BERGEN COUNTY UTILITIES AUTHORITY

FINAL PROJECT REPORT

IMPACT ANALYSIS OF SEWAGE TREATMENT PLANT DISCHARGES ON THE WATER QUALITY OF THE LOWER HACKENSACK RIVER

APPENDIX A - PART II

NUTRIENT DYNAMICS OF THE TIDAL MARSHES AND MUDFLATS OF THE HACKENSACK RIVER ESTUARY

Submitted to

Clinton Bogert Associates

SEPTEMBER 1990

Najarian Associates, L.P.
Eatontown, New Jersey

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NUTRIENT DYNAMICS OF THE TIDAL MARSHES AND MUDFLATS OF THE HACKENSACK RIVER ESTUARY

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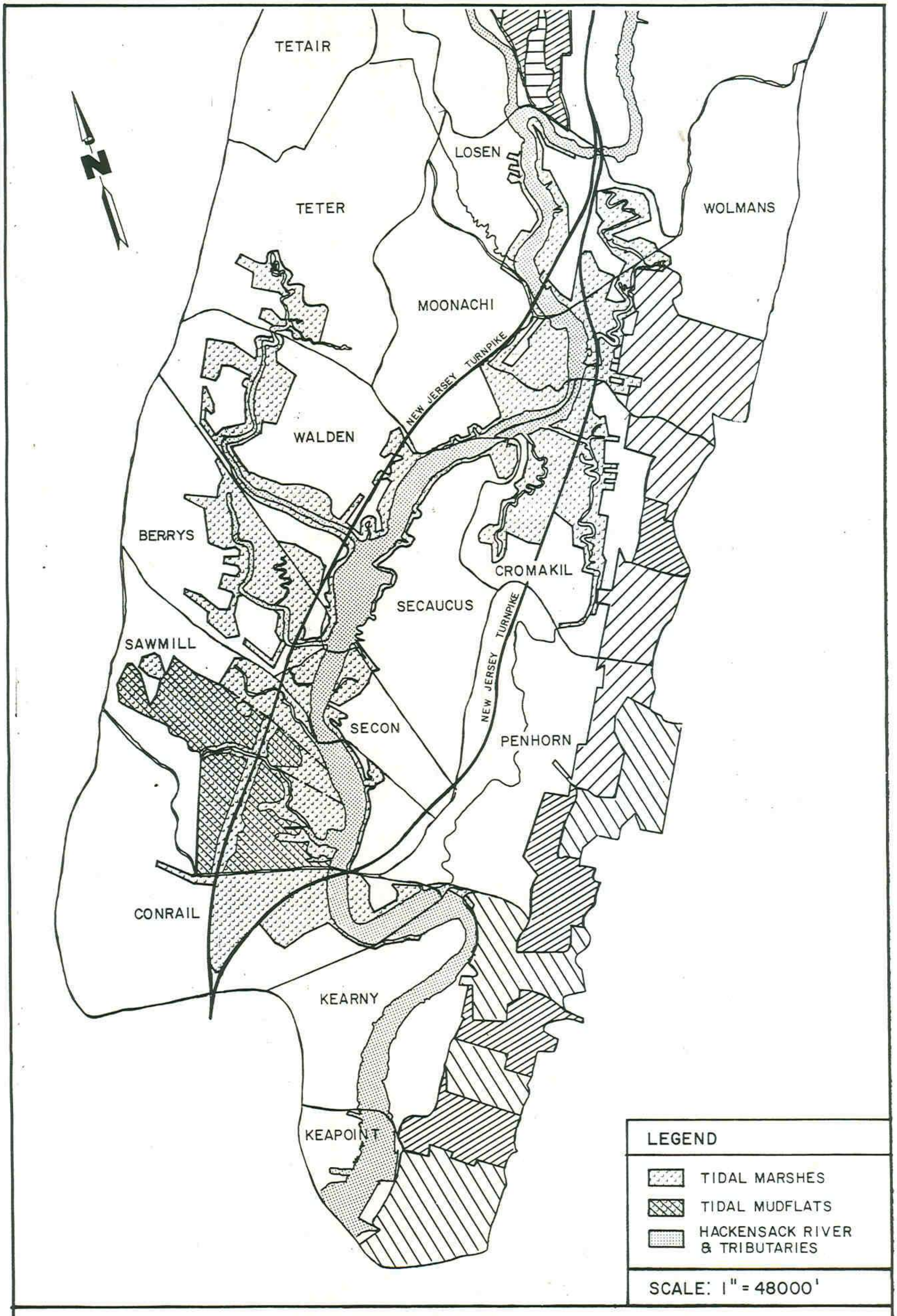

FIGURE 1.2 : TIDAL WETLANDS IN THE HACKENSACK RIVER BASIN

COMPARISON OF NET MASS — S14 TO S15

S14 - JULY 1989

	Flow (cfs)	Bod5	NH3	NO3	NO2	TKN	Total N NO2+3+TKN	DO	Sal (ppt)	TPO4	Ch-a	TSS
NET FLUX - CYCLE 1 07/26/89 21:00-08:59 Net Mass (lbs/cycle)	-535885	-471	-89	295	41	-584	-249	714	-489593	-25	13074	-13144
NET FLUX - CYCLE 2 07/26/89 09:00-21:59 Net Mass (lbs/cycle)	536541	654	47	-6	39	17	50	-1614	146779	31	-10396	5770

S15 - JULY 1989

	Flow (cfs)	Bod5	NH3	NO3	NO2	TKN	Total N NO2+3+TKN	DO	Sal (ppt)	TPO4	Ch-a	TSS
NET FLUX - CYCLE 1 07/26/89 21:00-08:59 Net Mass (lbs/cycle)	-333311	-189	-9	25	26	-228	-177	391	-135850	-54	-2363	-20044
NET FLUX - CYCLE 2 07/26/89 09:00-21:59 Net Mass (lbs/cycle)	341955	96	-35	9	26	533	567	-548	-42683	20	4457	-9965

NET CHANGE IN MASS—JULY—S14-S15

	Flow (cfs)	Bod5	NH3	NO3	NO2	TKN	Total N NO2+3+TKN	DO	Sal (ppt)	TPO4	Ch-a	TSS
CYCLE 1	-202574	-282	-80	270	15	-356	-71	322	-353743	29	15437	6900
CYCLE 2	194586	557	83	-15	13	-517	-518	-1067	189462	11	-14853	15735
NET	-7988	275	3	255	28	-873	-589	-744	-164281	40	584	22635

****

AUGUST DATA

S14 - AUGUST 1989

	Flow (cfs)	Bod5	NH3	NO3	NO2	TKN	Total N NO2+3+TKN	DO	Sal (ppt)	TPO4	Ch-a	TSS
NET FLUX - CYCLE 1 08/07/89 13:00-18:59 Net Mass (lbs/cycle)	729170	513	87	-64	45	650	631	-350	-1164351	238	238	-11700
NET FLUX - CYCLE 2 08/08/89 19:00-06:59 Net Mass (lbs/cycle)	-681182	43	93	-72	-15	238	150	272	-74107	-18	1535	-1982

S15 - AUGUST 1989

	Flow (cfs)	Bod5	NH3	NO3	NO2	TKN	Total N NO3+TKN	DO	Sal (ppt)	TPO4	Ch-a	TSS
NET FLUX - CYCLE 1 08/07/89 13:00-18:59 Net Mass (lbs/cycle)	411971	227	52	46	-3	-137	-94	-374	405648	135	-2917	-4602
NET FLUX - CYCLE 2 08/08/89 19:00-06:59 Net Mass (lbs/cycle)	-399007	156	-128	-99	19	-1	-81	422	-221576	-29	1484	10558

COMPARISON OF NET MASS— AUGUST DATA—S14-15

	Flow (cfs)	Bod5	NH3	NO3	NO2	TKN	Total N NO2+3+TKN	DO	Sal (ppt)	TPO4	Ch-a	TSS
CYCLE 1	317199	285	35	-109	48	786	725	24	-1569999	103	3155	-7098
CYCLE 2	-282175	-113	221	26	-34	239	232	-150	147469	11	51	-12540
NET	35024	172	256	-83	14	1025	956	-125	-1422530	114	3206	-19638

****

1. INTRODUCTION

The Hackensack River and its tributaries drain a 197-square mile watershed. The upper, freshwater portion contains a number of reservoirs which supply potable water to northern New Jersey. The Oradell Reservoir serves as the head of tide for the Hackensack River Estuary. The estuary extends about 22 miles from the Reservoir to Newark Bay, draining approximately 84 square miles. Figure 1.1 shows the Hackensack River watershed.

The water quality of the lower Hackensack River is effected by various point and non-point sources of pollutants. This study has provided an in-depth assessment of the major pollutant sources within the lower Hackensack River Watershed and has developed strategies for water quality enhancement of the river. The overall approach was the adaptation of appropriate hydrodynamic and water quality models to the River and its watershed. Details of the modeling effort are described in Appendix A, Part 1 of this study.

The dominant ecological feature of the tidal Hackensack River is the approximately 2,500 acres of tidal wetlands which occupy the Hackensack Meadowlands and surrounding areas. Based on studies of their ecological functions, tidal wetlands are thought to influence the nutrient dynamics of their flooding waters. The water quality in the lower Hackensack River may be affected by these extensive wetlands, particularly with regard to nutrient release or uptake. Therefore, an assessment of the nature and magnitude of the nutrient fluxes in these tidal wetlands was required as input to the water quality model for the estuary. However, the ecological research community is not in agreement as to the magnitude or direction of such fluxes and the important factors regulating nutrient exchange in estuaries are still under investigation.

Therefore, no data were available to estimate the magnitude of nutrient fluxes between the tidal wetlands and the estuarine Hackensack River. This study was conducted to assess the nutrient dynamics in the tidal wetlands of the Hackensack estuary and provide loading estimates for input to the water quality model of the estuary.

1.1 ECOLOGICAL HISTORY OF THE HACKENSACK MEADOWLANDS

The lower Hackensack River Basin is underlain by the sedimentary sandstones and shales of the Newark Group. The River valley was scoured by glaciers, and the retreat of the last glacier deposited a layer of glacial till which is composed of mixed sand, gravel and clay. Layers of peat and organic soils cover the glacial deposits in the tidal wetlands areas. Further details regarding the characteristics of the lower Hackensack River and its watershed are provided in Chapter 2 of Appendix A, Part 1 of this report.

The tidal wetlands of the Hackensack Meadowlands have been affected by human activity for over three centuries. Historically, the basin was once the site of one of the largest Atlantic White Cedar (Chamaecyparis thyoides) bogs on the eastern seaboard. Early Dutch settlers harvested the cedar for building materials, diked and drained the wetlands, and used the land for agriculture. In the mid-nineteenth century, land companies drained the marshes to the north of the existing meadowlands, particularly in the areas surrounding Berry's Creek. Later, local mosquito control commissions tide-gated, diked and drained enormous areas of cedar bog and emergent marsh. The subsequent dry soil conditions eliminated most of the remaining cedar stands. Increasing acreage of natural salt marsh was changed to freshwater marsh and to uplands. In the uplands, the peat eventually sank as it dried, leaving the elevation of the soil surface below sea level (State of New Jersey, 1984).

In 1922 the Oradell Dam was constructed to impound the upstream, fresh water portion of the Hackensack River at New Milford. This restricted much of the fresh water flow in the river and salt water intruded into the estuary, completely altering the salinity regime of the system. The growth of coastal commerce required the dredging of the Hackensack River channel which changed the estuarine hydrodynamics. The once shallow estuary became a deeper, muddy tidal river fringed with marshland, in which fresh and tidal flows were controlled by human activity (State of New Jersey, 1984).

Phragmites australis, a pollution-resistant and somewhat salt water tolerant grass, invaded most of the diked and tidally flowed areas in the basin. The optimal location for Phragmites australis is at elevations above mean high water. A hurricane in 1950 broke many dikes and tidegates, re-opening much of the reclaimed, but low-lying, land to tidal inundation. In particular, the Sawmill Creek subbasin was flooded regularly and vast mudflats formed in areas where the original peat had sunk below sea level. Over the four decades since the hurricane, salt marsh cordgrass (Spartina alterniflora) has become a significant component in the wetland community in the Sawmill Creek area, slowly invading the shallow mudflats. Spartina alterniflora has also colonized areas where stands of the once dominant Phragmites australis have died off due to prolonged inundation and higher salinities. However, Phragmites australis has survived in areas where it might not be able to colonize and has not been out competed by Spartina alterniflora in all portions of Sawmill Creek (Kraus and Smith, 1986).

The dynamic nature of the Sawmill Creek ecosystem is demonstrated by the change in vegetation observed in its wetlands over the past forty years. Table 1.1 summarizes data from Kraus and Smith (1986) for the Wildlife Refuge in Sawmill Creek. In 1989 Najarian Associates, L.P. calculated the acreage occupied by each ecological community within the entire Sawmill Creek system with cooperation from the Hackensack Meadowlands Development Commission (HMDC). At that time, mudflats occupied ± 780 acres; Spartina alterniflora, ±131.acres; and Phragmites australis, ± 279.8 acres. Clearly, the 1989 analysis encompassed a larger area than that studies by Kraus and Smith and so the 1989 figures are not directly comparable to those provided in Table 1.1.

TABLE 1.1: Acreage Occupied by Three Ecological Communities over Time in The Sawmill Creek Basin

YEAR	MUDFLAT	MARSH S. Alterniflora	MARSH P. Australis
1950	0.0	0.0	589.0
1963	490.3	1.8	96.9
1972	410.0	68.8	110.2
1985	402.2	74.4	212.1

Source: Kraus and Smith, 1986 and Najarian Associates, L.P.

Another example of ongoing change in the Hackensack Estuary is a marsh renovation project in Mill Creek. The renovation consists of lowering the marsh surface elevation, removing Phragmites australis, and planting Spartina alterniflora. Clearly, through natural and human-influenced processes, the composition of the tidal wetland community in the estuary continues to evolve (Kraus and Smith, 1986).

In 1989 the Hackensack River estuary contained approximately ± 2,543 acres of tidally inundated wetlands of which ± 2,240 acres were Phragmites australis, ± 298 acres were Spartina alterniflora, ± 9 acres were other tidal wetland plants such as Spartina patens, Scirpus validus, Pluchea camphorata, and ± 780 acres were mudflats (in the Sawmill Creek basin). Figure 1.2 illustrates the distribution of tidal wetlands and mudflats in the Hackensack River estuary. Table 1.2 lists the acreage of tidally inundated wetlands (maximum elevation of 4.0 feet above mean sea level NGVD) and mudflats in the Hackensack River estuary listed by subcatchments used in the study (see Appendix A, Part 1 of this study for description of the Model segmentation).

TABLE 1.2: Area Occupied by Tidally Inundated Wetlands and Mudflats in the Hackensack Meadowlands by Species (in ACRES)

Model Drainage Subbasin	Phragmites	Spartina alterni-	Spartina	Scripus	Pluchea	Total
Berrys	225.1	5.4	1.3	-	-	231.8
Conrail	292.5	4.9	0.9	-	3.7	298.3
Cromakil	331.6	118.7	-	-	-	450.3
Kearny	3.3	0.8	-	-	-	4.1
Losen	193.1	5.4	-	0.9	-	199.5
Moonachie	125.7	5.8	-	-	-	131.5
Penhorn	2.3	0.0	-	-	-	2.3
Sawmill	285.7	131.8	0.8	-	-	418.3
Secaucus	44.6	4.7	-	-	-	49.3
Secon	114.8	3.3	1.4	-	-	119.5
Teter	78.3	0.0	-	-	-	78.3
Walden	281.0	11.1	-	-	-	292.1
Wolmans	262.3	5.7	-	-	-	268.0
Total:	2240.2	297.6	4.4	0.9	3.7	2543.1

*Subcatchments as defined for use in the DNM Model in Volume I of this Report.

1.2 NUTRIENT DYNAMICS AND PROCESSES IN TIDAL WETLAND ECOSYSTEMS

Tidal wetland systems have generally been assumed to be highly productive systems, providing nutrients that support the productivity of estuarine and coastal waters. However, as described in Section 1.3, research into the nature and magnitude of such exchanges has provided more questions than it has answered. The following paragraphs summarize the current theory regarding nutrient dynamics in tidal wetlands.

Tidal marshes and mudflats are dynamic systems that, by their nature, must accrete at a rate greater than or equal to the rise in sea level in order to survive. Thus, over the long term, most tidal wetlands are sinks for suspended sediments. Younger coastal wetland systems expand rapidly, whereas older systems tend to be more stable and may eventually shrink in size if expansion is impossible, such as along the rocky coast of New England.

The Hackensack Meadowlands, particularly the Sawmill Creek subbasin is a young, evolving ecosystem. As described in the previous section, Spartina alterniflora is colonizing the vast mudflats and replacing Phragmites australis in many areas of the estuary. The northern section of the Meadowlands, dominated by Phragmites australis, is also accreting at a rapid rate (approximately 1 inch per year). As accreting systems, these marshes would tend to act as net sinks of suspended sediments to which nutrients may be adsorbed (HMDC, 1989). Marshes also accrete due to build-up of organic matter formed in situ. This organic matter may also be a sink for nutrients.

The movement of tidal waters over the marsh surface acts to physically aerate the water. It is reasonable to assume that this is the most important source of dissolved oxygen (DO) to the tidal waters flooding the marshes. In addition, photosynthetically active plants and associated algae uptake nutrients and produce oxygen during daylight hours of the growing season. This oxygen enters the water column as DO when the marsh is flooded. At night plants consume oxygen during photorespiration but this sink of DO is usually relatively small compared to the production of oxygen during the daytime. Thus, marshes often act to export DO, particularly during the growing season.

The nitrogen cycle in a marsh is complex and the nature and magnitude of each component is only partially understood. Bacterial nitrogen fixation ($N_2 \rightarrow$Organic-N) in the rhizosphere ("root atmosphere") is the dominant process in the nitrogen cycle in marshes. When plants senesce in a marsh, the above-ground components become detritus which are a source of inorganic nitrogen to the estuary. The below-ground components decompose, are stored in the sediments and are recycled during the following growing season. Denitrification ($NO_3 \rightarrow N_2$) also occurs in marsh sediments and results in a loss of inorganic N from the marsh to the atmosphere. Some dissolved inorganic N, as NH_3-N or NO_3-N, is periodically released from the marsh through porewater losses at low tide, leaching from leaves and stems during senescence, and surface runoff during storm events.

Dissolved organic N is also lost from senescing plants. The source of N-nutrients for the plants exists in the pool of sediment N, accumulated from sedimentation (water column), decomposition (recycled plant material), and nitrogen fixation (atmosphere). Although some nutrient exchange with the water column does occur, marshes are predominantly closed systems acting as nitrogen transformers as the plants utilize remineralized nutrients year after year (Howes et al., 1986). In general, marsh vegetation tends to import inorganic nitrogen and export organic nitrogen (Whitney, 1989; Wolaver et al., 1983). In a nutrient-rich system like the Hackensack River estuary, the nutrient dynamics may be very different.

Mudflats, characterized by extensive, unvegetated sediments and associated algae and bacteria, have a different nutrient exchange regime than marshes. The large surface area exposed at low tide allows direct gas exchange to take place at the sediment surface for significant periods of time. Nitrogen fixation is a minor process in mudflats because of the lack of a rhizosphere habitat for the nitrogen-fixing bacteria. Denitrification is more important in mudflats because of the large resident population of bacteria in the anaerobic soils, and because it is not competing with plant uptake of inorganic N. Photosynthetic algae and bacteria may contribute significant amounts of DO to the water column. Additionally, sheet movement physically aerates the water column as the tides move across the large surface area of shallow mudflats (Seitzinger, 1987).

1.3 SUMMARY OF LITERATURE ON WETLAND-ESTUARINE AND MUDFLAT-ESTUARINE NUTRIENT EXCHANGE

Numerous researchers have measured nutrient exchange between estuaries and adjacent marshes and mudflats over the past thirty years. However, no consensus has been reached regarding the roles of marshes and mudflats in the nutrient dynamics of estuaries. One of the major reasons is that the estimation of these dynamics from direct measurements of wetland-estuarine nutrient exchange has proven to be extremely difficult. Problems encountered in long-term net flux measurements range from complex estuarine hydrodynamics to site specific marsh ecosystem dynamics. The most critical component of flux estimation is obtaining accurate water exchange measurements, since the calculation of net mass transport is based upon these data. Several different approaches have been used to obtain correct water flux measurements, including current meters, tide height and hypsographic curves, bathymetry, or others. None have proven entirely satisfactory in all situations.

In addition to different flow measurement techniques, sampling intensity and duration vary widely in the literature. Sampling methods vary from measurements taken every half-hour over one tidal cycle to those taken every four-hours over four cycles. The interval between sampling events also varies from weeks to months. The vast differences in methodology used by researchers in water flux and nutrient flux estimates may explain some of the variation in the results from these studies and makes it very difficult, if not impossible, to compare results from different estuarine ecosystems. Site-specific hydrodynamic, biological and water quality conditions further complicate such comparisons.

Nixon (1980) has written an excellent summary of the results of flux research completed between 1963 and 1979. Since that time, approximately ten additional studies have been published. Tables 1.3 and 1.4 summarize the research to date on marsh-estuarine and mudflat-estuarine nutrient dynamics and provide the authors descriptions of seasonal and annual estimates of net import, export, or lack of exchange of nitrogen-series nutrients. Many of these studies included year-round data, however only the July, August and November, and Annual flux estimates of inorganic nitrogen are presented here for the purpose of comparison with the data obtained in this study.

The results from flux studies on marsh-estuarine interactions indicate that the dynamics of ammonia (NH_4) and nitrate (NO_3) exchange in salt marshes are variable and do not appear to be correlated with salinity. Although most of the studies reported a net annual import of total inorganic nitrogen (which includes dissolved and particulate inorganic nitrogen), seasonal export of NH_4, NO_2 or NO_3 often occurred. Welsh (1980), in Connecticut, and Woodwell (1979), in New York, found export of NH_4 in the summer and import in the winter, while Stevenson et al. (1976) and Heinle and Flemer (1976), both in Maryland, and Valiela et al. (1978), in Massachusetts, reported import of NH_4 in the summer and export in the winter. Whiting (1989), in South Carolina, reported import of NH_4 throughout the year. In general, when researchers found import of inorganic nitrogen, they found a concomittant export of organic nitrogen, particularly with the ebbing tide.

Research in the Hackensack River Estuary by Mattson and Vallario (1976) (not included in the summary tables because total nitrogen was not reported by nitrogen species) indicated that the estuary as a whole exported total nitrogen (inorganic and organic nitrogen) in the summer and in the winter. However, the upper section of the estuary near Mill Creek showed a net import of total nitrogen, while the Sawmill Basin showed a net export of total nitrogen. The net export in the lower section of the estuary was attributed to nutrient sources from sewage treatment plants, industrial overflow, and landfills. Marshes, in general, appear to act as nitrogen transformers, importing dissolved inorganic nitrogen and exporting dissolved and

TABLE 1.3: SUMMARY OF RESEARCH ON SEASONAL & ANNUAL NUTRIENT FLUX BETWEEN TIDAL MARSHES AND ESTUARINE WATERS (E = EXPORT FROM MARSHES TO ESTUARY; I = IMPORT TO MARSHES FROM ESTUARY; O = NO NET EXCHANGE)

TIDAL MARSH AND ESTUARY STUDY			JULY			AUGUST			NOVEMBER			ANNUAL		
AUTHORS	LOCATION	SALINITY	NH4	NO2	NO3	NH4	NO2	NO3	NH4	NO2	NO3	NH4	NO2	NO3
1	MD	0-5	I	I	I	I	I	I	E	E	E	E	E	E
2	MD	0-9	I	I	I	I	E	E	E	E	E	E	E	E
3	VA	0-7										E	I	I
4	VA	0-12										I	I	I
5	VA	0-12	E	I	I	I	E	I	I	I	I	I	E	I
6	NH	0-31	I	I	E	I	E	E	I	I	E	I	I	I
7	MD	0-30			E			E			I			E
8	LA	0-30						E			E			E
9	DE	10-28										I	I	I
10	CT	15-25	E	E	I	E	I	E	I	I	I	E	I	I
11	GA	20-23										O	O	O
12	DENMARK	25-30	E		E	E		E	I		I	I		I
13	NY	26	E	E	E	E	I	E	E	I	I	E	I	I
14	MA	30-32	I		I	I		I	E		E	E		E
15	SC	30-34							E					
16	SC	30-34											I*	I*
17	SC	30-35	I	I*	I*	I	I*	I*	I	I*	I*	I	I*	I*

1. Stevenson et al. (1976)
2. Heinle and Flemer (1976)
3. Axelrad (1974) as presented in Nixon (1980)
4. Axelrad (1974) as presented in Nixon (1980)
5. Wolaver et al. (1983)
6. Daly and Mathieson (1981)
7. Correl (1981)
8. Stern et al. (1986)
9. Lotrich et al. (1977) as presented in Nixon (1980)
10. Welsh (1980)
11. Haines et al. (1976) as presented in Nixon (1980)
12. Jensen et al. (1985)
13. Woodwell et al. (1979)
14. Valiela et al. (1978)
15. Kjerfve et al. (1981)
16. Spurrier et al. (1988)
17. Whiting (1989)

* = NO3 + NO2

TABLE 1.4: SUMMARY OF RESEARCH ON SEASONAL AND ANNUAL NUTRIENT FLUX BETWEEN TIDAL MUDFLATS AND ESTUARINE WATERS (E = EXPORT FROM MUDFLATS TO ESTUARY; I = IMPORT TO MUDFLATS FROM ESTUARY)

			JULY			AUGUST			NOVEMBER			ANNUAL		
AUTHORS	LOCATION	SALINITY	NH4	NO2	NO3	NH4	NO2	NO3	NH4	NO2	NO3	NH4	NO2	NO3
1	VA	0	E		I	E		I						
2	VA	0-10	E		I	E		I	E		I	E		I
3	LA	<1				E	I*	I*	E	I*	I*	E	I*	I*
4	CT	15-25	I	I	I	I	I	I	E	E	E	I	E	I
5	CANADA	20-28			I			E			E			E
6	LA	25				E	E*	E*	E	E*	E*	E	E*	E*
7	DENMARK	25-30							E		E			

1. Cerco (1988)
2. Simon (1988)
3. Teague et al. (1988)
4. Welsh (1980)
5. Keizer et al. (1989)
6. Teague et al. (1988)
7. Jensen et al. (1985)

* = NO3 + NO2

particulate organic nitrogen. However, the dynamics of any particular system appear relatively unpredictable.

The results of most flux studies on mudflat-estuarine interactions indicate net import of NO_3 and export of NH_4 throughout the year. Teague et al. (1988) reported a net export of inorganic nitrogen both in August and November. However, Welsh (1980) found a distinct seasonality to inorganic nitrogen flux, with consistent import of NH_4, NO_2 and NO_3 during the July and August and export of those parameters in November. During the same time frame, she reported the opposite pattern in the adjacent marshes (export of inorganic nitrogen in the summer, import in the fall) and suggested that the mudflat was removing the pulses of nutrients released from the marsh.

Clearly, marsh-estuary, mudflat-estuary, and marsh-mudflat nutrient dynamics are complex. This complexity, along with the difficulties of measuring flows in an estuary and the inherent variability of estuarine water quality, make nutrient fluxes in these systems difficult to quantify. Continued efforts to refine flux measurements will provide further insight into the dynamics of estuarine ecosystems.

2. METHODS

This study was designed to explore the nutrient dynamics in the wetlands of the lower Hackensack River to determine their impacts on the water quality regime of the Estuary. In particular, this study was designed to examine the nutrient dynamics in three different ecosystems: wetlands dominated by Spartina alterniflora; wetlands dominated by Phragmites australis; and mudflats. The study included two scales of investigation: microscale experiments in small areas of marsh and mudflat; and macroscale experiments in the tidal creeks draining the wetlands. The microscale experiments were designed to provide estimates of the direct exchange between an isolated area of marsh or mudflat. The macroscale experiments were designed to analyze the dynamics of an entire wetland system which might contain more than one wetland ecosystem and other possible pollutant sources such as an STP on Mill Creek and two major landfills on Sawmill Creek. Thus, the macroscale experiments were designed to investigate the interaction between the wetlands and the other pollutant sources in the ecosystem.

The sampling plan was also designed to provide data for the sediment nutrient and oxygen demand, and denitrification study conducted by Jay L. Taft, Ph.D. The benthic stations, described below, were sampled for those analyses. The results of that study are provided in Appendix A-2-3.

Possible study areas were identified from United States Geological Survey (USGS) 7-1/2-minute topographic quadrangle maps, from 200-scale HMDC topographic maps, and from other HMDC data based on ecological communities, size, surrounding land use and accessibility. The potential study areas were investigated during a river boat survey conducted by Najarian Associates, L.P. on September 7, 1988. The survey team included Jay L. Taft, Ph.D. of Harvard University, one staff member from General Testing Corp. and four staff members from Najarian Associates, L.P. The tributaries considered were Moonachie Creek, Mill Creek, Sawmill Creek, and Berry's Creek. Two of these, Mill Creek and Sawmill Creek, were targeted for the November 1988 study. A third tributary, Berry's Creek, was added at a later date for the July and August 1989 surveys.

2.1 MACROSCALE EXPERIMENTS - TRIBUTARY SAMPLING

2.1.1 Sawmill Creek

Sawmill Creek is the tributary with the greatest tidal exchange with the main Hackensack River. This basin contains extensive tidal marshes (±412 acres) and mudflats (±780 acres). The marshes are dominated by Spartina alterniflora and Phragmites australis (see Figure 1.1). As shown in Table 1.1, above, the acreage of Phragmites australis is shrinking as that of Spartina alterniflora increases. The change in vegetation is the continuing result of the re-inundation of the system with saline water following the hurricane of 1950 and of increased sedimentation. The low salt marsh provides habitat for a variety of vertebrate and invertebrate fauna.

The mudflats dominating the system are large open areas which are flooded at every high tide, but become exposed mudflats during low tides. Horned pond weed and algae reside in the water column and on the mud surface while a host of invertebrates live in the upper few centimeters of the sediment. The mudflats are essential in the life cycle of many waterfowl, shore birds, fish and shellfish, providing them with food and habitat. The shallow waters allow photosynthesis to occur in the plants which occupy the water column and on the surface of the mudflat which adds oxygen to these waters (State of New Jersey, 1984).

The head of Sawmill Creek is flanked by the two largest active landfill (HMDC/MSLA 1C and HMDC Balefill Sanitary Landfills) in the Hackensack Rive watershed. These landfills have been suspected of being potentially large source BOD and nutrients to Sawmill Creek and the Hackensack River (NJDEP, 1985). N data is available that accurately measures those loadings. HMDC monitors seve wells to sample the leachate from these landfills. Some of this recent data was obtained for this study; no additional monitoring was conducted.

Four water quality stations (S1 - S4) and five benthic stations (S1 - S4 and S2A) were sampled within Sawmill Creek; two water quality and benthic stations (M2 and M3) were sampled in the tidal marsh impoundment (see Section 2.2.2); and one water quality and benthic station (M1) (see Section 2.2.1) and one denitrification station (N1) were sampled in the mudflat embayment within the Sawmill Creek subbasin. Figure 2.1 illustrates the location of these sampling stations. Each of these stations were sampled in November 1988, July 1989, and August 1989, except M1 which was not sampled in August 1989.

Station S3 is located in Sawmill Creek at the New Jersey Turnpike crossing. Approximately 498 acres of the Sawmill Creek basin drain to this station, almost all of it mudflat. The HMDC Landfills are located upstream of this station. Station S4 is located at the head of the Creek, adjacent to the landfills. Station S1 is located at the mouth of the Creek.

2.1.2 Berry's Creek and Berry's Creek Canal

Berry's Creek drains a substantial tidal marsh system occupying <u>+</u>219 acres. The system is dominated by <u>Phragmites</u> <u>australis</u>. The surrounding upland land use is predominantly industrial.

Two sampling stations were installed within Berry's Creek (S14 and S15) as shown on Figure 2.1. These stations were sampled in July 1989 and August 1989.

Berry's Creek Canal drains a large industrial/commercial watershed in its upstream end, <u>+</u>128 acres of tidal marsh dominated by <u>Phragmites</u> <u>australis</u> in the central section, and dredge spoil fill in its lower end. Three benthic stations (S6, S7 and S8) were sampled within the canal reach as shown on Figure 2.1. Each of these benthic stations was sampled in November 1988 and August 1989.

2.1.3 Mill Creek

Mill Creek is the only tributary sampled that enters the Hackensack River from the east. A sewage treatment plant discharges ±2.8 million gallons per day (mgd) of secondary-treated effluent to the upper portion of the Creek. Tidal marshes exist along the entire eastern side of the Creek. The lower section of the Creek is the site of an extensive marsh renovation project, which has involved lowering the marsh surface, removal of Phragmites australis, and subsequent planting of Spartina alterniflora.

Four sampling stations were installed within Mill Creek; three in the Creek (S9, S9A and S11) upstream of the mitigation site and one at the sewage treatment plant (S10) to monitor the quality of its effluent. These stations are shown on Figure 2.1. Stations S9, S10, and S11 were sampled in November 1988, July and August 1989; S9A was sampled in July and August 1989.

2.2 MICROSCALE EXPERIMENTS

In addition to the instream sampling stations, water quality and sediment samples were collected from a mudflat embayment and a tidal wetland impoundment in the Sawmill Creek basin. Each of the macroscale experiments included more than one ecosystem or possible source of nutrient loading. The microscale experiments were designed to evaluate effects from the marsh and mudflat alone. It was anticipated that these results could be used in conjunction with the macroscale experiments to develop loading estimates that could be extrapolated to all of the mudflats and tidal wetlands within the Hackensack Estuary.

2.2.1 Tidal Mudflats

A representative tidal mudflat in the Sawmill Creek subbasin was chosen for the experiment (see Figure 2.2). The ±34.7 acre mudflat embayment was located adjacent to the HMDC Kingsland Landfill, bounded by HMDC access roads on the north, south and east, and the PSE&G powerline dike road on the west. Elevations ranged from -1 to +6 feet NGVD. The only source of water in the mudflat embayment was tidal exchange; a retaining wall forty feet deep separated the mudflat from the landfill, preventing potential contamination by leachate. One large channel (elevation -2.7 feet NGVD), one small channel (elevation +0.9 feet NGVD), and one culvert (elevation -0.24 feet NGVD), drained the mudflat embayment. Since the large channel was the path for approximately 95% of the tidal volume, it was chosen as the site for representative sampling of tidal height and water quality (Station M1). A 200-scale topographic map supplied by HMDC (1985) was used to estimate acreage and tidal volumes at 0.1 foot elevation intervals. This information was used to calibrate flow using measurements taken during the study.

2.2.2 Tidal Marsh

A representative tidal marsh in the Sawmill Creek subbasin was chosen for the experiment (see Figure 2.3). The tidally inundated portion of the ±3.5 acre marsh was dominated by Spartina alterniflora (67%) and Phragmites australis (33%). Phragmites australis and Panicum virgatum were dominant at elevations greater than mean high water (approximately elevation 3.7 feet NGVD). The tidal marsh impoundment topographic map and vegetation map are included as Figures 2.4 and 2.5. The marsh was located in an impoundment bordered on the north by Kingsland Ditch, on the south by Sawmill Ditch, on the east by the New Jersey Turnpike, and on the west by the Transco gas pipeline access road. Elevations ranged from -1 to +8 feet NGVD.

The impoundment was inundated and drained through one 48-inch corrugated aluminum pipe culvert with tidal waters from Sawmill Ditch; this pipe was selected as the monitoring location (Station M2). Because only one inlet/outlet linked the marsh impoundment with the Sawmill Creek basin, it was anticipated that accurate volume, flow, and water quality measurements would be possible. The entire impoundment was surveyed by Najarian Associates, L.P. and a topographic map with a one-foot contour interval was generated. This map and tidal elevation measurements were used to calculate incremental tidal volumes, providing an additional check for flow measured during the study. The aerial extent of each plant species also was mapped.

2.3 SAMPLING METHODS

Sampling was conducted during November, 1988 and July and August 1989 at the instream "S" stations. The November surveys were conducted at a time when tidal wetland plants were senescing. The July and August surveys were selected as the period of greatest DO depletion in the River, and as a time when tidal wetland plants were growing rapidly. Water quality data were collected at each of the instream "S" stations at two-hour intervals over four consecutive tidal cycles during the November sampling period and over two consecutive cycles in July and August. The water quality parameters sampled are listed in Tables 2.1 to 2.3. The data were collected during dry weather periods to avoid confounding effects of stormwater runoff.

The survey times and water quality parameters sampled at the tidal mudflat (M1) and tidal marsh (M2, M3) stations were identical to those sampled in the tributaries, except that no sampling was done at Station M1 in August. During the November 1988 survey, Station M1 was sampled every 2 hours for approximately 48 hours, spanning four tidal cycles. Sampling at the marsh stations (M2, M3) in November occurred at a frequency of every hour only during the residence time of the tide on the marsh, a period of approximately 7 hours for each tidal cycle, for four tidal cycles. That is, sampling began when the tidal waters reached the marsh surface and ended when tidal waters dropped below the marsh surface. Flow was estimated using hand-held flow meters at each sampling time at Stations M1 and M2. In addition, staff

TABLE 2.1: SUMMARY OF PARAMETERS MEASURED DURING NOVEMBER 1988 SAMPLING PERIOD

PARAMETERS/STATION	M1	M2	M3	S1	S2	S2A	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13		N1	N2
TIDE/FLOW	X	X	X				X							X						
TEMPERATURE	X	X	X	X	X		X	X					X	X	X	X	X		X	X
TURBIDITY	X	X	X	X	X		X	X					X	X	X	X	X			
SALINITY	X	X	X	X	X		X	X					X	X	X	X	X		X	X
pH	X	X	X	X	X		X	X					X	X	X	X	X		X	X
CHLOROPHYLL-A	X	X	X	X	X		X	X					X	X	X	X	X			
DO	X	X	X	X	X		X	X					X	X	X	X	X		X	X
C-BOD5	X	X	X	X	X		X	X					X	X	X	X	X			
NH_3-N	X	X	X	X	X		X	X					X	X	X	X	X		X	X
NO_2-N	X	X	X	X	X		X	X					X	X	X	X	X		X	X
NO_3-N	X	X	X	X	X		X	X					X	X	X	X	X		X	X
TKN	X	X	X	X	X		X	X					X	X	X	X	X		X	X
TOTAL PHOSPHORUS	X	X	X	X	X		X	X					X	X	X	X	X			
ORGANIC PHOSPHORUS	X	X	X	X	X		X	X					X	X	X	X	X			
ORTHO-PHOSPHORUS	X	X	X	X	X		X	X					X	X	X	X	X			
TSS	X	X	X	X	X		X	X					X	X	X	X	X			
BENTHIC	X	X	X	X	X	X	X	X		X	X	X	X		X					
N_2																			X	X

LEGEND:

M1 MUDFLAT EMBAYMENT
M2 MARSH IMPOUNDMENT S
M3 MARSH IMPOUNDMENT N

N1 DENITRI MUDFLAT @ M1
N2 DENITRI RIVER @ W4

S1 SAWMILL BOUNDARY S
S2 SAWMILL BOUNDARY N
S2A SAWMILL MIDSTREAM
S3 SAWMILL TPKE
S4 SAWMILL LANDFILL
S5 N ARL STP

S6 BERRYS CANAL BOUNDARY
S7 BERRYS CANAL MID
S8 BERRYS CANAL UPPER
S9 MILL CREEK BOUNDARY
S10 SECAUCUS STP
S11 MILL CREEK UPPER

S12 PSE&G INTAKE
S13 PSE&G DISCHARGE

TABLE 2.2: SUMMARY OF PARAMETERS MEASURED DURING JULY 1989 SAMPLING PERIOD

PARAMETERS/STATION	M1	M2	M3	S1	S2	S2A	S3	S4	S6	S7	S8	S9	S9A	S10	S11	S14	S15		N1	N2
TIDE/FLOW	X	X	X				X							X		X				
TEMPERATURE	X	X	X	X	X		X	X				X	X	X	X	X	X		X	X
TURBIDITY																				
SALINITY	X	X	X	X	X		X	X				X	X	X	X	X	X		X	X
pH	X	X	X	X	X		X	X				X	X	X	X	X	X		X	X
CHLOROPHYLL-A	X	X	X	X	X		X	X				X	X	X	X	X	X			
DO	X	X	X	X	X		X	X				X	X	X	X	X	X		X	X
C-BOD5	X	X	X	X	X		X	X				X	X	X	X	X	X			
NH_3-N	X	X	X	X	X		X	X				X	X	X	X	X	X		X	X
NO_2-N	X	X	X	X	X		X	X				X	X	X	X	X	X		X	X
NO_3-N	X	X	X	X	X		X	X				X	X	X	X	X	X		X	X
TKN	X	X	X	X	X		X	X				X	X	X	X	X	X		X	X
TOTAL PHOSPHORUS	X	X	X	X	X		X	X				X	X	X	X	X	X			
ORGANIC PHOSPHORUS	X	X	X	X	X		X	X				X	X	X	X	X	X			
ORTHO-PHOSPHORUS	X	X	X	X	X		X	X				X	X	X	X	X	X			
TSS	X	X	X	X	X		X	X				X	X	X	X	X	X			
BENTHIC																				
N_2																			X	X

LEGEND:

M1 MUDFLAT EMBAYMENT
M2 MARSH IMPOUNDMENT S
M3 MARSH IMPOUNDMENT N
N1 DENITRI MUDFLAT @ M1
N2 DENITRI RIVER @ W4

S1 SAWMILL BOUNDARY S
S2 SAWMILL BOUNDARY N
S2A SAWMILL MIDSTREAM
S3 SAWMILL TPKE
S4 SAWMILL LANDFILL

S6 BERRYS CANAL BOUNDARY
S7 BERRYS CANAL MID
S8 BERRYS CANAL UPPER
S9 MILL CREEK BOUNDARY
S9A MILL CREEK BELOW STP

S10 SECAUCUS STP
S11 MILL CREEK UPPER
S14 BERRYS CREEK @ TPKE
S15 BERRYS CREEK

TABLE 2.3: SUMMARY OF PARAMETERS MEASURED DURING AUGUST 1989 SAMPLING PERIOD

PARAMETERS/STATION	M1	M2	M3	S1	S2	S2A	S3	S4	S6	S7	S8	S9	S9A	S10	S11	S14	S15		N1	N2
TIDE/FLOW		X					X							X		X				
TEMPERATURE		X		X	X		X	X				X	X	X	X	X	X		X	X
TURBIDITY																				
SALINITY		X		X	X		X	X				X	X	X	X	X	X		X	X
pH		X		X	X		X	X				X	X	X	X	X	X		X	X
CHLOROPHYLL-A		X		X	X		X	X				X	X	X	X	X	X			
DO		X		X	X		X	X				X	X	X	X	X	X		X	X
C-BOD5		X		X	X		X	X				X	X	X	X	X	X			
NH_3-N		X		X	X		X	X				X	X	X	X	X	X		X	X
NO_2-N		X		X	X		X	X				X	X	X	X	X	X		X	X
NO_3-N		X		X	X		X	X				X	X	X	X	X	X		X	X
TKN		X		X	X		X	X				X	X	X	X	X	X		X	X
TOTAL PHOSPHORUS		X		X	X		X	X				X	X	X	X	X	X			
ORGANIC PHOSPHORUS		X		X	X		X	X				X	X	X	X	X	X			
ORTHO-PHOSPHORUS		X		X	X		X	X				X	X	X	X	X	X			
TSS		X		X	X		X	X				X	X	X	X	X	X			
BENTHIC	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X			
N_2																			X	X

LEGEND:

M1 MUDFLAT EMBAYMENT	S1 SAWMILL BOUNDARY S	S6 BERRYS CANAL BOUNDARY	S10 SECAUCUS STP
M2 MARSH IMPOUNDMENT S	S2 SAWMILL BOUNDARY N	S7 BERRYS CANAL MID	S11 MILL CREEK UPPER
M3 MARSH IMPOUNDMENT N	S2A SAWMILL MIDSTREAM	S8 BERRYS CANAL UPPER	
N1 DENITRI MUDFLAT @ M1	S3 SAWMILL TPKE	S9 MILL CREEK BOUNDARY	S14 BERRYS CREEK @ TPKE
N2 DENITRI RIVER @ W4	S4 SAWMILL LANDFILL	S9A MILL CREEK BELOW STP	S15 BERRYS CREEK

gauges were secured in place adjacent to the location at which flow was measured, and tidal elevation height was recorded at each sampling time.

During the July 1989 survey, samples at both the mudflat and marsh stations were collected at half-hour intervals. During low-flow periods, two half-hour samples were combined using flow-weighted compilation. This reduced the number of samples that needed to be analyzed during low flow periods when little change in mass flux was anticipated. Flow was estimated using hand flow meters at each sampling time. Staff gauges were used to record tidal elevations at the time of each sampling. A stilling well with an internal tide gauge was installed at Stations M1 and M2 with a continuous chart recorder as a check on manual recoding of observations on the staff gauges.

During the August 1989 survey, only Station M2 was sampled. Samples were taken every half hour and they were not composited. Flow and tidal elevation were recorded in the same manner as the July 1989 survey.

Tidal wetland acreage for the entire Hackensack Meadowlands was determined from available data. Topographic maps and aerial photographs, both at 200 scale, were obtained from HMDC. Tracings were made of the 0- and 4-foot elevation contours which were copied onto the aerial photographs. HMDC staff marked the limit of tidally inundated wetlands, the location of all tide gates, and the location and extent of Phragmites australis, Spartina alterniflora, Spartina patens, Scirpus validus, Pluchea camphorata on each map. Tibbet-Abbot-McCarthy & Staten Consultants, Inc. (TAMS) located the extent of each of the wetlands mitigation areas created by Hartz Mountain in the Belmans, Cromakill, and Mill Creek tributaries. TAMS also provided a written estimate of the acreage of newly created marsh dominated by Spartina alterniflora, upland islands, and open water for each mitigation site. Once this information was recorded on the tracings, the areas of all tidally inundated wetlands and mudflats were digitized by Najarian Associates, L.P. staff. The acreage example, in several instances the location of the sampling site did not provide a simple channel that could be used to generate an elevation to volume rating curve.

Based on the available data, two methods were used to calculate flows: 1) determination of flows through use of the DNM model; and 2) calculation of flows from elevation and flooded area data. The following paragraphs describe each method.

Method 1 employs the DNM hydrodynamic model to generate flow. The model is based on the one-dimensional continuity and momentum equations. Details regarding the model may be found in Appendix A, Part 1 of this study. The model was used to generate flows at Stations S9 and S9A in Mill Creek and Stations S14 and S15 in Berrys Creek. Water surface elevation data was collected at the mouth of the Hackensack River estuary (Station H1) for the relevant time period. The calibrated DNM Model was exercised for the appropriate sections of the estuary at half-hour increments from which flows at one-minute increments were determined.

The second method calculated flow from the rate of change of the volume of water inundating the marsh or flowing in the channel with respect to time:

$$Q_n = dV/dt$$

$$dV = V_{n+1} - V_n$$

$$dt = t_{n+1} - t_n$$

where: Q_n = Average Flow Rate between time t_n and time t_{n+1}

V_n = Volume at Time t_n

t_n = Time of n^{th} Observation

estimates were calculated for each tributary (see Table 2.4) and for each subcatchment basin defined for modeling purposes (see Table 1.2 and Appendix A, Part 1).

TABLE 2.4: Tidally Inundated Wetland Acreage by Tributary

TRIBUTARY	Phragmites australis	Spartina alternifl.	Spartina patens	Scripus validus	Total
Belmans	176.98	3.69	-	0.92	181.59
Cromakill	110.41	67.02	-	-	177.43
Mill	166.76	53.28	-	-	220.04
Doctors	259.20	5.82	-	-	265.02
Berrys Canal	128.63	0.14	-	-	128.77
Berrys Creek	212.25	5.41	1.30	-	218.96
Sawmill	279.79	131.54	-	-	411.33
TOTAL	1334.02	266.90	1.30	0.92	1603.14

Benthic data were collected and analyzed at each sampling station during November 1988 and August 1989. The methodology for benthic sampling in the tributaries, mudflat, and marsh was identical to that used for the main-stem of the Hackensack River as described in Appendix A, Part 1.

Tidal elevation was monitored continuously at Station H1 for the duration of each sampling period survey to provide a forcing function to drive the DNM model hydrodynamics (see Appendix A, Part 1 of this report).

2.4 FLOW CALCULATION

As noted above, an accurate time history of flow at a sampling site is essential for the accurate calculation of the mass transport through a system. The nature of the flow systems under study presented difficulties in direct measurement of flow. For

For the July data at Stations M1 and M2, a polynomial or series of polynomials did not adequately fit the data. The data were corrected manually by drawing a smooth curve which was then electronically digitized. Based on that elevation data, flows were computed as described above. During July and August, flow data was available at Station M2. This data was compared to the calculated flows, with good results.

2.5 MASS FLUX CALCULATIONS

As discussed above, time series of flow data were generated at one-minute intervals for all applicable stations. Concentration data for water quality constituents were collected at approximately one-half hour to one hour intervals at each station. The water quality data were linearly interpolated to produce a water quality concentration time series at one-minute intervals.

The mass flux of each constituent was then calculated by integrating the product of the flow times the concentration at one-minute intervals for each half tidal cycle. The integration was conducted from slack tide to slack tide (zero flow). This integration may be represented by:

$$\text{Mass Flux} = \int_{t}^{t+T/2} (Q*C)*\delta t$$

Where: Q = Instantaneous Flow
C = Concentration
T = Tidal Cycle Period

The integration was carried out numerically. A mass flux time series was generated at one-minute increments by multiplying flow rate by concentration. These fluxes were multiplied by the time step, one minute) and summed over a half tidal cycle. This can be represented by:

This technique was used at the Tidal Mudflat Embayment Station (M1), the Tidal Marsh Impoundment Station (M2) and at Sawmill Creek at the New Jersey Turnpike Bridge (S3). The volume of water flooding the embayment, impoundment or marsh was based on the measured elevation and the associated volume at that elevation from a rating curve. The 'rating curve' was constructed by measuring the surface area of the embayment or impoundment between one foot elevation contour intervals using an electronic digitizer on a 200-scale topographic map at Stations M1 and S3 (HMDC, 1985). Najarian Associates, L.P. surveyed the area surrounding Station M2 and produced a 30-scale topographic map with one-foot contours to supplement the 200-scale HMDC maps. The collected surface area data at 1-foot intervals were interpolated to 0.1-foot intervals. The volume at a specific elevation was then calculated by multiplying the surface area in each 0.1-foot interval by the 0.1-foot depth and summing those volumes up to the elevation in question.

Flows were then calculated by determining the difference in volume stored between two time periods and dividing that difference by the elapsed time. The elevation data were smoothed to eliminate discontinuities in the data. Several methods were used to smooth the data. For the November data at Station M1, the August Data at Station M2, and all of the data at Station S3, a cubic polynomial was fitted independently to each rising and falling limb of the elevation curve. Separate curves were needed because asymmetry in the water surface elevation time series did not allow a good fit for a quartic polynomial over a complete tidal cycle. Linear interpolation was used to smooth the periods when the different polynomials joined, if needed. At Station M2 in November, a quartic polynomial was independently fit to each complete tidal cycle. In addition, flows were assumed to be negligible at elevations below one (1) foot at Station M2 as the marsh surface is generally at elevations above one foot. A time series of water surface elevations was generated at one-minute intervals from these polynomials. Flows were calculated from these data as described, above.