THE INTERPLAY OF DREDGING AND DISCHARGES: A CONCEPTUAL MODEL OF CONTAMINATION IN THE LOWER PASSAIC RIVER

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ABSTRACT

The Passaic River has served as a center for industry since the American Revolution. It has also served as a means for conveyance for the disposal of industrial and municipal wastes for nearly the same period. The river was extensively channelized for navigation during the first half of the 20th century. However, maintenance dredging was not routinely performed for much of the channel as navigational needs declined in the latter half of the 20th century. The extensive dredging of the river followed by a failure to maintain the channel has created a unique setting for the trapping of sediments in the Lower Passaic. The coincidence of the navigational and industrial events has resulted in a uniquely large inventory of highly contaminated sediments whose fate is currently the subject of much discussion. In support of the jointly sponsored remedial investigation (US EPA, US ACE-NY and NJ DOT) for the Lower Passaic River Restoration Project, Malcolm Pirnie, Inc. conducted an extensive geochemical evaluation of the historical data relating to contamination in the Lower Passaic River. In this evaluation, we examined the vertical and horizontal extent of contamination in the Lower Passaic River as well as evidence to identify contamination source areas. In addition to the use of historical geochemical data, we also evaluated historical bathymetric data and incorporated the results of a 15.5-mile side-scan sonar survey conducted in 2005. Recent investigations of the river have provided additional information on the history of contamination, showing the decline over time for various contaminants, including 2,3,7,8-TCDD, PCBs, mercury, PAHs, and lead. Additionally, recent core data also documents the potential depth of some contaminants, providing perspective on the history of their releases. In this paper, the various data sources are integrated to construct a conceptual site model for the Lower Passaic. The complete geochemical report and other information can be found at http://ourpassaic.org.

Keywords: Dioxin, channelization, estuary, urban rivers, river restoration

INTRODUCTION

The Passaic River is currently undergoing a remedial investigation jointly sponsored by the US Environmental Protection Agency. (US EPA), the US Army Corps of Engineers-New York District (US ACE) and the New Jersey Department of Transportation (NJ DOT). Malcolm Pirnie, Inc. is conducting this investigation, entitled the Lower Passaic River Restoration Project (herein referred to as the Study), for the sponsoring agencies. As part of the investigation, Malcolm Pirnie, Inc. has conducted an extensive geochemical evaluation of the historical data and conducted several field investigations relating to contamination in the tidal Passaic River. Theses efforts are part of an interagency effort involving the three sponsoring agencies as well as the National Oceanic and Atmospheric Administration (NOAA), the US Fish and Wildlife Service (US FWS) and the New Jersey Department of Environmental Protection (NJ DEP) to remediate and restore the complex ecosystem of the tidal portion of the Passaic River, herein referred to as the Lower Passaic River. The Lower Passaic River is a 17-mile, tidally influenced river located in northeastern New Jersey that discharges to the northwest corner of Newark Bay, a part of

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the New York-New Jersey Harbor complex. The Study Area represents 118 square miles and is defined as the Lower Passaic River and its basin, which comprises the tidally influenced portion of the river from the Dundee Dam [River Mile (RM) 17.4] to Newark Bay, and the watershed of this river portion, including the Saddle River, Second River, and Third River (see Figure 1). Much of the shoreline of the Lower Passaic has been highly modified to maintain bank stability. The lower 6 miles of the river is highly urbanized with significant development on the natural floodplains and sheet piling or other man-made structures along the shore.

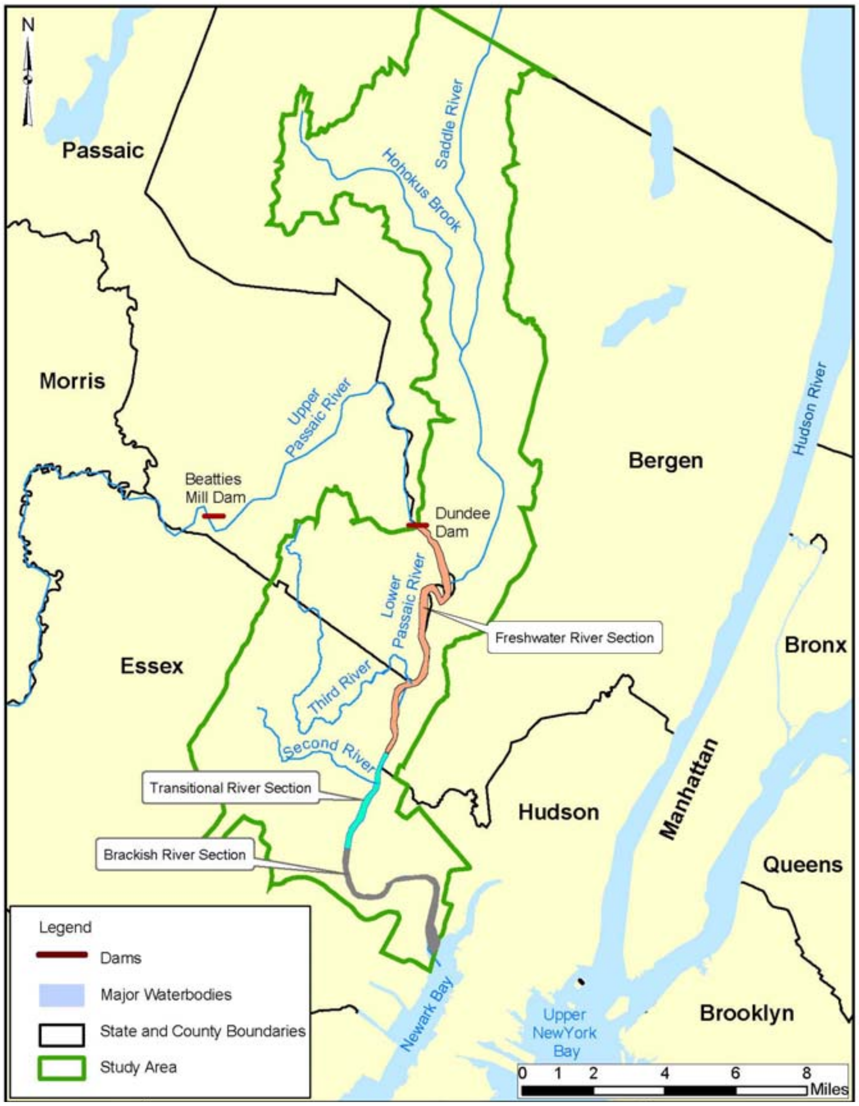


Figure 1. Study area location map.

Urbanization and development have degraded the sediment and water quality in the Lower Passaic River. Several contaminants have been identified as posing a potential risk to human health and the ecosystem, including but not limited to the following: 2,3,7,8-tetrachloro dibenzodioxin (2,3,7,8-TCDD), polycyclic aromatic hydrocarbons (PAHs), PCBs, DDT, mercury, and lead. The Upper Passaic River and its watershed (the area impacting the Passaic River above the Dundee Dam) represent the upstream boundary condition for the Study Area. The Study Area does not include the watershed upriver of the dam or the portion of the watershed that is located in the State of New York. As will be discussed later, the Upper Passaic River is also impacted by contamination, which in turn affects the Lower Passaic River to some degree.

For purposes of the Study, the Lower Passaic River was divided into 3 river sections based on their relationship to the typical tidal range of the salt front, which is defined as the upstream-most extent of the salt intrusion originating from Newark Bay. The lower Passaic is subject to a large daily tidal displacement, with the salt front moving on the order of several miles with each tidal cycle. The salt front is most commonly found between RM 6 and RM 10, although it is often found outside this range at peak tidal periods. This range (RM 6 to RM 10) is defined as the Transitional River Section, while the Freshwater River Section (RM 10 to RM17.4) and Brackish River Section (RM 0 to RM 6) are located upriver and downriver, respectively. The location of the salt front is also subject to a variety of environmental factors besides tidal forcing, including the volume of freshwater flow in the river and tributaries as well as storm-related events which impact the water elevation in Newark Bay.

HISTORY OF THE LOWER PASSAIC RIVER

The Passaic River was one of the major centers of the American industrial revolution, with early manufacturing, particularly cotton mills developing in the area around the Great Falls in Paterson, NJ. In subsequent years, a multitude of industrial operations sprung up along the banks of the Passaic, as the cities of Newark and Paterson and their suburbs also grew. The Passaic has been used as a major means of conveyance for both municipal and industrial discharges from the mid 19th century to the present time. Besides sewage, these waste streams delivered a number of toxic compounds, including the compounds listed previously.

An important component of the river's development and urbanization was the channelization of the river to permit commercial vessels to travel into the city of Newark and beyond. Several large dredging projects were undertaken at the beginning of the 20th century to create a ship channel to RM 15. The federally mandated channel depths are given in Table 1.

Table 1. Lower Passaic River federal channel parameters.

Reach[7]	Depth (ft)	Channel Width (ft)
RM -0.2 to 2.2	30	300
RM 2.2 To 4.3	20	200
RM 4.3 to 6.9	20 (only constructed to 16 ft)	200
RM 6.9 to 7.9	16	200
RM 7.9 to 15.2	10	200

Iannuzzi et al., 2002 summarized the volumes of sediment removed for various reaches and years. This information is summarized in Figure 2. The figure shows the total volume of sediment removed on five-year increments. The figure also shows the portion of the dredge volume removed from the Lower Passaic below RM 2. The diagram clearly shows a decline in the volumes of sediment removed from the Lower Passaic over time. Additionally, the diagram shows that the vast majority of the dredging since the 1940s has taken place below RM 2. Channel depths upstream of this river mile were not maintained and began to fill in over time. As will be shown below, upwards of 10 feet of sediment have accumulated in some portions of the channel since the original dredging of the river.

[7] River miles are referenced to the project-defined river mile scale. This scale is offset from that used by the USACE by approximately 0.2 miles.

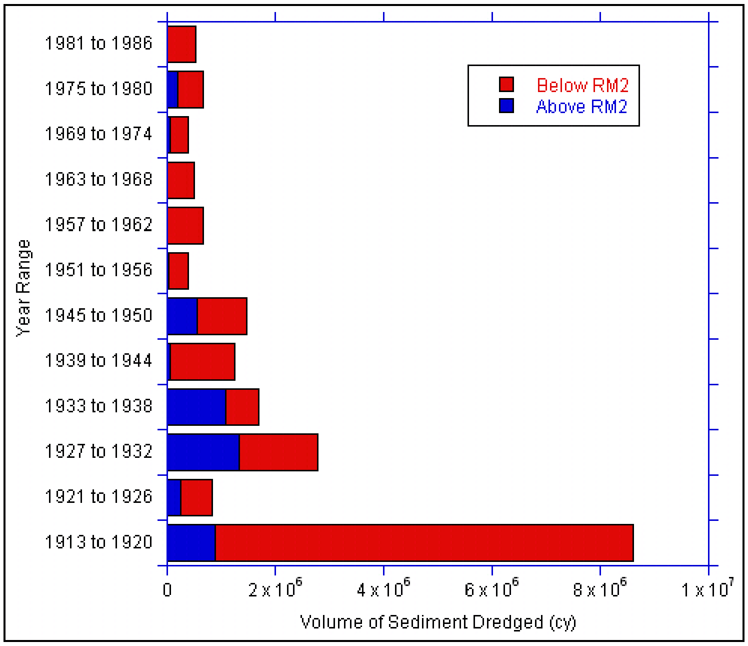


Figure 2. The history of dredging in the lower Passaic River.

Industrial development along the river has included many different operations, including but not limited to manufactured gas plants, paper manufacturing and recycling facilities and chemical manufacturing facilities. These plants have all used the river for wastewater disposal, disposing of chemical contaminants in these waste streams as well. The coincidence of chemical disposal in the river along with the construction and subsequent limited maintenance of the navigation channel in the Lower Passaic created an ideal situation for the accumulation of thick beds of contaminated sediments.

ESTUARINE FLOW CONSIDERATIONS

Because of the two-layered flow condition typical of estuary circulation, estuaries such as the Lower Passaic tend to trap sediments delivered from upland regions. The salt front, in particular, is the section of the estuary where sediment deposition tends to be most rapid. These sediments tend to build up until a major storm or flow event of sufficient magnitude occurs, removing much of the sediment deposited since the last major event and carrying the sediments out to sea. In this manner, the bottom elevation of the estuary is established over time by the mass of solids delivered and the strength and frequency of major transport events. In the case of the Lower Passaic, the creation of a navigation channel deepened the river bottom well beyond what was normally maintained by natural processes. Thus estuarine circulation served to trap solids in those channel sections that were not maintained. Since the 1940s, the river has delivered sufficient material to build up many feet of recent deposition, yielding an average rate of deposition substantially greater than what would normally occur.

MAJOR COMPONENTS OF THE CONCEPTUAL SITE MODEL

The major components of the conceptual site model fall under four areas, the physical setting, the chemical setting, the contaminant inventories and impacts to Newark Bay. The main aspects of each of these components are described in the sections that follow.

Physical Setting

The Lower Passaic River is a partially stratified estuary wherein the degree of stratification and the location of the salt front at any point in time reflect a dynamic balance between the freshwater flow and the tidal exchange with Newark Bay. Tidal displacement is the Lower Passaic is quite large, with the salt front moving several miles during each tidal cycle. The combination of a relatively narrow river cross section and the strong tidal flows yield tidal velocities that are quite high, reaching several feet per second and serving to homogenize sediments over much of the Lower Passaic prior to deposition.

The combination of tidal and freshwater flows also combine to cause highly variable rates of annual deposition, with some years showing a net loss of solids from the Lower Passaic while other years showing a net solids gain. At least since the construction of the navigation channel, the river bottom has been and continues to be net depositional over time. A series of bathymetric surveys of the river bottom provide a basis to assess the annual rates of deposition across the period 1989 to 2004. Annual sediment deposition averaged approximately 70,000 cubic yard/year during this period, which is roughly equivalent to one inch of sediment accumulation over the Lower Passaic River bottom (RM 0 to 17) or 1.5 inches over the lower 7 miles. Approximately 90 percent of this accumulation occurs in the RM 0 to 7.

Sedimentologically, the river bed of the Lower Passaic can be divided into two main domains. The upper region (RM 8 to 17.4) is largely comprised of coarser grained sediments, with relatively few areas of fine-grained sediments. This region is largely non-depositional. The lower region (RM 0 to 8) is primarily comprised of fine-grained sediments, which represent more than 80 percent of the river bottom. The identification of these areas was primarily derived from a side-scan sonar survey conducted in 2005 (Aqua Survey, 2005). Figure 3 presents an example of the side-scan sonar output near the boundary between the two domains. For the purposes of this discussion, fine-grained sediment refers to areas identified as silt or silt-and-sand. Coarse-grained sediment is defined as sand, sand-and-gravel or gravel. These side-scan sonar classifications were confirmed by direct sampling of the river bottom.

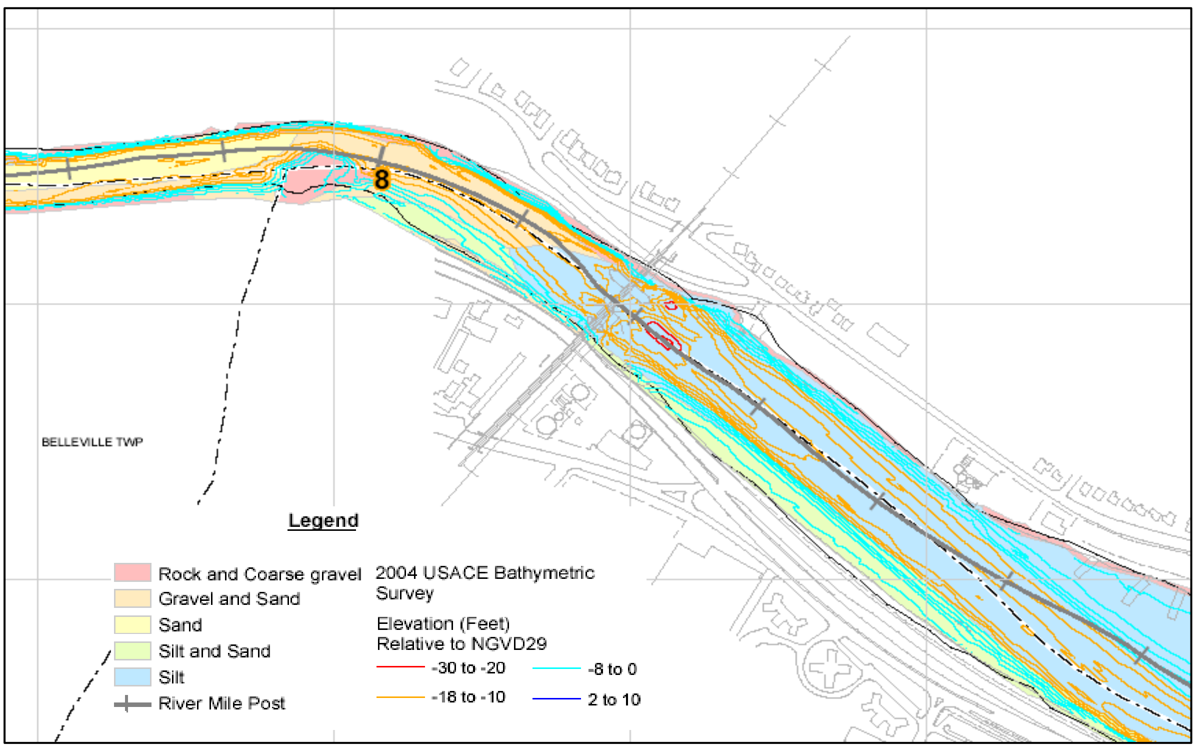


Figure 3. Side-scan sonar survey interpretation of lower Passaic River bottom sediments near RM 8.

An analysis combining the side-scan sonar with the bathymetric data showed the basis for the change in river domain at RM 8. This analysis is illustrated in Figures 4 and 5. Figure 4 shows the relationship between river cross section at mean low water and the percentage of the river bottom as fine-grained or coarse-grained sediment. For cross sections greater than about 3,700 sq ft, the river bottom is greater than 80 percent fine grained sediment. For cross sections less than this value, the river bottom can vary but tends to be primarily coarse-grained sediment. In Figure 5, the variation of cross sectional area with river mile is shown. Notably, cross sectional areas below RM 8 are nearly always greater than 3,700 sq ft, correlating with the high percentage of fine-grained sediment in this region. Above RM 8, cross sections tend to be less than 3,700 sq ft and correspondingly high in coarse-grained sediment areas.

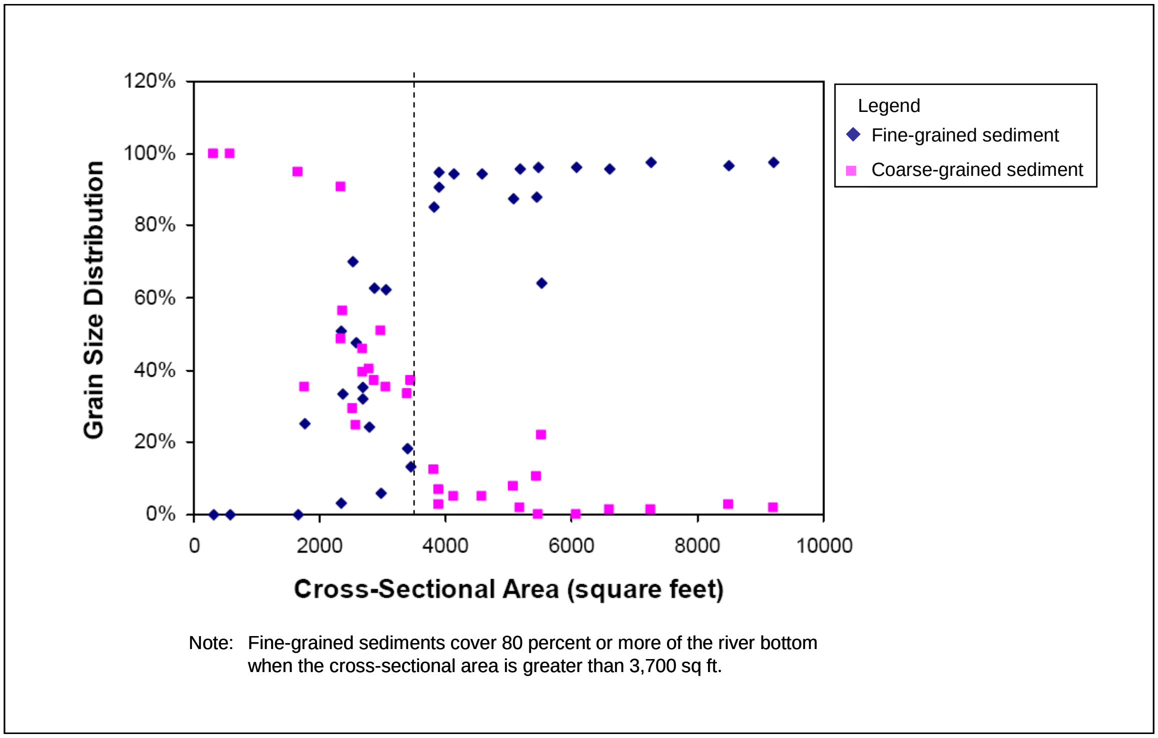


Figure 4. Variation of lower Passaic River sediment type with river cross-sectional area.

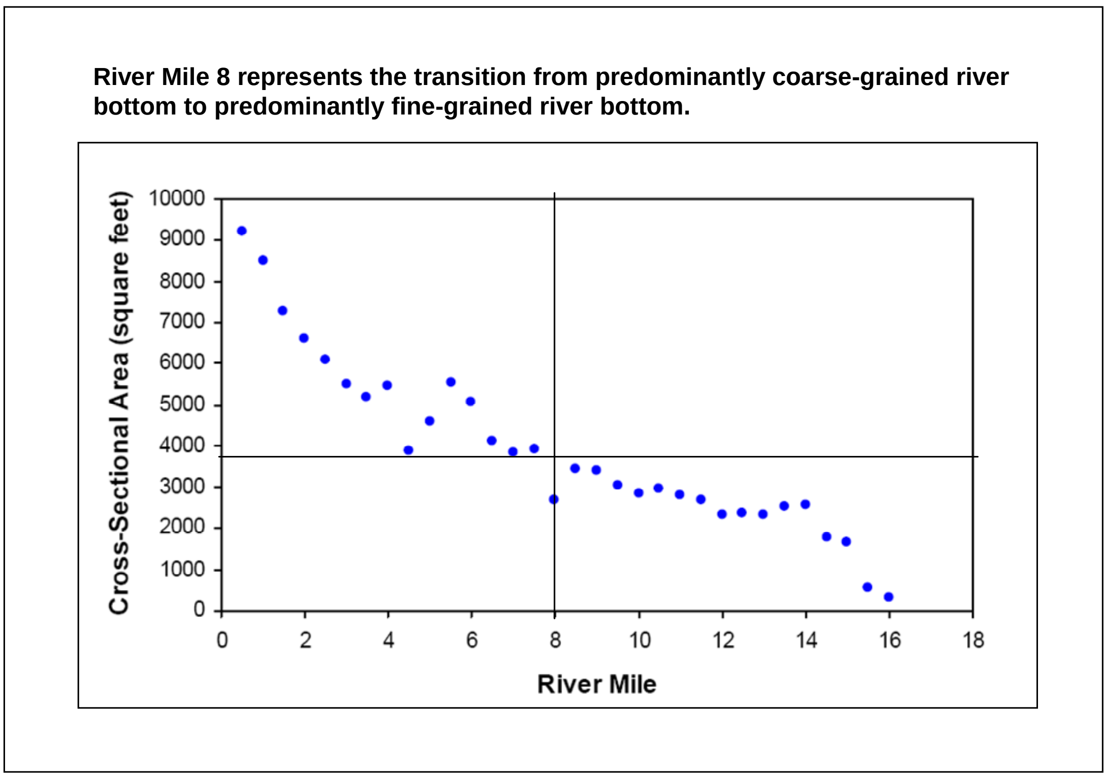


Figure 5. Variation of lower Passaic River cross-sectional area with river mile.

Given the high percentage of fine-grained areas below RM 8, a series of more limited (RM0.9 to 7 only) bathymetric surveys were used to identify those areas in RM 0.9 to RM 7 which appear to be depositional or erosional on a routine basis, that is, from year to year. These areas are identified in Figure 6. The figure shows that most of this region is routinely depositional although there are scattered areas regularly undergoing erosion. In particular, there are several areas centered on the river bends near RM 3.5 that represent large areas of erosion. However, the occurrence of erosional areas throughout RM 0.9 to RM 7 reflects the very dynamic nature of sediment deposition and erosion in the river. It is believed that some or all of these erosional areas are responsible for the on-going release of some contaminants, particularly 2,3,7,8-TCDD from the river bed. A detailed examination of sediment deposition rates in the Lower Passaic River (RM 0 to 7) indicates a high degree of spatial heterogeneity with local rates varying from about -6 inch/year of erosion to about +8 inch/year of deposition.

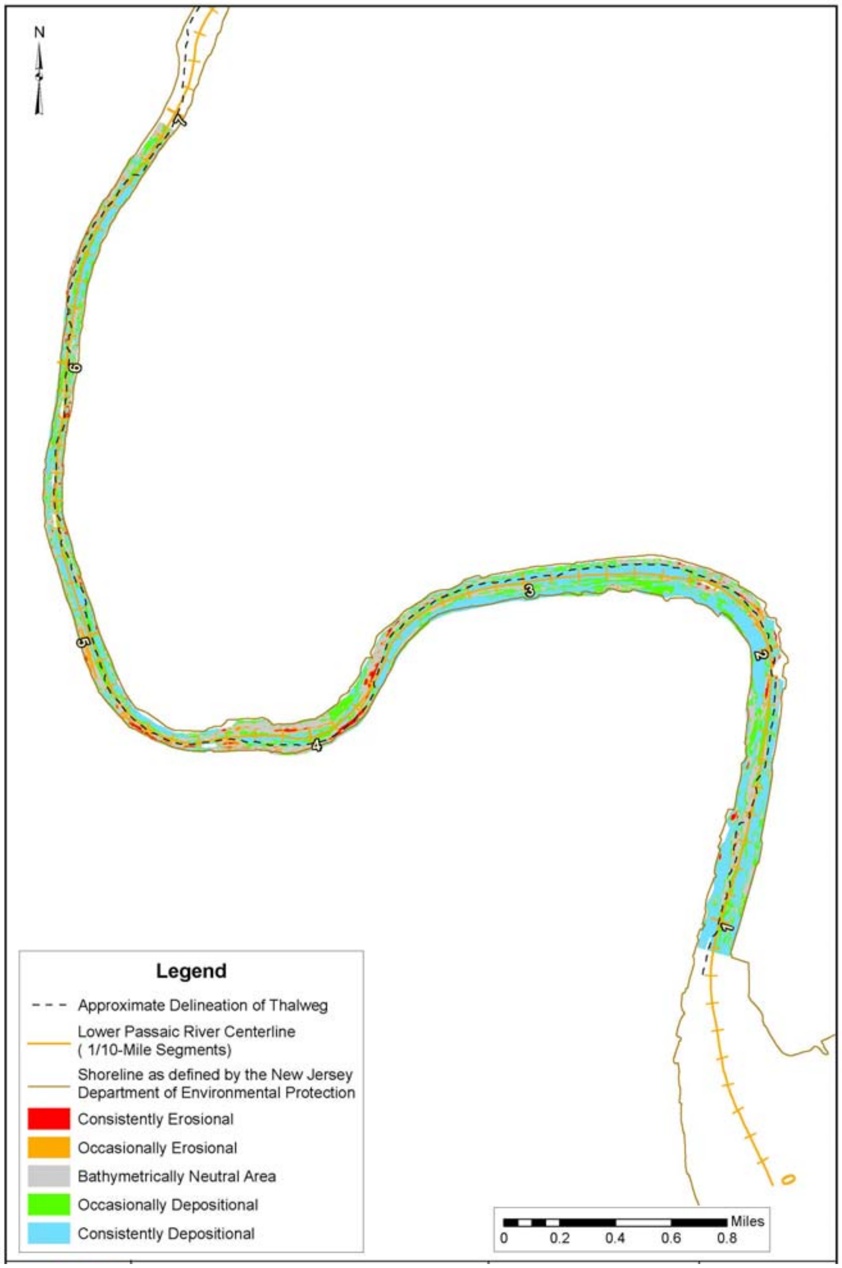
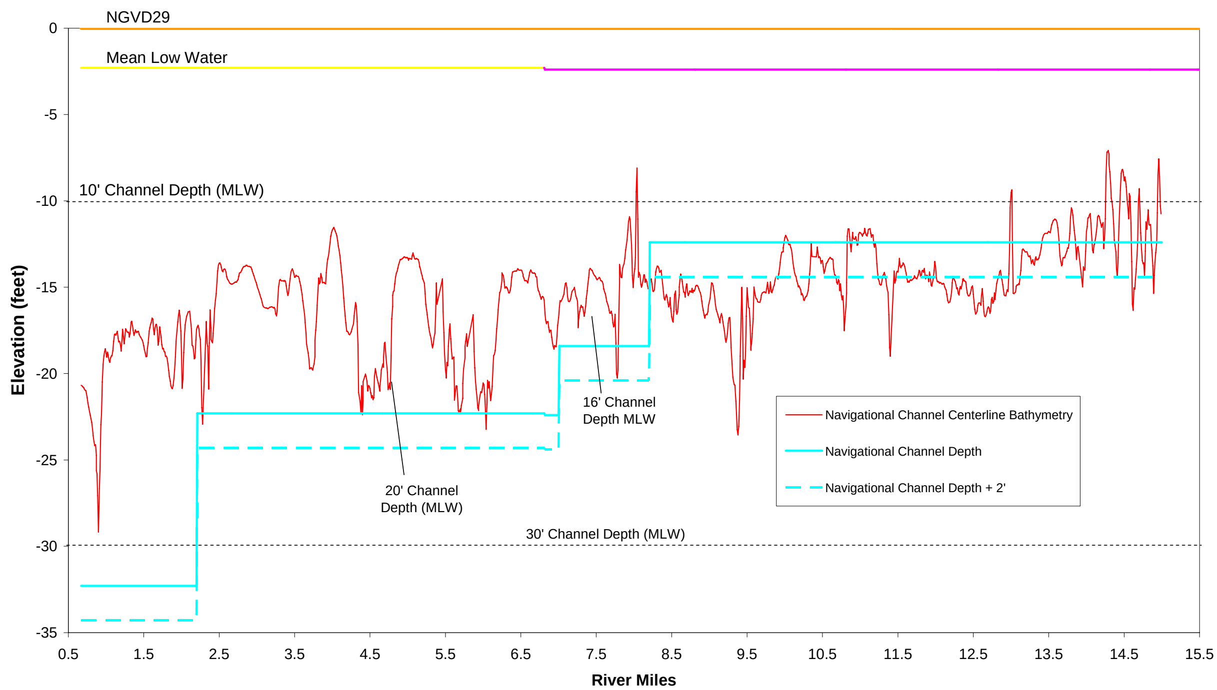


Figure 6. Depositional and erosional areas in the lower Passaic River.

The current estuarine setting is not naturally occurring and has been greatly affected by anthropogenic activity in and around the river. Dredging of the Lower Passaic began in the early 20th century (Iannuzzi, et al., 2002), significantly altering the river channel geometry. Prior to the channel dredging of the early 20th century, the Lower Passaic was a relatively shallow estuary, probably not deeper than 15 feet in the center throughout much of its length. (Chant, 2005). Historical dredging served to create a deep channel relative to prior conditions, greatly enhancing the rate of sediment accumulation in the dredged areas. In particular, the dredged channel probably permitted a much more extensive and permanent salt intrusion, enhancing the rate of sediment trapping in the Lower Passaic. Based on US ACE records (see Figure 2), it does not appear that this channel was regularly maintained, permitting a large volume of recent sediment to accumulate over time. External loads of particle-reactive contaminants from industrial and possibly municipal waste streams served to extensively contaminate these sediments prior to deposition on the river bottom. (This is further discussed below.)

Historical deposition rates were probably higher than those currently, enhanced by the trapping of suspended matter by the more extensive salt wedge present immediately after the initial channel dredging. Based on solids balance considerations, the current head-of-tide solids load (79,000 cy/yr, Lowe et al., 2004) to the Lower Passaic is greater than the annual average rate of accumulation in the Lower Passaic. Additional solids represent a net load of solids delivered to Newark Bay. However, the historical rates of sediment accumulation in the Lower Passaic were probably too large to be sustained solely by the Passaic's head-of tide solids loads, suggesting that a net solids transport from Newark Bay supplied the additional solids. This observation is based on the estimated volume of contaminated sediments that accumulated after 1940, roughly 6.5 million cubic yards as of 1995. The estimated rate of solids delivery at the head-of-tide would not deliver sufficient solids to create the estimated 6.5 million cubic yards deposited.

Perhaps most important to the current concern over contamination, sufficient solids deposition has occurred in the Lower Passaic to begin to affect the channel flow (i.e., the original channel dug in the early 20th century has largely been filled. The magnitude of the 20th century deposition is illustrated in Figure 7, which shows the current depth of the river channel as well as the original dredged elevations as reported in US ACE records. For the region below RM 8, the river has accumulated much sediment; over 15 ft in some areas. Also notable in the diagram is the absence of substantive channel deposition above RM 8. This evidence is consistent with the observations of recent deposition rates and sediment texture which change markedly across RM 8. As noted in Table 1, the constructed channel depth was substantially shallower above RM 8 (10 ft) than below RM 8 (16 ft or more). A final observation can be made from Figure 7. There is a pronounced change in bottom elevation in the current channel around the northern end of the federally mandated channel, i.e., RM 14.5 to 15.5. The rise in the river floor probably prevents the salt front from extending beyond this area under all but the driest conditions. This limitation on the salt intrusion has potential implications for the upriver transport of contaminants released downriver and is further discussed below.



Note: The original channel dredged depths are shown as specified with an additional two-foot band below the planned dredge depth. The contracts at the time of construction would have called for the removal of sediment to the specified depth but the dredger would also have been compensated for dredging up to an additional 2 feet. As a result, the original channel floor would have been constructed to lie between the specified depth and the 2-ft band shown.

Figure 7. Comparison of current river channel elevation and the constructed depths of the lower Passaic River channel.

Given the amount of deposition, the high observed tidal velocities and the presence of erosional areas throughout the lower seven miles of the Lower Passaic as well as the continued presence of several historical contaminants in very recently deposited sediments, it appears very likely that some of the historical contaminated sediment deposits created when the channel was deeper are no longer be stable and may now be undergoing erosion. A particular area of concern is the area near RM 3.5 where the river turns sharply and erosional areas are observed on the outsides of the bends. The reworking of the historical sediments is suspected of being an on-going source of contamination to other areas of the Lower Passaic.

Chemical Setting

The chemical contamination associated with the Lower Passaic is primarily driven by the contaminant burdens contained within Lower Passaic River sediments. While there may be on-going external sources, the concentrations within the sediments are responsible for much of the contamination within the water column (HydroQual, 2006). In fact the legacy of contamination in the Passaic probably extends back to at least the turn of the 20th century. Based on observations made with dated sediment cores, historical loads of mercury, PAHS, arsenic predate or coincident with the original channel construction. Sands underlying the thick silt beds are contaminated with these compounds. This contamination may extend to a prehistoric sediment horizon referred to as the red-brown clay.

Dated sediment cores also provide a record of more loads of contamination to the Lower Passaic. For example, initial loads of DDT occur in the late 1930s and predate the appearance of major loads of 2,3,7,8-TCDD. Initial loads of 2,3,7,8-TCDD appear in the mid to late 1940s and peak in the 1950s. This peak occurs after the peak loads of DDT. PCB loads appear in the mid 1950s, peaking in the 1960s, making PCBs the most recent of the contaminants. These cores also date the histories of mercury and cadmium. Peak releases of mercury and cadmium occur in the early 1960s. However, both metals are present well above background concentrations throughout the core record, predating the appearance of DDT. PAH contamination is unique in its temporal distribution, with the highest concentrations observed in the deepest core layers, gradually declining to the most recent deposition.

Dated cores collected above head-of-tide on the Upper Passaic do not provide as extensive a historical record. Nonetheless, the core data are sufficient to suggest that the majority of historical loads of cadmium, lead, mercury, and Total PCB to the Lower Passaic originated in the Upper Passaic River above the Dundee dam. Historical loads of copper were more evenly split between Upper Passaic and Lower Passaic sources. Dated sediment cores from the Upper and Lower Passaic River further indicate that relatively little of the Total DDT and much less than 1 percent of the 2,3,7,8-TCDD contamination in the Lower Passaic River originated above the Dundee Dam historically.

The same dated cores that document the magnitude of the historical loads also show that current loads throughout the Lower Passaic are substantively lower. To illustrate this, the first diagram in Figure 8 shows the profiles of three dated cores from the Lower Passaic, obtained at three separate locations, RM 1.4, 2.2 and 11. Evident in each core is a nearly two order-of-magnitude decline in concentrations from the 1950s to the present. These core results also document another important aspect of the Lower Passaic's contamination. Despite the distance separating the cores, they all record similar contaminant loading histories at similar concentrations. This is direct evidence of the effectiveness of tidal mixing in the Lower Passaic. Essentially, this evidence indicates that sediments are well homogenized prior to deposition, particularly within the last 20 years. By inference, this suggests that variations in local concentrations reflect variations in deposition history more than proximity to source. Essentially, the presence or absence of an interval of high concentration within the sediments at a given location is most likely the result of whether or not the location was depositional at the time the highly contaminated sediments were created and whether subsequent events served to erode these layers after deposition. Thus thick sequences of contaminated sediments will tend to have similar inventories of contaminants regardless of their location in the river.

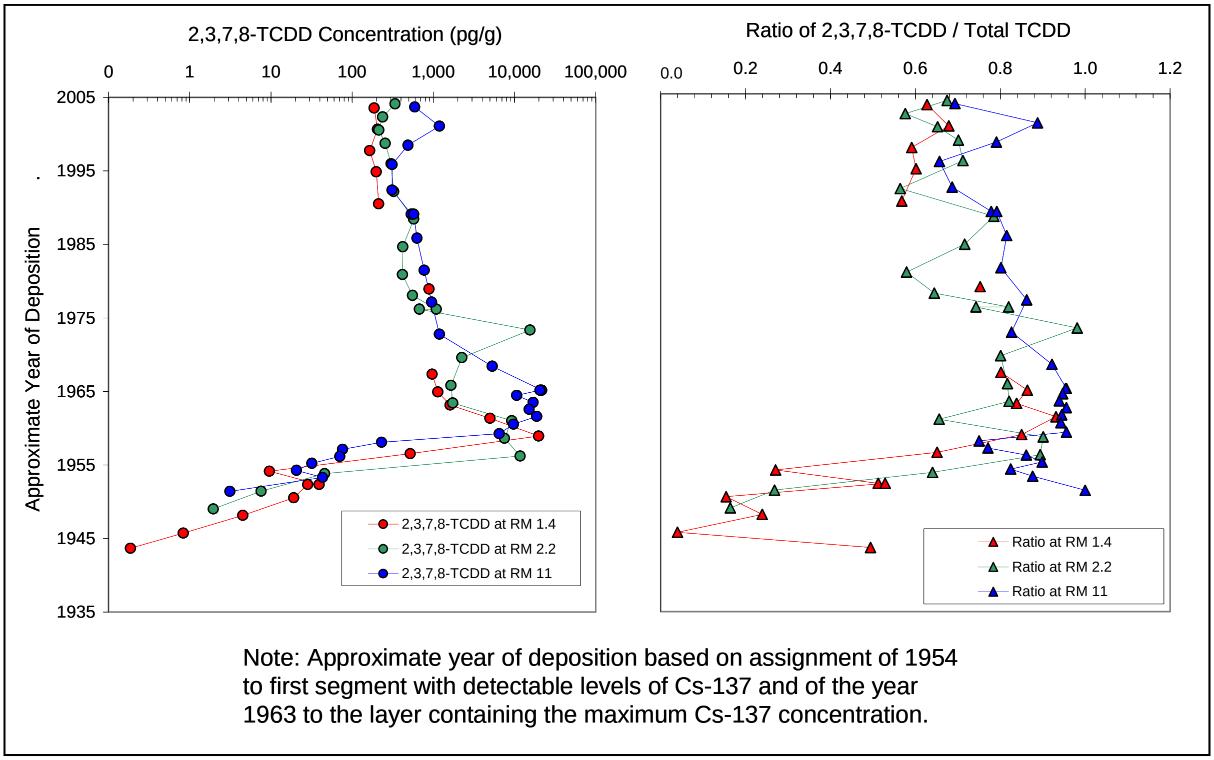


Figure 8. 2,3,7,8-TCDD concentration and ratio to total TCDD versus approximate year of deposition.

Further evidence for tidal mixing can be observed in the second diagram of Figure 8. This diagram shows the ratio of 2,3,7,8-TCDD to total tetrachloro dibenzodioxin (2,3,7,8-TCDD/Total TCDD). Based on the work of Chaky, 2003, this ratio is diagnostic of the Passaic River source. The consistency of this ratio throughout these cores post 1945 is indicative of a single source of dioxin, distributed by tidal mixing throughout the Lower Passaic. In contrast to the ratio of the Passaic source, the 2,3,7,8-TCDD/Total TCDD ratio in sewage effluent and atmospheric deposition is 0.05 and 0.06, respectively. Notably, ratios approaching levels are observed in the pre-1940s sediments at concentrations orders of magnitude lower than the post 1940s deposition.

Ratio analysis has provided additional insight on other contaminants as well. Ratio analysis of metal contamination in the Lower Passaic River (RM 0.9 to 7.0) showed little variation in the metals pattern. Similarly, analysis of surface metal concentrations also showed relatively little trend with river mile. Like the 2,3,7,8-TCDD results, this evidence demonstrates the homogeneity of surficial sediments in the Lower Passaic River and indicates the effectiveness of tidal mixing.

Ratio analysis of Total PAH shows that the majority of PAH contamination in the sediments is derived from combustion-related processes. The ratio "fingerprint" suggests that Total PAH originates from two sources coal tar residue (a by-product of manufactured gas plants) and urban background combustion. Of these two sources, coal tar wastes are the dominant source based on the prevalence of coal tar-like PAH ratios in more contaminated sediments. The same analysis essentially rules out creosote-derived contamination and suggests only minor portions of the sediment PAH contamination are derived from a petrogenic source (e.g., oils spills).

Recent core samples (ca. 1986-1995-check date) from above Dundee Dam suggest that the Upper Passaic may still represent an important source of cadmium, mercury and lead to the Lower Passaic, unlike 2,3,7,8-TCDD and DDT which primarily originate in the Lower Passaic. The Total PCB source upriver of the Dundee Dam in 1963 accounted for the majority of the Total PCB load in the Lower Passaic River. However, recent evidence suggests that currently (circa 1995), the Upper Passaic River Total PCB source has become less important relative to the Total PCB load occurring within Lower Passaic River. Nevertheless, the Upper Passaic River source may still comprise one third of the Total PCB loading in the Lower Passaic River.

Contaminant Inventories

The combination of the navigational dredging activities and the long and extensive history of contaminant discharges to the Lower Passaic River have served to create a uniquely large inventory of highly contaminated sediments contained within a relatively small area. Other major Superfund sites may have similar volumes of contaminated sediments (e.g., Hudson River PCB site at 2.6 Mcy and Fox River PCB site at 8 Mcy) but these inventories are spread over much greater distances than the 17 miles of the Lower Passaic. While data are not sufficient to assess the volume of contaminated sediment for the entire Lower Passaic, the volume is estimated at 5 to 8 million cubic yards for RM 1 to RM 7, with an average depth of contamination ranging from 7 to 13 feet. The evidence from the side-scan sonar and bathymetric surveys suggest that the conditions observed in RM 1 to 7 probably also apply over the area RM 0 to 8, suggesting that the actual inventory of contaminated sediments is probably 33 percent greater (based on the ratio of 8 to 6) than the values listed here. The volume of dioxin-bearing sediments is somewhat small than the overall contaminated sediment volume since several contaminants are present at greater depths than 2,3,7,8-TCDD. The estimate of dioxin-bearing sediment volume ranges from 5 to 6.5 Mcy for RM 1 to 7.

The mass of contaminants contained within the sediments is also quite large as shown in Table 2. The mass of 2,3,7,8-TCDD represents one of the largest site inventories in the US.

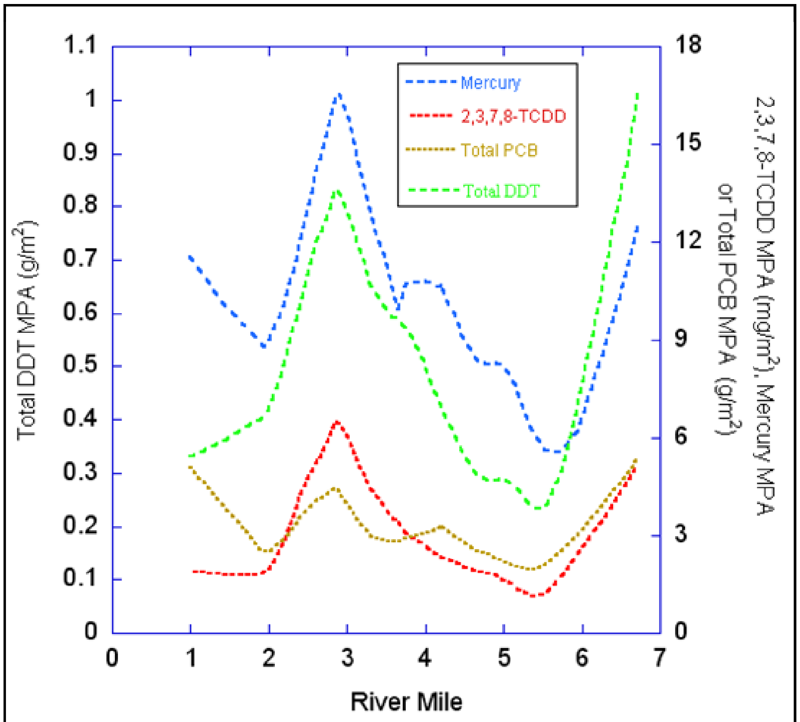
Table 2. Summary of contaminant inventory estimates.

Inventory Estimate	Total DDT (Metric tons)	2,3,7,8-TCDD (kg)	Mercury (Metric tons)	Total PCB (Metric tons)
Based on measured core intervals only	6.4	20	24	6
Based on measured and extrapolated core profiles	11	29	37	8
Percent Increase[8]	72 percent	45 percent	54 percent	33 percent

[8] Percent increase is relative to the interpolated mass estimate.

The uncertainties associated with these estimates arise from lack of horizontal coverage and lack of "completeness" in the vertical direction. As mentioned above, the physical survey data suggest at least 2 additional miles of the Lower Passaic may contain substantive inventories. Additionally, there are large distances between many of the cores located within RM 1 to 7, adding some uncertainty to the estimated volumes although the direction of any correction is not know. Finally, many of the cores used in the estimates were not "complete", that is, they did not penetrate and capture the entire sequence of contaminated sediments. These cores were extrapolated based on profiles observed in other cores. The range in volume estimates given above (5 to 8 Mcy), reflects this uncertainty, with the lower value based only on the measured core intervals, and the larger value incorporating the extrapolated mass estimates.

The contaminant inventories are not evenly distributed and vary along the length of the Lower Passaic River with maximum values occurring near RM 1 to 2, RM 3 to 4, and RM 6 to 7. However, the coring data that forms the basis for these inventories indicate a high degree of local spatial heterogeneity, suggesting that localized areas of relatively higher concentrations typically described as "hot spots" do not exist. Instead, "hot" regions of the river typically exist on the scale of a mile or more, nearly bank to bank in lateral extent. Despite the observations of local spatial heterogeneity, the inventories of four contaminants examined in detail were shown to correlate, indicating that their inventories coincide in space and are consistent with the anticipated geochemical behavior of the compounds (see Figure 9). Essentially, when a location has a locally high inventory of any one of these four contaminants, the other contaminants will also be concentrated at that location. It is anticipated that similar behavior will be exhibited by any hydrophobic compound in the Lower Passaic River. As noted previously, the variations in inventory are not believed to represent proximity to external point sources but rather, variations in the rate of deposition, with sites with higher rates of deposition generating higher contaminant inventories. Both the coring data as well as the bathymetric survey analyses done for the Lower Passaic suggest a high degree of spatial heterogeneity in inventory and deposition rate, supporting this premise.

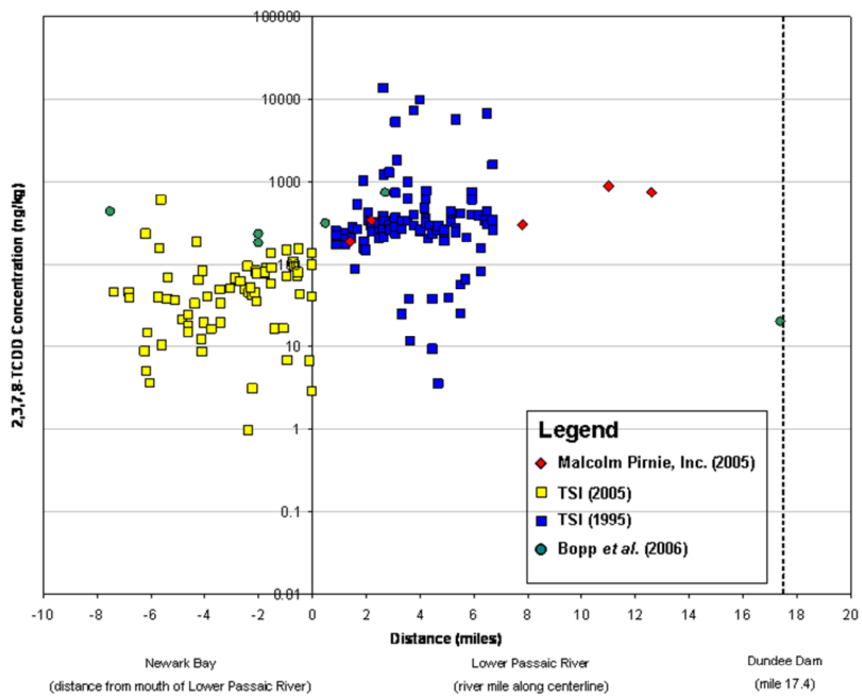


Note: Lines represent a weighted average of the sediment inventory for each of the contaminants as a function of river mile.

Figure 9. Variation of contaminant inventory with river mile in the lower Passaic River.

Impacts to Newark Bay

The Passaic River is the main source of freshwater to Newark Bay and a major source of contaminants to the bay as well. Solids delivered from the Lower Passaic to Newark Bay contain contaminant levels similar those found in surficial sediments of the Lower Passaic. As a result, for several contaminants examined, the history of contamination observed in the Lower Passaic sediments is also observed in Newark Bay. For example, dated sediment cores for the Lower Passaic River (RM 1 to 7) are consistent with the observations by Bopp et al. (1991) and Chaky (2003) for Newark Bay, specifically that the major releases of 2,3,7,8-TCDD begin in the 1950s and peak in the early 1960s. The history of DDT releases observed in the Lower Passaic was also consistent with the observations for Newark Bay mad by Bopp et al. and Chaky. Similarly, the diagnostic ratio of 2,3,7,8-TCDD/Total TCDD of 0.7 to 0.8 can be used to trace Lower Passaic River PCDD throughout the Newark Bay complex. Recent surficial samples from Newark Bay suggest the mixing of high ratio, high 2,3,7,8,-TCDD concentration sediments from the Passaic with low ratio, low concentration sediments from the Arthur Kill and Kill van Kull, creating gradients in the ratio and the 2,3,7,8,-TCDD concentration across Newark Bay (see Figure 10).



Note: Malcolm Pirnie Inc (2005) represents 2003-2005 time horizon; TSI (2005) represents 0-6 inches of sediment; TSI (1995) represents 0-6 inches of sediment; Bopp et al., (2006) represent 1985-1986 time horizon. These results document the homogeneity of surficial Lower Passaic sediments and the concentration gradient of Newark Bay. The Arthur Kill and Kill van Kull are both located near RM -8 in the diagram.

Figure 10. Variation of 2,3,7,8-TCDD with river mile in the lower Passaic River and Newark Bay

Using the historical observations of 2,3,7,8-TCDD and the 2,3,7,8-TCDD/Total TCDD ratio, it was possible to construct concurrent mass balances for solids, 2,3,7,8-TCDD and Total TCDD in Newark Bay, refining the solids balance analysis performed by Lowe et al. (2005). Based on the concurrent mass balances, the Lower Passaic River comprises approximately 10 percent of the total amount of solids accumulating in the bay and more than 80 percent of the 2,3,7,8-TCDD accumulating in Newark Bay. No other single source delivers more than 10 percent of the total 2,3,7,8-TCDD load.

The solids mass balance framework constrained by the dioxin mass balances provided a means to examine mercury in Newark Bay. The mercury mass balance shows that, despite the high mercury concentrations located in the Lower Passaic River relative to Newark Bay, the Lower Passaic River is only responsible for approximately 20 percent of the total mercury load to the bay. Moreover, the known sources of mercury to the bay cannot account for the annual accumulation of mercury in the sediment beds of Newark Bay. The "missing" mercury source represents the largest single "source" of mercury to the bay, constituting approximately 35 percent of the annual mercury load. The next largest "source" is the solids delivered by the Kill van Kull, which represent about 30 percent of the annual mercury load to Newark Bay. Note that these percentages are subject to revision when more data for Newark Bay and the Kills become available. Nonetheless, a large source of mercury to Newark Bay remains unknown.

The dioxin mass balances document the solids contribution that must arise specifically from the Passaic. Despite the observation that the Lower Passaic River has experienced a net deposition of sediment for a long period of time, the recent (ca. 1995) solids mass balance indicates that upriver solids are transported through the Lower Passaic River into Newark Bay, and potentially beyond. Estimates suggest that 20 to 50 percent of the upriver solids are eventually transported out of the Lower Passaic River. The estimated current (circa 1995) total annual loads of mercury and 2,3,7,8-TCDD to Newark Bay are approximately 400 kilogram/year and 14 gram/year, respectively.

SUMMARY

Since the American Revolution, the Passaic River has been the center of the industrialized areas and hence served as a place for the disposal and municipal wastes. Due to the lack of maintenance dredging for the navigational channel in the second half of the 20^{th} century, the river becomes effective in trapping sediments. As sediments were rapidly accumulating, the industrial discharges of dioxins, DDT, PCB, PAHs, mercury lead and other contaminants were also occurring. Given the hydrophobic nature of these contaminants, they quickly became attached to the particles in the water column. The occurrence of the salt intrusion in the Lower Passaic tended to keep these contaminated particles in the Lower Passaic, where they formed the thick sequences of contaminated sediments documented by the various coring studies of the river. As a result, the Lower Passaic River contains a massive volume of contamination, estimated in the range of 5 to 8 million cubic yards. Sediment core data record the long history of contamination in this system, with some contaminants apparently present in the system near the turn of the 20th century. Contaminant inventories are highest in regions of highest deposition, such as RM 2 to 3. However, the spatial heterogeneity in both the coring and bathymetric survey data suggests the occurrence of broad areas of contamination with locally variable inventories, instead of readily definable "hot spots." Contaminant behavior is well predicted by geochemical theory, as demonstrated by coincident inventories of several contaminants. Several important contaminants originate in the Upper Passaic River, above the Dundee Dam, including mercury, lead, and cadmium. Conversely, Total DDT and 2,3,7,8-TCDD clearly originate in the Lower Passaic River. Total PCB loads appear to have changed over time with the Upper Passaic River most important historically but apparently less important relative to Lower Passaic River loads currently. Review of the surface sediment contamination and sediment erosional patterns suggests some specific areas may represent important sources for the re-release of contamination from the sediments. In the absence of known external sources to the Lower Passaic, the erosion of historical contaminant inventories such as those indicated by the bathymetric surveys has been and continues to be a major source of contaminants to the Lower Passaic and Newark Bay. In fact, the Lower Passaic River remains the major source of 2,3,7,8-TCDD contamination to the sediments of Newark Bay. The complete geochemical report that is the basis for this paper as well as other information can be found at http://ourpassaic.org.

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