SUMMARY

Introduction

This Comprehensive Conceptual Site Model (CSM) Report presents a review of the available data and associated analyses to develop an overall understanding of the physical and chemical processes that transport contaminants from sources to receptors in the Lower Passaic River. Because of the extensive amount of data available, the CSM is based on a large number of analyses, and its conclusions are confirmed by various lines of evidence and interpretations from different perspectives. In this Summary, the evidence to support the major conclusions of this report is summarized along with the conclusions themselves. The intention of this chapter is to provide an integrated view of contamination in the Lower Passaic River. The summary information provided here does not follow the outline of the report, but rather integrates information from multiple chapters to describe the multiple lines of evidence to support each conclusion.

History of the River

An understanding of the unique history of the Lower Passaic River was an essential component in the development of the CSM. The extraordinary depth of the contaminated sediment inventory (Figures 13-22, 13-23, 13-29 through 13-33) and the persistently high concentrations of contaminants in the surface sediments (Figure 14-4) long after some of the most significant discharges ceased, can only be understood in the light of the river's history. Starting in the late 1800s, the Passaic River was one of the major centers of the American industrial revolution, with a variety of manufacturing and industrial operations located along its banks. These industries, including manufactured gas plants, paper manufacturing and recycling facilities, and chemical manufacturing facilities, used the river for wastewater disposal. The Lower Passaic River was also a recipient of municipal wastewater discharges. Various waste streams have delivered a number of contaminants, including but not limited to 2,3,7,8-tetrachlorodibenzo-p-dioxin (2,3,7,8-TCDD), polycyclic aromatic hydrocarbon (PAH) compounds, polychlorinated biphenyls (PCBs),

dichlorodiphenyltrichloroethane (DDT) and other pesticides, mercury, lead and other metals into the river.

In the early 1900s, a navigation channel was created from River Mile (RM)0 to RM15 for commercial vessels to travel to the city of Newark and beyond. Historical dredging served to create a deep channel (Figure 2-14), which then rapidly filled with sediment when maintenance of the channel largely ceased after the 1950s. The coincidence of chemical waste disposal into the river with the cessation of channel maintenance created an ideal situation for the accumulation of thick beds of contaminated sediments (see Chapter 2).

Hydrographic Setting

Watershed and Land Use

The Lower Passaic River is part of the New York-New Jersey Harbor Estuary, which encompasses an area of over 42,000 square kilometers. The Lower Passaic River is connected to the New York-New Jersey Harbor Estuary through Newark Bay. This connection allows for the exchange of solids and the associated contaminants between the Lower Passaic River and the estuary.

The Lower Passaic River flows through some of the most urbanized and industrialized areas of New Jersey, including the city of Newark. According to the 2000 United States Census, approximately 2.8 million people reside in the New Jersey counties of Essex, Bergen, Hudson, and Passaic, which encompass the Study Area (United States Census Bureau, 2007). The watershed of the entire Passaic River is 923 square miles, with 118 square miles in the Lower Passaic River Study Area. Existing land use conditions in the Lower Passaic River Study Area are 85 percent urban, and 15 percent forests, wetlands, and other land uses. The remaining 805 square miles of the watershed drain to the Upper Passaic River, which flows into the Lower Passaic River over the Dundee Dam at RM17.4. This portion of the watershed contains large areas of urban and suburban development but also includes a higher percentage of forested and agrarian areas (see Chapter 2).

Freshwater Flows

Freshwater flow is one of two major sources of solids to the Lower Passaic River. With these solids come several important contaminants (*e.g.,* PCBs, PAHs and heavy metals). There are four major freshwater discharge points to the Lower Passaic River: the Upper Passaic River at Dundee Dam (RM17.4), the Saddle River at RM15.2, the Third River at RM11, and the Second River at RM8.4. The Upper Passaic River is the largest of these flows, draining 805 square miles. The Saddle River drains 60 square miles, and the Third and Second Rivers drain nearly equal areas, at about 12 sq mi each. Besides these tributaries to the Lower Passaic River, there are numerable storm water outfalls (SWOs) and combined sewer overflows (CSOs). These serve to drain the remainder of the Lower Passaic River watershed.

The average annual flow at Dundee Dam is estimated at 1,200 cubic feet per second (cfs), based on United States Geological Survey (USGS) records at Little Falls and a drainage area correction to Dundee Dam. The Saddle River annual flow is 110 cfs. The freshwater flow from the remaining tributaries, SWO and CSO drainage is approximately 100 cfs in total. Thus, the delivery of water at Dundee Dam represents roughly 85 percent of all the freshwater and associated suspended solids entering the Lower Passaic River (see Chapters 2, 18and 19).

CSOs and SWOs represent a small percentage of the total freshwater flow to the Lower Passaic River, less than 3 percent. As part of the 2008 storm event sampling effort, a sufficient number of samples were obtained from CSOs to characterize their inputs to the river and show them to be minor contributors of contamination for nearly all contaminants (see Chapters 8 and 19).

Most SWOs in the Study Area do not enter the Lower Passaic River directly but reach the river via one of the tributaries. The few SWOs that directly discharge to the Lower Passaic River represent less than 2 percent of the total freshwater flow. Many of these SWOs enter via discharge pipes that are frequently below the high tide level. Thus water

and sediments from the river are able to enter many of these discharge systems at high tide during dry periods. This process impacted many of the SWO samples collected for this effort. However, a simple resolution of this issue was provided by the smaller tributaries, since they are basically just very large stormwater outfalls due to their urban land drainage (see Chapter 8).

Tidal Forcing

Tidal currents play a major role in mixing contaminants attached to suspended sediments in and settling out of the water column from one end of the Lower Passaic to the other. The high tidal velocities associated with the daily movement of the salt intrusion serve to resuspend and transport surficial sediment particles.

Due to the countercurrent flow between the freshwater and the underlying salt intrusion, the salt intrusion tends to gather suspended matter, slowing and reducing its transport out to Newark Bay. The movement of the salt intrusion, responding both to tidal forcing and variations in freshwater flow, mixes suspended solids along the river, which are variously transported with the currents in the freshwater flow, slowed and accumulated by the countercurrent flow of the salt intrusion, and resuspended both by freshwater and saline flows where they interact with the sediment bed. In a single day, the high tide and low tide salt front locations are generally 4 miles apart, representing tidal mixing over nearly one quarter of the length of the Lower Passaic River (Figures 10-20 and 10-22). Based on the last 30 years of flow data, the high tide salt front location was above RM9.6 more than 20 percent of the time, and the low tide salt front was below RM2 over 20 percent of the time. On an annual basis, this would represent more than 4 months where the daily salt front oscillation extended to either end of the river. The other 60 percent of the time the salt front is estimated to range between RM2 and RM9.6, with a daily 4 mile tidal excursion (see Chapter 10).

The observations regarding the relatively long distance affected by the salt intrusion, the speed and frequency at which the salt front can migrate from one end of the estuary to the other and the 4-mile daily tidal excursion describe a dynamic estuarine tidal setting.

These observations also describe the types of processes that would result in extensive tidal mixing of suspended solids as well as upriver tidal transport of solids. These observations provide a physical explanation for the relatively similar contaminant concentrations in the surface sediments of any given year over the past 20 years from RM2 to RM12 (Figure 13-4).

Characteristics of the Boundary Conditions

For the purposes of the RI/FS Study and the Comprehensive CSM, the domain is the Lower Passaic River sediment beds and water column. The boundary conditions for this domain are physical features along the river, including the Upper Passaic River at the head-of-tide just below Dundee Dam, the confluence of the river with Newark Bay, dams on the Second River and Saddle River, the head-of-tide on Third River, CSO and SWO outfalls, groundwater inputs, and atmospheric exchange. The conclusion from the boundary condition analyses are described below.

- Upper Passaic River (above the head-of-tide at RM17.4) represents the upper boundary of the Lower Passaic River (see Chapter 6). Chemical concentrations and contaminant patterns in suspended matter and sediment trap samples collected just below Dundee Dam at the Ackerman Avenue Bridge near RM17.1 compare well with concentrations in beryllium-7 (Be-7) bearing (recently deposited) sediment samples collected above the dam These results show that Dundee Lake recently-deposited surface sediments are representative of what is carried into the Lower Passaic River on suspended sediments from the Upper Passaic River (see Chapter 5).

    - The mean 2,3,7,8-TCDD concentration in suspended solids originating from the Upper Passaic River (as inferred from recently-deposited, Be-7 bearing surface sediment samples and sediment trap samples at Dundee Dam) (1.9 nanograms per kilogram of sediment [ng/kg]) is two orders of magnitude lower than the mean in the Lower Passaic River recently deposited surface sediment samples (370 ng/kg). Recently deposited surface sediment concentrations of 2,3,7,8-TCDD (1.9 ng/kg) in the Upper Passaic River are significantly lower than the historic concentrations

above Dundee Dam, dated from 1975 and 1963 at 7.6 ng/kg and 22 ng/kg , respectively. Based on these measurements, the Upper Passaic River is not a significant source of 2,3,7,8-TCDD.

- The mean Total PAH concentration (70 miligrams per kilogram of sediment [mg/kg]) in suspended solids (as inferred from recently-deposited surface sediment and sediment trap samples) from the Upper Passaic River at Dundee Dam is significantly higher than that observed in the surface sediments of Newark Bay (mean of 18 mg/kg) or the Lower Passaic River (mean of 40 mg/kg). Recently deposited surface sediment concentrations of total PAH in the Upper Passaic River (70 mg/kg) are twice the corresponding values for 1990 in the Upper Passaic River (30 mg/kg), and continue to be a significant source to the Lower Passaic River.

- Analysis of PCB congener patterns suggests that Upper Passaic River suspended matter contains higher levels of Aroclors 1254 and 1260 than the sediments of the Lower Passaic River. However, the Lower Passaic River congener pattern correlates more closely to the Upper Passaic River surface sediment congener pattern than the Newark Bay congener pattern. Recently-deposited surface sediment total PCB concentrations in the Upper Passaic River at Dundee Dam average 540 micrograms per kilograms of sediment (µg/kg) and no decline in concentrations is observed since 1990. The Upper Passaic River contributes a significant load of PCBs to the Lower Passaic River, whose mean total PCB concentration in recently-deposited surface sediments is 1,200 µg/kg

- Recently deposited surface sediments from the Upper Passaic River (and by inference suspended matter) contain comparable concentrations of dieldrin (10 µg/kg) relative to the Lower Passaic River (11 µg/kg), while the concentrations of DDT and its metabolites above the dam (56 µg/kg) are three times less than those detected in the Lower Passaic River (150 µg/kg). DDT and its metabolites are slowly declining over time in the Upper Passaic River, however, dieldrin is increasing with time in both the Upper and Lower Passaic River, indicating continuing sources to both parts of the river.

- The mean mercury concentration in recently-deposited surface sediment in the Upper Passaic River (and by inference Upper Passaic River suspended matter)is 0.66 mg/kg, which is low compared to the mean mercury concentrations in recently-deposited surface sediment concentrations in Lower Passaic River (1.9 mg/kg). Concentrations of mercury in the Upper Passaic River have declined over time, although there has been little or no decline in the concentration since 1990. Lower levels of chromium were also detected in recently-deposited surface sediments in the Upper Passaic River at Dundee Dam relative to those of the Lower Passaic River (31 mg/kg versus 120 mg/kg).

- The major tributaries discharging to the Lower Passaic River include: Saddle River, Third River and Second River, with estimated annual solids loads of 4,100 cubic yards, 850 cubic yards, and 990 cubic yards, respectively (see Chapter 7). The characterization of contaminated solids in the tributaries as defined by Be-7 bearing surface sediment, water column suspended solids and sediment trap sampling data can be summarized as follows:

  - The mean 2,3,7,8 TCDD concentration in tributary suspended solids (as inferred from recently-deposited surface sediment and sediment trap samples) is 3.3 ng/kg. Like the Upper Passaic River solids, the mean tributary concentration is over two orders of magnitude lower than the main stem Lower Passaic River concentration of 370 ng/kg in recently-deposited surface sediments..

  - The mean tributary recently-deposited surface sediment Total PAH concentration is 160 mg/kg, which is greater than the concentrations measured in the main stem of the Lower Passaic River (mean of 40 mg/kg) and northern Newark Bay (mean of 18 mg/kg). The mean PCB concentration in recently-deposited surface sediments and sediment traps from the tributaries is 1,100 µg/kg, and is comparable to that of the Lower Passaic River recently-deposited surface sediments (1,200 µg/kg). High flow events occurring during sampling may have resulted in the higher measured concentrations on suspended matter in these tributaries. PAH and hydrocarbon measurements that suggest that the tributaries are a potential source of contamination must be considered within the framework

of sampling. Because most tributary sampling events with high levels of PAHs were collected during rain-driven events, it is likely that the flushing of hydrocarbons from streets and nearby land areas created a transient spike of contaminant concentrations. These data must also be considered in light of the comparatively low total solids contributions from the tributaries, which diminishes their impact on the PCB and PAH budgets of the Lower Passaic River.

  - Relative to the recently deposited surface sediments of the main stem of the Lower Passaic River, the tributaries have higher mean surface sediment concentrations (and by inference, suspended matter concentrations) of dieldrin (44 µg/kg vs. 11 µg/kg) and of total DDT (310 µg/kg vs. 150 µg/kg).

  - Comparison of metals detected in the tributaries to the levels detected in the Lower Passaic River recently deposited sediments shows that the tributaries are not important sources of these contaminants. Mean metals concentrations for copper (110 mg/kg), lead (180 mg/kg) and mercury (0.44 mg/kg) are all lower than the mean values observed in the Be-7 bearing sediments of the Lower Passaic River (160, 200, and 1.9 mg/kg, respectively).

- Point discharges including CSOs and SWOs constitute another set of boundary conditions investigated in this CSM (see Chapter 8). The characterization of suspended solids from these point discharges is summarized as follows:

  - The CSO mean concentration of 2,3,7,8-TCDD (2 ng/kg), is two orders of magnitude lower than the mean concentration of recently-deposited surface sediments within the Lower Passaic River (370 ng/kg). The mean ratio of 2,3,7,8-TCDD to Total-TCDD in the CSOs (0.1) is low compared to that calculated for sediments in the Lower Passaic River (0.7). The CSO mean ratio of 2,3,7,8-TCDD to Total-TCDD compares well to that reported for the largest sewage treatment plant in New York City, the Newtown Creek POTW as characterized by sediments from Newtown Creek (0.05).

- For SWOs, the mean 2,3,7,8-TCDD concentration (22 ng/kg) is more than one order of magnitude lower than that of the Lower Passaic River sediments (370 ng/kg, RM2 to RM12.5), and roughly one order of magnitude higher than that of the tributaries, with means ranging from 2.0 to 4.0 ng/kg. Conversely, the 2,3,7,8-TCDD to Total-TCDD ratio of the SWOs ranges from 0.1 to 0.8, with an mean of about 0.4, while the ratio in the tributaries average 0.1. These observations suggests that most of the SWO samples were collected too close to the outfalls to the river and were therefore affected by the tidal exchange, which probably transported river sediments into the SWO systems during high tides, yielding the high 2,3,7,8-TCDD concentrations and 2,3,7,8-TCDD to Total-TCDD ratio relative to the tributaries.

- The mean Total PCB concentration on suspended solids from the CSOs (1,100 ug/kg) is comparable to the concentrations on recently-deposited surface sediments in the Lower Passaic River (1,200 µg/kg, RM2 to RM12.5) and is double the concentrations found on recently-deposited surface sediments in Newark Bay (570 µg/kg) and the Upper Passaic River (540 µg/kg). Given that the solids loads from these point sources are only a few percent of the solids loads from the Upper Passaic River or Newark Bay these discharges do not represent substantive PCB loadings to the Lower Passaic River.

- While the mean concentrations of the low molecular weight (LMW) PAHs, high molecular weight (HMW) PAHs, and Total PAH for the CSOs (5.4, 34 and 39 mg/kg, respectively) are comparable to that of the recently-deposited surface sediments in the Lower Passaic River from RM2 to RM12.5, the mean PAH concentrations from the SWO samples (15, 180, and 200 mg/kg, respectively) are about three to five times higher than that of the Lower Passaic River recently-deposited sediments from RM2 to RM12.5. Again, since the solids loading from the SWOs is very small, their PAH input remains a minor contribution to the PAH burden on the sediments of the Lower Passaic River.

- Dieldrin was not detected in any of the CSO samples, but the mean concentration in the SWO samples is higher than that of the recently-deposited surface sediments in the Lower Passaic River (90 µg/kg versus 11 µg/kg, respectively). The 4,4'-DDD, 4,4'-DDE and 4,4'-DDT mean concentrations in the CSO/SWO samples are comparable to the mean concentration in the Lower Passaic River.

- Comparison of mean metals concentrations detected on suspended solids from the CSO and SWO samples to sediments in the Lower Passaic River indicate: 1) Mean chromium and lead concentrations detected on suspended solids in the CSO/SWO samples are comparable to that of the recently-deposited surface sediments in the Lower Passaic River from RM2 to RM12.6 and 2) Detected iron concentrations in the SWO samples are about two times higher than that detected in the CSO samples and the recently-deposited surface sediments of the Lower Passaic River.

- The Contaminant Assessment and Reduction Program (CARP) CSO/SWO data was compared to the 2007-2008 CSO/SWO data (refer to Figures 8-6 and 8-7). These figures show box and whisker plots for different contaminants. For all contaminants except Total PCB, the mean concentration of the 2007-2008 CSO dataset is lower than that of the CARP data provided by New Jersey Department of Environmental Protection (NJDEP).

- To quantify the importance of groundwater and pore water contaminant inputs to the Lower Passaic River, a numerical model of groundwater transport through the sediment bed was used. The results of the analysis, based on conservative assumptions for several inputs parameters, suggest that advection of pore water has negligible effect on contaminant transport in the Lower Passaic River. There is less than a 1 percent chance that more than approximately 2 percent of the dichlorodiphenyldichloroethylene (DDE) and benzo[a]pyrene loads in the river are due to pore water fluxes. There is virtually no chance that more than approximately 2 percent of the river's loads of other contaminants are transported via the pore water (See Chapter 9).

- Atmospheric deposition is not significant source of contamination to the Lower Passaic River for various reasons listed in Chapter 9.

River Geometry and Sediment Characteristics

The Lower Passaic River's cross sectional area declines steadily inland, with a pronounced change around RM8, the same location as an observed major change in sediment texture, discussed below. The river's sediment surface represents roughly 940 acres, of which 620 acres lie downstream of RM8. The average channel depth is roughly 11 feet below mean low water with an average daily tidal elevation change of 5 feet. Thus daily tidal exchange represents a significant volume of the river, roughly a 50 percent increase in height and volume from low to high tide. The floor of the channel is greater than 8 feet below mean low water all the way to RM12. Beyond this point, the floor of the channel rises rapidly with river mile, reaching sea level (NGVD 1929) by RM15.5 and actually extending to 10 feet above sea level near the foot of Dundee Dam (see Chapter 2).

A side scan sonar survey completed in 2005 provides a detailed picture of the sediment texture and the areal extent of different sediment types between RM0 and RM16. Over 90 percent of the lower 8 miles of the river is classified as "silt" and "silt-and-sand", while less than 30 percent of the region above RM8 contains those classes of silt. The rest of the river bottom (less than 10 percent below RM8 and over 70 percent above RM8) is classified as "sand', "gravel-and-sand" and "rock-and-gravel". In terms of total "silt" or "silt-and-sand" area, 85 percent of this area is found below RM8. Of the total "sand", "gravel-and-sand" and "rock-and-gravel" areas, 75 percent of these classes is found above RM8 (See Chapter 11.)

Both the channel bathymetry and the sediment texture describe the Lower Passaic River as two distinct physical regions. Above RM8, sediment textures and channel geometry suggest an area of high velocities and associated coarser sediment. Below RM8, the wider channel geometry presumably yields slower river velocities resulting in the finer sediments deposited there. These observations cannot be taken as indications of sediment

deposition rates but only the types of sediment deposited. As discussed below, both areas are subject to similar rates of sediment deposition and erosion.

External Solids Loads and Deposition within the Lower Passaic River

Empirical Mass Balance (EMB)

The EMB provides a quantitative mechanism to establish the importance of each potential source of COPC to the Lower Passaic River and to aid decision-making regarding remedial alternatives for the river. The EMB is a receptor-type chemical mass balance model, where the total contaminant mass present in the sediments of the receptor (*i.e.*, the recently deposited, Be-7 bearing sediments in the Lower Passaic River) is the sum of the mass contributions from the individual sources, including the Upper Passaic River (above Dundee Dam), Saddle River, Third River, Second River, CSOs, SWOs, resuspension of legacy sediments/historical inventories within the Lower Passaic River, and Northern Newark Bay. The formulation of the EMB is presented in Chapter 18 and the results are presented in Chapter 19. The resuspension source signature was represented by the 1995 0 to 6 inch surface sediment concentrations. Contaminant inputs from atmospheric deposition, groundwater, and New Jersey Pollutant Discharge Elimination System (NJPDES) permitted discharges have been determined to be negligible for the system (see Chapter 9). Because the data from the SWO samples seems to have been compromised by the intrusion of Lower Passaic River sediments into the SWOs and because Second River is a channelized stream that is largely storm water, the contribution from Second River and the SWOs was combined in the model and the chemical characteristics of both were based on samples taken in Second River. The model inputs, evaluation along with the solids balance and fate and transport for the various contaminants can be summarized as follows:

- Thirteen chemicals (copper, chromium, mercury, lead, trans-chlordane, 4,4'-DDE, 2,3,7,8 TCDD, total TCDD, total PCB, benzo(a)pyrene, fluoranthene, iron and TOC) were used to optimize the EMB model. An additional nine chemicals (arsenic, cadmium, cobalt, nickel, zinc, benzo(a)anthracene, chrysene, indeno[1,2,3-cd]pyrene, and pyrene) were used to validate the model. Model estimated receptor concentrations

were generally within 26 percent of the observed values, with a few exceptions. These exceptions occurred for chemical with very high variability.

- Re-running the EMB with iron normalized input instead of gross concentrations, and excluding PAHs, which show no variation with iron in the system, resulted in a comparable solids balance estimate relative to that obtained by using gross concentrations. The solids balance for the iron normalized simulation suggest: 42 percent resuspension, 25 percent Newark Bay, 27 percent Upper Passaic River, and 6 percent combined tributaries, CSOs and SWOs.
- While the solids balance obtained using the gross concentrations is comparable to results obtained using iron normalized concentrations (as the model inputs are comparable), the slight differences in relative solids contribution from Newark Bay and the Upper Passaic River can affect the mass balance for some of the contaminants.

External solids loads estimates

For the Upper Passaic River at Dundee Dam, the annual solids load based on data is approximately 27,000 metric tons (mt) of sediment per year, or 50,000 cubic yard per year (cy/yr) at a density of 0.7 metric tons per cubic meter (mt/m^3). Additional freshwater contributions to the Lower Passaic River downstream of the dam bring this total to between 50,000 and 60,000 cy/yr, including tributary, CSO and SWO contributions. Tributary and SWO solids loads were based on the measured solids loads at the USGS station on the Saddle River at Lodi, with a correction for drainage area. No data were available to directly estimate the CSO contribution for the Lower Passaic River. Lacking supporting data, the annual CSO solids load value for the Lower Passaic River was based on the sewer-shed area and a solids yield per unit area comparable to that of the tributaries. A comparable load estimate can also be obtained from a separate CSO solids load calculation provided in Lowe *et al*. (2005).

While the freshwater delivery of solids is relatively well characterized by direct measurements and drainage area-based arguments, the exchange of the solids with Newark Bay is not so well defined. This component of the solids balance was estimated

using the EMB and the Newark Bay mass balance. These analyses indicate that the solids exchange with Newark Bay is comparable to the freshwater solids delivery. Specifically, the solids balance from the EMB for the Lower Passaic River indicates that Newark Bay solids comprise roughly half of the annual net accumulation occurring between RM2 and 12. Below RM2, the fraction of Newark Bay solids increases steadily (see Chapters 18, 19 and 21).

Annual Rate of Deposition

Detailed sediment stability analyses were conducted using bathymetric surveys spanning 1989 to 2007, along with supporting grain size and side scan survey information, to understand erosion and deposition over time in the river. The oldest (1989) and newest (2007) surveys form the best basis to estimate the long term rate of deposition, at roughly one inch per year for the entire Lower Passaic River. This represents an annual volume on the order of 65,000 cy/yr. Notably, this rate is very similar to the estimate of the annual freshwater solids delivery (50,000 to 60,000 cy/yr) to the Lower Passaic River; however, as noted above, solids from also Newark Bay play a major role in the Lower Passaic River.

The short time intervals between the seven surveys taken between 1995 and 2004 show that the distribution of neutral, depositional, and erosional areas is highly variable, shifting unpredictably from year to year (Figure 11-4). Over time, individual areas are subjected to alternatively erosional and depositional conditions that must ultimately result in a net mixing of sediments within much of the Lower Passaic River (see Chapter 11).

Distribution of Deposition and Erosion

The bathymetric surveys also show extensive gross transport of sediment between surveys, with the sediment volumes of gross deposition and erosion being 2.25 and 1.25 times greater, respectively than net deposition. These results suggest that eroded sediments comprise more than half of the gross sediment deposition on an annual basis. Data indicate that all portions of the river contribute to the resuspension of sediment, and therefore also contribute to the release of contamination from legacy sediments.

However, it can be shown that above RM8 the sediments being resuspended do not contain as much silt (the greatest vector for particle-born contamination) as downriver of RM8 (see Chapter 11).

Fine-grained sediments below RM12 are shown (in Chapters 14 and 16) to be the primary carriers of 2,3,7,8-TCDD. Weighting surface area, fine-grained sediment content and sediment resuspension rate, the region below RM8 is responsible for about 88 percent of the resuspended fine-grained sediment contaminated with 2,3,7,8-TCDD. Further evidence for the importance of the region below RM8 to controlling the redistribution of 2,3,7,8-TCDD contamination arises from an examination of the percentage of resuspension to gross deposition along the river. Again the sediments below RM8, specifically those between RM2 and RM8, have the highest percentages of any area substantively contaminated with 2,3,7,8-TCDD.

The detailed comparison of sedimentation rates prepared for this report demonstrates that the entire Lower Passaic River is dynamic, experiencing periods of net deposition and periods of net erosion at most locations but at different times. Silt and total fine grained sediment percentages below RM8 for the 1989 to 2004 and the 1989 to 2007 bathymetric evaluations were calculated using three different methods to evaluate the importance of this area to resuspension of legacy sediment contamination to the Lower Passaic River. Based on the silt surface area calculation, this region contains 85 percent of all fine grained sediment. Considering the sediment textures and their respective silt content, the majority (85 to 87 percent) of the surficial fine-grained sediment occurs below RM8. Combining sediment texture surface area, sediment texture fine grained sediment content and the rate of resuspension by sediment texture area indicates that RM0 to 8 is responsible for 70 to 77 percent of the overall rate of fine-grained sediment resuspension, but more importantly, RM0 to RM8 is responsible of roughly 88 percent to 93 percent of all potentially 2,3,7,8-TCDD contaminated resuspended fine grained sediments, which are largely limited to below RM12. In all cases, these calculations indicate that RM0 to RM8 is responsible for approximately 70 percent to 87 percent of all the fine grained sediments resuspension from RM0 to RM14.5, and approximately 88 percent to 93

percent of 2,3,7,8-TCDD-bearing fine grained sediment resuspension below RM12 (See Chapter 11).

Sediment Resuspension in the Passaic River

The EMB solids balance, based on gross concentrations of contaminants, suggests that resuspended solids account for about 46 percent of the total solids in recently deposited sediments in the Lower Passaic River. Newark Bay and the Upper Passaic River accounted for about 27 percent and 22 percent of the solids delivered to the Lower Passaic River, essentially equal in their contributions. The tributaries, CSOs and SWOs together contribute about 5 percent of the solids (see Chapter 19). The EMB's estimate of a significant resuspension source is consistent with independent observation from bathymetric change analysis.

Fate and transport analysis suggests that external contaminant sources (by themselves) cannot account for the observed COPC concentrations in the Lower Passaic River's recently deposited surface sediments, indicating that an internal source, or more specifically sediment resuspension, is contributing to the contaminant burden of recently deposited surface sediments in the river. With the exception of trans-chlordane, the tributaries and the CSOs/SWOs were minor contributors to the contaminant burden in the river. The following findings summarize the contribution of resuspension to the burden of specific contaminants in the Lower Passaic River:

- For 2,3,7,8- TCDD and Total TCDD, no significant external contaminant source exists, and the resuspension of legacy sediments accounts for more than 90 percent of the dioxin burden in recently deposited sediment.
- For total PCBs, the resuspension of legacy sediments contributes approximately 70 percent of the contaminant burden to the river. The Upper Passaic River and Newark Bay contribute 15 percent and 10 percent of Total PCB, respectively.
- HMW PAHs, represented by benzo[a]pyrene and fluoranthene, show higher concentrations in the Upper Passaic relative to the concentrations in the Lower Passaic River. It is not surprising that the Upper Passaic River contributes about 30

percent of the PAH contamination to the Lower Passaic River. Resuspension of the historical inventory accounts for about 50 percent of the PAH contaminant burden of the Lower Passaic. The tributaries and SWOs contribute about 10 percent of the PAH contamination and the CSOs contribute less than two percent. The LMW PAH mass balance inferred from the solids balance for Phenanthrene suggest ~75 percent resuspension contribution and only 18 percent from the Upper Passaic River. The LMW PAH estimates are less certain than the other contaminants, however, since a closed mass balance could not be attained for this contaminant group.

- The fate and transport of DDE, copper, chromium, mercury and lead in the Lower Passaic River is dominated by sediment resuspension, with this source accounting for at least 66 percent. For DDE, copper, chromium and mercury the contribution from Newark Bay (at least 20 percent) is more than twice that from the Upper Passaic River. For lead, Newark Bay and the Upper Passaic are equal contributors, each with 15 percent the lead burden in the river.

- About half the trans-chlordane burden in the Lower Passaic River can be explained by resuspension. Roughly equal (~20 percent) contributions originate from the tributaries and Upper Passaic River. Trans-chlordane represents the only significant contribution from the tributaries in the mass balance calculations.

Long Term Solids Balance and the Links to Newark Bay

The importance of the Lower Passaic River's link to Newark Bay was demonstrated in the combined solids and dioxin mass balance analysis conducted as a part of this report.

Currently, Newark Bay is estimated to provide half of the annual net accumulation in the Lower Passaic River between RM2 and RM12, and a greater fraction between RM0 and RM2. During the period 1945 to 1989, the minimum contribution by Newark Bay would have been two-thirds to three quarters of the annual accumulation, assuming no export of Upper Passaic River solids to Newark Bay. In many respects then, the combination of the channel construction and neglect along with the large available source of solids from Newark Bay served to trap the contamination discharged to the Lower Passaic River and prevent a much greater environmental impact. In contrast, the current contributions from

Newark Bay are much lower, indicating a less efficient trapping mechanism and likely greater export of Lower Passaic River solids than has occurred in the past (see Chapter 21).

The parallel analyses of current solids balances for the Lower Passaic River and Newark Bay permits a direct comparison of their solids exchange. The solids balance for the Lower Passaic River indicates that annual accumulation is equivalent to the annual freshwater delivery, but the chemical mass balance indicates that half of the net deposition must originate from Newark Bay. This indicates that, at a minimum, a volume of Lower Passaic River solids equal to half of the solids delivery from the freshwater discharges must reach Newark Bay. To the extent that additional Newark Bay solids must be present in the Lower Passaic River in order to contribute half of the net solids accumulation, these extra solids must also be returned to Newark Bay. Given the equal importance of the 2 solids sources to net accumulation, it is likely that the water column inventories of freshwater and Newark Bay solids are also equivalent in size. This yields the following solids balance with exchange to Newark Bay:

50,000 to 60,000 cy from freshwater discharges
+ 50,000 to 60,000 cy from Newark Bay
- 65,000 cy net annual accumulation
40,000 to 55,000 cy

Thus 40,000 to 55,000 cy are mixed within the Lower Passaic River and transferred back to Newark Bay. By comparison, the solids balance to Newark Bay based on simultaneously balancing solids, 2,3,7,78-TCDD and Total TCDD requires a net input of solids from the Lower Passaic River of 35,000 cy. These solids balances agree quite closely and within their associated uncertainties. (See Chapter 21)

In total, these solids balances document both the historical importance of the Newark Bay solids to the Lower Passaic River as well as the ongoing exchange of sediments (and contaminants between the river and the bay.

Analyses of recently deposited sediments in Newark Bay show varying concentration gradients occurring simultaneously in different areas of Newark Bay. These data suggest that the bay cannot be depicted as a completely mixed system. The tidal and wind-driven currents are not sufficient to completely blend and distribute contaminated sediments throughout the bay. Note that the Newark Bay locations are discussed here with respect to distance from the Lower Passaic River; consequently RM-3 indicates a distance of 3 miles into the bay from the mouth of the river, which is located at RM0. In this characterization, the bay is divided in to southern (from RM-3 to RM-4.6) and northern (RM-0.45 and RM-1.9) sections. A summary of conclusions regarding sediment contamination in Newark Bay is provided below:

- The only major source of 2,3,7,8-TCDD to Newark Bay is the Lower Passaic River. Concentrations of 2,3,7,8-TCDD show a decreasing north-to-south concentration gradient in Newark Bay at depositional locations both in the channel and on the shoals. Furthermore, a decrease in the 2,3,7,8-TCDD/Total TCDD ratio across the Bay, from approximately 0.6 in the northern end to 0.3 in the southern end, reflects the mixing of highly-contaminated Lower Passaic River sediment with relatively cleaner sediments originating in Upper and Lower New York Bay.
- PCB congener concentrations in Southern Newark Bay (0.90 to 22 µg/kg) are lower than values reported for the mouth of the Lower Passaic River. In addition, the southern bay has PCB congener patterns that are different from patterns in the Lower Passaic River. Conversely, the northernmost samples have PCB congener patterns more similar to those patterns observed in the Lower Passaic River. The surface sediment PCB congener concentrations for these northern locations ranged from 2.5 to 67 µg/kg for the individual PCB congeners. In general, concentrations of contaminants measured in the southern part of Newark Bay are assumed to represent the contaminant loads that would be present throughout the bay if the release of contaminated sediments from the Lower Passaic River were to be controlled by a remedial action.

- The PAH pattern was observed to be variable but without any trend through the bay, even though a Total PAH concentration gradient exists from north to south in the bay. The surface sediment concentrations for the individual PAH compounds ranged from 200 to 640 µg/kg, with mean concentrations ranging from 300 to 580 ug/kg for the individual PAH compounds. On average, the concentrations of PAH compounds near the mouth of the Lower Passaic River were 3 to 4 times higher than the corresponding concentrations measured in the southern samples. The surface sediment concentrations for the northern locations ranged from 690 to 2,800 µg/kg for the individual PAH compounds, with mean concentrations ranging from 900 to 2,400 µg/kg among the PAH compounds.

- DDE was the only pesticide consistently detected during the Newark Bay Phase 1 Remedial Investigation conducted by Tierra Solutions in 2005 due to difficulties with analytical sensitivity. No concentration gradients were observed for the pesticides. The mean DDE concentration for the southern locations was approximately 18 µg/kg and the mean concentration for the northern locations was approximately 32 µg/kg.

- No strong north-south concentration gradient was observed for the metals among the 16 depositional locations (Be-7 bearing samples; refer to Figure 6-11), although local maximum concentrations were observed. Note that near RM-1.5, the metals concentrations were higher than other locations, which suggests a source originating in the port channels on the bay.

- Using a two end-member mixing model to examine the strong gradient in both the absolute 2,3,7,8-TCDD concentration as well as the change in the 2,3,7,8-TCDD/Total TCDD ratio observed across the bay,, the analysis indicates that (1) sediments are mixed at relatively short distances prior to placement on the bay floor, only to be resuspended by an ensuing tide. 2) the sediments in the northern bay, having been transported up through the bay by tidal action, constitute an appropriate end member for the empirical mass balance presented in this Comprehensive CSM.

Sediment Contamination at the Surface

Surface sediments represent the primary matrix of exposure for many of the animal species that inhabit the Lower Passaic River. The sediments are also the primary reservoir of contamination supplying contaminants for water-column based exposures to biota and humans. Finally, these sediments are the reservoir for downstream transport of contaminants to Newark Bay.[1] Four surveys were conducted between 1995 and 2008 that can be used to describe surface concentrations in the Lower Passaic River.

Most of the contaminants examined by the 1995 and 1999-2000 studies show a broad range of concentration values (an order of magnitude or more) in any given river mile interval, with very little or no discernible trend with respect to distance along the river. That is, the concentrations are everywhere variable but, importantly, there is little or no trend of the mean or median with river mile. This means that there is no single point source or that riverine mixing of suspended matter is sufficient to eliminate local concentration maxima prior to deposition.

A 2008 coring program collected samples from 0 to 6 inches in fine-grained sediment deposits (areas classified as "silt" or "silt-and-sand") above RM8 and confirmed the absence of trend with river mile for most contaminants seen in the earlier studies. An additional observation from these samples, however, is the lack of decline in the concentration of the 0 to 6 inch layer with time. In fact some of the contaminants appear higher above RM8 than below it, although most differences were not statistically significant. This observation suggests that the 0 to 6 inch layer in fine-grained sediments is everywhere similar. The lack of decline relative to 1995 levels may also suggest a slower rate of recovery than even the long half lives predicted from the dated sediment cores. Because of the lack of trend with river mile, risk assessment exposure point concentrations can be represented by a mean value for the river as a whole.

[1] As will be discussed later, the contamination of the surface layer must be replenished from deeper sediments in order to sustain the very slow recoveries observed in dated sediment cores.

While samples obtained from 0 to 6 inches can characterize mean local contamination levels, the fact that they may represent many years of deposition in a single interval means that they make it difficult to directly compare contaminant concentrations discharged within the same time period. Because the age of sediment in Be-7 bearing sediments is well known (6 to 12 months), these samples provide an integrated picture of the last 6 to 12 months of sediment transport at each sampling location. Contaminant concentrations in recently deposited sediments (Be-7 bearing sediments) obtained along the length of the Lower Passaic River show little or no trend with river mile between RM2 and RM12, despite different loading histories and different source areas for the large number of contaminants within the Lower Passaic River, confirming the observations made with the 0 to 6 inch samples described above. Based on the 2007 surface sediment sampling program, recently deposited sediments between RM2 and RM12 are the most similar while locations upstream and downstream of this interval show more rapidly changing and substantive contaminant concentration gradients with river mile. The lack of trend in Be-7 bearing sediments over such a long distance (RM2-RM12) is direct chemical evidence for the process of tidal mixing and sediment resuspension. The absence of trend with river mile over this interval is most evident when normalizing to a tracer for fine-grained particles (i.e., iron), the primary transport medium for these contaminants (see Chapter 14).

Concentrations and patterns of contamination in suspended solids collected during large volume water column sampling were statistically compared to corresponding results in recently deposited sediments to determine if they possess the same contaminant patterns. Results of this analysis indicate 1) PCB congener patterns are similar between large volume and surface sediment samples. 2) Concentrations and the ratio of 2,3,7,8-TCDD/Total TCDD in suspended solids are consistent with values in surface sediments. 3) A principal component analysis performed on all classes of contaminants further confirmed the hypothesis that the suspended solids possess the same contaminant pattern as the recently deposited surface sediments. 4) The principal components further suggest that the properties of recently deposited Lower Passaic River sediment results can be

bounded by the end members corresponding to the source areas, including: Newark Bay, the Upper Passaic River, all the tributaries, CSOs/SWOs and the legacy sediments.

General conclusions regarding surface contamination in the Lower Passaic River sediments are provided below:

- All metals concentrations show a gradual increase in concentration from Newark Bay to approximately RM5, followed by a gradual change in the slope of the curve and a decrease in concentration from RM10 to RM15. The concentration in the center of the river (approximately RM8) is generally about twice the concentration at RM1. When the metals concentrations are iron normalized, the variability in the metals concentrations between RM2 and RM12.5 is removed. This indicates that the variation in metals concentration between RM2 and RM12.5 is due to the amount of fine-grained particles at each location.
- The Dundee Lake sediment samples generally have metals concentrations that are equivalent to the Lower Passaic River samples at RM14. Most metals had much higher concentrations in the water column samples taken just below the Dundee Dam at RM17.1. When normalized to iron, the ratios for most metals in these samples varied between the ratios of Lower Passaic River samples at RM14 and those at RM10.
- The contribution of Newark Bay sediments on the metals concentrations in the Lower Passaic River is more significant for aluminum, chromium and copper than for cadmium (and lead to some extent). The effect of Newark Bay sediments on mercury concentrations in the Lower Passaic would fall somewhere in between the two groups.
- The effect of the tributaries on the copper and lead concentrations in the Lower Passaic River is greater than for any other metals; however, because the contribution of sediment from each of the tributaries is very small compared to other major sources, the overall load of metals from the tributaries is not significant.

- Greater volumes of aluminum, copper and lead are contributed to the system through CSOs and SWOs; however, because the flow volume is low compared to other sources, the overall load from these sources is generally very low.
- The concentration plots for the pesticides 4,4'-DDE, total DDT, and total chlordane show relatively little trend with river mile between RM2 and RM12 along the Lower Passaic River, with DDE and total DDT experiencing a drop in concentration by an order of magnitude between RM10 and RM15. Dieldrin concentrations gradually increase from RM1 to RM14. When normalized by total organic carbon (TOC), dieldrin and chlordane have a slight increasing trend up the river, while DDE drops slightly from RM1 to RM12 and then more rapidly to RM14.
- Pesticides patterns in Newark Bay and the results of the EMB indicate that Newark Bay is a greater contributor of DDT contaminants than of either chlordane or dieldrin to the Lower Passaic River.
- The Dundee Lake samples generally had pesticide concentrations similar to those found in the Lower Passaic River, indicating that the Upper Passaic River may be currently contributing these contaminants to the Lower Passaic River sediments.
- The tributaries appear to play a much larger role in contributing dieldrin and chlordane than they do with regard to contributing the DDT compounds. Since the tributaries contribute a small fraction of the solids load in the Lower Passaic River, their role is likely not as significant as other larger sources, even though the concentrations are higher.
- CSO and SWO pesticide concentrations are close to levels found in the Lower Passaic River, with the exception of dieldrin, which was not detected in the CSOs, and chlordane, which had high (up to 10 times the river levels) concentrations in the CSOs. Like the tributaries, CSOs and SWOs contribute only small fractions of the river's solids load and so, are not likely to contribute a major portion of the pesticide load, even if the concentrations are comparatively higher.
- The plots of PAH concentrations versus river mile indicate that the main stem Passaic River samples vary erratically, with little discernible trend. Newark Bay end members have relatively low concentrations, generally 10 to 20 percent of the main stem samples. Dundee Lake samples are usually higher than samples taken in the Lower

Passaic River, varying from 100 to 200% of the main stem concentrations. The tributary samples vary widely, but have higher PAH concentrations relative to the main stem of the river. This high tributary PAH concentration is likely attributed to rain-driven events (e.g., roadway runoff) during the selected sampling intervals. While CSO sample concentrations were approximately equal to Lower Passaic River sediment samples, SWO samples had concentrations of PAH up to 50 times the river samples.

- Normalization to iron or TOC did not reduce the variability in PAH concentrations; however the analysis indicates that Newark Bay is no more than a minor contributor of PAH to the Lower Passaic River. The Upper Passaic River, however, is likely a significant source. Some PAH may be contributed from resuspension, but the variation in PAH concentrations, even when normalized to iron, indicate that resuspension within the Lower Passaic River is not a major source.
- Both the concentration and the TOC normalized concentration for several PCB congener coelutions and Total PCB are strikingly similar. PCB concentrations generally increase from the mouth of the river to approximately RM5. This is followed by a drop in concentration and then a return to higher concentrations. A larger drop in concentration then occurs between RM12 and RM15. Relative to the source areas, a large portion of the PCB load in the Lower Passaic River must come from internal sources, i.e., resuspension of legacy material within the main stem.
- 2,3,7,8-TCDD generally increases from the mouth of the river to approximately RM12. The concentrations then experience a sharp drop of more than one order of magnitude between RM12 and RM15. Similar effects are seen when the dioxin concentration is normalized to TOC.
- Newark Bay dioxin concentrations and TOC normalized ratios are lower than those found in the main stem of the river. Dundee Lake samples, representing the Upper Passaic River suspended solids, are also lower for both the measured concentration and dioxin-TOC ratios. The samples from the tributaries, and the CSOs all had low dioxin concentrations and dioxin-TOC ratios, generally two to three orders of magnitude below the values reported for the nearest main stem samples. These lower concentrations in the sources areas suggest that none of these sources contribute

significant dioxin load to the river. The dioxin must therefore come from an internal source, by inference, the resuspension of legacy material in the deeper sediments of the river. This conclusion is bolstered by an analysis of the 2,3,7,8-TCDD to Total TCDD ratios, which show a unique signature for dioxin in the river. None of the measured sources show a ratio that was comparable to that found in the river. (As discussed above, SWO samples were believed to influenced by sediment exchange with the Lower Passaic River and thus were not considered representative of the true SWO solids contribution.)

- Surface sediment concentrations (0 to 6 inch) in low resolution cores collected above RM8 in 2008 were statistically compared to surface sediment concentrations (0 to 6 inch) from cores collected between RM1 and RM7 in 1995. The results show no statistical differences between the two groups for metals, pesticides, PAHs and PCBs. While concentrations of 2,3,7,8-TCDD and Total TCDD were significantly higher above RM8 relative to values below RM8, the diagnostic ratio of 2,3,7,8-TCDD/Total TCDD was not significantly different. These results suggest the surface sediments have not substantively declined, despite the elapsed time (13 years) between the two data sets.

History of Contamination

Dated sediment cores were used to describe the history of contamination in the Lower Passaic River. Cores were obtained along the main axis of the river as well as from above Dundee Dam. These cores chronicle the history of contaminant loads because they contain an increment of sediment deposition from each year. The age of any given interval in these cores was established using radionuclide dating. Radionuclide chronologies were established based primarily on cesium-137 (Cs-137) (which has a half-life of 30 years). The sedimentation rate and a core chronology were established for five sediment cores located at RM1.4, RM2.2, RM7.8, RM11, and RM12.6 and the core collected in the Upper Passaic River above Dundee Dam. Because of the similarities in the depositional areas that yield dated sediment cores and recently-deposited sediments (Be-7 bearing sediments), dated sediment cores can also be described as a long-term record of successive, Be-7 bearing deposits.

These dated sediment cores were used to establish the release histories of the major contaminants to the Lower Passaic River. Nearly all contaminants reach significant maximum concentrations (implying maximum loads) between the mid-1950s and early 1970s. A few contaminants, like PAH compounds, exhibit an earlier maximum. These cores also document the decline in contaminant concentrations to the present. Most contaminants, like 2,3,7,8-TCDD, mercury and PCBs, exhibit a gradual decline to the most recent layers. These declines were examined in light of the trends exhibited in the dated sediment core obtained above Dundee Dam, representing the background load from the Upper Passaic River. The trend in this core along with concentrations from sediment traps and Be-7 bearing samples from the tributaries and suspended matter samples from the CSOs, was used to describe baseline suspended matter concentrations, and by inference baseline loads, external to the Lower Passaic River. The difference between these concentrations and those found in the dated sediment cores for the Lower Passaic River describes the rate of decline for the flux of contaminants due to Lower Passaic River resuspension and input by Newark Bay. Because of the distinctly lower levels of contamination in Newark Bay sediments and their dependence on Lower Passaic River, this rate of decline can largely be assigned to the decline in resuspension-related contamination alone.

For these contaminants, it was possible to establish a half life for the decline of the loading due to resuspension of legacy sediments. The shortest half life was 20 years, for both 4,4'-DDE and Total PCBs. The half life for 2,3,7,8-TCDD was 25 years while the half life for mercury, lead and copper was 30 years or more. Two of the COPCs examined showed no statistical decline with time, (*i.e.,*chlordane and HMW PAHs) while dieldrin exhibited a statistically significant trend of increasing over time (see Chapter 20).

The convergence of most of the COPCs on 20 to 30 year half lives suggests a similar or single mechanism is responsible for their release. This, of course, is the resuspension of legacy sediments. The gradual decline of the pool of contaminated sediments is reflected in these half life calculations. The longer or non-extant or existing declines of chlordane

and HMW PAHs reflect the much greater importance of the load from the Upper Passaic River to their continued presence in the sediments of the river. The rising trend for dieldrin in the Lower Passaic River is indicative of a local source, since this contaminant was banned more than 20 years ago. This is discussed further below.

While the dated sediment cores obtained for this investigation represent a limited number of locations, the evidence from the recent, Be-7 bearing sediments as well as from other dated sediment cores obtained by Bopp *et al.,*1991a and by TSI in 1995 confirms the observations. In particular, all of the cores document the characteristic peak of 2,3,7,8-TCDD in the late 1950s or early 1960s. The cores also document similar peak concentrations (*e.g.,* 10 to 20 µg/kg of 2,3,7,8-TCDD) regardless of river mile and the high 2,3,7,8-TCDD to Total TCDD dioxin ratio that is characteristic of post-1940s dioxin contamination in the Lower Passaic River. Thus while this analysis has relied on five very detailed core chronologies to establish the history of contaminant loads, there, in fact, are a large number of cores that support this interpretation.

The contaminant histories serve two important purposes. The first, described above, is to document the history of contaminant loads and the consistency of those loads across the Lower Passaic River (This consistency is further discussed below as part of the evidence for a second source of 2,3,7,8-TCDD). The second is to form a basis to extrapolate to future conditions under MNR as well as after different remedial options. In the latter case, it is the half lives of contaminant concentration decline, derived for the Lower Passaic River resuspension term, that describe how this process will decline in areas unaffected by the remedy (see Chapters 13 and 20.)

The following is a summary of detailed findings from the high resolution core evaluations:

- The ratio of 2,3,7,8-TCDD/Total TCDD was calculated at various depths for further evaluation (Figure 13-7). Despite some variability in the data, the consistency of the ratio is quite evident, with a ratio of 0.7 or more reflecting the history of production and discharge of PCDDs into the Lower Passaic River. For example, at Tierra

Solutions, Inc. (TSI) location 272 (RM 6.3), the ratio is consistent from the surface to a depth corresponding to the 1970s time horizon. The ratio then increases in the 1960s as the 2,3,7,8-TCDD concentration increases by two orders of magnitude. This change in the ratio and increase in concentration likely reflects the active production and discharge of PCDD in the 1960s, which released a mixture with a higher ratio. At the bottom of the core, circa 1940, the ratio dramatically drops to a background signature of 0.05 or less, representing atmospheric deposition, upriver sediment transport, and sewage discharge (Chaky, 2003) and reflecting conditions before the production of (2,4,5-trichlorophenoxy)acetic acid and PCDD along the Lower Passaic River. At the same time, the 2,3,7,8-TCDD concentration also drops from 10 µg/kg to 0.02 µg/kg.

- Downcore profiles for Total PCB show that the Total PCB profiles do not vary substantively spatially and temporally in the cores examined; implying that number of local sources of Total PCB have remained relatively constant over time.. Total PCB and individual congener profiles show peak concentrations in the 1960s time horizon, from cores at RM1.4, RM 2.2, and RM11.
- Downcore profiles for PAHs showed that Total PAH was present in nearly all sediment samples at nearly all depths. Sediment cores in 1995 were 'incomplete' (*i.e.*, did not penetrate the full depth of contaminated sediment) with respect to PAH contamination, because detected Total PAH concentrations did not reach a maximum value and subsequently decline to background concentrations. Rather, Total PAH concentrations reached their maximum value at the core bottom, suggesting that the collected cores were not advanced deep enough to capture the full inventory of Total PAH and that the peak loading of Total PAH likely occurred prior to the 1940s, which is the deepest temporal extent of most of the dated sediment cores. As for 2005 high resolution cores, Total PAH concentrations vary by a factor of two from 1980 to 2005 but with no particular trend with time, suggesting that the Total PAH contaminant load to the Lower Passaic River has not changed significantly over this period. An increase in Total PAH concentration is observed in the 1960s.
- Downcore profiles of pesticide compounds for the 1995 TSI cores (14 locations), including aldrin, dieldrin, Total Chlordane, and Total Endrin, were limited because of

analytical detection and quantification issues. Downcore profiles of Total DDT for the 1995 TSI cores were similar to 2,3,7,8-TCDD trends with depth.

- Based on the 2005 high resolution cores, DDE concentrations have slowly declined over the past 25 years, with the range of annual concentrations varying by a factor of two or less (Figure 13-25). Dieldrin concentrations also peaked in the 1960s with notably higher concentrations at RM11 and RM12.6. Unlike DDE, dieldrin concentrations were in decline until the period between 1987 to 1995, and since that time a significant rising trend in dieldrin concentration is observed.
- The ratio of 4,4'-DDT to 2,3,7,8-TCDD was examined to further highlight the importance of tidal mixing. In most years the ratio of 4,4'-DDD to 2,3,7,8-TCDD is uniform from RM1.4 to 12.6, except for two distinct periods (1960-1963 and 1999-2001). The first of these periods corresponds to the period of higher 2,3,7,8-TCDD concentration during the active release of 2,3,7,8-TCDD in the system. The second period is coincident with the high concentration of 2,3,7,8-TCDD observed in the high resolution cores at RM11 and RM12.6, corresponding to a localized event occurring in the upper portion of the study area in around 2000-2001.
- The 1995 metal downcore profiles showed the following: 1) No concentration trend for antimony, beryllium, or thallium due to a lack of detectable concentrations. 2) Conversely, arsenic, barium, copper, lead, and nickel showed increasing concentrations with depth, suggesting that peak loadings for these metals are probably located deep in the sediment bed, below the depth of core penetration. 3) Cadmium, chromium, mercury, and silver also showed increasing concentrations with depth; however, concentrations appear to peak in the 1960 time horizon. 4) Consistent profiles from one sampling location to another, suggesting little spatially variability and that tidal mixing is sufficient to reduce gradients in both metal loads and concentrations prior to deposition, or metal loads arise sufficiently far enough upriver that their levels in suspended solids are well mixed prior to deposition in the Lower Passaic River.
- The 2005 dated sediment core profiles for mercury, cadmium, lead, chromium, copper, lead, and nickel show that metal concentrations varied approximately one order of magnitude or less over time with peak concentrations occurring in the 1960s.

Evidence for Longitudinal Mixing

The previous sections of this narrative describe the basic observations made from the various investigations grouped according to the investigation type (*i.e.,*bathymetric study results, surface sample results, sediment coring results). In this section and the ensuing sections, the narrative will explore evidence for some of the more importance conclusions across investigations.

Beginning with evidence for the extent and speed of longitudinal mixing, nearly every sampling program provides evidence in this regard. It is observed that measurements of recently deposited sediments along the main stem of the Lower Passaic River show little or no trend in contaminant concentration with river mile between RM2 and RM12. However, above and below these river miles, sediment contaminant concentrations change rapidly. Notably these river miles correspond to the extreme ends of the salt front migration, indicating a coincidence between the region of similar recent deposition and regular salt front migration.

From the bathymetric data analysis, measurements of sediment resuspension and deposition suggest that the rates and magnitudes of these processes are similar from RM2 to RM12, with markedly higher rates of deposition below RM2 and high rates of erosion above RM12. The coincidence of this region of similar deposition and resuspension rates with the main region of the salt front migration suggests that the tidal energies play an important role in the deposition and resuspension processes over the 10 mile stretch and serve to reduce surface concentration gradients over this region. For constituents whose Upper Passaic River, legacy sediment and Newark Bay concentrations are not very different (*e.g.,* mercury, PCBs, lead), the longitudinal sediment mixing occurs sufficiently fast that essentially no gradient is observed. Even for contaminants like chromium, which has a fairly different mainstem concentration from its end members, the resuspension process is enough to eliminate any measureable gradient across this region.

Measurements of 2,3,7,8-TCDD and the 2,3,7,8-TCDD/Total TCDD ratio, specific tracers for the fine-grained sediments of the Lower Passaic River, decline rapidly with river mile upstream of RM11, suggesting that tidal mixing, as tracked by dioxin concentrations, is unable to transport Lower Passaic River contamination much beyond RM11. This is consistent with the low frequency of occurrence for the high tide salt front above RM12 (less than 7 percent of the time) and the high rates of erosion upstream, indicating that the salt front may be effectively restricted to RM12 or below and that little fine-grained sediment deposition occurs upstream of this river mile.

The dated sediment cores also show evidence of the effectiveness of mixing. For 2,3,7,8-TCDD as well as other contaminants associated with the legacy contamination of the Lower Passaic River (*e.g.,* chromium and PCBs), the dated sediment cores at RM1.4 and RM12.6 show distinctly lower concentrations over the last 25 years of deposition as compared to the three middle cores at RM2.2, RM7.8, and RM11. This evidence documents the trends in the recently deposited surface sediment back through time.

Lastly, the principal components analysis conducted as part of this investigation shows the suspended matter samples collected in December 2005 are more similar to the surface sediments of the Lower Passaic River than they are to any other external source or Newark Bay. The agreement of contaminant pattern between the suspended matter and the entire suite of Be-7 bearing sediments indicates the close link between suspended solids and the river surface and again that the river is able to keep the pool of recently deposited material relatively homogeneous and distinctly different from the external solids sources.

All of the above observations clearly support the ability of the river to smooth sediment concentration gradients over time. However, these lines of evidenced do not provide strong evidence on the time scale of the smoothing process. For contaminants with long histories and no recent major discharges, it is likely that the lack of a longitudinal gradient form RM2 to RM12 reflects both the river's impact on recent deposition as well as the "recent deposition" of decades ago supplying the resuspension of legacy sediment.

That is, the river has blended the surficial deposits that supply the legacy sediment for resuspension.

Several lines of evidence suggest the time scale of mixing. For example, the year 2000 dioxin release event near RM11 is documented in three cores, at RM7.8, RM11, and RM12.6. In each case the magnitude of the peak corresponding to the release event agrees within 10 percent, suggesting that the release event was spread over a distance of 5 miles at approximately the same time, resulting in no measureable gradient over this distance. The event is not observed in the cores well downstream suggesting that the mixing associated with this event could not completely disperse the release over the apparently short period time it was present in the river.

A second line of evidence arises from the 2,3,7,8-TCDD contamination itself. As will be further discussed later in this narrative, there is strong evidence for a second important source of 2,3,7,8-TCDD at RM11. While the gradients in 2,3,7,8-TCDD are quite evident beyond RM 2 and RM12, there is a measureable but weaker gradient across this 10 mile stretch as well. The concentration of 2,3,7,8-TCDD declines about 50 percent across this distance, accompanied by a change in the dioxin ratio, from 0.75 to 0.65. These changes are unimportant for the EMB, since the 50 percent variation in concentration is very small compared to the orders of magnitude difference between Lower Passaic River sediments and the concentrations on external solids. However, this gradient in recently deposited sediment indicates that the river cannot entirely eliminate the gradient within 6 to 12 months, the age of the recently deposited sediments.

A similar observation can be made for dieldrin, which exhibits a concentration maximum near RM 15. Between RM12 and RM2, the TOC-normalized dieldrin concentration declines about 50 percent, similar to the decline observed in 2,3,7,8-TCDD. While the decline is less than that observed from RM15 to RM12, it is still telling that the river is unable to eliminate this gradient in less than 6 to 12 months. However, the data still provide some evidence for the scale of mixing. Despite the 50 percent gradient across the

10 mile stretch, it is also evident that for RM11 to RM2, the concentration varies less than 25 percent.

The lines of evidence from 2,3,7,8-TCDD and dieldrin indicate that the river can readily achieve fairly thorough mixing on the scale of 4 to 5 miles and perhaps more on scale of less than 1 year. However, the time frame to create homogeneous sediments over a longer distance is unclear. The dated sediment cores provide the last line of evidence in this regard.

In addition to the 2,3,7,8-TCDD release at RM11 around the year 2000, the dated sediment cores also show earlier evidence of a dioxin release at this river mile. As will be discussed below, during the 1960s and early 1970s, both 2,3,7,8-TCDD and DDT were regularly discharged into the river. Since both are particle reactive, their discharges establish a ratio that cannot be changed unless another source of one or the other is added to the river. At the time, much of the 2,3,7,8-TCDD and DDT discharges were attributed to the Lister Avenue site, and the cores at RM1.4 and 2.2 indicate a single 2,3,7,8-TCDD to DDT ratio, as would be expected. During this same period, however, the cores at RM11 and RM12.6 suggest a much higher 2,3,7,8-TCDD to DDT ratio, with comparable levels of 2,3,7,8-TCDD, and a higher 2,3,7,8-TCDD to Total TCDD ratio than that observed downstream. These changes in ratio clearly indicate an upstream source of 2,3,7,8-TCDD, since there would be no other way to change these ratios. Pertinent to the mixing discussion at hand, the evidence for this discharge at RM11 disappears in the early 1970s, with a relatively rapid convergence to the 2,3,7,8-TCDD to DDT ratios seen downstream. Given the rapidity of this change, the data suggest that the river was able to greatly reduce the gradient in this ratio with river mile in roughly five years, based on the temporal resolution available from the cores.

In total, the evidence for longitudinal mixing in the Lower Passaic River is extensive. Be-7 bearing sediments are clearly mixed over distances of 4 miles or more in 6 to 12 months. Longer scale mixing is also accomplished by the river, on the scale of the RM2 to RM12 interval over a period of the order of 5 years. The implications of this mixing

are an important component of the understanding if the river, since it is clear that this mixing has served to largely eliminate local contaminant maxima as well as to spread contamination throughout the Lower Passaic River. RM12 appears to be the natural boundary for upstream transport of downstream contamination but fine-grained sediments everywhere below this river are comparably impacted. (See Chapters 10, 11, 13, 14 and 15)

Source Analysis

- The ratios of heavy metals are similar in one-mile segments in the Lower Passaic River (RM1 to RM7), suggesting that the sources of much of the metal contamination are likely upriver of RM7. These metals sources must be far enough upriver so that by the time contaminated sediments are transported to RM7 they are well-mixed, yielding consistent mass fraction patterns. Furthermore, the metal ratios for cadmium, lead and mercury above Dundee Dam compare to the main stem of the Lower Passaic. There is a difference in copper ratios between Dundee Dam and the Lower Passaic, suggesting a Lower Passaic copper source that accounts for roughly half of the copper inventory below Dundee Dam.
- The ratio of 2,3,7,8-TCDD/Total TCDD suggests that the Passaic River is an important source of PCDD into the Hudson-Raritan Estuary due to tidal mixing. The arithmetic mean for the ratio from RM2 to RM12.5 is 0.7, and the consistency of this ratio throughout the lower 10 miles of the Passaic River suggests a single source of 2,3,7,8-TCDD or mixing of unique sources in the Lower Passaic River water column by tidal action. This ratio, which is distinctly different from other inputs [i.e., atmospheric deposition and sewage discharge (<0.06)], can be used to fingerprint Lower Passaic-related polychlorinated dibenzodioxins (PCDD) contamination throughout the Passaic River and Newark Bay.
- Total DDT concentrations increase by a factor of 3 to 4 below the dam, suggesting that the contaminant load below the dam is approximately 2 to 3 times greater than the contaminant load above the dam. Furthermore, the ratio of 2,4'-DDT to the sum of all isomers averages about 0.20, which is consistent with the commercial composition of DDT that is applied agriculturally.

- Comparison of PCB congener patterns in the Dundee Dam surface sediments to corresponding PCB patterns in the Lower Passaic River indicate that Dundee Dam sediments contain higher levels of Aroclors 1254 and 1260 than the sediments of the Lower Passaic River. The difference in pattern shift suggests that while the Dundee Dam solids are supplying a significant contaminant load of heavy PCB congeners to the Lower Passaic River, a second source exists on the river that is supplying or adding a significant source of lighter molecular weight PCB congeners to the river.
- Statistical correlation analysis shows that the Dundee Dam PCB congener pattern is more closely correlated with the Lower Passaic River surface sediment congener pattern than the Newark Bay congener pattern. These results, combined with observed Total PCB concentration gradients from the Lower Passaic River to Newark Bay, suggest that the Upper Passaic River has a stronger impact on the Lower Passaic River PCB concentrations than Newark Bay and that the Lower Passaic River is likely contributing some portion of the PCB contaminant burden to Newark Bay.
- The Dundee Dam contribution for Total PCB relative to the Lower Passaic appears to have changed over time. In 1963, it appeared that the Upper Passaic River was responsible for much of the Total PCB burden of the Lower Passaic River. In the 1985-1995 period, however, the importance of this flux has diminished such that downriver concentrations increased by roughly three fold, suggesting an ongoing Lower Passaic River source of Total PCB, which may be as much as two times greater than the Upper Passaic River source.
- PAH indicator ratios used to fingerprint the PAH sources in the Lower Passaic suggest that:
    - 94 percent of the 1995 sediment samples examined had a fluoranthene plus pyrene ratio greater than 0.4, suggesting a predominantly combustion-derived source. This finding is further bolstered by the observation that the proportion of 4-ring, 5-ring, and 6-ring PAH compounds to Total PAH exceeds 0.5 in the majority of samples. The wide range of values observed for the latter ratio, 0.3 to 1, suggests the possibility of multiple combustion related sources in the system.
    - Further analysis into the combustion related sources was performed using double-ratio scatter plots established end member sources characteristic of coal tar (a by-

product of manufactured gas plants), creosote, and urban background. The Lower Passaic River PAH data suggest that two sources exist: a coal-tar related source and an urban background source. Moreover, the majority of the sediment data represent a mixture of these two sources. (Creosote does not appear to be an important PAH source in the river.)

- Another observation of the impact of tidal mixing is that the recently deposited surface sediment samples taken in the 2007/2008 sampling events have relatively constant concentrations when normalized to iron and/or TOC from RM2 to RM12. With the exception of PCB and pesticides, the concentrations of most PAHs, metals, 2,3,7,8-TCDD and Total TCDD between RM2 and RM12 are elevated and significantly different from sediments below RM2 and above RM12.
  - That said, 2,3,7,8-TCDD concentrations in the surface sediments from RM11 and RM12.6 were notably about 2 to 3 times higher than concentrations reported for the other three cores at RM1.4, RM2.2, and RM7.8 (Table 13-2). Likewise, the Total TCDD concentration for these two cores was about 2 to 3 times higher than the reported concentration in the other cores (Figure 13-6). A closer examination of the two upriver cores (RM11 and RM12.6) suggests the occurrence of a localized event occurring relatively recently, affecting only the upper portion of the Lower Passaic River. Prior to this event, the 2,3,7,8-TCDD concentrations throughout the Lower Passaic River tracked quite closely (less than a factor of two variation among the 5 cores) for the last 20 years.
  - A ratio of 2,3,7,8-TCDD/Total TCDD of 0.7 ±0.1 (±1 sigma) was calculated for surface sediment in the Lower Passaic River from both the 1995 TSI and 2005 high resolution core data (RM1.4 to RM12.6). The consistency and uniqueness of this ratio suggests either a single source of 2,3,7,8-TCDD or, alternatively, a limited number of unique sources whose discharges are mixed in the water column by tidal circulation. Moreover, the calculated ratio of 0.7 ±0.1 can be used to “fingerprint” Passaic-related PCDD contamination throughout the Lower Passaic River and Newark Bay.

The Case for Two Dioxin Sources

The evidence accumulated by this report as well as by others, documents the occurrence of a second source of 2,3,7,8-TCDD to the Lower Passaic River, centered on RM11. Based on the evidence, this source began discharging as early as the 1960s and apparently stopped or greatly diminished their discharges in the 1970s. More recently, a large discharge event in the vicinity of RM11 occurred around the year 2000. The following is a description of the main lines of evidence.

Dated sediment cores provide the strongest evidence for this source. The cores at RM7.8 and RM11 clearly document a large release of 2,3,7,8-TCDD around year 2000, more than tripling the ambient concentrations of 2,3,7,8-TCDD in the five miles. The core at RM12.6 also documents this event at the same magnitude but places it a few years later. The uniqueness of the dioxin pattern in this layer among all three cores confirms this as a single event affecting all three cores. No dioxin patterns similar to those found in the *circa* year 2000 layer have been observed since 1980, nor after the event, indicating this discharge had not been active between 1980 and *ca.* 2000, nor has it discharged since.

These same dated sediment cores show a uniquely high 2,3,7,8-TCDD to 4,4'-DDE ratio for most of the 1960s and early 1970s. Given the similarities of the geochemistries of these contaminants and the known discharges at the Lister Avenue facility, the change in the ratio of these two compounds in the upstream cores relative to the downstream ones can only occur as the result of additional 2,3,7,8-TCDD discharges in the area. The period of this discharge appear to end fairly abruptly, with the ratio of 2,3,7,8-TCDD to 4,4'-DDE becoming fairly similar throughout the river by the late 1970s, based on the core chronologies.

The 2,3,7,8-TCDD to Total TCDD ratio recorded in the dated sediment cores also provides evidence for a second source in this area. Specifically, the ratio is uniquely high in the core at RM11 for much of the 1960s and 1970s and tends to be higher than the downstream cores up to the present time. This evidence also suggests that this source are

has had a long term influence on this coring location, causing the slightly higher ratios over time.

Work conducted by Hansen (2002) on the pattern of dioxin contamination in the Lower Passaic River led him to the conclusion that a second source of dioxins was present. He based this on a principal components (PC) analysis of multiple dioxin congeners is samples obtained as part of the 1995 sediment coring efforts conducted by TSI.

The last line of evidence for this source comes from the recently deposited sediments collected in 2007. These samples document an elevated concentration as well as a higher 2,3,7,8-TCDD to Total TCDD ratio at RM10 to RM11 relative to all locations upstream or downstream, indicative of a local source.

One important consideration regarding this source is the magnitude of its discharge and its area of influence. While the source near RM11 has clearly affected local concentrations of 2,3,7,8-TCDD, the amount of sediment impacted is almost certainly less than that downstream. In particular, the estimates of 2,3,7,8-TCDD inventories in fine-grained sediments and the spatial extent of those areas in 2008 above RM8 are clearly smaller than those found downstream. In general the sediments below RM8 tend to have lower 2,3,7,8-TCDD to Total TCDD ratios, suggesting that the contamination downstream of RM8 was probably more closely connected to the downstream source. A more thorough analysis of the 2,3,7,8-TCDD to Total TCDD and the 2,3,7,8-TCDD to 4,4'-DDE ratio may provide further clues as to the relative magnitude of these sources.

Evidence for Sediment Resuspension

Like the case of longitudinal mixing, the evidence for resuspension comes from several investigations. The physical evidence for sediment resuspension has been extensively discussed above and is only outlined here (see Chapter 11). In particular, the analysis of the bathymetric data has shown that the gross rate of sediment resuspension (*i.e.,* gross rate of erosion) is greater than the net rate of deposition for much of the Lower Passaic River, but in particular, for the region between RM2 and RM12. In this river section, the

ratio of erosion to net deposition is 60:40 or 1 ½ inches of erosion for every inch of net deposition. In terms of the gross deposition, the solids deposited annually are three fifths resuspended materials derived from the river bottom and two fifths new material. At this high a fraction of resuspended solids, it is clear that the resuspending material can only be about 1.5 to 2 times more contaminated, on average, than the mean of the recently deposited sediment. Otherwise the mixture will exceed the observed concentration in recently deposited sediments. Both the longer term and shorter term bathymetric comparisons document relatively large fractions of resuspended sediments, with the shorter term comparisons yielding the higher rate, as anticipated.

The geochemical evidence for resuspension of legacy sediments is also quite clear. There are several contaminants whose concentrations in recently deposited sediments are distinctly higher than those found on solids from external source to the lower Passaic River. These contaminants include: 2,3,7,8-TCDD, Total PCBs and chromium. In each instance, the addition of Lower Passaic River legacy sediments is required to bring the mixture of Newark Bay and Upper Passaic River solids to the concentrations observed in Be-7 bearing sediments. Given the large volume of sediments deposited each year, the required volume of resuspended sediments is large as well.

Since the bathymetric observation indicate that the resuspending sediment mixture can only represent an mean that is 1.5 to 2 times greater than the Be-7 bearing sediment, this rules out several of the possible resuspension solids sources, including the relatively high concentration estimate derived form the length weighted average of the dated sediment cores. While this mixture can satisfy the chemical mass requirements mathematically, it would constitute too small a volume to satisfy the bathymetric observations. To this end, the mean concentrations of the 1995 0 to 6 inch layer were applied and found to yield a satisfactory fit in terms of both chemistry as well as sediment mixing volume. This is not to say that the layer was an exact fit but rather it is a good approximation to the average properties of the resuspending material.

The Sediment Inventory and the Importance of Deeper Legacy Sediments

As discussed throughout this report, the coincidence of the channel construction, the cessation of its maintenance and the extensive period of industrial discharges has produced a very large inventory of contaminated sediments. Based on sediment coring results and a comparison of historical construction records and current bathymetry, the region below RM8 has accumulated thick beds of contaminated sediment, over 15 feet or more in some areas. Two inventory estimates were generated for the mass of each of four contaminants (2,3,7,8-TCDD, mercury, Total DDT and Total PCBs) in the Lower Passaic River for RM0.9 to RM7. The first estimate was based on an interpolation of core measurements; the second was based on the extrapolation of the core measurements where the core did not establish the depth of contamination. The interpolated volume is considered a minimum estimate due to the uncertainties in depth of contamination. The extrapolated inventory represented an increase of 33 to 72 percent over the interpolated estimate, depending on the contaminant. The sediment volume is estimated at 5 to 8 million cubic yards for RM0.9 to RM7, with an average depth of contamination ranging from 7 to 13 feet.

The evidence from the side-scan sonar and bathymetric surveys suggests that the conditions observed in RM0.9 to RM7 also apply over the area of RM0 to RM8. To estimate the sediment volume from RM7 to RM8 and from RM0 to RM0.9, the conditions in the one-mile lengths of river adjacent to these stretches were extrapolated. These calculations were performed for mercury to obtain the total volume of contaminated sediment as well as the entire mass of mercury, because mercury is one of the oldest (deepest) contaminants. They were also performed for 2,3,7,8-TCDD to obtain an estimate of the 2,3,7,8-TCDD inventory for the lower 8 miles in total. The estimated volume of contaminated sediment from RM0 to RM8 thus calculated approaches 10 million cubic yards. This represents an increase of 25 to 50 percent over the original estimates of contaminated sediments in RM0.9 to RM7. The inventory of mercury in the sediments between RM0 to RM8 is estimated at 50 metric tons, and the inventory of 2,3,7,8-TCDD is estimated at 33 kilograms.

The extensive deposition below RM8 is estimated at over 8 million cubic yards (Mcy) of contaminated sediment, containing over 37 metric tons of mercury, 8 metric tons of PCBs and most importantly to this system, over 29 kilgrams of 2,3,7,8-TCDD. Peak concentrations of these contaminants range from 10 times the current concentration for mercury to nearly 1000 times for 2,3,7,8-TCDD. Thus these materials represent a very large, highly contaminated reservoir of relatively recent (post-1950) sediments.

The inventory above RM8 is appreciably smaller, due largely to its lack of thick, fine-grained sediment deposits. This area was studied as part of the 2008 sediment core collection program, a more limited survey than that conducted in 1995. Nonetheless, the results show good consistency and provide a reasonable basis for estimating the contaminant inventories in fine-grained sediments above RM8. As a percentage of the total inventory below RM8, the inventory above RM8 is generally less than 3 percent for Total DDT and 2,3,7,8-TCDD, major contaminants associated with Lower Passaic River discharges. For Total PCBs and mercury, the sediment inventory estimate above RM8 is larger, at 24 and 8 percent respectively. This is somewhat expected for these compounds since they have historical loads originating from the Upper Passaic. In total, the lower 8 miles of the river contains roughly 97 percent of the 2,3,7,8-TCDD inventory for the entire Lower Passaic River and 80 percent or more of the other three contaminants examined.

Inventories of these four contaminants were shown to correlate, indicating that their inventories coincide in space and are consistent with the anticipated geochemical behavior of the compounds. 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. Contaminant inventories vary along the length of the Lower Passaic River with maximum values occurring near RM1 to RM2, RM3 to RM4, and RM6 to RM7. That said, the coring data indicate a high degree of 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.

One of the more important observations concerning these reservoirs of contaminant mass is the local degree of variability in the sediment inventory. In general, the inventories exhibit a high degree of variability at any river mile from RM1 to RM15 with little trend to the mean or median. The inventories of all four contaminants examined generally trend together, indicating that for the most part, inventory is largely a function of the local deposition rate and not proximity to the source. 2,3,7,8-TCDD is a good example of this. As discussed above, there is clear evidence for two sources of 2,3,7,8-TCDD to the river. An examination of the sediment inventory as a function of river mile does not exhibit any significant trend that can be attributed to the source outfalls. Rather, the inventory of 2,3,7,8-TCDD largely coincides with the inventories of mercury, DDT and PCBs, indicative of the relationship between deposition rate and inventory for the Lower Passaic River. In particular, the shallower fine-grained sediment deposits above RM8 are characteristically lower in all contaminants, reflecting the thinner sediment deposits and by inference, the lower rate of deposition above RM8 in general.

A median test was performed to statistically compare the MPA estimates above RM8 with the MPA estimates based on measured and extrapolated data below RM8. For all four evaluated contaminants the graphical comparison indicates that the median estimated MPA for individual coring locations below RM8 is consistently greater than that above RM8. The median test performed on the MPA below RM8 (estimated using the extrapolated cores) and above RM8 showed that the median for below and above RM8 is statistically different for all contaminants.

Based on the thickness of deposition in the lower 8 miles, it is clear that high rates of deposition existed for quite some time. However, rates over the last 18 years have clearly slowed, with high average rates of deposition (greater than 1 inch per year) still in evidence only downstream of RM2. For the region between RM2 and RM12, deposition rates are significantly slower than this, averaging 0.3 inches per year for the period 1989

to 2007. The slow rates of deposition above RM2 indicate that in these regions the existing sediment inventories are not being rapidly buried. In fact, it is likely that the slow rates of deposition and the active reworking of the river surface (as documented by the bathymetric surveys) are responsible for the continued presence of high concentrations at the river's surface layer despite the passage of time since release.

The observation of extensive sediments inventories created by high deposition rates that have since declined provides a potential explanation for the continued presence of high contaminant concentrations at the river's surface. As recently as 2008, concentrations of 2,3,7,8-TCDD in excess of 10 µg/kg (10,000 ng/kg) have been found in the 0 to 6 inch layer of the sediments. There many such examples in the 1995 TSI core collection data set as well. It can be inferred from these observations that the lack of sediment deposition along with ongoing reworking of the river bottom serves to routinely expose these older sediments, adding their contamination to the pool of sediments available for resuspension. This condition would suggest that the river bottom elevation is approaching steady state, an observation also suggested by correlation coefficients (R). Chant of Rutgers University (Chant, 2005). Under a steady state setting, the rates of contaminant concentration decline would be expected to slow, an inference consistent with the most recent observations from the dated sediment cores. In this condition, the regular re-exposure of older, more contaminated sediments would prevent a more rapid recovery, thus yielding the long half lives estimated from the dated cores. (See Chapters 13, 16, and 20.)

Impact beyond the Passaic: A Mass Balance for Newark Bay

The impacts from the sediments of the Lower Passaic River are not limited to the river itself but also impact downstream areas. Although the EMB documents the occurrence of solids transfer from Newark Bay to the Lower Passaic, there is also direct evidence for the transfer of Lower Passaic River contamination to Newark Bay. Because Newark Bay is connected tidally with the Lower Passaic River, it was necessary to evaluate the impact of Passaic-contaminated sediment on the bay. Mass balance estimates for the bay were prepared and involved the simultaneous balancing of solids, 2,3,7,8-TCDD, and Total

TCDD. The impact of the Lower Passaic River can be estimated from the level of 2,3,7,8-TCDD in the bay, tagged with the dioxin ratio that is characteristic of the river's contamination. The mass balance for 2,3,7,8-TCDD indicates that the total mass of 2,3,7,8-TCDD entering Newark Bay from the Lower Passaic River is approximately 9 grams/year, resulting in an mean Newark Bay surface concentration of 0.05 µg/kg. The concurrent solids balance shows the Lower Passaic River sediments to comprise approximately 11 percent of the solids load to Newark Bay and approximately 70 percent of the 2,3,7,8-TCDD accumulating in the bay. No other single source delivers more than 15 percent of the total 2,3,7,8-TCDD load (See Chapter 21).

A mercury mass balance for the bay was also completed as part of this analysis. In the previous estimate, the results suggested that a large source of mercury to the bay was unaccounted for. In this analysis, the use of Be-7 bearing sediment concentrations yielded a substantially lower estimate of the mean mercury concentration in recent deposition in the bay. The previous data used were simply surficial sediment samples but not shown to be Be-7 bearing. The revised mass balance calculations indicated that the total mass of mercury entering Newark Bay from known source areas is 230 kilograms per year, which yields an estimated mean Newark Bay sediment concentration for mercury of 1.35 mg/kg. This calculated concentration is nearly matches the measured mean Newark Bay sediment mercury concentration of 1.37 mg/kg. Given the close agreement between model and measured concentrations, the mercury mass balance is considered closed and no missing source of mercury is identified by this analysis. Of the annual load of mercury to the bay, the Lower Passaic River is responsible for about 35 grams per year or 15 percent of the annual load to the bay (See Chapter 21).

The conclusions from these analyses are as follows:

- The solids accumulating in Newark Bay (approximately 343,000 cubic yards) are predominantly from the Kills (~83 percent), followed by the Passaic River with a contribution of 11 percent.

- While the Kills are the dominant source of solids, the Lower Passaic River is the dominant source for 2,3,7,8-TCDD, delivering approximately 68 percent of the total

load. Contributions of 2,3,7,8-TCDD from CSOs and SWOs to the bay are insignificant (0.2 percent).

- Application of the solids balance obtained for the dioxins to mercury accommodated the sources and sinks of mercury within 1 percent. For mercury, the Kill van Kull remains the largest source, with a contribution of 57 percent, followed by equal contributions (16 percent) from the Lower Passaic and Arthur Kill. The Hackensack River and the CSOs/SWOs contribute 7 percent and 3 percent of the mercury burden in the bay, respectively.

Biological Uptake

Biological uptake of contamination from the Lower Passaic River represents an important pathway for human exposure as well as an important pathway for impacts to biota. Using the large data sets available for three animal species (blue crab, mummichog and white perch), the spatial distribution of animal body burdens with river mile were examined and the tissue-sediment ratio (TSR) and a biota-sediment accumulation factor for each species were estimated for 2,3,6,8-TCDD and mercury. In general, significant trends were not observed between the species' tissue contaminant concentration and river mile. The general lack of significant trends is consistent with the lack of a significant trend observed for the contaminant concentrations in sediments with respect to river mile. As well, it is reflective of the mobility of these species and their consistent exposure to the contaminants throughout the lower seven miles of the river. Although the mobility and extent of area covered by the blue crab is more limited when compared to the mummichog and white perch, this was not a significant factor for exposure with respect to river mile over a five year period.

One noted exception to the above observations, the mummichog data showed a significant trend, exhibiting a factor of two decrease in 2,3,7,8-TCDD tissue concentration with decreasing river mile in RM7 to RM1. (The mummichog mercury tissue concentration did not show significant correlation with river mile.) It is interesting to note that 2,3,7,8-TCDD concentrations in Be-7 bearing surface sediments exhibit a factor of two decline between RM11 and RM1, which corresponds well to the observed

factor of two decline in mummichog tissue concentrations from RM7 to RM1 for this contaminant (See Chapter 22).

The TSR values were less than one for both 2,3,7,8-TCDD and mercury, indicating that although the contaminant concentration is greater in the sediment than in the tissue, the contaminants are still impacting the tissues of biota from three trophic levels, represented by blue crab, mummichog and white perch. Decreasing trends in TSR were observed in blue crab and white perch for 2,3,7,8-TCDD over the five-year period; however, the small sample sizes available for this analysis must be taken into account before any significant conclusions can be made with respect to decreasing 2,3,7,8-TCDD exposure over time. For blue crab, the 1995 and 2000 datasets were based on only 6 and 7 tissue samples, respectively, whereas in 1999 there were 56 to 65 sample points. For white perch, no tissue data were available for 1995, and the 1999 and 2000 datasets had 29 and 35 samples, respectively. An attempt to normalize tissue concentration to lipid content and sediment concentration to TOC using the Biota-Sediment Accumulation Factor (BSAFs) did not reveal any additional information to augment the observations made in the tissue concentration versus river mile or TSR analyses.

Implications for the Future: Contamination in the Lower Passaic River under Monitored Natural Recovery (MNR) and Three Remedial Options

The extensive analyses described in this report were primarily intended to develop a thorough understanding of the contaminant fate and transport within the Lower Passaic River. As such, these analyses were assembled here to create a comprehensive conceptual site model of the river and its contaminants, which has been briefly outlined in this summary narrative. The conceptual site model described herein has been able to draw upon many lines of evidence to document the importance of the legacy sediments, the existence of 2 dioxin sources, the effectiveness and mechanism of longitudinal mixing, the current levels of contamination, the history of discharges to the river, the connection with Newark Bay, the magnitude of the sediment inventory and its distribution throughout the river. These components of the CSM form the basis for forecasts of future

conditions in light of several remedial options. As part of the forecast analysis, three future conditions were simulated, as follows:

- No Action/Natural Recovery
- Remediation of the Primary Erosional/Depositional Zones (representing isolation of one third of the river bottom)
- Bank-to-Bank Remediation of RM0 to RM8

Each of the active remediation options considered here will have significant impacts on the contaminant loads in the sediments in the Lower Passaic River following their estimated completion in 2018, when compared to the No Action option. Though less dramatic, all contaminants have a better long-term (2075) forecast concentration for the active remediation alternatives than No Action. The degree of improvement in the long term sediment concentrations over No Action is largely a function of the source of the contaminant. Sediment dioxin concentrations, which originate largely from an internal source (resuspension), are most dramatically reduced by the active remediation options. Contaminants such as PAH, which have a significant external source, are impacted immediately upon remediation of the surface, but the improvement wanes as contaminated sediments from external sources are deposited on top of the clean surface and subsequently may resuspend and continue mixing with the river's solids load.

There is a significant improvement in long term contaminant concentrations in the biologically active zone (*i.e.,* top six inches of the sediment) for the RM0 to RM8 remedial option over the Primary Erosional Zone and the Primary Inventory Area remediation alternative. The RM0 to RM8 remediation alternative isolates more than twice the erosional silt area than the other and its effect on the contaminant concentrations is marked. 2,3,7,8-TCDD, the main driver in the risk assessment, experiences the greatest drop in concentration for each remediation scenario (see Chapter 20). The RM0 to RM8 remediation alternative also provides substantive short-term benefits for several contaminants. Specifically, for several COPCs, surface concentrations remain below the PRGs for as much as 30 years after remediation, providing at least a temporary respite from these contaminants.

Narrative Summary

In summary, this Comprehensive Conceptual Site Model represents the integration of a wealth of information on the Lower Passaic River, its physical setting and its contaminant burden. Multiple lines of evidence were used to characterize many of these features, yielding well founded precepts about the river and its behavior. The newest data permitted better resolution of the time estimates for longitudinal mixing, suggesting two time intervals and distances for mixing; distances of 5 miles can be well mixed over periods of 12 months or less while longer distances appear to require several years. These mixing scales are responsible for the high degree of agreement among Be-7 bearing sediments that is characteristic of the RM2 to RM12 region of the river

The main reservoir of contaminated sediments was shown to fall below RM8, with inventories upstream of this river mile, generally shallower and less massive. Bathymetric evidence documented the extensive cycling of suspended matter and provided a set of physical measurement to constrain the ratio of resuspension to net deposition. Notably, the ratio is greater than unity. Resuspension of fine-grained sediments was shown to occur primarily downstream of RM8, with this region responsible for 85 percent or more of the 2,3,7,8-TCDD-contaminated fine grained sediments. The upriver most extent of 2,3,7,8-TCDD contamination was shown to be RM12, although other contaminants clearly exist beyond this location. Also of note, at least 2 lines of evidence exist to document a second source of 2,3,7,8-TCDD to the Lower Passaic River, one whose dioxin ratio is similar but slightly higher than the ratio observed in much of the river.

The EMB successfully synthesized the COPC concentrations in recently deposited sediments based on the known levels of contamination in the external sources to the Lower Passaic plus a significant sediment resuspension flux. For the most part, the calculations bore out the hypotheses of the conceptual site model in this regard, such as the importance of resuspension and the loads originating from the Upper Passaic River. The solids contribution to the Lower Passaic River from Newark Bay was a significant

component of the solids balance for the Lower Passaic River, but a comparable mass of solids at Lower Passaic River sediment concentrations must also be transported to Newark Bay on an annual basis. The associated contaminant transport from Newark Bay to the river was minor (20 percent or less for all contaminants except mercury), which confirmed an original important premise of the CSM, *i.e.,* Newark Bay is not an important source of contamination to the Lower Passaic River. The EMB results combined with the dated sediment core chronologies enabled the calculation of the impacts of two remedial options relative to No Action and showed a substantial improvement in surface sediment concentrations of 2,3,7,8-TCDD as a result of remediating RM0 to RM8. Based on the analysis, No Action will require more than 100 years to achieve a comparable reduction in the surface concentrations for nearly all COPCs in the Lower Passaic River.