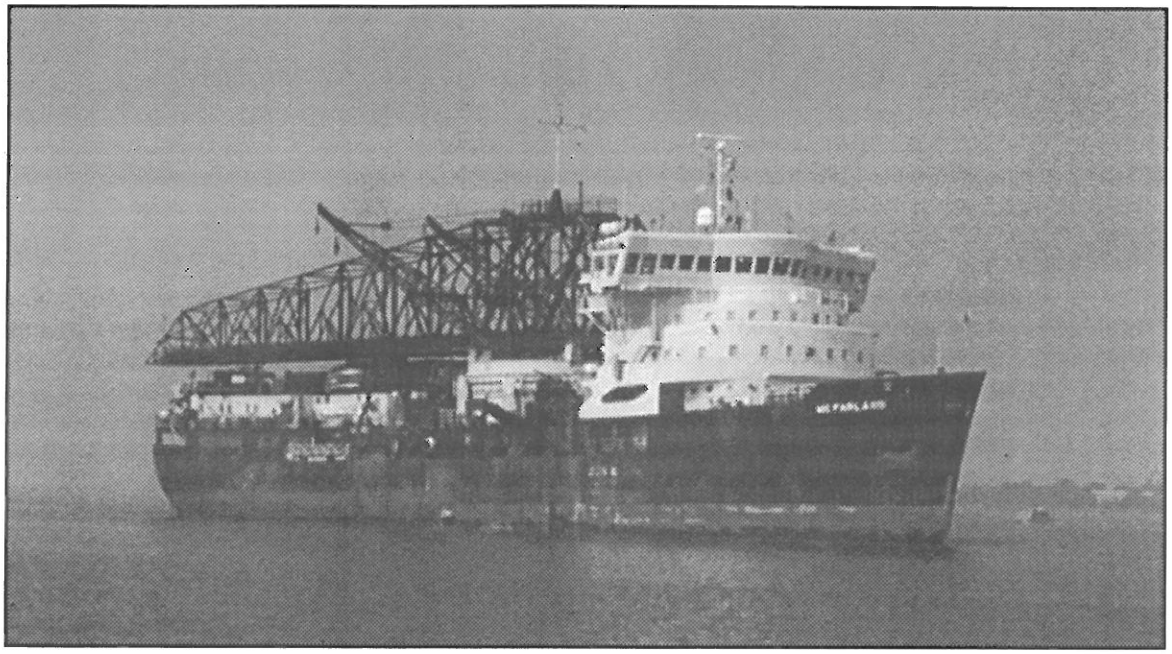

**Figure 1. Hopper Dredge McFarland (courtesy of Waterways Experiment Station)**

Hopper dredges, like the McFarland, are self-propelled ships equipped with propulsion machinery, hoppers for dredged material storage, and dredge pumps. Dredged material is hydraulically raised through trailing dragarms in contact with the channel bottom and is discharged into the hoppers. The material is then held in the hoppers until placed at the disposal site.

Hopper dredges are often loaded past the point of overflow for economic reasons. As the hopper is filled, dredged material is stored in the hopper bins until overflow begins. The density of the hopper contents is increased by allowing the low density supernatant to overflow back into the waterway. As the low-density supernatant overflows, the average density of the hopper contents increase. Thus, more material can be transported per trip to the disposal site or facility. This practice of overflowing hoppers to achieve a high-density load is referred to as economic loading.

In considering overflow, there is normally a tradeoff between the potential economic benefits and potential environmental effects. Overflow results in increased water column turbidity, and supernatant solids may be re-deposited near the dredge site. Also, if sediments are contaminated, the overflow may result in some release of contaminants to the water column. Therefore, the relationship between dredge production, density of the hopper load, and the rate of material overflow are important variables in maximizing the efficiency of the dredging operation while minimizing contaminant release.

State environmental resource agencies have expressed concerns regarding the turbidity, sedimentation of suspended solids, and potential contaminant release from overflow, due to the presence of oyster seedbeds in some areas near the navigation channel. Currently, overflow is not permitted at any location within the Delaware River Basin.

There is a significant potential for economic benefits to overflow in certain reaches of the project if the impact due to overflow is environmentally acceptable. The Philadelphia District therefore, initiated an evaluation of the practice of overflow for select portions of the Delaware River and Delaware Bay to determine if overflow for those reaches can meet applicable water quality standards. The District requested assistance from the Environmental Laboratory, U.S. Army Engineer Research and Development Center at the Waterways Experiment Station in conducting a study of overflow in the Delaware River/Bay system.

This study helped to quantify the degree of turbidity, suspended solids and contaminant release generated by overflow and the dispersion of the overflow plume in reaches near the oyster seedbeds. Reaches in the Delaware River Basin where overflow would be acceptable were determined.

## Study Location

Two test areas were selected in the Delaware River, Philadelphia to the Sea, Federal Navigation Channel (Figure 2). Study areas were selected in conjunction with recommendations from the New Jersey Department of Environmental Protection (NJDEP) and Delaware's Department of Natural Resources and Environmental Control (DNREC). These areas were selected on the basis of historical knowledge of the Delaware Basin, and known locations of material types (sand, silt and clay) within the river. The first site was located at the Brandywine range in the lower Delaware Bay (mile marker 17.7), and was selected to represent a predominantly coarse-grained material. The second site was located at the Deepwater Point range just below the Delaware Memorial Bridge (mile marker 67.9), and was selected to represent a typical fine-grained material. All the proposed activities for the study were reviewed with members of the Delaware River Fish Cooperative Technical Committee prior to submitting applications to the respective regulatory offices for Water Quality Certification (WQC) approvals.

## Purpose and Scope

The purpose of this study was to evaluate the efficiency of economic loading of a hopper dredge and the physical and chemical characteristics of hopper overflow for the Delaware River dredging project. The study was designed to evaluate the effectiveness of increasing the hopper load during overflow and to determine the physical and chemical characteristics of the overflow into the Delaware River.

The study involved the following activities:

a. Loading data collection - measurements of the load in the hopper at and following overflow

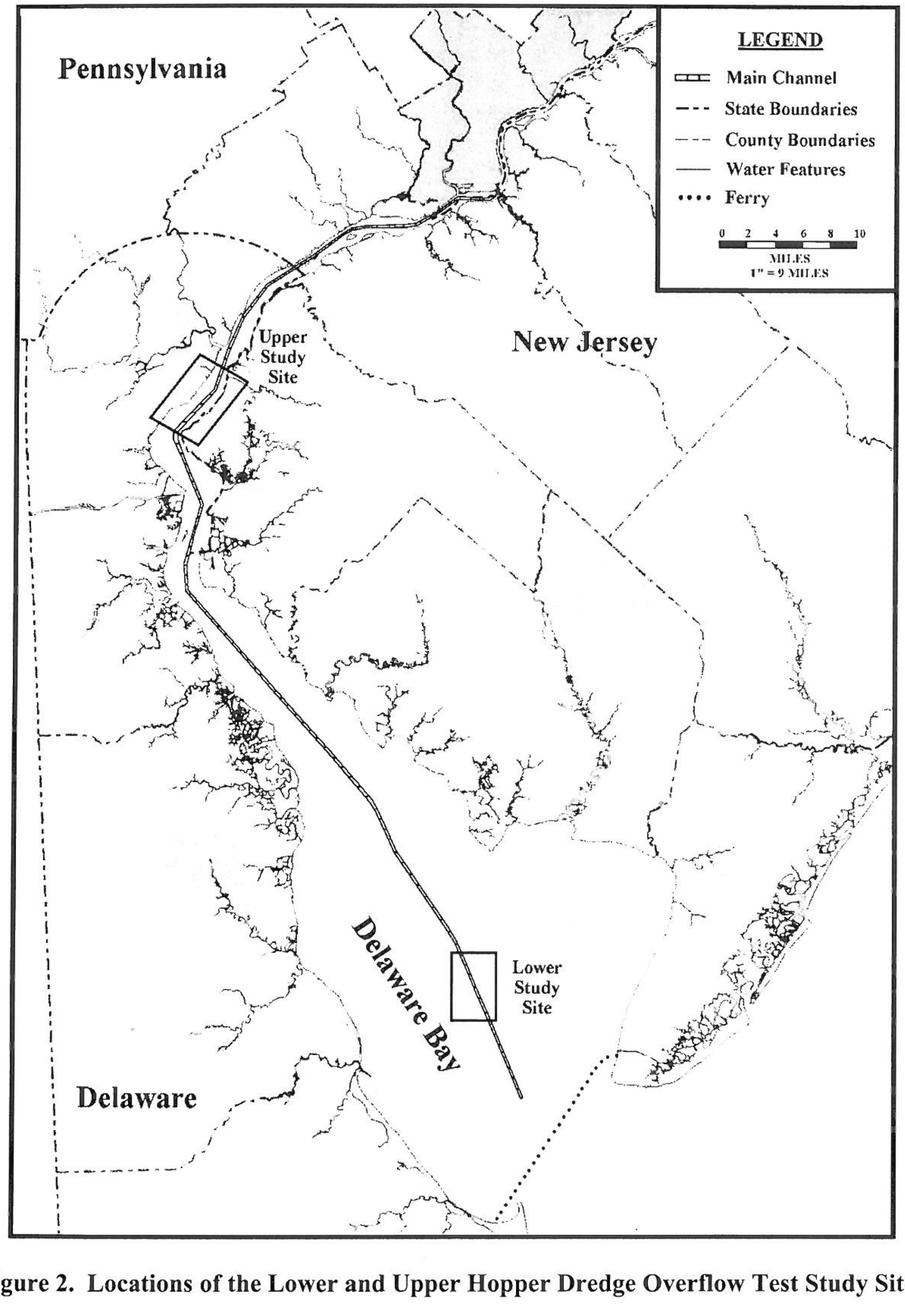

Figure 2. Locations of the Lower and Upper Hopper Dredge Overflow Test Study Sites

b. Characterization of in-situ sediment - physical and chemical analysis including elutriate testing
c. Hopper inflow monitoring - physical and chemical analysis
d. Hopper contents monitoring - physical and chemical analysis
e. Hopper overflow monitoring - physical and chemical analysis
f. Plume monitoring - physical and chemical analysis; and in-situ turbidity measurements
g. Sedimentation assessment - photo imagery of recent sediment deposits
h. Elutriate and Bioassay Testing - elutriate tests and acute toxicity testing on a fish and a crustacean species were performed for purposes of prediction and potential effects of overflow for the entire project

These activities provided information to characterize the in-situ sediment, hopper inflow as pumped from the draghead, and hopper overflow. Measurement of the material density in the hopper, solids concentration, particle size, and rate of overflow provided information for the development of hopper filling relationships. Elutriate tests were performed to predict the contaminant release back into the water column. These test results were also compared with the data results of the hopper overflow for consistency in sample analysis. Samples taken from the water column defined the relative difference between sediment re-suspended by the draghead and that caused by overflow. One overflow and one non-overflow dredge pass or overflow event was monitored in each of the two reaches of the river.

## SAMPLING OPERATIONS AND DATA ANALYSIS

The Dredge McFarland was used on September 15th and 16th 1998 to dredge in the two test reaches. The field sampling and monitoring was conducted during representative hopper operations with and without overflow in both reaches.

The tasks described in this paper were the responsibility of the U.S. Army Engineer Research and Development Center (ERDC) at the Waterways Experiment Station, Vicksburg, MS, with support provided by the Philadelphia District. The Philadelphia District provided the necessary boats and personnel to assist the ERDC in all field monitoring, in-situ data collection, and sample collection. ERDC personnel were present at the dredging site during the monitoring effort to direct the field efforts and assist in data and sample collection. ERDC performed all subsequent laboratory testing of samples, data analysis, and report preparation.

### Hopper Loading Characteristics

At a minimum, it was necessary to have a complete record of the dredge operating variables during the monitoring and sampling periods. In addition to this standard dredge data, the time and duration of overflow during sampling events were recorded along with loading charts using the dredge McFarland's automated charts.

The loading data provided by the Philadelphia District for the coarse-grained site is shown in Figure 3. Loading volumes are based on calculations using historical density data in the area being dredged. At the coarse-grained site, it took 9 min of dredging to reach overflow status. During the first 9 min, material increased at a rate of 112.4 $m^3$/min (147 $yd^3$/min). Once overflow began, the increase in material loading was determined to be 22.9 $m^3$/min (30 $yd^3$/min). Overflow continued for 57 min with a gain of 130 percent realized. At the end of the overflow period the hopper was full of sediment.

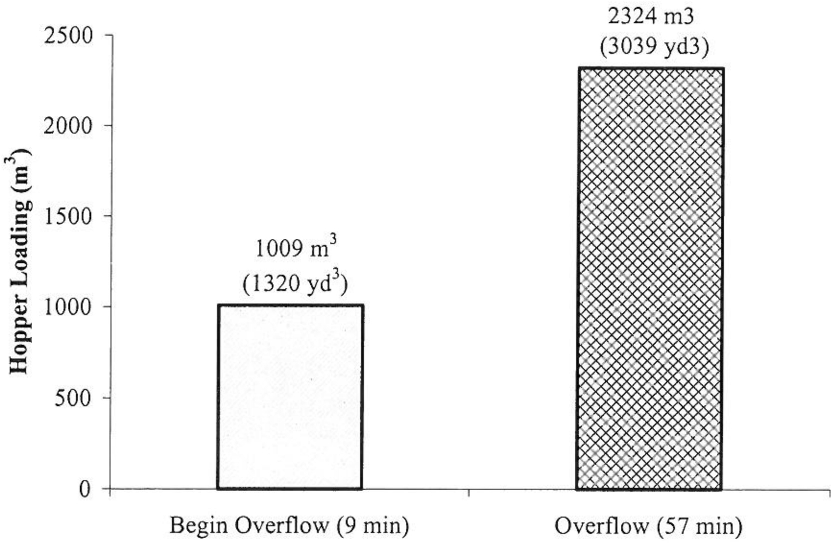

**Figure 3. Hopper Loading at Coarse-Grained Site**

The loading diagram for the fine-grained site is shown in Figure 4. For this site the dredge operated 13 min before overflow began. During this first 13 min of dredging, material increased at a rate of 66.5 $m^3$/min (87 $yd^3$/min). Once overflow began, the increase in material loading was determined to be 7.6 $m^3$/min (10 $yd^3$/min). Overflow continued for 21 min with a gain of 18 percent realized. The percent gain realized for the coarse reach was interpolated for 21 min and was found to be 48 percent so that a comparison could be made during the same timeframe between the two sites.

These results are consistent with the material composition at the two sites. The coarse-grained site would be expected to settle at a more rapid rate, therefore, showing a significant gain in material. Whereas, the fine-grained material would tend to stay in suspension, resulting in most of the sediment being discharged out the overflow. Because of the large amount of gain realized at the coarse-grained site, a rate of return of about 50 to 60 percent may be realized based on the amount of material retained in the hopper and the round trip travel time required to the dump site. Basically, for every 3 days of non-overflow dredging, approximately the same amount of material can be removed by allowing overflow dredging in a 2-day period. This percent return

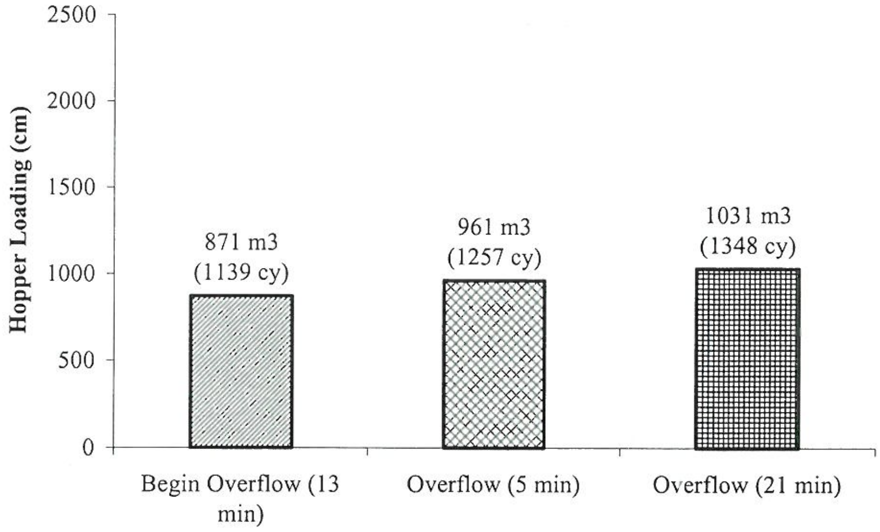

**Figure 4. Hopper Loading at Fine-Grained Site**

also assumes that the material being discharged in the overflow settles in the navigation channel and will require re-dredging the area. At the fine-grained site the rate of return is negligible because of the small gain in load achieved. This is also based on round trip travel time required to the pump-out site, material being discharged in the overflow settling in the navigation channel and requiring re-dredging of the area. If re-dredging the area at either site is not required, then the percent return estimated at those sites may increase.

### In-Situ Sediment and Background Water Samples

On September 14th, in-situ sediment and site water were collected at the two study sites prior to dredging to provide samples for sediment and water characterization and elutriate testing. Fifteen sediment samples were taken at even intervals in a transect along which the dredge was expected to pass during overflow and non-overflow conditions. Composited samples were also obtained for elutritate testing.

The composited sediment samples at the coarse-grained site show the proposed dredged area to average 97-percent sand. The range was less than 1 percent ± of the average value (96.5 to 97.7 percent). Background water chemical concentrations were compared with the contaminants of concern as listed in the "acute marine objectives for toxic pollutants for the protection of aquatic life in the Delaware River estuary." This information can be found in the Delaware River Basin Commission West Trenton, New Jersey, Administrative Manual-Part III, Water Quality Regulations, October 23, 1996. The only parameter found to be above the standard was background dissolved copper. The standard for copper is 5.3 μg/l and the background value was 13 μg/l.

The composited sediment samples at the fine-grained site show the proposed dredged area to average 33-percent sand. The range for sand was from 18 to 50 percent. Background water concentrations for the contaminants of concern were all below the more stringent of the freshwater or marine stream quality objectives for acute toxicity standards as found in the Delaware River Basin Commission West Trenton, New Jersey, Administrative Manual-Part III, Water Quality Regulations, October 23, 1996. Only two exceedances were found in the dissolved overflow water. Endrin was measured at a concentration of 0.0754 μg/l as compared to the standard of 0.019 μg/l. Zinc was measured at a concentration of 131 μg/l as compared to the standard of 95 μg/l.

### Hopper Inflow

The sediment slurry that was picked up by the draghead and transported through the hydraulic suction line was sampled as it entered the hopper (in 3-min intervals during filling and overflow). Grab samples at the inflow port(s) were collected and analyzed for solids concentration and appropriately composited and analyzed for grain size distribution, particle size distribution of fines, and chemical concentrations. The composited samples represented sediment from five equal time intervals during hopper loading. Samples collected for grain-size distribution at the hopper inflow at the coarse-grained site averaged 84-percent sand. Samples collected for grain-size distribution at the hopper inflow at the fine-grained site averaged 12-percent sand.

### Hopper Contents

As material is pumped into the hoppers, a layer of high density settled material is formed in the lower portion of the hopper with a layer of water with suspended material in the upper portion of the hopper. The vertical distribution of suspended material density or concentration in the upper portion of the hopper was measured. These data, in conjunction with overflow concentration data, can be used to determine when an economic load is achieved and when material density in the hopper is at a maximum. A second use for hopper vertical density measurements is to examine the potential for equipment modification, such as introducing settling tubes to enhance solids settling rates in hopper bins. Hopper sampling at three depths (surface, mid-depth, and bottom) was taken at the beginning of overflow and at the end of overflow. Three locations in the hopper were sampled.

Suspended solids concentrations in the hopper at the coarse-grained reach were <15 g/l. This indicates that settling was occurring very rapidly. Although the samples should be representative of the water column, it should be realized that the agitation occurring inside the hopper will keep the material in suspension for an extended period of time. Therefore, when the sample was collected, the material being agitated quickly settled and was not collected in the 250 ml sample bottle.

Suspended solids concentrations in the hopper at the fine-grained reach were upwards of 150 g/l at the bottom and approximately 80 g/l at the surface. It is expected that high concentrations of suspended solids would be found in the water column as the hopper agitates the fine-grained material and keeps it in suspension. The high concentrations of suspended solids at the surface indicate that a large amount of the material was lost to overflow in the fine-grained reach.

## Hopper Overflow

Because of the high-expected variability of the hopper overflow, 40 samples were taken for suspended solids determination for each overflow period. Samples were composited for chemical contaminant determination of chemical concentrations, grain size, particle size distribution of fines, and toxicity testing.

Samples collected for grain-size distribution at the hopper overflow at the coarse-grained site averaged 81.1-percent sand with a range from 24.4 to 96.1 percent. Composites of five samples were obtained and the average grain-size distribution was 78.1 percent with a range from 66.7 to 87.7 percent. This shows that a large amount of the sandy material was being agitated in the hopper and being washed out during overflow. This is consistent with the loading data that shows a loading of about 112.4 $m^3$/min (147 $yd^3$/min) before overflow and an average loading of about 22.9 $yd^3$/min (30 $yd^3$/min) over the 57-min period during overflow. However, the rate of loading in the initial stages of overflow was likely much higher with the material in the overflow increasing as the hopper filled and retention time was decreased. None of the chemistry parameters analyzed in the overflow samples collected at the coarse-grained site exceeded marine acute objectives as listed in the Delaware River Basin Water Quality Regulations for dissolved criteria limits. Although the background value for copper (13 μg/l) exceeded the criteria (5.3 μg/l) as shown above, the dissolved value for copper in the overflow was 5 μg/l, indicating a scavenging of metals by the suspended material during the dredging and overflow process.

Samples collected for grain-size distribution at the hopper overflow at the fine-grained site averaged 12.2-percent sand with a range from 6.2 to 31.2 percent. Composites of five samples were obtained and the average grain-size distribution was 10.6 percent with a range from 9.3 to 11.6 percent. The suspended solids concentrations in the overflow averaged 110 g/l over the total overflow period of 21 min. The solids concentrations were essentially consistent throughout the overflow period, indicating little retention of the fine material in the hopper once overflow began. A large amount of material, about 59.6 $m^3$/min (78 $yd^3$/min) or about 89 percent of the inflow is being lost to overflow. Zinc (131 μg/l) and endrin (0.0754 μg/l) were the only two chemical parameters measured in the overflow that exceeded the more stringent acute objectives of the freshwater and marine stream quality standards (95 μg/l for zinc and 0.019 μg/l for endrin) as listed in the Delaware River Basin Water Quality Regulations for dissolved criteria limits. The value for endrin exceeded standards only by a factor of 4, indicating that both water quality objectives could be met a short distance from the point of overflow. None of the other chemistry parameters analyzed in the overflow samples collected at the fine-grained site exceeded the acute objectives.

## Plume Monitoring

Plume monitoring provided an evaluation of the amount of sediment in the water column resuspended by the operating draghead vs. the amount of sediment contributed by overflow. Data on plume concentrations as a function of distance and time provided information to determine an appropriate buffer distance from the oyster beds in which overflow should be restricted. Differentiation between the magnitude of sediment plumes caused by the draghead and plumes from overflow materials required monitoring both overflow and non-overflow periods. Monitoring one dredge pass without overflow and one dredge pass with overflow was the minimal plume monitoring effort. To reduce the variability of results between tests, the dredge was required to be moving in the same direction relative to the current flow for every overflow and non-overflow test monitored. Plume monitoring also provided information on contaminant dispersion in the water column.

Plume monitoring required two boats. One boat was positioned behind the hopper dredge in its path immediately after it passed and began sampling the water column to evaluate the rate of settling of the plume. The other boat towed a turbidimeter (in-situ type probe) across the plume to give information on lateral plume dispersion. Thus, the duration and geometry of the plume could be estimated. Both boats in the monitoring area carried out background sampling immediately before the dredging began.

Lateral plume dispersion measurements were made at mid-depth by locating the turbidimeter probe at the mid-point of the water column. Background turbidity was extensively measured. The boat towing the turbidimeter monitored distance from the dredge, using a range finder and hand bearing compass, and distance from the anchored sample boat. The whole plume was traversed, going outside of the plume at each extreme of the turbidity plume.

While the mobile boat was measuring lateral plume dispersion, the anchored boat measured decay of the plume as it settled through the water column. Water samples were taken at the surface (less than 1-m deep), mid-depth, and near bottom (within 1 to 2 m of the bottom). Fifteen samples at three depths for a 50-min period were taken to characterize background TSS conditions and about thirty samples at three depths in a 30-min timeframe were taken to characterize the overflow plume after the dredging pass. The latter sampling protocol was also used for the non-overflow sediment plume measurements

TSS was measured for all plume samples and a compositing scheme was used to reduce the number of samples for chemical analysis. Three composite samples for the plume monitoring were obtained (one at each of the three depths) by mixing portions of the samples taken at all three depths over one-third of the plume monitoring effort. Chemical analysis included heavy metals, PCBs and PAHs and provided data on potential contamination of the water column by the dredging operation.

Monitoring of the sediment plumes was accomplished using a boat-mounted 1200-kHz Broad-Band Acoustic Doppler Current Profiler (ADCP). The instrument collects velocity vectors in the water column together with backscatter levels to determine the position and relative intensity of the sediment plume. A MicroLite recording instrument with an Optical Backscatterance (OBS) Sensor (a type of nephelometer) was towed by the second vessel at a depth of 15 ft to measure turbidity and solids concentration data at 0.5-sec intervals. Navigation data for monitoring was obtained by a Starlink differential Global Positioning System (GPS). The GPS monitors the boat position from the starting and ending points along each transect.

## Plume for Coarse-grained Material

At the coarse-grained site, transects were monitored in each test area to obtain the background levels of suspended materials prior to dredging activities. Eight minutes following the dredge passing during non-overflow dredging shows the level of suspended material to be returning to background levels. No lateral dispersion of the plume out of the channel was observed during the non-overflow dredging operation.

During overflow dredging, a wider transect was performed to determine the lateral extent of the plume. No significant change above background levels could be detected. At 1-hr elapsed time following the end of the overflow dredging operation, the levels of suspended material were found to have returned to background conditions. Again, no lateral dispersion of the plume out of the channel area was observed.

Figure 5 is a surface profile of the solids concentrations measured during non-overflow and overflow conditions. Both sets of data fall within the minimum and maximum range of the background solids concentrations measured prior to dredging. Figure 6 is a mid-depth profile of the solids concentrations. Because of the narrow range between the measured values of the minimum and maximum range, both the non-overflow and the overflow measured solids concentrations were above the maximum range. Figure 7 is a bottom profile of the solids concentrations and can be described much like that of the surface profile in that both sets of data fall within the minimum and maximum range of the background solids concentrations. In all three instances, there is not a significant difference in the solids concentrations measured during non-overflow and the solids concentrations measured during overflow. Figure 8 shows that all solids concentrations measured during non-overflow and overflow fell within the total minimum and maximum range measured in the background prior to dredging.

## Plume for Fine-grained Material

At the fine-grained reach, during the non-overflow dredging operation, the tidal flow in the dredging area reversed from flood flow to ebb flow conditions. This accounts for the relative change in observed background levels taken before the non-overflow and overflow test dredging. At 19 min following the end of non-overflow dredging, the levels of suspended material had returned to background conditions. Despite the change in direction of flow in the dredging area, no lateral movement of the plume beyond the channel limits was observed.

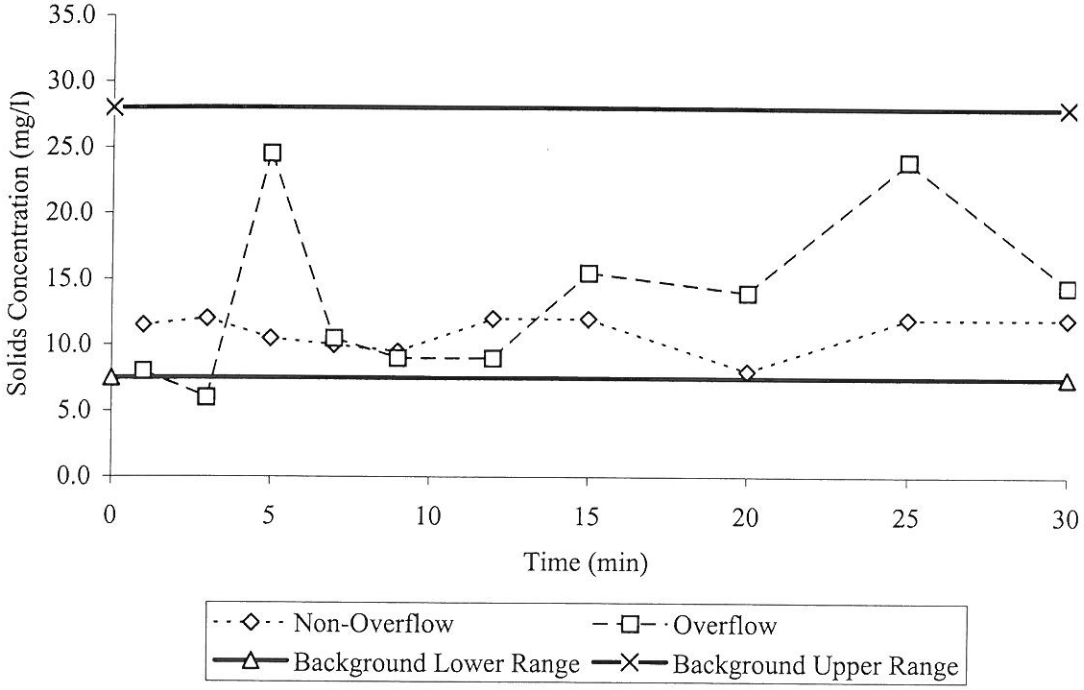

Figure 5. Plume Solids Concentration at Surface (Coarse-Grained Material)

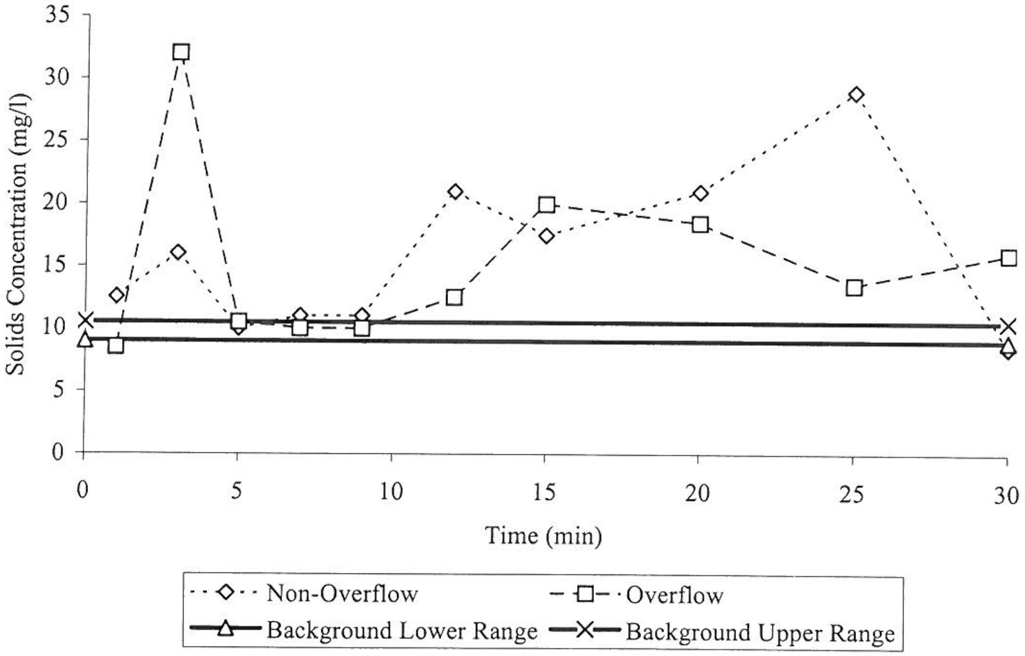

Figure 6. Plum Solids Concentration at Mid-Depth (Coarse-Grained Material)

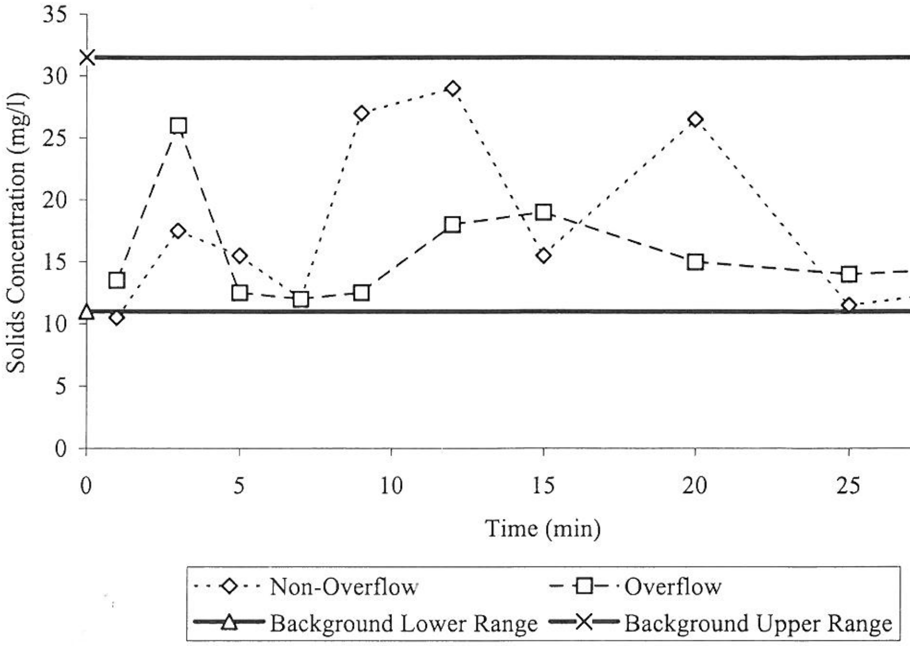

Figure 7. Plume Solids Concentration at Bottom (Coarse-Grained Material)

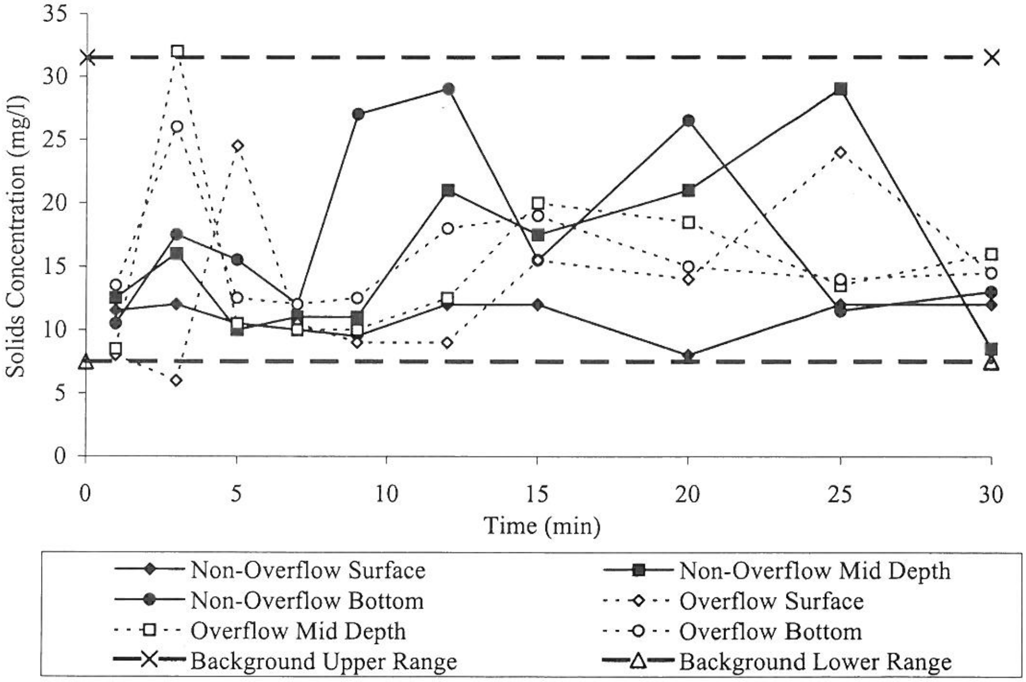

Figure 8. Plume Solids Concentration (Coarse-Grained Site)

Figure 9 shows the solids concentration as measured at the surface during non-overflow and overflow conditions. The overflow solids concentrations oscillate outside the maximum background solids concentration. Toward the end of overflow the concentrations fall back within the background range. Figure 10 shows the solids concentration as measured at mid-depth. The same pattern as the surface profile is exhibited. Figure 11 shows the solids concentration as measured at the bottom. The non-overflow solids concentrations remain within the measured range of the background; however, the overflow solids concentrations remain above the maximum background range throughout the duration of overflow. Figure 12 shows the maximum background range of solids concentration measured. The non-overflow solids measured are well within the total range while the overflow solids concentrations oscillate outside the maximum range. This is consistent since 70 percent or more of the material is fine-grained and would settle slowly.

## Sedimentation Assessment

One difficulty in assessing potential impacts of sedimentation resulting from hopper overflow is detection of thin overburdens in habitats in the vicinity of the dredging operation. Although thin (<5 cm) overburdens could have detrimental impacts, for example on the settlement and attachment of oyster larvae, this exceeds the detection limits of most conventional techniques. One method found to be effective in measuring sedimentation events of less than 1 cm is sediment-profiling imagery using a sediment profile camera. This technique involves insertion of a prism into the substrate through which images of the sediment-water interface are obtained. The images provide rapid, accurate measures of recent sedimentation, particularly if the overburden sediments are dissimilar from the ambient substrate. The images also provide indications of impacts to benthic communities (e.g., distribution and position of annelid worms and bivalve mollusks relative to the relict and overburden surface) and changes in physical/chemical conditions of the sediment (e.g., altered redox potential discontinuity, evidence of hypoxia). This camera system is unaffected by ambient turbidity. An attached plan-view underwater camera also provided surface photographs at the sediment profile stations.

Immediately prior to overflow conditions, an increase in the background suspended material was observed. This increase is assumed to be due to the increase in the ebb flow velocities and the resulting disturbance of bottom materials from near bottom velocities and not dredge plume dispersion. When hopper overflow conditions began the width of the transect was increased to observe the lateral extent of the dispersion of the dredge plume. After an elapsed time of 1 hr following the completion of the overflow dredging operation, levels of suspended materials had returned to background conditions. As in the previous dredge operations, no lateral dispersion of the dredge plume beyond the channel limits was observed to have occurred.

The sediment profiling camera system was deployed at the Delaware River overflow operation site. Because the area is tidally influenced, stations were occupied both up and down current from the dredging project. Stations were allocated to gather information for transects across several cross-sections of the river reach potentially influenced by overflow, including any charted oyster bars.

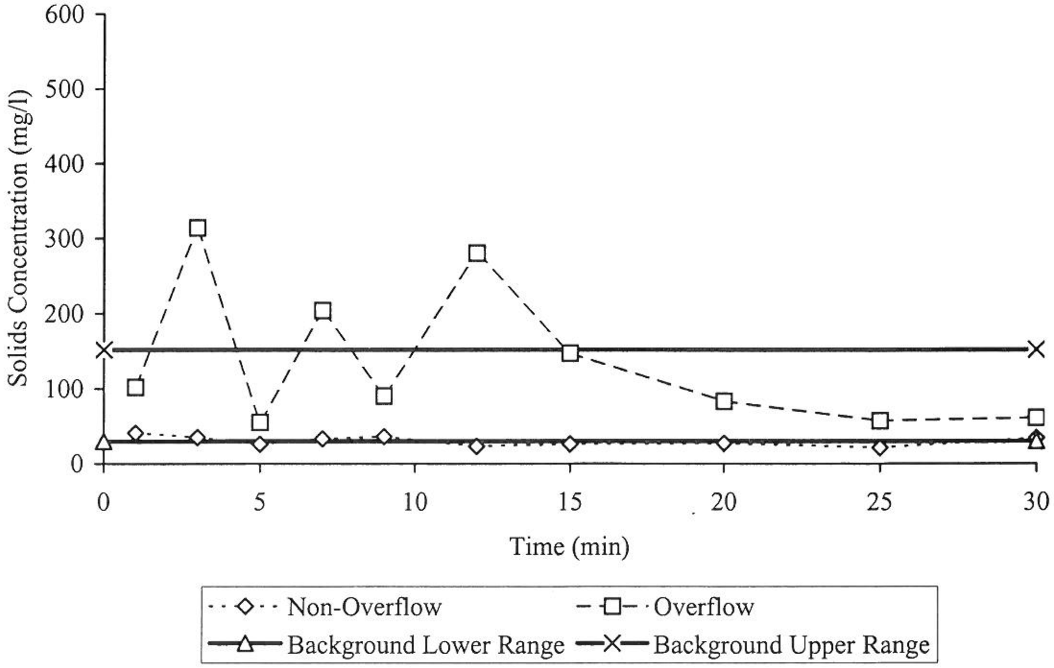

**Figure 9. Plume Solids Concentration at Surface (Fine-Grained Material)**

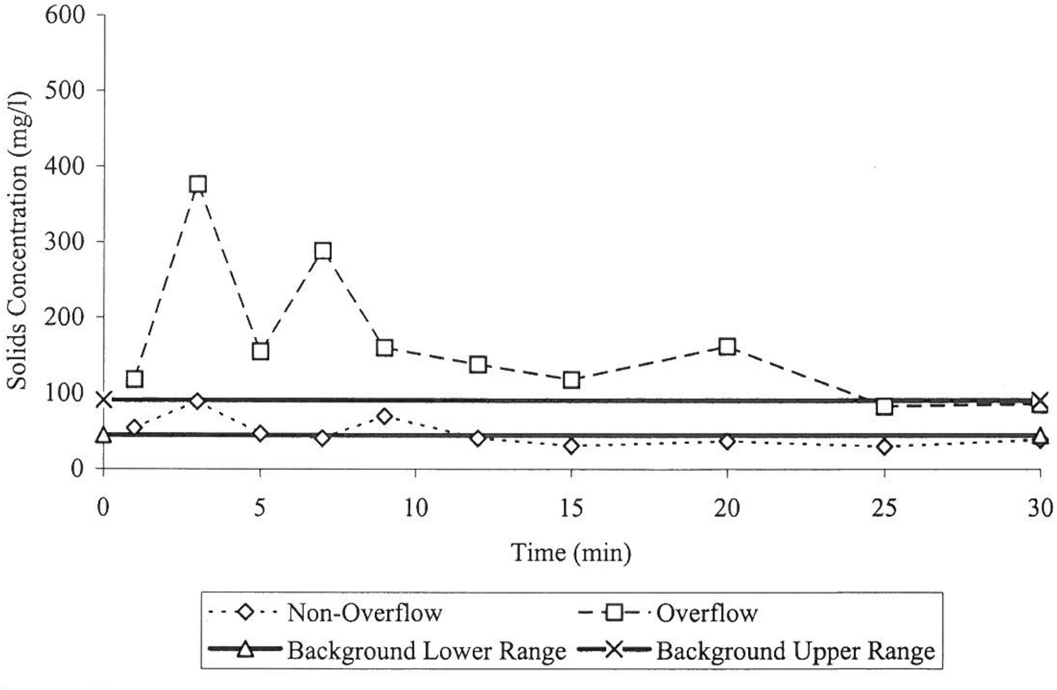

**Figure 10. Plume Solids Concentrations at Mid-Depth (Fine-Grained Material)**

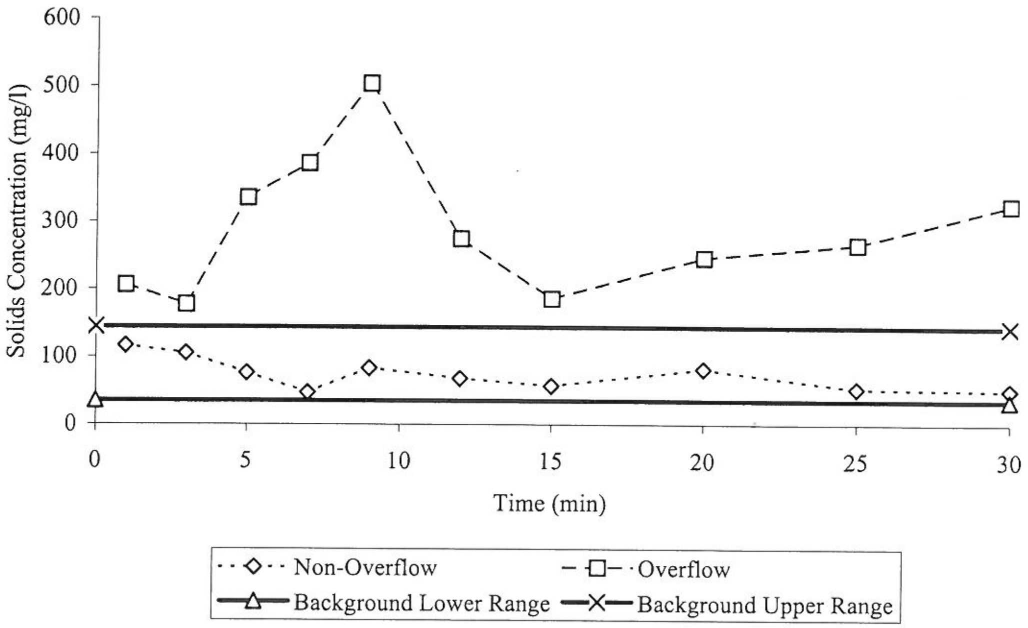

**Figure 11. Plume Solids Concentration at Bottom (Fine-Grained Material)**

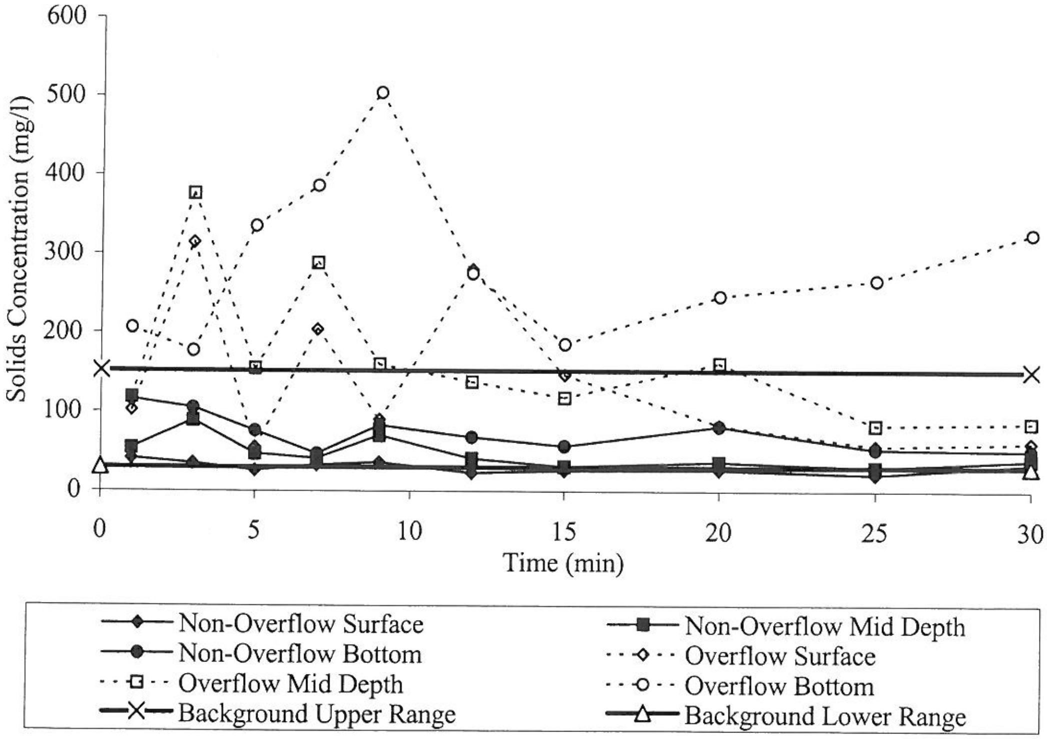

**Figure 12. Plume Solids Concentration (Fine-Grained Site)**

Sediment profile images from a total of 14 stations were analyzed from the coarse-grained site. There was evidence that recent sedimentation had occurred at several of the stations within the channel, possibly a result of the dredging operations. Gray colored suspended material, indicative of hopper overflow material, was observed at two of the stations. Four of the stations had layering from grain-size changes, but are assumed to have occurred because of normal sediment transport processes rather than hopper overflow operations.

Sediment profile images from a total of 41 stations were analyzed from the fine-grained site. No evidence of recent physical disturbance was detected at any of the stations, but material that could have come from the hopper overflow was observed at one station. Five of the stations on the edge of the channel had grain-sized layering with sands on the surface overlaying clayey sediments. Since the sediments in the channel were finer silts and clays it was unlikely that the layers at the channel edge stations were the result of the dredging operations. Three of the stations on the edge of the channel had sediment layering with amphipod and worm tubes which could not have re-established living position in the short interval between dredging and sampling. Flocculent sediment layers, thin layers of unconsolidated surface sediments, occurred at six shoal stations and one channel edge station. Based on their color tones, all flock layers appeared to be composed of background sediments and not hopper overflow or dredged material.

No indication of newly deposited dredged material was observed at stations outside the edge of the navigation channel at either study site. Although the sampling station coverage was not extensive, given the relatively short duration of the tests, the risk of significant sedimentation as a consequence of the hopper dredging operations appears largely restricted to the bottom and side slopes of the channel.

### Standard Elutriate Tests

The standard elutriate analysis was performed using the composited in-situ sediment and site water. The purpose of the standard elutriate testing was to gain data on possible application of the test for prediction of overflow contaminant concentrations. The mean predicted dissolved values from the elutriates were calculated using the EFQUAL computer program, a module of the ADDAMS software package (Palermo and Schroeder 1991). The elutriate test was conducted using standard procedures (USEPA/USACE 1998).

At the coarse-grained site, background dissolved copper was the only contaminant of concern that was predicted to be above the standard. The program predicted that copper would be discharged at 7 μg/l which is above the marine objective acute criteria, but is well below the background value of 13 μg/l. Therefore, a dilution of the background with respect to copper would naturally occur due to the dredging operation and a mixing zone would not be required. The actual value recorded at the hopper overflow (effluent) for copper was 5 μg/l, which was below both the background and the standard of 5.3 μg/l

At the fine-grained site, the predicted dissolved value of selenium was 24.3 μg/l. The more stringent acute value of the freshwater or marine stream quality standard for selenium is 20 μg/l and the background was found to be 19 µg/l. The actual value recorded at the hopper overflow for selenium was 14.2 µg/l, which is below the criteria and the background value, which would indicate a natural dilution of the contaminant of concern during dredging operations. Again, because of this natural dilution, a mixing zone would not be required.

At both reaches, the predicted elutriate values appear somewhat conservative when compared with the overflow values. The close agreement of the elutriate values with the actual overflow values indicate that the elutriate test can be used as a valid predictor of overflow quality for the Delaware River.

**Bioassay**

Samples were taken at the hopper overflow for use in a 96-hr water-column bioassay. This portion of the study will help in determining the possible biological effects of water column exposure to Delaware River overflow.

Two species were used in performing the bioassays, the mysid shrimp, a crustacean species, *Mysidopsis bahia* and the inland silverside, a fish species, *Menidia beryllina.* These species were selected based on conversations with personnel from the Delaware Department of Natural Resources and Environmental Control. The filtered elutriate was diluted with standard laboratory control seawater (6-ppt salinity for the fine-grained site and 30-ppt salinity for the coarse-grained site) to yield the following concentrations: 0 percent; 6.25 percent; 12.5 percent; 25 percent; 50 percent; and 100 percent elutriate. Each treatment was replicated five times. The trimmed spearman-karber method was used to calculate $LC_{50}$ values.

Survival in test concentrations from the coarse-grained site ranged from 100 to 88 percent for *Mysidopsis bahia* and from 88 to 68 percent for *Menidia beryllina.* Exposures in elutriate test concentrations from the coarse-grained site did not adversely affect survival of either test species. Since neither test species had mortality values greater than 50 percent, an $LC_{50}$ value could not be calculated.

Survival in test concentrations from the fine-grained site ranged from 90 to 0 percent with 0 percent survival in the 50 and 100 percent exposures for *Mysidopsis bahia.* Survival for *Menidia beryllina* ranged from 98 to 0 percent with 4 to 0 percent survival in the 50 and 100 percent elutriate treatments. An $LC_{50}$ value of 30.04 percent was calculated for *Mysidopsis bahia* and an $LC_{50}$ value of 31.66 percent was calculated for *Menidia beryllina.* Mortality observed from exposures in elutriate test concentrations was attributed to the high level of $NH_3$. In the short term, high levels of $NH_3$ are common in predominately fine-grained sites during dredging operations.

## SUMMARY AND CONCLUSIONS

Based on the results of the study, the following conclusions can be made:

a. Loading data at the coarse-grained site shows a gain of 130 percent over a period of 57 min after overflow began. Based on the round trip travel time required to the disposal site and the amount of material retained in the hopper, rates of return greater than 50 percent may be realized for the coarse-grained material. Loading data at the fine-grained site shows a gain of 18 percent over a period of 21 min after overflow began. Based on the round trip travel time required to the pump-out site and the amount of material retained in the hopper, there was no economic benefit to overflow for the fine-grained material. In both instances, rates of return are also based on the assumption that all material in the overflow will return to the channel and will require re-dredging.

b. Using the same economic assumptions as discussed above, about a 20-percent return may be realized from a material containing about 60-percent sand and about a 40-percent return may be realized from a material containing about 80-percent sand.

c. Based on the water chemistry analysis at the two sites, no contaminants of concern were found to be a problem because of the dredging operation. None of the contaminants of concern exceeded water quality objectives in the overflow at the coarse-grained site. At the coarse-grained site only, dissolved copper was found in the background to be above the standard. Samples taken for dissolved copper at the hopper overflow, however, were within standards. This indicates a scavenging of the metal by the suspended material occurred during the dredging and overflow process. At the fine-grained site, only zinc and endrin were measured at the overflow to be above the standard. However, the predicted elutriate for both zinc and endrin were measured at below detection levels.

d. The plume study results showed that the coarse-grained material settled quite rapidly and that no lateral dispersion of the plume out of the channel was observed. No significant change above background levels could be detected. At 1 hr elapsed time following the end of the overflow dredging operation, the levels of suspended material were found to have returned to background conditions. At the fine-grained site, an increase in the suspended material was observed. However, after an elapsed time of 1 hr following the completion of the overflow dredging operation, levels of suspended materials had returned to background conditions. Again, no lateral dispersion of the dredge plume beyond the channel limits was observed to have occurred

e. The sedimentation portion of the study confirmed what was observed during the plume study. At the coarse-grained site, there was evidence that recent sedimentation had occurred at several of the stations, possibly a result of dredging operations. But no indication of newly deposited dredged material was observed at stations outside the edge of the navigation channel. At the fine-grained site, some sediment layering was found even though no evidence of recent physical disturbance was detected at any of the stations. Again, no indication of newly deposited dredged material was observed at stations outside the edge of the navigation channel.

f. Although the sampling station coverage was not extensive, the risk of significant sedimentation as a consequence of the hopper dredging operations appear to be restricted to the bottom and side slopes of the channel.

g. The elutriate test results were consistent with and slightly conservative as compared to the overflow samples, indicating that the elutriate test is a valid prediction of overflow quality for the Delaware system.

h. The bioassay analysis showed no adverse effects to exposures of fish and crustaceans species being exposed to the elutriate samples from the coarse-grained site. Some species mortality were observed using elutriates from the fine-grained site, but was determined to be caused from high levels of $NH_3$, which is a common short term byproduct of dredging in fine-grained material.

i. The overall results of the study indicate that overflow meets the applicable water quality objectives and has no measurable physical impact outside the navigation channels. The loading data indicate that overflow in coarse-grained reaches results in significant load gains, while load gains in fine-grained reaches are small.

Based on the results of the study, the Philadelphia District has requested approval for overflow in the coarse-grained portion of the project.

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Palermo, M.R. and Schroeder, P.R. (1991). *"Documentation of the EFQUAL Module for ADDAMS: Comparison of Predicted Effluent Water Quality with Standards".* Technical Note EEDP-06-13, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

USEPA/USACE. (1998). *"Evaluation of Dredged Material Proposed for Discharge in Inland and Near-Coastal Waters - Testing Manual".* EPA-823-B-98-004, U.S. Environmental Protection Agency, Washington, D.C.

# ASSESSMENT OF CONTAMINANT ISOLATION AT THE DUWAMISH SUBAQUEOUS CAPPING SITE

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## ABSTRACT

Subaqueous capping is a remediation technique by which contaminated sediments are physically isolated in an aquatic environment by the placement of clean material over the sediment. Capping isolates the contaminants from biota in the water column and surface sediments. In this paper the projected long–term effectiveness of a cap at a dredged material disposal site is evaluated using monitoring data and computer simulations. Field measurements at the Duwamish Waterway dredged material disposal site in Seattle, Washington, were made to evaluate the movement of contaminants from the contaminated dredged material deposit into the cap material. These measurements were made at three representative locations and at depths that include the cap and extend well into the contaminated deposit. The U.S. Army Corps of Engineers RECOVERY version 3.0 model was used to predict contaminant migration and distribution in the cap as a function of time. Vertical contaminant concentration profiles from monitoring data and computer simulation indicate that a very slight movement of the contaminants has occurred and that the cap has performed as expected. In addition, comparison between measured data and numerical simulation results verifies the applicability of the RECOVERY model in predicting contaminant migration in the system.

## INTRODUCTION

A remediation option for contaminated bottom sediments is to place a cap that isolates the contaminants from bottom dwelling biota. Proper capping effectively reduces and possibly prevents negative ecological impacts by restricting the migration of contaminants into the biologically active surficial sediment and the water column. A cap composed of clean sediments acts as a buffer and retardant that restricts contaminant migration.

Contaminant flux from the contaminated sediments into the water column takes place due to the presence of a concentration gradient between the water column and the sediment pore water. In

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addition, the settling of suspended sediments and the resuspension of bottom sediments influence contaminant flux between the water column and the sediment bed. A cap acting as a buffer between the water column and the contaminated sediment reduces or prevents the direct exchange between the two media. An additional contaminant flux occurs by diffusion from the contaminated sediment layer to the clean deep sediment underneath.

Cap thickness is considered one of the most important factors in cap design. Proper cap designs account for the effect of bioturbation, erosion, consolidation, sediment mixing, and other operational constraints to prevent the migration of contaminants to the water column and the biologically active surficial sediment.

In disposal operations in ocean waters or waterways, contaminated dredged material is placed to form a mound on the bottom of the disposal site and is subsequently capped with clean material to form a larger mound. Laboratory studies (Brannon et al., 1987) have shown that the presence of a 50 cm cap of sand, silt, or clay was sufficient to prevent the migration of contaminants from dredged material into biota.

A field demonstration of capping was conducted in a subaqueous depression of the Duwamish Waterway in Seattle, Washington. The disposal site consisted of a previously dredged depression located in approximately 22 m of water. The depression is about 30 m wide, 91 m long, and 1.8 m deep. Sumeri (1984) presents the planning for the capping operation as well as for the dredging and disposal operation at the site, and Truitt (1986) reported the monitoring results for material placement during the capping operation. The latter also reported that contaminated material exited the split–hull, bottom dumping barge rapidly descending in a well–defined cohesive mass; the uncontaminated sandy dredged material was applied successfully as a cap without displacing the softer contaminated material.

Brannon and Poindexter–Rollings (1990) presented the results of the investigation on the 18–month post–disposal behavior of the capped deposit including consolidation of the dredged material, stability of the cap and effectiveness of contaminant isolation by the cap. The 5–year and 11–year post–disposal behaviors of the cap in isolating the contaminants were reported by SAIC (1996) and Sumeri (1996). Both studies indicate that contaminant migration from the contaminated dredged material to the clean cap was minimal. The data presented by SAIC (1996) forms the basis for this assessment study.

## MODEL DESCRIPTION

Pollutants in bottom sediments can be released by resuspension of particles, mixing by benthic organisms, and diffusion from the sediment pore water. On the other hand, pollutants in the water column can be transferred to the sediment layer by settling and to the atmosphere by volatilization. This section describes the modeling framework of the RECOVERY model version 3. A more thorough description of the RECOVERY model is presented in Ruiz et al. (2000). The model was developed to assess the impact of capping with clean material on the migration of contaminants from bottom sediments. Modeling assumes the overlying water is well–mixed and the contaminant follows reversible linear equilibrium sorption and first–order decay kinetics.

As shown in Figure 1, the system is idealized as a well–mixed surface water layer underlain by a vertically–stratified sediment column. The sediment is well–mixed horizontally but segmented vertically into a well–mixed surface layer and deep sediment. The latter is segmented into layers with varying thicknesses, porosities, and contaminant concentrations.

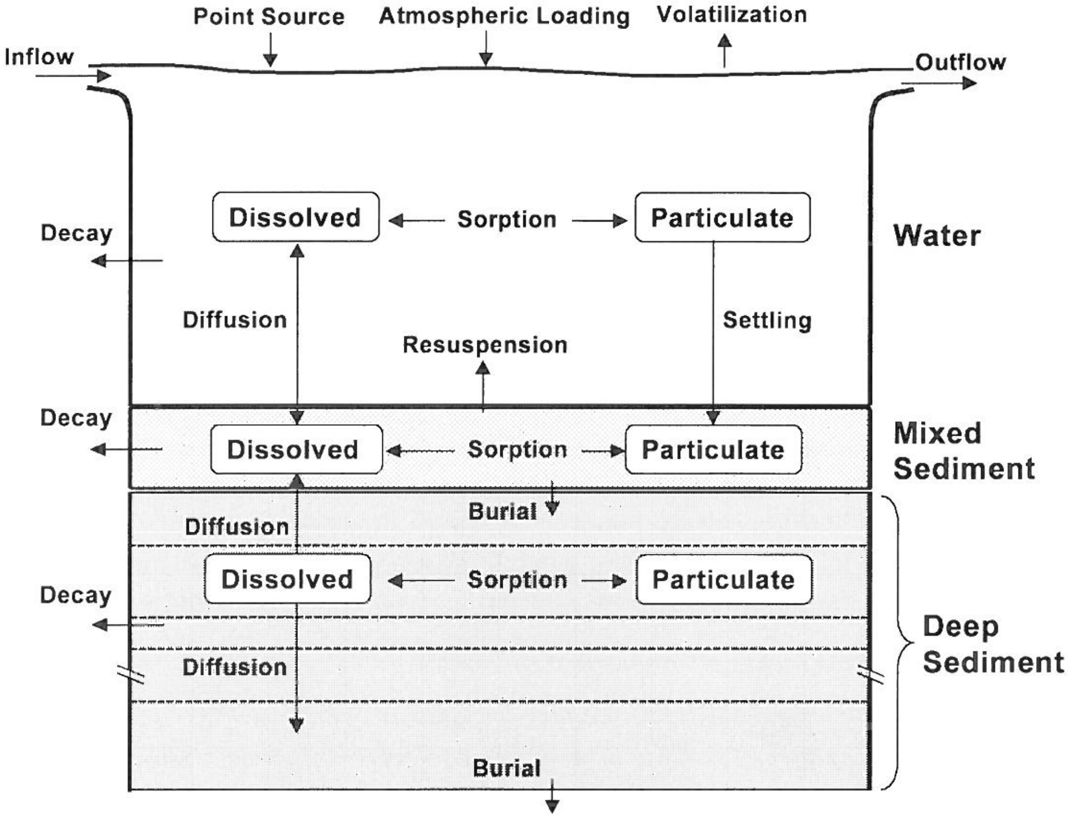

Figure 1. Schematic of the sediment–water system as modeled in RECOVERY (modified from Boyer et al., 1994).

The discretized sediment layer configuration permits modeling situations in which contamination is layered, and hence it is ideal for capping scenarios and for sites where contamination occurred over a long period of time. The specification of a mixed surface layer accounts for the unconsolidated layer which is observed at the surface of sediments due to bioturbation and mechanical mixing.

The mathematical formulation for contaminant mass balance for a single contaminant in the water column, the mixed sediment layer, and the deep sediment, respectively, is presented below. These equations also include the interaction and transfer of contaminant mass among the three components of the system.

Equation 1 is the contaminant mass balance of a single contaminant in the water column.

$$V_w \frac{dc_w}{dt} = Q\,c_i - Q\,c_w - k_w V_w\,F_{dw}\,c_w - k_v V_w\,c_w - v_s\,A_w\,F_{pw}\,c_w + v_r A_m c_m + v_d A_m\left(F_{dp} c_m - F_{dw} c_w\right) + W \qquad (1)$$

Equation 2 is the contaminant mass balance of a single contaminant in the mixed sediment layer.

$$V_m \frac{dc_m}{dt} = -\,k_m V_m c_m + v_s A_w F_{pw} c_w - v_r A_m c_m - v_b A_m c_m + v_d A_m\left(F_{dw} c_w - F_{dp} c_m\right) + v_d A_m\left(F_{dp} c_s(0) - F_{dp} c_m\right) \qquad (2)$$

Equation 3 is the contaminant mass balance of a single contaminant in the deep sediment.

$$\frac{\partial c_s}{\partial t} = \phi\,F_{dp}\,D_s \frac{\partial^2 c_s}{\partial z^2} - v_b \frac{\partial c_s}{\partial z} - k_s c_s \qquad (3)$$

In these equations, $V_w$ = volume of water body, $m^3$; $c_w$ and $c_m$ = concentrations of toxicant in water and mixed sediments, respectively, $mg/m^3$; $c_i$ = inflow concentration, $mg/m^3$, which reflects both direct and tributary loadings; t = time, years; Q = flushing flow rate, $m^3/yr$; $k_w$ = decay rate constant of the contaminant in the water, $yr^{-1}$ ; $k_v$ = volatilization rate of contaminant, $yr^{-1}$; $v_s$ = settling velocity of particulate matter, m/yr; $A_w$ and $A_m$ = surface areas of water and mixed sediment, respectively, $m^2$; $F_{pw}$ = fraction of contaminant in particulate form in the water; $v_r$ = resuspension velocity of sediments, m/yr; $v_d$ = diffusion mass–transfer coefficient at the sediment–water interface, m/yr; $F_{dp}$ = ratio of contaminant concentration in the sediment pore water to contaminant concentration in total sediment; $F_{dw}$ = fraction of contaminant in the dissolved form in the water; and W = external loads, mg/yr (assumed to be zero for CAD sites). In Eq. 2, $V_m$ = volume of mixed layer, $m^3$; $k_m$ = the decay rate constant of the contaminant in the mixed layer, $yr^{-1}$; $v_b$ = the burial velocity, m/yr; and $c_s(0)$ = the contaminant concentration at the top of the deep contaminated layer, $mg/m^3$. Eq. 3 is the advection–diffusion–decay equation where $c_s$ = the contaminant concentration in the deep sediments, $mg/m^3$; $\phi$ = the sediment porosity; $D_s$ = diffusion rate in the sediment pore water, $m^2/yr$; z = depth into the sediment, m, where z = 0 at the top of the deep sediments; and $k_s$ = the decay rate constant of the contaminant in the deep sediments, $yr^{-1}$.

In addition to the contaminant mass, the sediment mass must be conserved. The velocity terms $v_s$, $v_r$, and $v_b$ in Eqs. 1 and 2 are computed according to the following steady–state mass balance for mixed–sediment layer

$$v_s A_w s_w - (v_r + v_b) A_m (1 - \phi) \rho_p = 0 \qquad (4)$$

where $\rho_p$ is the density of the sediment solids, g/m$^3$. The framework assumes that suspended solids concentration, $s_w$ in g/m$^3$, is given.

In the numerical solution, initial concentrations must be specified. Constant contaminant concentrations are used in the water column and in the mixed layer while a concentration profile may be specified for the deep sediment based on the physical situation. The boundary conditions for the solution assume that no contaminant migration takes place at $z = \infty$.

The physical system modeled in RECOVERY in which the sediment layer configuration is segmented into layers of variable thickness, porosities, and contaminant concentration underlain by an uncontaminated region is useful for capping sites where contamination occurs over a long period of time, i.e. contamination may be layered. Therefore, RECOVERY is used as a tool for simulating the effects of capping contaminated sediments with clean sediments as an isolation technology. In this paper, the RECOVERY model was applied to simulate contaminant migration into the capped dredged material deposit in the subaqueous depression at the Duwamish Waterway in Seattle, Washington.

## PROJECT DESCRIPTION

In March 1984, the U.S. Army Corps of Engineers, Seattle District, created a confined aquatic disposal (CAD) site in the Duwamish Waterway. The project was conducted to demonstrate the feasibility of CAD technology. The USACE dredged sediments contaminated with metals and PCBs from a shoaling area of the Duwamish River and placed the material in a depression in the West Waterway in 22 m of water. The depression is 30 m wide, 91 m long, and 1.8 m deep and located in a depositional area where about 0.5 m of deposition occurred between 1968 and 1984. The material was then capped with clean sand dredged from an upstream settling basin that was known to have clay balls. These clay balls would have higher contaminant concentration than the clean sand. The Duwamish mound had the initial cross–sectional configuration of a truncated cone 1.8 m in height, 93 m in diameter, with side slopes of approximately 1:17. The mound was composed of 0.9 m of contaminated dredged material with side slopes of 1:20, overlain by a sand cap. The cap was typically 0.3–0.61 m deep across most of the disposal site, with the central portion of the site showing a cap thickness of at least 0.91 m. A typical vertical section of the site with the cap in place is shown in Figure 2.

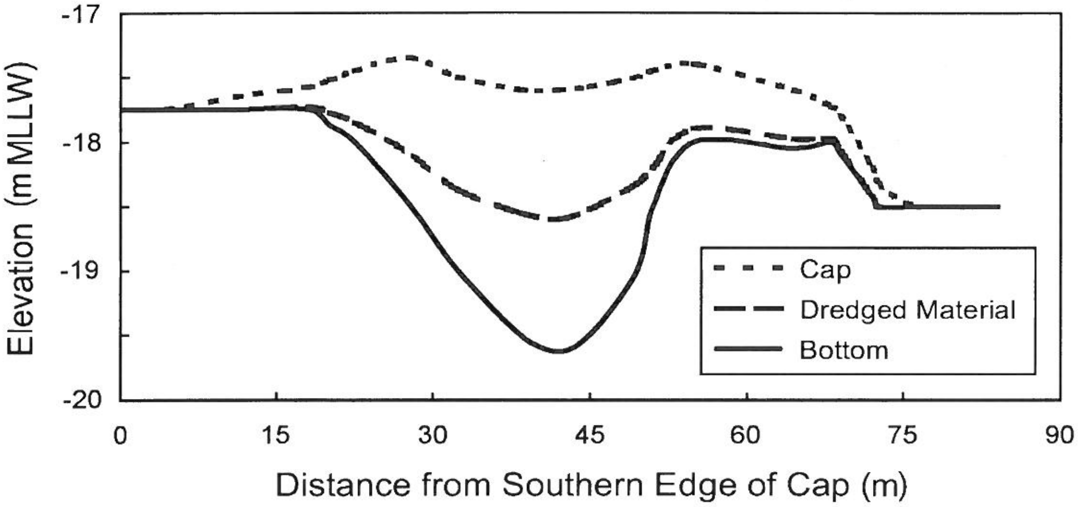

Figure 2. Representative cross section of the Duwamish Disposal Area with cap.

Sediment cores were taken from the contaminated shoal and at the disposal sites before capping using a vibracore sampler with a 76.2-mm diameter and 6.1-m long core barrel. Additional borings were made at the disposal site following placement of the contaminated dredged material and then at intervals of 2 weeks, 6 months, 18 months, 5 years and 11 years. The 18-month, 5-year and 11-year samples were taken at nearly the same locations (as close as practically possible) to minimize variability in sediment samples. Table 1 includes the results of chemical testing of the dredged material prior to the capping operation (Brannon and Poindexter-Rollings 1990). These data indicate much higher levels of Cu, Zn, Pb, and PCB than did the cap material. Results for the two composite samples from the cap material are presented rather than their average to illustrate the variability of the contaminants in the cap.

Table 1. Initial chemical concentrations in mg/kg of dry sediment weight.

| | Chemical Constituent (mg/kg) | | | | |
|---|---|---|---|---|---|
| Material | Cu | Pb | Zn | Aroclor 1242 | Aroclor 1254 |
| Dredged Material | 130 | 190 | 240 | 1.4 | 3.1 |
| Cap Sample 1 | 22 | 21 | 52 | ND | ND |
| Cap Sample 2 | 15 | 5 | 72 | 0.07 | 0.06 |
| Disposal Area | 40 | 36 | 75 | ND | ND |

ND – Not Detected

Data from Brannon and Poindexter-Rollings (1990).

After capping, sediment core samples were collected at three locations labeled as VDQ, VDR, and VDS and are shown on the elevation contour plot of the site in Figure 3. At each sampling location, a core sample was collected through the sandy cap material into the underlying contaminated sediment.

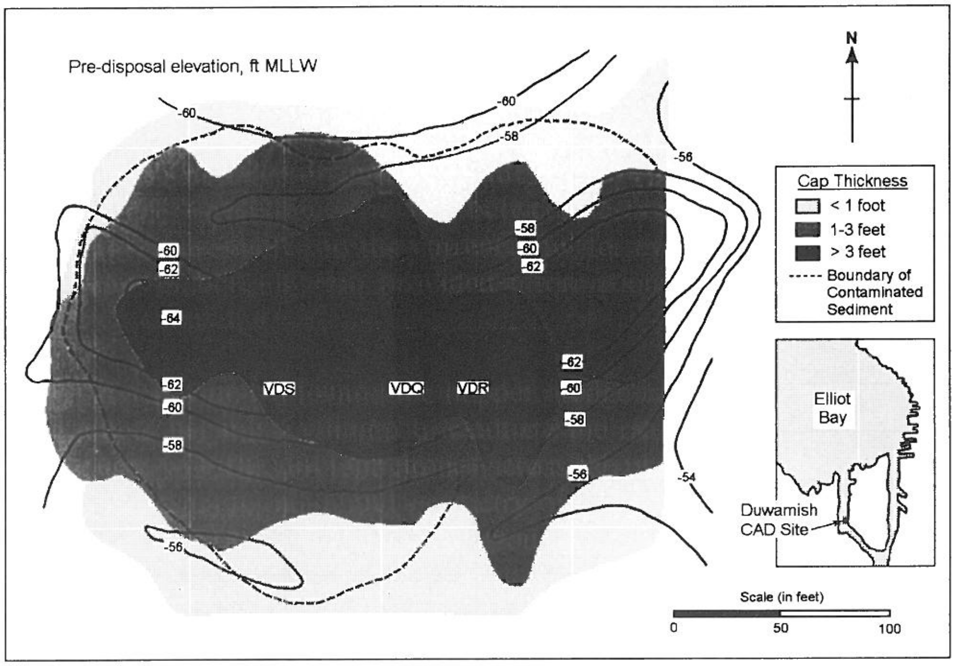

Figure 3. Elevation contour plot of the Duwamish Project showing three sampling locations, VDQ, VDR, and VDS.

In the 1995 investigation, subsamples were collected from each Vibracore 15 cm below the sand cap/contaminated sediment interface, 15 cm above the interface, as well as 30 cm, and 45 cm above the interface. A total of 10 cm of material was retained for each interval to provide adequate material for the required analysis (i.e., the +15 cm interval was collected from +10 cm to +20 cm of the core sample). However, the 1989 samples were collected at intervals smaller than 10 cm. The +45 cm samples were archived from each station pending the results of the initial chemical analysis. In addition, a surface sample (top 10 cm) was collected at station VDQ and analyzed for the full Puget Sound Dredged Disposal Analysis (PSDDA) conventionals and chemicals of concern. Three cores were collected at station VDQ to obtain enough surface sediment for all analyses.

The vibracore subsamples collected from the Duwamish CAD site were analyzed for Cu, Pb, Zn, and PCBs (Aroclors 1242 and 1254). In addition, samples VDQ–1, VDQ–2, and VDQ–5 were analyzed for PSDDA conventionals, and VDQ–5 was also analyzed for the PSDDA chemicals of concern. A summary of the 1989 and 1995 sediment chemistry results is presented in Table 2.

Table 2. Sediment chemistry results for the Duwamish CAD.

| Station | Distance from Interface(cm) | Cu (mg/kg) | | Pb (mg/kg) | | Zn (mg/kg) | | PCB 1242 (µg/kg) | | PCB 1254 (µg/kg) | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Sampling Event | | 1989 | 1995 | 1989 | 1995 | 1989 | 1995 | 1989 | 1995 | 1989 | 1995 |
| VDQ | 45 | 16.1 | NA | 7.8 | NA | 56.3 | NA | 20U | NA | 155 | NA |
| | 30 | 12.3 | 14 | 3.6 | 11.7 | 49.8 | 61.2 | 20U | 13J | 20U | 15J |
| | 15 | 12.8 | 17.2 | 4.4 | 12.2 | 52.5 | 54.2 | 20U | 32 | 125 | 40 |
| | –15 | NC | 91.8 | NC | 123 | NC | 257 | NC | 500 | NC | 490 |
| | –30 | 133 | NC | 165 | NC | 338 | NC | 6200 | NC | 6300 | NC |
| VDR | 45 | 13.5 | NA | 4.5 | NA | 48.8 | NA | 20U | NA | 20U | NA |
| | 30 | 13.4 | 16.1 | 3.6 | 7.8 | 51.3 | 60.3 | 20U | 19U | 20U | 19U |
| | 15 | 12.1 | 16.7 | 4.6 | 9.5 | 50.4 | 55.9 | 20U | 19U | 20U | 13J |
| | –15 | NC | 148 | NC | 224 | NC | 194 | NC | 97 | NC | 240 |
| | –30 | 138 | NC | 195 | NC | 430 | NC | 650 | NC | 1500 | NC |
| VDS | 45 | 15.2 | 37.9 | 7.5 | 18 | 54.6 | 64.7 | 20U | 25 | 50 | 50 |
| | 30 | 12.7 | 63.1 | 5.6 | 84.5 | 51.6 | 205 | 20U | 280 | 20U | 470 |
| | 15 | 12 | 18.3 | 3.5 | 11 | 47.5 | 63.9 | 20U | 31 | 20U | 36 |
| | –15 | NC | 142 | NC | 211 | NC | 395 | NC | 4600 | NC | 3400 |
| | –30 | 102 | NC | 172 | NC | 264 | NC | 140 | NC | 220 | NC |

NC = not collected. NA = not analyzed (archived). U = Chemical was not detected. J = Result is considered an estimated value; the value was below the laboratory practical quantification limit (PQL) but above the method detection limit (MDL).

A sediment vertical profiling system (SVPS) survey was also conducted at the Duwamish CAD site to determine the current condition of cap sediments and assess the health of the biological community. A Benthos Model 3731 Sediment–Profile Camera was used to collect high–resolution in situ sediment profile images at the CAD site. In addition to the sampling locations at the CAD site, two additional stations were also sampled to document off–cap sediment conditions. A total of 102 images was collected during the Duwamish CAD site SVPS. Following a visual assessment of all collected SVPS images, a computer image analysis system was used to analyze selected slides for physical and biological parameters. The parameters include grain–size major mode, prism penetration depth, boundary roughness, depth of apparent Redox Potential Discontinuity (RPD), infaunal successional stage, mud clasts, organism sediment index (OSI), and sediment layer thickness (cap layer). A minimum of one image was analyzed for each station. At 20% of the stations, a second image was also analyzed for quality assurance and quality control (QA/QC).

## PARAMETER SELECTION

The RECOVERY model utilizes sediment, water column and pore water data to model the vertical migration of contaminants. For the Duwamish CAD site, most of these data are available from the surveys conducted by the USACE; the rest are calculated or assumed. The first parameter, residence time, does not affect migration of contaminants between deep sediment layers. Prediction of contaminant migration between deep sediment layers, i.e., the cap material and the contaminated dredged material, is the primary objective of modeling for cap design verification. Residence time was estimated to be 0.08 years based on estimates of tidal flushing of the epilimnion at the site. The surface area of the contaminated dredged material following spreading was measured to be 5400 $m^2$. Therefore, for a water depth of 17.4 m, the flow through at the site was calculated to be $1.17 \times 10^6$ $m^3$/yr.

The SVPS survey discussed earlier indicated small sediment deposition activity at the site. A suspended solids concentration of 20 g/$m^3$ is typical of low depositional rates. Suspended sediment concentration does not affect contaminant migration between deep sediment layers; hence, use of a typical value is sufficient. The organic content of the suspended solids was estimated to be 5%. Burial velocities were assumed to be $2 \times 10^{-2}$ m/yr. The burial velocity was based on observation of 0.3–0.5 m of sediment deposition over a period ranging from 1968 to 1984. The resuspension velocity was estimated to be $5 \times 10^{-6}$ m/yr which is a typical value for deep slowly moving waterway exhibiting a fluff layer. The settling velocity was computed to be 1752 m/yr using the solid mass balance relationship (Eq. 4). Material properties of the cap and dredged material were obtained from Brannon and Poindexter–Rollings (1990) and are presented in Table 3.

Table 3. Material characteristics.

| Property | Capping Material | Dredged Material |
|---|---|---|
| Specific Gravity | 2.78 | 2.48 |
| Porosity | 0.37 | 0.52 |
| Organic Content | 2.2% | 8% |

The computer model assumes the presence of a thin, completely mixed layer of sediment at the interface with the water column. The mixed layer thickness is a function of the disturbance of sediment surface and varies with the sediment grain size distribution and the bioturbators in the benthic community. Due to the absence of a benthic community at the site, the top 1 cm of the cap was assigned to be the mixed layer in all simulations. Since there is little disturbance at the top of the cap, the porosity of the mixed layer was assumed to be the same as that of the cap. The deep sediment thickness was assumed to be 1.51 m with a porosity of 0.37 in the top 0.61 m representing the average cap thickness and a porosity of 0.52 in the bottom 0.90 m of deep sediment representing the contaminated dredged material.

The chemical properties of the PCB Aroclors present in the Duwamish dredged material were taken from the RECOVERY model data base (Ruiz and Gerald 2000). The molecular diffussivities of the three heavy metals examined were taken from Thibodeaux (1996). The distribution coefficientsof the three heavy metals were estimated using empirical pH–dependent relationships developed by the U.S. EPA (1990). A summary of the chemical properties of the contaminants assessed at the Duwamish CAD site is shown in Table 4. The decay coefficients for all contaminants were set to zero. Initial concentrations of contaminants in the cap and in the dredged material were assumed to be uniformly distributed; the concentrations used are listed in Table 1. However, metal contaminant concentrations for the capping material are the averages of the values for the two samples reported in Table 1.

Table 4. Chemical properties of contaminants.

| Property | Cu | Pb | Zn | PCB 1242 | PCB 1254 |
|---|---|---|---|---|---|
| Molecular diffusivity ($cm^2/sec$) | $7.33x10^{-6}$ | $9.45x10^{-6}$ | $7.15x10^{-6}$ | $5x10^{-6}$ | $5x10^{-6}$ |
| Henry's constant ($atm-m^3/gmole$) | NA | NA | NA | 0.00198 | 0.0083 |
| Distribution coefficient (L/kg) | 85 | 1150 | 140 | -- | -- |
| Octanol–water partitioning coef. ($mg/m^3$–octanol/$mg/m^3$–water) | NA | NA | NA | $1.29x10^4$ | $1.1x10^6$ |
| Molecular weight (g/gmole) | 63.5 | 207.2 | 65.4 | 266.5 | 328.4 |

## ANALYSIS OF RESULTS

The measured data shown in Table 2, in general, indicates that there was a slight increase in metal concentrations above the interface between cap and contaminated sediments at stations VDQ and VDR from 1989 to 1995. However, PCB concentrations have changed little between sampling events at these stations. The overall distribution of metals and PCB concentrations at stations VDQ and VDR does not indicate upward migration of contaminants into the cap sediments. The difference in metal concentrations may be due to differences of sample collection methods between surveys. During the 1989 survey, subsample intervals collected from each core were less than the 10–cm interval collected during the 1995 survey.

At station VDS, metals and PCBs appear to have increased significantly above the interface between contaminated and cap material. The highest concentrations were found within the 30–cm depth interval. However, metals and PCBs in the cap material above and below this depth interval were found to be lower in concentration. The distribution of contaminants at station VDS suggests that the core may have contained a lens of contaminated material or clay balls in the sand cap located approximately 30 cm above the contaminated dredged material. This thin deposit of contaminated material would have occurred during cap placement and not from migration above or below this depth. Clay balls of higher contamination were also known to exist in the capping material. Outlier tests on the data presented in Table 2 indicate that the majority of the data collected at location VDS were outliers.

The physical, hydrological and chemical data described above are used to simulate contaminant migration at the Duwamish site. Simulation results (solid lines) are shown in Figures 4 through 13 for the 5– and 11–year post capping concentration profiles along with the measured data (symbols) excluding the outliers. The figures also include a dashed line indicating the initial concentrations in the cap and dredged material. The simulation results and the data indicate a slight migration of contaminants from the contaminated dredged material into the cap material. Furthermore, the effect of sediment burial over the period of simulation is clearly shown by the accumulation of material above the cap (above 61 cm from the interface). In all cases presented, contaminants have moved slightly into the accumulated sediments.

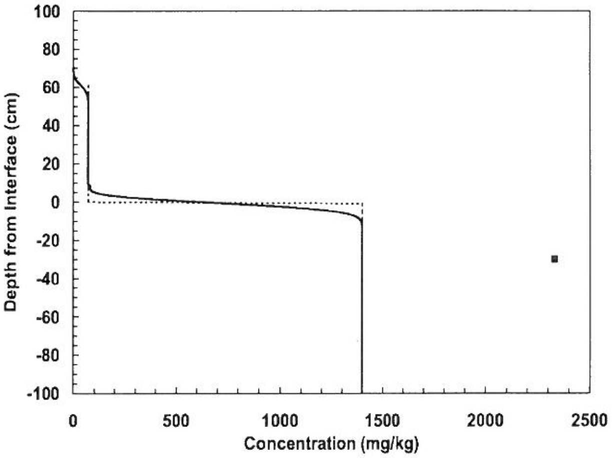

Figure 4. Aroclor 1242 – 5 year.

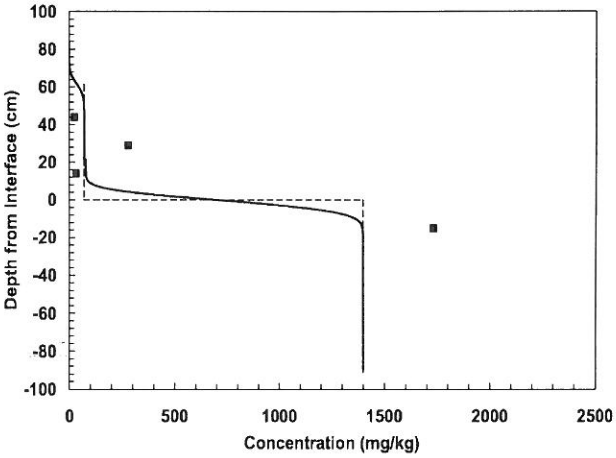

Figure 5. Aroclor 1242 – 11 year.

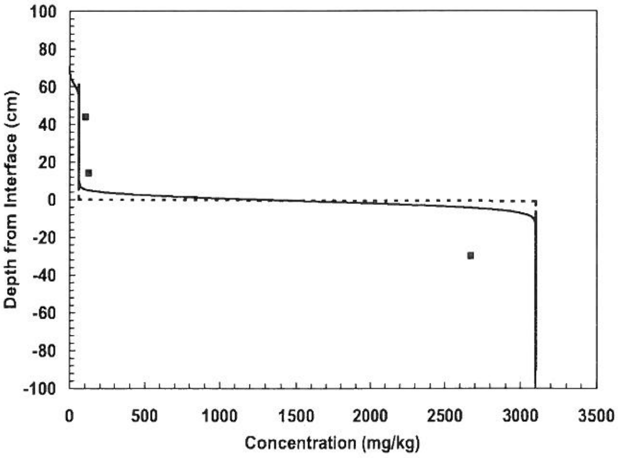

Figure 6. Aroclor 1254 – 5 year.

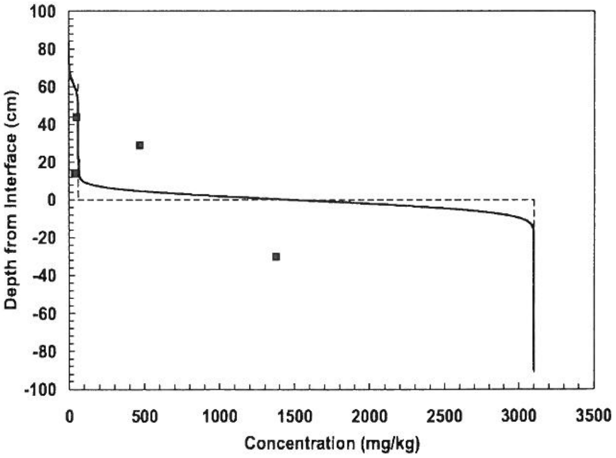

Figure 7. Aroclor 1254 – 11 year.

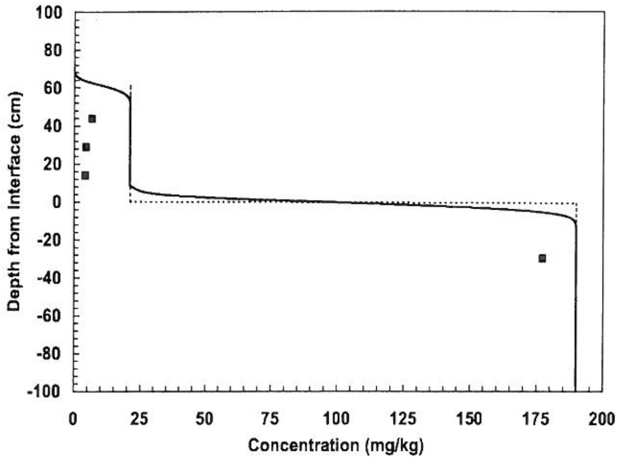

Figure 8. Lead – 5 year.

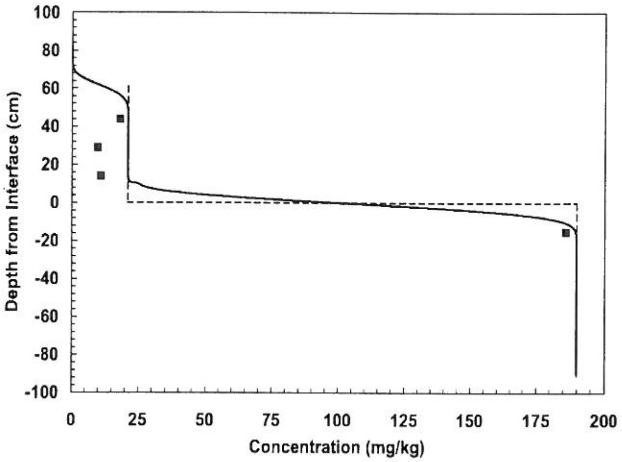

Figure 9. Lead – 11 year.

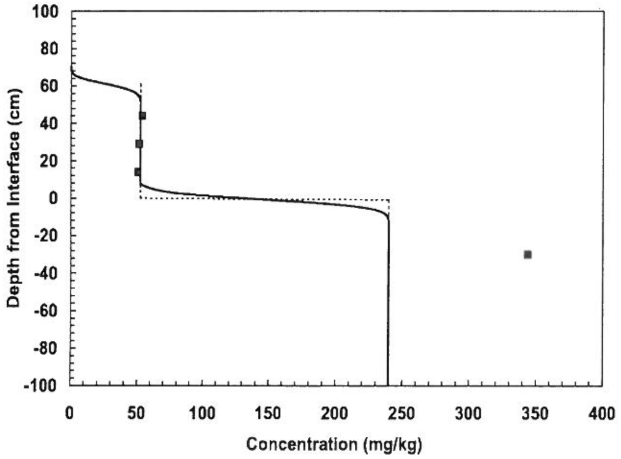

Figure 10. Zinc – 5 year.

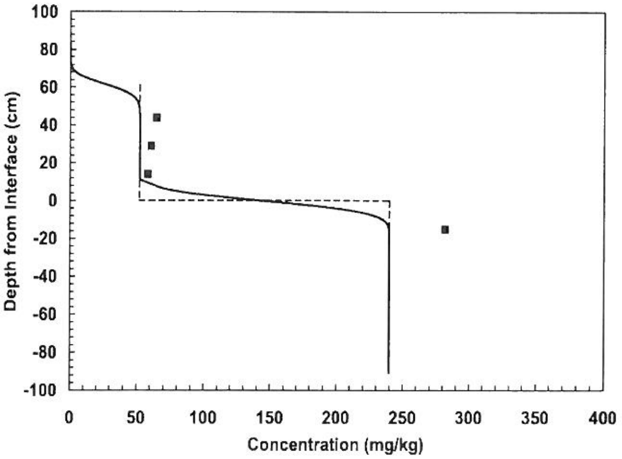

Figure 11. Zinc – 11 year.

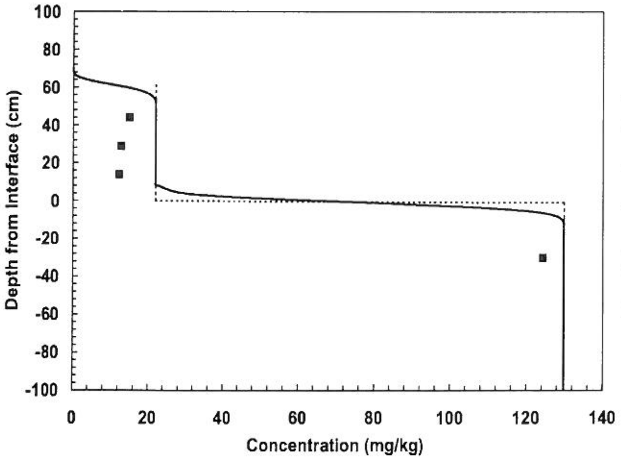

Figure 12. Copper – 5 year.

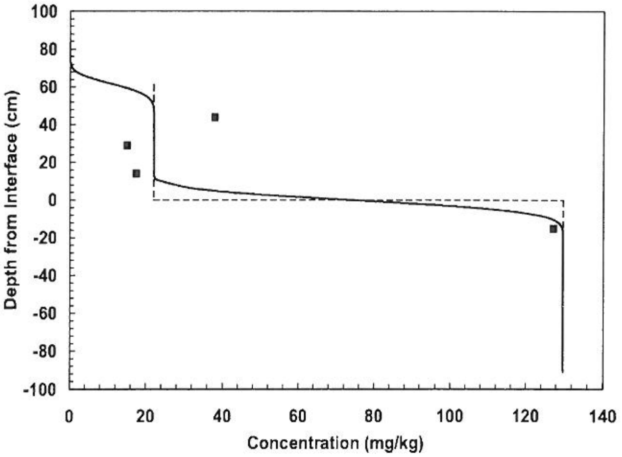

Figure 13. Copper – 11 year.

It is important to note that the field data were collected at different times. The initial concentrations used in the simulation were measured before the contaminated dredged material and the cap material were placed at the Duwamish depression. In the numerical simulation, uniform initial contaminant concentrations in the cap and the dredged material were used. Furthermore, the 5– and 11– year sampling events did not necessarily reflect the concentrations at the same locations and depths. Therefore, in light of the above, the simulation results presented in Figures 4 through 13 provide good agreement with the modeled situation and indicate only a slight migration of the contaminants into the cap and that the newly deposited sediment on top of the cap provided further isolation of the contaminants from the water column.

## CONCLUSIONS

The assessment of behavior of the cap at the Duwamish site indicates that the contaminants in the capped sediments are restricted from migrating into the relatively clean cap. Evaluation of the chemical data collected at the site and compared with RECOVERY numerical model confirms that the cap has performed effectively in isolating the contaminants from biota in the water column and surface sediments. In summary, this study verifies the applicability of the model in evaluating subaqueous capping scenarios and in assessing the long–term effectiveness of the cap.

## ACKNOWLEDGMENTS

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$$y = a + b + cx^2 \tag{1}$$

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