United States
Environmental Protection
Agency

Great Lakes National
Program Office
536 South Clark Street
Chicago, Illinois 60605

EPA-905/4-79-029-J

Volume 10

EPA

The IJC Menomonee River Watershed Study

Effects of Tributary Inputs On Lake Michigan During High Flows

FOREWORD

The Environmental Protection Agency was established to coordinate administration of the major Federal programs designed to protect the quality of our environment.

An important part of the Agency's effort involves the search for information about environmental problems, management techniques, and new technologies through which optimum use of the nation's land and water resources can be assured and the threat pollution poses to the welfare of the American people can be minimized.

The Great Lakes National Program Office (GLNPO) of the U.S. EPA, was established in Region V, Chicago to provide a specific focus on the water quality concerns of the Great Lakes. GLNPO also provides funding and personnel support to the International Joint Commission activities under the U.S.- Canada Great Lakes Water Quality Agreement.

Several land use water quality studies have been funded to support the pollution from Land Use Activities Reference Group (PLUARG) under the Agreement to address specific objectives related to land use pollution to the Great Lakes. This report describes some of the work supported by this Office to carry out PLUARG study objectives.

We hope that the information and data contained herein will help planners and managers of pollution control agencies make better decisions for carrying forward their pollution control responsibilities.

Madonna F. McGrath
Director
Great Lakes National Program Office

EPA-905/4-79-029-J
December 1979

Effects of Tributary Inputs on Lake Michigan During High Flow

Volume 10

by

R. Bannerman
J.G. Konrad
and
D. Becker
Wisconsin Department of Natural Resources

for

U.S. Environmental Protection Agency
Chicago, Illinois

Grant Number R005142

Grants Officer
Ralph G. Christensen
Great Lakes National Program Office

This study, funded by a Great Lakes Program grant from the U.S.EPA, was conducted as part of the Task C-Pilot Watershed Program for the International Joint Commission's Reference Group on Pollution from Land Use Activities.

GREAT LAKES NATIONAL PROGRAM OFFICE
ENVIRONMENTAL PROTECTION AGENCY, REGION V
536 SOUTH CLARK STREET, ROOM 932
CHICAGO, ILLINOIS 60605

DISCLAIMER

This report has been reviewed by the Great Lakes National Program Office of the U.S. Environmental Protection Agency, Region V, Chicago, and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

PREFACE

The effects of 1. the combined loadings of the Menomonee, Milwaukee and Kinnickinic Rivers during high flows and 2. wind-induced suspension of sediment on the water quality of the Milwaukee Harbor and its vicinity are investigated. Estimates indicate that a significant portion of the annual loadings of pollutants--suspended solids, total- and soluble-P--from the rivers and a sanitary treatment plant are retained in the habor due to deposition. About 70% of the suspended solids discharged from the Menomonee River is retained annually in the inner harbor. The dispersion pattern of pollutants entering the inshore zone is manifested as small islands of turbid water and continuous plume is observed during heavy storm events. The transport and amount of pollutants reaching the inshore zone is modified by harbor current patterns and structures and wind direction. Resuspension and/or shoreline erosion contributes a significant increase in the suspended solids annual loading to the inshore zone.

CONTENTS

FIGURES

TABLES

1. INTRODUCTION

The water quality of Lake Michigan in the vicinity of the Milwaukee Harbor is impaired relative to the water further offshore (1,2). One source of pollutants to the Milwaukee Harbor and its vicinity is the combined discharge from the Milwaukee, Menomonee and Kinnickinnic Rivers. The overall objective of this study was to determine the effects of the inputs from these three urban river basins on Lake Michigan water quality during high river flows. Since the three rivers discharge to the Milwaukee Harbor, the effect of the Menomonee River inputs on Lake Michigan water quality were not isolated from the other two rivers.

The study was part of Task D of the Pollution from Land Use Activities Reference Group (PLUARG) objective to diagnose the degree of impairment of Great Lakes water quality. Since the three urban rivers are tributary to the Milwaukee Harbor, the study also provided an opportunity to observe the effects of a large enclosed harbor on the transport of pollutants to Lake Michigan. The specific objectives of the study, as outlined in subactivities 3-1 and 3-3 of Task D, were 1. to determine the effect of pollutant materials discharged from the rivers on water quality in the vicinity of the Harbor during high flows, 2. to determine the extent of dispersion in Lake Michigan of particulate and soluble material contributed by the rivers and 3. to investigate the question of wind-induced resuspension and its relative importance as a pollutant source. While previous studies (3) have documented the degraded water quality in the Milwaukee Harbor and its vicinity in general terms, the present study objectives address the quantification of pollutant loadings and description of the mechanisms controlling the transport and dispersion of pollutants.

To fulfill the specific objectives of the project, the study plan centered on obtaining estimates of water quality throughout the Milwaukee Harbor and its vicinity during periods of high river flow and during wind-induced suspension of sediment. Water quality surveys were conducted on 11 occasions, starting with a snowmelt event on February 13, 1976. Overflights during three of these surveys provided imagery from which water quality values could be extrapolated to non-sampled areas and dispersion patterns of pollutants could be evaluated. Measurements of current velocities and direction in the Milwaukee Harbor were used to evaluate the pollutant transport mechanism.

For purposes of analysis, the Lake Michigan-Milwaukee Harbor study area was divided into four regions: The inner harbor, the outer harbor, the inshore zone and the offshore zone (Fig. 1). The inner harbor was bounded upstream by the point on the rivers where the lake and harbor seiche effects were no longer apparent and downstream by the outermost point of the shipping channel. The outer harbor is delineated by the inner harbor and shoreline on the west and the breakwater on the east. The inshore zone is that portion of

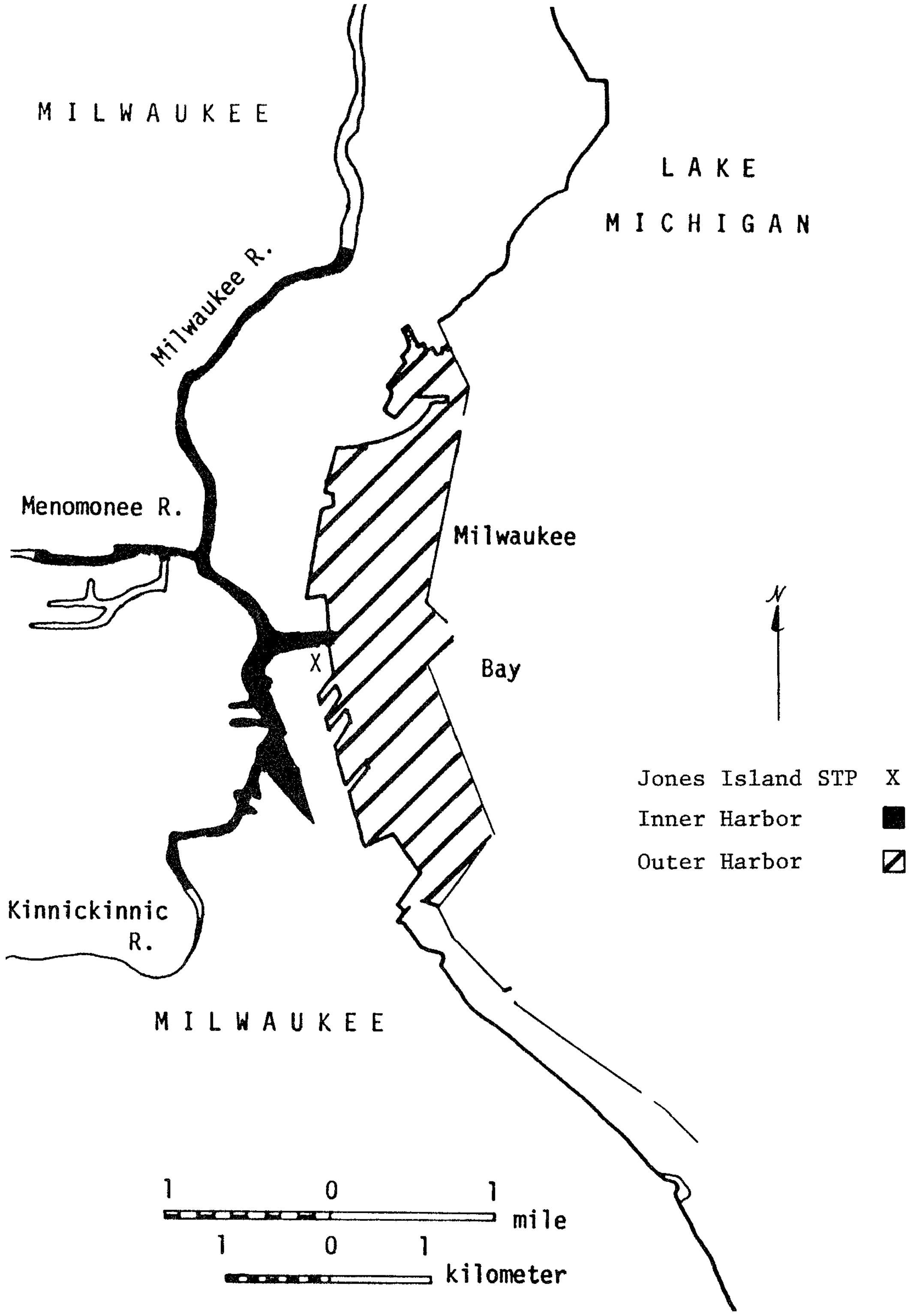

Fig. 1. Milwaukee Harbor.

the lake within 5 km of the breakwater or the shoreline. The offshore zone is the lake beyond the inshore zone.

The Milwaukee, Menomonee and Kinnickinnic Rivers drain watersheds that contain rural and urban land uses and have a combined area of approximately 2200 km (850 mi). These rivers have a combined mean annual flow of 14.7 cms (520 cfs) discharging to the inner harbor. Individual mean annual flows are: The Milwaukee - 11.6 cms (410 cfs), the Menomonee - 2.6 cms (90 cfs), and the Kinnickinnic - 0.6 cms (20 cfs). The Jones Island Sewage Treatment Plant (STP), which discharges into the outer harbor, had a mean flow for 1976 of 6.2 cms (219 cfs). For purposes of this analysis the inner harbor was considered to discharge into the outer harbor.

The physical characteristics of the inner and outer harbors make each distinct from the other. The inner harbor has depths in the range of 2.1 to 8.8 m (7 to 29 ft), and an approximate surface area and volume of 92 ha (227 acres) and 6.2×10^6 m^3 (220×10^6 ft^3), respectively. The outer harbor has a wider range of depths (1.2 to 11 m or 4 to 36 ft) and greater surface area and volume [525 ha (1300 acres) and 36.8×10^6 m^3 (1300×10^6 ft^3), respectively]. The inner harbor includes primarily a shipping channel, docking areas and the channelized downstream reaches of the three rivers. The outer harbor closely resembles a lake with two tributaries (the inner harbor and the STP) and the three points of discharge, i.e., the three major openings along the 8.6 km (5.3 mi) breakwater.

The inshore zone, which shares the breakwater as a boundary with the outer harbor, is the recipient of the discharge from the three breakwater openings, and, in turn, interfaces with the offshore zone in a much less controlled manner. The inshore zone depths range from 8.5 to 16.5 m (28 to 54 ft), with greater depths occurring with greater distance from the shoreline and breakwater.

The bottom sediments of the outer harbor and the inshore zone have been characterized (2). The dominant sediment type reported for the outer harbor was organic silt, with a thickness of 1.3 to 15 cm (0.5 to 6 in). The inshore zone bottom was primarily silty clayey sand, with significant areas of gravel, hard bottom, and till.

2. SUMMARY AND CONCLUSIONS

The effects of the combined inputs from the Menomonee, Milwaukee and Kinnickinnic Rivers on Lake Michigan water quality were investigated. Estimates of annual river loadings indicated the Menomonee River usually discharged 50% of the annual river loadings reaching the Milwaukee Harbor and the effect of the Menomonee River on Lake Michigan water quality could not be isolated from that of the Milwaukee and Kinnikinnic Rivers. The study focused on the area around the Milwaukee Harbor and the area was divided into four regions: The inner and outer harbors and inshore and offshore zones. The inner harbor was bounded upstream by the point on the river where the lake and harbor seiche effects were no longer apparent and downstream by the outermost point of the shipping channel. The outer harbor was separated from the inshore zone by the breakwater and the inshore zone extended 5 km (3.1 mi into the lake. Water quality surveys were conducted in the study area during periods of high and low flow in the rivers. The parameter list included nutrients, suspended solids and metals.

The water quality surveys indicated that the concentration levels of the measured parameters decreased with increasing distance from the confluence of the rivers. Each of the four regions were characterized by a different set of concentrations. Average concentrations of suspended solids in the inner and outer harbors, and inshore and offshore zones were 19, 9, 3 and 1 mg/L, respectively. This phenomenon occurred during baseflow and runoff event flow periods. The large concentration gradient of the parameters from the outer harbor to the inshore zone indicated the effectiveness of the breakwater as a barrier to mixing of the waters in the two zones. This pattern of degradation of water quality points both to the rivers and the Jones Island Sewage Treatment Plant (STP) as sources of pollutants to the harbor and the inshore zone. The STP has a mean annual flow of 6.2 cms (219 cfs) and contributes a major portion of the total annual pollutant loading to the harbor. The runoff events surveyed had an immediate effect on harbor water quality. However, only the concentrations for suspended solids and total organic-nitrogen were higher than the baseflow values in the inner harbor for most events. The water quality of the inshore zone usually was not degraded during high flow periods. Although more pollutants were available in the harbor for transport to the inshore zone, an insufficient portion of the pollutants were transported during most events to increase concentrations in the inshore zone. Only the February 13 and 25, 1976 snowmelt runoff surveys showed slightly elevated suspended solids concentrations, and the exceptionally large rain event on July 18, 1977 produced elevated suspended solids and chlorides in the inshore zone. The results of the event surveys indicated that the current patterns in the harbor and harbor structures were modifying the transport of pollutants to the inshore zone.

Current directions and velocities at the harbor mouth opening (between the inner and outer harbors) and at the central breakwater opening (between the outer harbor and the inshore zone) were measured to characterize the mechanism controlling the transport of pollutants between regions. Measurements indicate this transport to be controlled more by the action of the lake and harbor seiches than by the combined flow from the rivers. The seiche has been observed to cause the direction of flow for different strata or for the entire water column to reverse itself during runoff events at the harbor mouth and at the central breakwater opening. This oscillation of flow between regions results in a pulsing of the event-generated pollutants from the more polluted region to the less polluted region across these two boundaries. The pulsing phenomenon also was verified by the water quality at the central breakwater opening alternating between that of the inshore zone and the harbor. The size of the plug of pollutants is dependent largely on the characteristics of the seiche for any period. This apparent pulsing occurs during times of event and baseflow. An exception to the pulsing, seiche-controlled pattern probably occurs during times of exceptionally large event flows, when a relatively consistent flow of water could be expected to move outward into the inshore zone with short residence time in the harbor. On July 18, 1977, the flow at the surface was not observed to reverse direction for the period of measurement. Although the results of watershed studies have indicated a large portion of the pollutants were discharged to the harbor during high flow periods, the net transport of event and baseflow water to the inshore zone was apparently more dependent on harbor current patterns. The harbor current patterns and structures were able to impose a significant residence time on all pollutants discharged into the harbor before entering the inshore zone.

In an attempt to quantify the average annual amounts of pollutants reaching the inshore zone, a mass balance equation was used. Residence times were estimated to be 5 and 6 days for the inner and outer harbors, respectively. The residence times were averages for all conditions and probably decrease significantly for the portions of pollutants discharged to the inner harbor during periods of high flows. The percentage of the total annual loadings to the harbor entering the inshore zone was estimated to be 45% for suspended solids, 61% for total-phosphorus, and 35% for soluble-phosphorus. Although the percentages were only gross estimates, they demonstrated that a significant portion of the annual loading from the river and STP were retained in the harbor. Although the portion of the event pollutants retained in the harbor was not known, it was estimated that 70% of the suspended solids discharged from the Menomonee River during events was retained annually in the inner harbor. The amount of suspended solids in the plume for the July 18, 1977 event was estimated to be 5% of the total suspended solids entering the inshore zone each year. The pollutants associated with the particulate matter obviously were settling out during their residence time in the harbor. Higher concentrations of total-phosphorus, organic-nitrogen and metals in the harbor bottom sediments relative to the river and lake sediments provided further evidence that pollutants were deposited in the harbor.

The dispersion pattern of pollutants reaching the inshore zone was manifested as small islands of turbid water in the inshore zone or a narrow band of turbid water along the outside of the breakwater. Only during the July 18, 1977, event was a continuous plume observed (4 km directly east into the lake from the breakwater central opening). A plume from the breakwater northern opening extended approximately 2.5 km in a northeasterly direction on July 18, 1977. On July 19, the breakwater central opening visible plume had not dispersed but rather had grown slightly larger (to 5 km in east-west extent), and a plume out of the breakwater southern opening extended approximately 2.5 km parallel to the shore. Since the surface values of suspended solids were higher than the bottom values, it is assumed that the plume extended down to the thermocline. The dispersion of pollutants in the inshore zone would be highly variable and dependent upon the direction of the wind. The summer current has a weak tendency to go in a southerly direction and the winter currents have a strong tendency to go in a northerly direction.

Resuspension and/or shoreline erosion was responsible for elevating the levels of suspended solids along the shore in the vicinity of the Milwaukee Harbor on April 8, 1976. A significant runoff-event had not occurred for almost 2 weeks. The values for suspended solids were higher than those observed in the inshore zone during the July 18, 1977, rain event. Approximately twice as much suspended solids was in the water column of the inshore zone in the vicinity of Milwaukee as a result of this resuspension/erosion event than was in the July 18, 1977 rain event plume. The amount of suspended solids in the inshore zone on April 8, 1976 represented about 12% of the annual suspended solids loading to the lake from the harbor. Resuspension and shoreline erosion could cause a significant increase in the suspended solids loading to the inshore zone each year.

3. RECOMMENDATIONS

1. Determination of the effect of the Milwaukee Harbor on pollutant transport to Lake Michigan is important in understanding the fate of land use related contaminants. The mass balance calculation for estimating the annual loadings to the inshore zone was limited by the availability of pollutant concentration values in the inner and outer harbors, the inshore zone, and in the Milwaukee River. Pollutant concentrations should be obtained on a seasonal basis at the USGS station on the Milwaukee River, at three sites in the inner harbor, at five sites in the outer harbor and at five sites in the inshore zone near the breakwater. Future mass balance calculations should be limited to seasonal loadings to avoid the potential distortion of averaging residence times for the entire year. Mass balance calculations for individual events would require more detailed sampling in the harbor before, during and after events.

2. Remote sensing data have been obtained to observe the dispersion pattern of the July 18, 1977 inshore zone plume. Extensive water quality data were collected concurrently in the lake, harbor and Menomonee River. The occurrence of this event near the end of the project period has not allowed time to evaluate all of the concentration data in conjunction with the remote sensing imagery. This evaluation should be continued to further characterize the dispersion patterns of the plume and possible event related loadings to the inshore zone. Future investigation of plume dispersion patterns should continue to use remote sensing imagery as a tool.

3. Although a large portion of the annual pollutant loading entering the inshore zone was discharged by the rivers, the amount and rates of loading to the inshore zone was regulated for the most part by the current patterns at the breakwater openings. Continuous monitoring of flow direction and velocity, and water quality indicators at the breakwater openings would improve the understanding of the net loading of pollutants to the lake.

4. Estimates of pollutant loading to the Lake Michigan inshore and offshore zones from the Menomonee, Milwaukee and Kinnickinnic River Watersheds should be reduced by some proportion to account for the retention of pollutants in the inner and outer harbors.

5. The inner and outer harbors should be considered areas of impaired water quality as a result of point and nonpoint source pollution.

4. FIELD ACTIVITIES

Water Quality Surveys

Water quality surveys were conducted from February 13, 1976 to July 18, 1977 during eight runoff events (including two snowmelts), two periods of baseflow and one period of wind-induced resuspension of sediment. All samples were collected from a Wisconsin Department of Natural Resources (WDNR) 6 m (20 ft) Starcraft. On event days, samples were collected as soon as possible after the event flows were detected. The dates, meteorological conditions and the peak Menomonee River flows during the water quality surveys are summarized in Table 1. The locations of the individual sampling sites for each survey are shown in Figs. 2 to 4. Sampling sites for event surveys were chosen along straight line transects from the end of the inner harbor, through the breakwater openings, into the inshore zone. The number of event survey sampling sites varied from two to six, depending on visible plume characteristics. The sampling sites for the wind-induced resuspension survey on April 8, 1976, were determined to enable interpretation of concurrent satellite imagery.

The samples were collected from the surface and at 7m below the surface in the harbor and at the surface and 10 m below the surface for the inshore area. The samples were collected with a clear PVC Kemmerer bottle and stored under ice in polypropylene bottles. The water samples were analyzed within 24 hr at the Wisconsin State Hygiene Laboratory using established procedures (4,5). The analyses performed for each survey included all or part of the following parameter list: Total- and suspended-solids, total- and soluble-phosphorus, organic-nitrogen, (nitrate + nitrite)-nitrogen, ammonia-nitrogen, chloride, alkalinity, total organic carbon, lead, zinc, cadmium, chromium, nickel and copper. Temperature and dissolved oxygen profiles were measured with a YSI dissolved oxygen meter, and secchi disc depths were recorded.

Remote sensing data were obtained during three of the water quality surveys. Overflights by NASA coincided with water quality surveys on February 25, 1976 and April 8, 1976. Information from these overflights has been described in a NASA report (6).

Sediment Surveys

Bottom sediment samples were collected in the harbor on April 8, 1976, and in the lake on April 19, 1976. Samples were collected using a weighted Ponar dredge and stored in widemouth jars. These sampling locations (Fig. 5) were chosen to represent areas of different sediment types and depositional rates. The harbor had not been dredged for 6 yr prior to the bottom sediment

Table 1. Sampling trips

Sampling date	Comments	Rainfall, cm	Wind direction	Avg. wind velocity, kmph	Peak flow at 70th St. cms	Peak flow at 70th St. time	Sampling times
2/13/76	Snowmelt		NW	21	2.2		
2/25/76	Snowmelt		SW	16	17.0	1845	1430 to 1650
4/8/76	Baseflow and resuspension; Harbor sediment		E	14	2.2		
7/28/76	Rain event	1.07	S-SE	16	9.7	0945	1220 to 1630
4/19/76	Sediment outside breakwater		SE	13	0.34		
8/28/76	Rain event	3.05	SW	21	30.0	0305	1430 to 1830
9/9/76	Rain event	2.29	NW	19	19.7	0320	1530 to 1750
5/11/77	Baseflow		NW	13	0.54		1045 to 1440
5/19/77	Baseflow		SE	13	0.54		1120 to 1625
6/28/77	Rain event	2.49	W	19	11.7	0930	1430 to 2000
6/30/77	Rain event	3.43	SE	24	33.6	1025	1530 to 1930
7/18/77*	Rain event	4.80	SW	19	83.4	0500	1315 to 1900

* Rain event started on 7/17/77; the amount of rainfall on this date was 3.38 cm with a peak flow of 88 cms observed at 70th St. at 0155 hr.

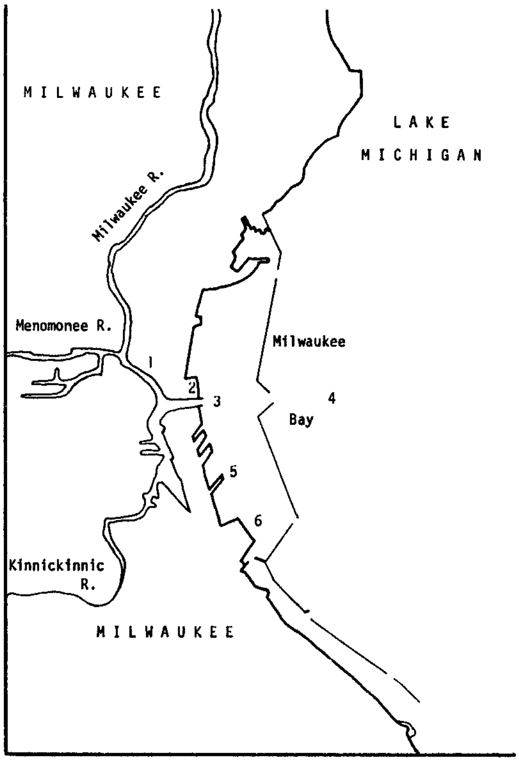

Fig. 2A. Sampling locations on 2/13/1976.

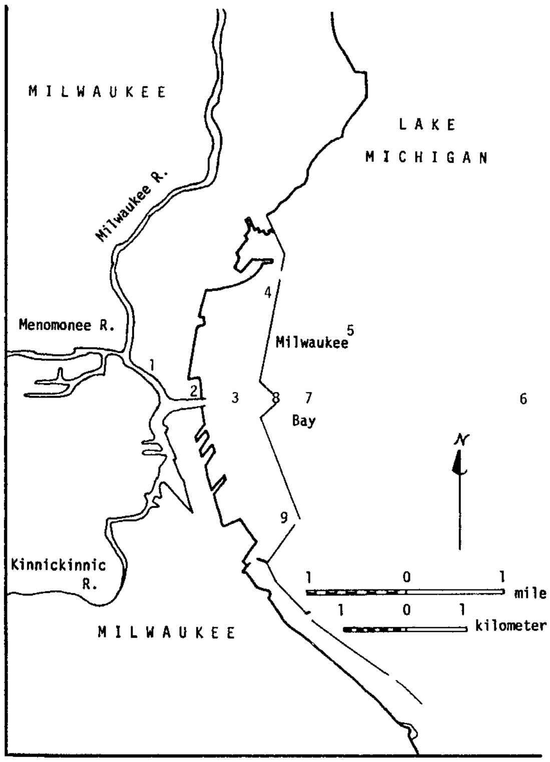

Fig. 2B. Sampling locations on 2/25/1976.

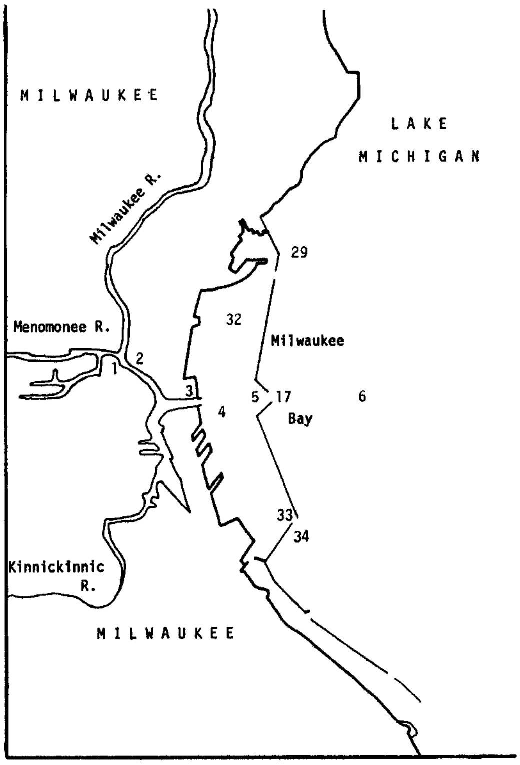

Fig. 2C. Sampling locations on 7/28/1976.

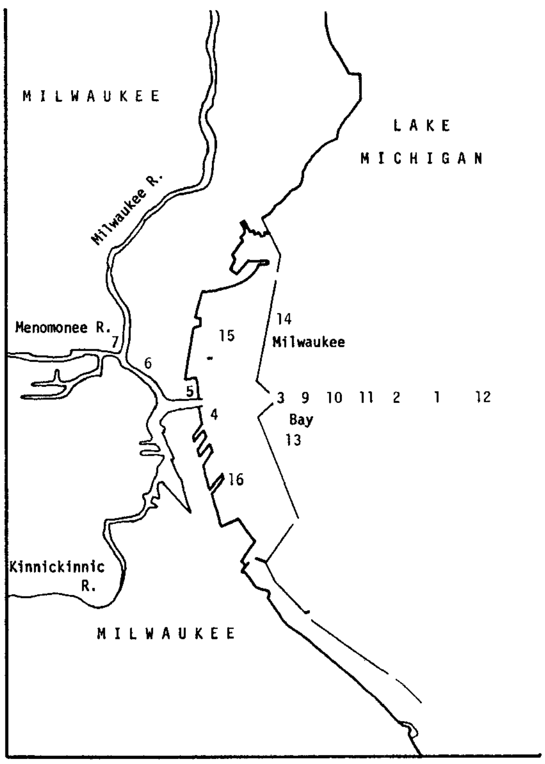

Fig. 2D. Sampling locations on 8/28/1976.

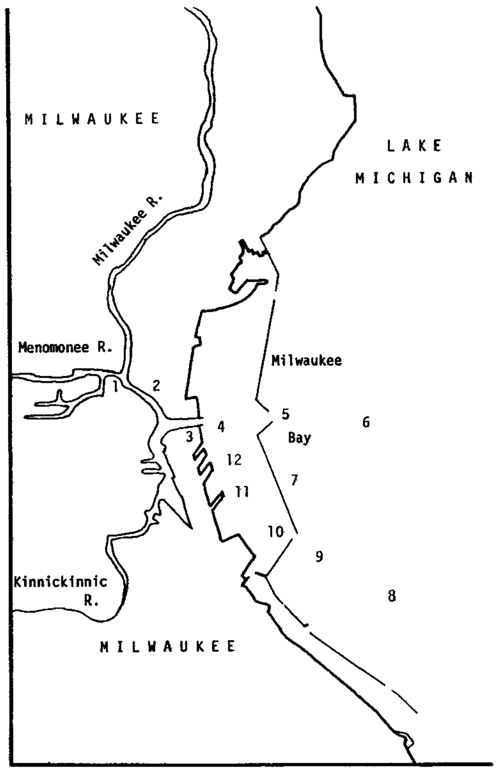

Fig. 3A. Sampling locations on 9/9/1976.

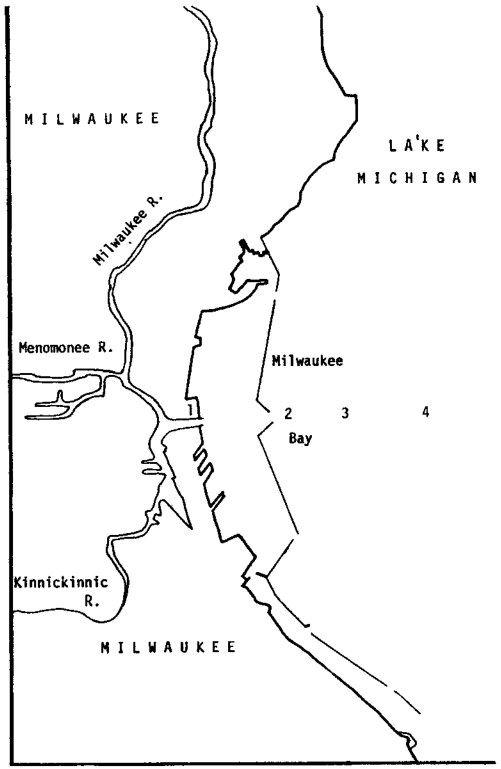

Fig. 3B. Sampling locations on 6/28 and 6/30/1977.

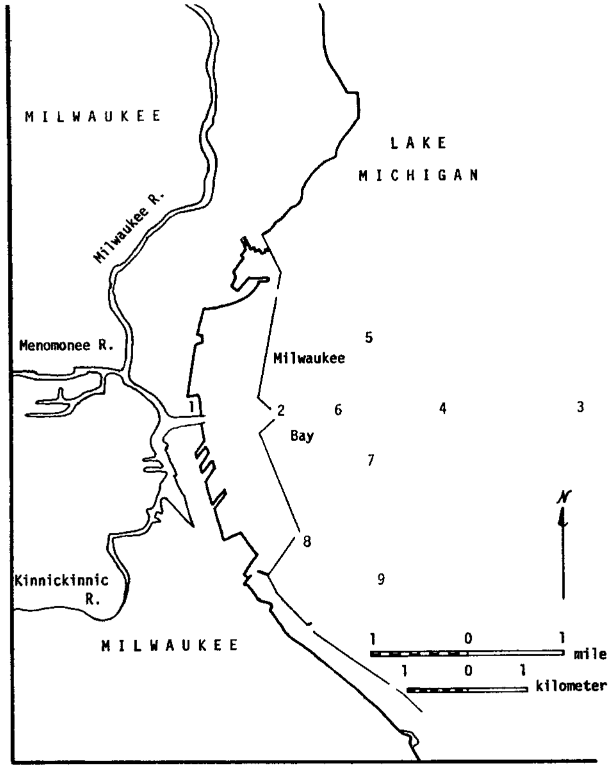

Fig. 3C. Sampling locations on 7/18/1977.

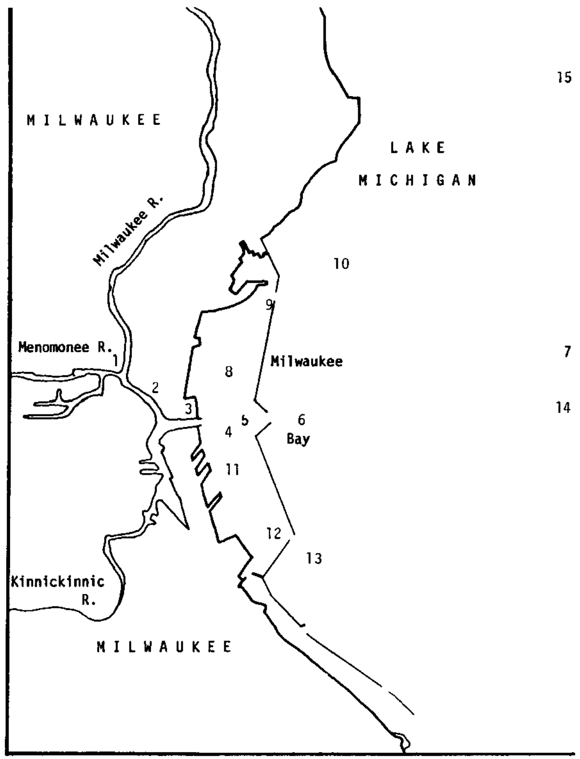

Fig. 4A. Sampling locations for baseflow and resuspension survey on 4/8/1976.

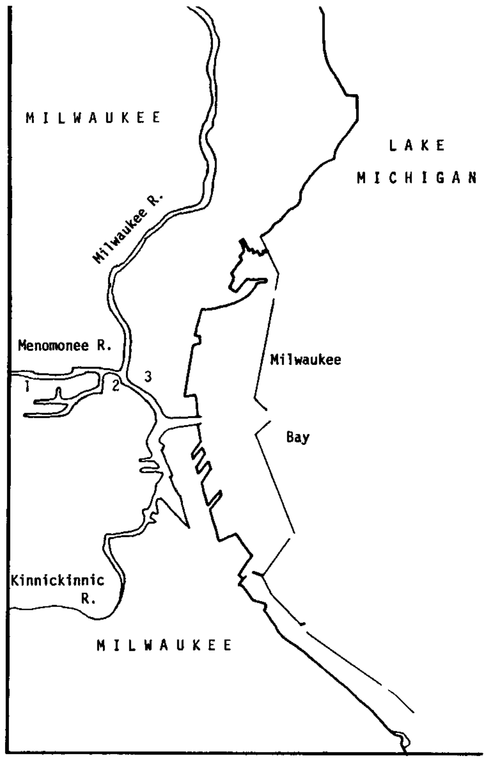

Fig. 4B. Sampling locations on 5/11/1977.

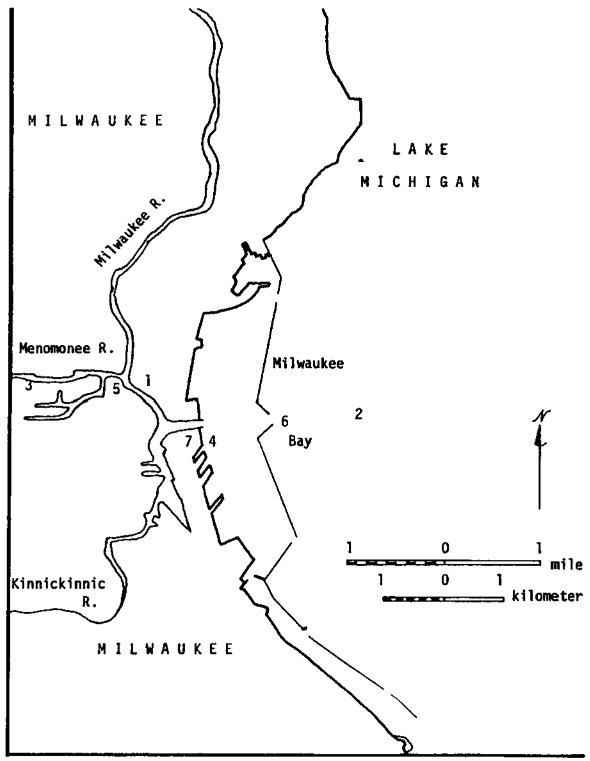

Fig. 4C. Sampling locations on 5/19/1977.

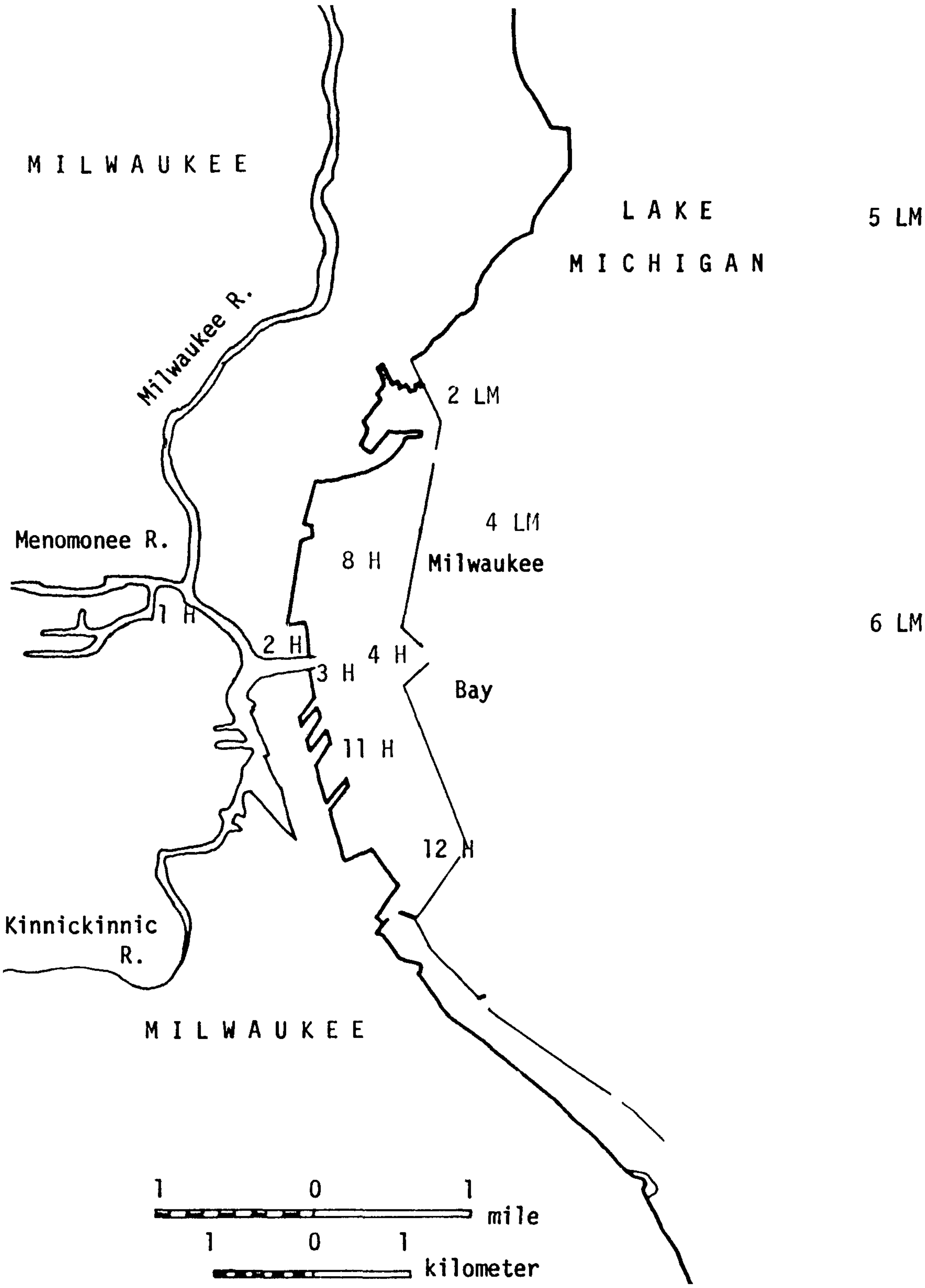

Fig. 5. Locations of bottom sediment sampling sites on 4/8/76 in the Harbor and on 4/19/76 in Lake Michigan proper.

survey. The sediments were analyzed for particle size, total phosphorus and Kjeldahl nitrogen by the Wisconsin Soil and Plant Analysis Laboratory, for chlorinated hydrocarbons by the Wisconsin Alumni Research Foundation (WARF) Institute, Inc., and for total metals by the Wisconsin State Hygiene Laboratory.

Current Measurements

The direction and velocity of the currents at the end of the inner harbor and in the breakwater central opening were measured on May 19, 1977, during a baseflow survey, and on June 28, June 30, and July 18, 1977, during runoff event surveys. Measurements were taken using an ENDECO current meter, which provides current direction and velocity, temperature and depth information. These measurements were recorded at 1.5 m (5 ft) intervals throughout the water column. The sampling boat, anchored and stabilized as much as possible during the time when readings were taken, was positioned near the middle of the 152 m (500 ft) wide, 9.1 m (30 ft) deep channel which occurred at both stations.

5. RESULTS AND DISCUSSION

Annual River and STP Loadings

The annual loading of pollutants to the Milwaukee Harbor from the three rivers and Jones Island STP were determined as an integral part of interpreting the results of the study. The annual loading of pollutants from the Milwaukee and Menomonee Rivers was calculated using a ratio estimator tested by the International Joint Commission staff and PLUARG investigators to be an efficient means of estimating tributary loadings (7). The ratio estimator (Eq. (1)) is a product of flow adjusted instantaneous load times a bias factor which accounts for bias in the form of negative or positive correlations between concentrations and flow.

$$\mu_y = \mu_x \cdot \frac{m_y}{m_x} \cdot \frac{\left(1 + \left(\frac{1}{n} \cdot \frac{S_{xy}}{m_y m_x}\right)\right)}{\left(1 + \left(\frac{1}{n} \cdot \frac{S_x^2}{m_x^2}\right)\right)} \qquad \text{Eq. (1)}$$

where μ_y is mean daily load, μ_x is mean daily flow for the water year, m_x is mean daily flow for days concentrations were determined, m_y is mean daily load for days concentrations were determined, and n is number of days concentrations were determined. The covariance S_{xy} and variance S_x^2 are estimated by:

$$S_{xy} = \frac{\sum_{i=1}^{n} x_i y_i - n m_y m_y}{n - 1}$$

$$S_x^2 = \frac{\sum_{i=1}^{n} x_i - n m_x^2}{n - 1} \qquad \text{Eq. (2)}$$

where x_i and y_i are the individual measured flows and calculated loadings, respectively, for each day concentrations were determined.

The equation produces an estimate of the mean daily load (μ_y). The ratio estimator also develops an estimate of the error in the loading value. The values used for concentrations in the Menomonee River were 1976 data obtained by the Menomonee River Pilot Watershed Study at the 70th Street Station. The concentration of various pollutants in the Milwaukee River were obtained from 1973, 1974 and 1975 U.S. Geological Survey (USGS) data obtained from the Estabrook Park Station in Milwaukee. Necessary flow data were obtained from USGS water year reports for the above station. The yearly loading values are shown in Table 2 for both rivers. The loading values from the Milwaukee River were generally higher with the values of soluble-P and chloride similar for both rivers. Based on the proportion of flow, the Kinnickinnic River pollutant loadings were considered to be 3% of the total loadings from the other rivers. The percentage of the combined river loadings due to runoff events was not calculated due to insufficient event data on the Milwaukee River. However, the results of the Menomonee River study have indicated about 20% of the suspended solids and about 50% of the other parameters were discharged during events. The annual loading of some pollutants for the Jones Island STP was determined by multiplying the average 1976 flow by the average effluent concentration for 1976 (Table 2). The STP had higher loadings of total-P and chloride than the combined loadings of the three rivers. The STP was a significant source of pollutants to the harbor area relative to the rivers. The combined loading from the river and STP obviously produced enough of an annual load to affect the water quality of the harbor area.

Water Quality Survey

The results of the event and baseflow water quality surveys demonstrated a general trend of improving water quality with each successive station from the inner harbor to the inshore zone, (Tables 3-19). An example of this trend was the decrease on August 28, 1976 in total- and suspended-solids, total- and soluble-P concentrations from 285, 18, 0.13 and 0.011 mg/L, respectively, at station 7 in the inner harbor to 185, 3, 0.02 and 0.003 mg/L, respectively, at station 1 in the inshore zone (Table 8). Averages of all the water quality data obtained in each zone further demonstrate the consistent differences in pollutant concentration between each zone. Part of the observed decreases in pollutant concentration was probably due to simple dilution. The magnitude of the differences, however, in such small distances indicated that water movement between the different zones was restricted. The results pointed out the effectiveness of the breakwater as a barrier to mixing between the water in the outer harbor and inshore zone. The differences in the levels of pollutants between the zones demonstrated that the water quality in the harbor zones was always impaired relative to the inshore zone. At all times the harbor zone was expected to be relatively degraded since it directly receives discharge from the rivers and STP. The concentrations in the harbor zones usually were higher at the surface, while the concentrations in the inshore zone usually were similar at both the surface and bottom. The exceptions to these trends were the high bottom concentration observed at all stations on February 13, 1976 and higher surface concentration in the inshore zone on July 18, 1977. The trend of higher surface concentrations was probably a result of the river and STP discharges staying at the surface when the harbor zones were stratified.

Table 2. Annual water ($m^3 \times 10^7$) and pollutant ($kg \times 10^4$) loadings to the Milwaukee Harbor

Source	Water	Solids		P		(NO_3+NO_2)-N	Cl	Pb
		Total	Suspended	Total	Soluble			
Menomonee River	8	6,200	1,500	2.8	1.2	13	1,250	0.87
Milwaukee River	36	16,000	1,430	7.6	5.5	36	1,200	3.5
Three Rivers combined**	45	23,000	3,000	10.7	6.9	50	2,520	4.5
STP	20	16,000	780	12.8	2.9		3,900	

*Menomonee River pollutant values were based on 1976 data, Milwaukee River values were based on 1973, 1974, 1975 data, and the STP values were 1976 data. The water data were averages of long term records.

**The Kinnickinnic River loading was considered to be 3% of the total loadings from the other two rivers.

Table 3. Water quality data in mg/L for two plume transects on 2/13/1976. See Fig 2A for station locations

Station No. and depth*	Solids		Total-P	Total alkalinity	Cl
	Total	Suspended			
			EAST		
1-Surface	584	15	0.16	182	200
Bottom	1086	15	0.30	238	450
2-Surface	288	10	0.08	134	58
Bottom	994	17	0.26	222	380
3-Surface	274	8	0.06	130	45
Bottom	400	22	0.16	142	96
4-Surface	168	4	0.02	104	13
Bottom	458	13	0.12	154	125
			SOUTHEAST		
5-Surface	274	5	0.77	128	50
Bottom	536	166	0.06	136	100
6-Surface	290	5	0.12	130	56
Bottom	286	5	0.06	131	52

*Bottom samples were taken 7 to 10 m below surface.

Table 4. Water quality data in mg/L for two plume transects on 2/25/1976. See Fig. 2B for station locations

Station No. and depth*	Solids		P		N		Cl	DO	Temperature, °C
	Total	Suspended	Total	Soluble	Total organic	$(NO_3 + NO_2)$			
					EAST				
1-Surface	580	18	0.21	0.090	0.90	1.76	140	12.0	2.1
Bottom	585	19	0.21	0.089	0.87	1.78	150	10.8	4.0
2-Surface	305	15	0.08	0.036	0.38	0.68	50	11.9	2.2
Bottom	455	13	0.17	0.087	1.12	1.44	90	11.8	1.8
3-Surface	275	11	0.07	0.027	1.50	0.59	40	12.0	2.0
Bottom	305	13	0.08	0.033	0.32	0.66	50	10.7	2.0
8-Surface	230	10	0.04	0.016	0.26	0.48	29	12.6	1.7
Bottom	300	13	0.08	0.033	0.53	0.66	55	11.0	1.9
7-Surface	180	8	0.02	0.006	0.54	0.28	11	13.1	1.2
Bottom	180	9	0.02	0.008	0.18	0.28	10	12.0	1.5
6-Surface	170	6	0.01	0.005	0.11	0.25	8	13.0	1.2
Bottom	165	6	0.01	0.005	0.50	0.24	8	13.2	1.0
					EDGE OF PLUME				
4-Surface	255	18	0.06	0.024	0.37	0.53	35	12.1	1.8
Bottom	305	62	0.16	0.027	0.49	0.57	40	11.4	1.7
9-Surface	280	11	0.07	0.027	0.34	0.55	45	12.2	2.0
Bottom	345	12	0.06	0.047	0.46	0.73	70	11.2	2.2
5-Surface	175	7	0.02	0.005	0.10	0.26	10	13.0	1.2
Bottom	170	9	0.02	0.005	0.15	0.25	8	13.2	1.0

*Bottom samples were taken at 7 to 10 m below surface.

Table 5. Metal concentrations in µg/L for two plume transects on 2/25/1976. See Fig. 2B for station locations

Station No. and depth*	Cd	Cr	Pb	Zn	Cu
		EAST			
1-Surface	0.3	5	27	40	13
Bottom	--	--	--	--	--
2-Surface	0.2	7	5	20	8
Bottom	<0.2	4	4	30	14
3-Surface	<0.2	<3	<3	20	19
Bottom	<0.2	<3	<3	20	6
8-Surface	<0.2	<3	<3	<20	7
Bottom	<0.2	<3	<3	20	6
7-Surface	<0.2	<3	<3	<20	6
Bottom	<0.2	<3	<3	20	6
		EDGE OF PLUME			
5-Surface	<0.2	<3	<3	<20	8
Bottom	<0.2	<3	<3	<20	14

*Bottom samples were taken at 7 to 10 m below surface

Table 6. Water quality data in mg/L for three plume transects on 7/28/1976. See Fig. 2C for station locations

Station No. and depth*	Solids		P		N		Total alkalinity	Cl	DO	Temperature, °C
	Total	Suspended	Total	Soluble	Total organic	(NO_3+NO_2)				
					EAST					
1-Surface	346	6	0.11	0.032	0.55	0.23	138	50	4.0	26
Bottom	292	4	0.12	0.052	0.48	0.21	142	35	3.5	20
2-Surface	312	6	0.12	0.048	0.94	0.21	140	44	3.5	24
Bottom	254	5	0.08	0.030	0.38	0.22	120	32	4.5	17
3-Surface	262	2	0.09	0.038	0.44	0.22	132	40	5.0	22
Bottom	184	3	0.07	0.019	0.30	0.22	110	14	6.5	15
4-Surface	234	0	0.07	0.004	0.56	0.35	112	30	8.6	20
Bottom	204	1	0.06	0.005	0.51	0.30	110	22	7.5	14
5-Surface	210	0	0.03	0.003	0.47	0.32	114	22	9.3	21
Bottom	154	0	0.01	0.003	0.20	0.20	112	8	10.2	11
17-Surface	156	0	0.02	<0.003	0.48	0.17	108	8	--	--
Bottom	190	0	0.02	0.003	0.31	0.25	112	6	--	--
6-Surface	162	0	0.01	<0.003	0.20	0.16	110	9	10.2	19
Bottom	158	0	0.02	<0.003	0.15	0.21	108	7	10.5	11
					SOUTHEAST**					
33-Surface	216	0	0.04	<0.003	0.41	0.32	116	24	9.2	20
Bottom	176	1	0.03	0.005	0.42	0.22	106	10	9.5	12
34-Surface	180	0	0.02	<0.003	0.25	0.20	108	11	10.2	19
Bottom	166	1	0.01	<0.003	0.22	0.20	108	8	9.8	10
					NORTHEAST**					
32-Surface	224	0	0.04	<0.003	0.55	0.33	112	29	9.8	21
Bottom	234	0	0.06	0.003	0.51	0.33	112	30	9.4	20
29-Surface	216	0	0.04	0.003	0.52	0.33	112	25	10.0	21
Bottom	168	0	0.02	<0.003	0.39	0.20	108	13	10.0	14

*Bottom samples were taken 7 to 10 m below surface.
**Stations 1, 2 and 3 are also included in these transects. See EAST transect for data.

Table 7. Metal concentrations in μg/L for three plume transects on 7/28/1976. See Fig. 2C for station locations

Station No. and depth*	Cd	Cr	Pb	Zn	Cu
		EAST			
1-Surface	<0.2	4	6	30	42
Bottom	<0.2	8	5	120	15
2-Surface	<0.2	5	<3	20	20
Bottom	<0.2	3	4	20	16
3-Surface	<0.2	4	3	30	16
Bottom	<0.2	<3	<3	40	11
4-Surface	<0.2	5	<3	20	32
Bottom	<0.2	7	<3	20	14
5-Surface	<0.2	<3	<3	20	12
Bottom	<0.2	<3	<3	<20	11
17-Surface	<0.2	<3	<3	<20	5
Bottom	0.34	<3	<3	<20	18
6-Surface	<0.2	<3	<3	<20	10
Bottom	<0.2	<3	<3	<20	12
		SOUTHEAST**			
33-Surface	<0.2	<3	<3	<20	10
Bottom	<0.2	<3	<3	<20	10
34-Surface	<0.2	<3	<3	<20	18
Bottom	<0.2	<3	<3	<20	11
		NORTHEAST**			
32-Surface	<0.2	<3	<3	<20	16
Bottom	<0.2	4	<3	<20	9
29-Surface	<0.2	<3	<3	<20	12
Bottom	<0.2	<3	<3	<20	7

*Bottom samples were taken at 7 to 10 m below surface.

**Stations 1, 2 and 3 also are included in these transects. See EAST transect for data.

Table 8. Water quality data in mg/L for three plume transects on 8/28/1976. See Fig. 2D for station locations

Station No. and depth*	Solids		P		N		Total alkalinity	DO	Temperature, °C
	Total	Suspended	Total	Soluble	Total organic	(NO_3+NO_2)			
					EAST-I**				
8-Surface	310	41	0.26	0.011	1.8	<0.02	84	0.2	23
Bottom	285	68	0.22	0.008	1.8	0.52	64	2.0	21
7-Surface	305	22	0.20	0.008	1.4	<0.02	110	0.3	26
Bottom	300	21	0.20	0.005	1.4	0.02	118	0.2	24
6-Surface	285	18	0.13	0.011	1.1	0.12	120	2.9	21
Bottom	270	32	0.15	0.013	0.87	0.18	120	4.8	17
5-Surface	240	8	0.09	0.015	0.75	0.20	116	5.1	18
Bottom	250	8	0.09	0.012	0.63	0.21	114	8.3	11
4-Surface	245	6	0.07	<0.003	0.81	0.22	116	7.5	18
Bottom	205	6	0.03	0.003	0.33	0.24	110	9.0	9
3-Surface	240	4	0.05	0.005	0.69	0.23	114	7.6	20
Bottom	215	3	0.05	0.005	0.63	0.23	118	7.4	19
2-Surface	210	3	0.03	<0.003	0.46	0.21	112	8.5	16
Bottom	205	2	0.02	0.003	0.27	0.24	108	8.6	16
1-Surface	185	3	0.02	0.003	0.49	0.16	108	8.8	19
Bottom	195	4	0.02	0.003	0.23	0.21	108	9.0	18
					EAST-II***				
9-Surface	225	2	0.05	0.004	0.66	0.23	116	7.7	18
Bottom	190	0	0.02	<0.003	0.35	0.25	110	9.6	8
10-Surface	205	2	0.03	0.003	0.41	0.24	112	9.0	13
Bottom	190	2	0.01	<0.003	0.47	0.26	110	9.6	7
11-Surface	205	3	0.02	0.003	0.42	0.23	110	9.2	13
Bottom	190	2	0.02	<0.003	0.26	0.26	110	9.8	7
12-Surface	190	1	0.01	0.003	0.57	0.17	108	9.0	17
Bottom	190	0	0.01	0.003	0.16	0.24	110	9.6	7
					EDGE OF PLUME				
13-Surface	210	2	0.02	0.003	0.42	0.24	110	9.4	13
Bottom	205	4	0.02	<0.003	0.25	0.25	110	9.7	7
14-Surface	200	2	0.02	<0.003	0.29	0.23	108	9.5	12
Bottom	210	14	0.02	<0.003	0.20	0.27	110	9.8	7
15-Surface	245	2	0.05	0.004	0.63	0.23	114	7.7	19
Bottom	260	48	0.16	0.003	1.1	0.25	110	8.8	10
16-Surface	195	1	0.04	<0.003	0.51	0.23	114	8.8	17
Bottom	180	0	0.02	<0.003	0.33	0.24	110	8.8	10

*Bottom samples were taken 7 to 10 m below surface.
**Samples collected between 1430 and 1615 hrs.
***Samples collected between 1650 and 1725 hrs.

Table 9. Metal concentrations in μg/L for three plume transects on 8/28/1976. See Fig. 2D for station locations

Station No. and depth*	Cd	Cr	Pb	Zn	Cu	Ni
			EAST-I**			
8-Surface	2.5	15	9	100	47	4
Bottom	3.1	12	10	80	32	4
7-Surface	2.6	13	11	90	47	4
Bottom	2.0	29	6	40	10	5
6-Surface	4.5	18	6	80	40	6
Bottom	2.5	36	25	80	32	4
5-Surface	0.7	11	8	60	24	4
Bottom	2.3	12	5	70	28	4
4-Surface	<0.2	3	<3	<20	19	2
Bottom	<0.2	<3	<3	<20	9	2
3-Surface	<0.2	<3	<3	<20	9	-
Bottom	<0.2	<3	<3	<20	6	-
2-Surface	<0.2	<3	<3	<20	4	-
Bottom	<0.2	<3	<3	<20	5	-
1-Surface	1.0	<3	<3	<20	18	-
Bottom	<0.2	<3	<3	<20	3	-
			EAST-II***			
9-Surface	<0.2	<3	<3	<20	20	2
Bottom	<0.2	<3	<3	<20	6	1
10-Surface	<0.2	<3	<3	<20	18	2
Bottom	<0.2	<3	<3	<20	4	3
11-Surface	<0.2	<3	<3	<20	8	2
Bottom	<0.2	<3	<3	<20	5	3
12-Surface	<0.2	<3	<3	<20	4	2
Bottom	<0.2	<3	<3	<20	10	3
			EDGE OF PLUME			
13-Surface	<0.2	<3	<3	<20	8	2
Bottom	<0.2	<3	<3	<20	3	2
14-Surface	<0.2	<3	<3	<20	8	6
Bottom	<0.2	<3	<3	<20	4	4
15-Surface	<0.2	3	<3	<20	13	3
Bottom	2.1	40	5	80	33	6
16-Surface	<0.2	<3	<3	<20	6	4
Bottom	<0.2	<3	<3	<20	6	3

*Bottom samples were taken 7 to 10 m below surface.
**Samples collected between 1,430 and 1,615 hr.
***Samples collected between 1,650 and 1,725 hr.

Table 10. Water quality data in mg/L for two plume transects on 9/9/1976. See Fig. 3A for station locations

Station No. and depth*	Solids		P		N		Total Alkalinity	DO	Temperature, °C
	Total	Suspended	Total	Soluble	Total organic	$(NO_3 + NO_2)$			
				EAST					
1-Surface	280	21	0.17	0.010	1.11	0.28	110	0.2	26
Bottom	260	16	0.17	0.007	0.76	0.21	126	2.2	19
2-Surface	285	68	0.16	0.008	1.04	0.24	128	0.9	23
Bottom	200	12	0.07	0.020	0.46	0.24	114	5.2	16
3-Surface	260	12	0.12	0.011	0.73	0.20	126	3.4	21
Bottom	175	8	0.07	0.008	0.24	0.27	112	6.2	15
4-Surface	205	8	0.06	0.010	0.42	0.41	114	7.4	18
Bottom	165	3	0.03	0.004	0.18	0.24	108	7.2	12
5-Surface	180	4	0.03	<0.003	0.32	0.30	110	9.1	18
Bottom	175	4	0.03	<0.003	0.25	0.26	108	9.2	12
6-Surface	160	2	0.01	<0.003	0.10	0.14	106	9.1	18
Bottom	160	4	0.02	0.020	0.12	0.23	108	8.8	17
				SOUTHEAST**					
12-Surface	200	5	0.05	0.004	0.39	0.38	112	8.4	18
Bottom	160	3	0.03	0.004	0.90	0.25	110	7.4	13
11-Surface	225	3	0.06	0.008	0.59	0.39	114	7.6	18
Bottom	205	5	0.04	0.004	0.36	0.35	112	7.9	18
10-Surface	180	6	0.03	<0.003	1.59	0.25	108	8.7	17
Bottom	180	5	0.03	<0.003	0.43	0.29	110	8.8	15
9-Surface	170	6	0.02	<0.003	0.24	0.20	106	9.2	17
Bottom	175	6	0.02	<0.003	0.23	0.23	108	9.0	11
8-Surface	170	5	0.02	0.004	0.74	0.21	106	9.2	17
Bottom	160	6	0.02	<0.003	0.18	0.21	108	9.2	17

*Bottom samples were taken 7 to 10 m below surface.

**Stations 1, 2 and 3 also are included in this transect. See EAST transect for data.

Table 11. Water quality data, current velocities and directions at harbor stations during three events

Time, hr	Depth, m	Suspended solids, mg/L	P, mg/L		Cl, mg/L	DO, mg/L	Temperature, °C	Current	
			Total	Soluble				Velocity, kmph	Direction, degrees
			STATION NO. 1* - HARBOR MOUTH - 6/28/1977						
1510	0	12	0.11	0.039	--	5.0	19	1.3	100
1515	7	14	0.07	<0.004	--	8.6	12	0.28	350
1630	0	10	0.12	0.031	--	3.8	20	0.74	80
1635	7	9	0.04	0.004	--	8.6	12	0.56	285
1815	0	9	0.09	0.017	--	4.6	19	0.46	65
1830	7	6	0.05	0.004	--	9.4	11	0.46	310
1905	0	8	0.10	0.014	--	8.0	18	0.46	75
1910	7	6	0.04	0.004	--	12.0	12	0.46	265
			STATION NO. 2* - BREAKWATER CENTRAL OPENING - 6/28/1977						
1530	0	6	0.04	<0.004	--	10.0	16	0.93	90
1540	7	4	0.02	<0.004	--	9.8	14	0.56	135
1720	0	6	0.05	0.006	--	8.2	17	0.37	140
1725	7	3	<0.02	<0.004	--	9.1	8	0.46	250
1845	0	4	0.04	<0.004	--	11.2	16	0.93	120
1850	7	4	0.04	<0.004	--	12.0	10	0.37	140
1925	0	4	0.04	<0.004	--	9.0	16	0.83	115
1935	7	2	0.02	<0.004	--	12.0	8	0.28	140
			STATION NO. 3* - 0.8 km EAST OF BREAKWATER - 6/28/1977						
1550	0	3	0.03	<0.004	--	12.0	15	--	--
1555	7	3	<0.02	<0.004	--	12.0	12	--	--
			STATION NO. 4* - 1.6 km EAST OF BREAKWATER - 6/28/1977						
1400	0	2	<0.02	<0.004	--	10.8	12	--	--
1405	7	2	<0.02	<0.004	--	11.6	10	--	--
			STATION NO. 1* - HARBOR MOUTH - 6/30/1977						
1515	0	35	0.12	0.011	--	8.9	16	0.56	277
1520	7	40	0.16	0.040	--	8.8	13	0.56	240
1700	0	27	0.12	<0.004	--	3.7	18	1.20	90
1710	7	34	0.12	0.012	--	5.7	16	0.65	208
1905	0	23	0.11	0.009	--	4.8	17	0.74	37
1915	7	25	0.08	0.009	--	7.4	13	0.30	218
			STATION NO. 2* - BREAKWATER CENTRAL OPENING - 6/30/1977						
1615	0	26	0.04	<0.004	--	10.5	10	0.37	283
1620	7	22	0.02	<0.004	--	10.7	10	1.57	227
1730	0	25	0.03	<0.004	--	10.5	10	0.74	158
1740	7	22	0.02	<0.004	--	10.4	10	0.83	345
1845	0	25	0.04	0.004	--	--	12	0.65	104
1850	7	26	0.04	0.006	--	--	12	0.46	172
			STATION NO. 1** - HARBOR MOUTH - 7/18/1977						
1330	0	57	0.20	0.041	36	3.0	24	1.11	90
1335	7	41	0.10	0.012	24	9.4	14	0.37	70
			STATION NO. 2** - BREAKWATER CENTRAL OPENING - 6/30/1977						
1445	0	25	0.12	0.019	26	6.3	20	0.56	120
1450	7	6	0.02	<0.004	11	11.0	10	0.83	290
1715	0	16	0.06	<0.004	20	--	19	0.46	330
1720	7	2	0.02	<0.004	9	--	8	0.93	250
1740	0	22	0.08	0.010	21	6.6	20	1.11	95
1745	7	15	0.06	0.050	20	8.5	15	1.20	90

*See Fig. 3B for station locations.

**See Fig. 3C for station locations.

Table 12. Water quality in mg/L in plume beyond breakwater during 7/18/1977 event

Station*	Time, hr	Depth, m	Secchi disc, m	Suspended Solids	P Total	P Soluble	Cl	DO	Temperature, °C
3. East of Breakwater 5 km	1535	0	1.5	6	0.02	<0.004	14	18	10
	1540	10	--	4	0.02	<0.004	8	10	12
4. East of Breakwater 2.5 km	1550	0	2.0	4	0.02	0.008	11	17	10
	1555	10	--	4	0.02	<0.004	8	9	12
5. NE of Breakwater 1.5 km	1600	0	--	4	0.02	<0.004	11	16	10
	1605	10	--	3	0.02	<0.004	8	8	12
6. East of Breakwater 1 km	1615	0	2.0	6	0.02	<0.004	13	15	10
	1620	10		4	0.02	<0.004	8	8	12
7. SE of Breakwater 1.5 km	1630	0	1.5	6	0.02	<0.004	12	14	11
	1635	10		4	0.02	<0.004	8	9	12
8. South Exit Breakwater	1645	0	0.75	12	0.02	<0.004	13	17	9
	1650	7		4	0.02	<0.004	8	10	11
9. SE of South Breakwater Exit 1.5 km	1700	0	1.0	6	0.03	0.008	11	14	10
	1705	10		4	0.02	<0.004	8	8	12

*See Fig. 3C for station locations.

Table 13. Water quality data in mg/L for three plume transects on 4/8/1976. See Fig. 4A for station locations

Station No. and depth*	Solids		P		N					
	Total	Suspended	Total	Soluble	Total organic	$(NO_3 + NO_2)$	Total C	Cl	DO	Temperature, °C
					EAST					
1-Surface	590	8	0.18	0.058	0.96	1.12	--	90	7.8	18
Bottom	408	9	0.12	0.060	0.83	0.78	--	38	9.0	14
2-Surface	438	6	0.14	0.058	0.76	0.85	--	50	8.9	14
Bottom	422	8	0.12	0.060	0.82	0.80	--	42	8.7	13
3-Surface	446	17	0.16	0.061	0.77	0.88	--	52	8.4	12
Bottom	348	12	0.12	0.036	0.77	0.59	--	46	9.0	10
4-Surface	348	5	0.10	0.036	0.57	0.59	10	48	9.4	10
Bottom	288	11	0.07	0.022	0.54	0.52	8	30	9.4	8
5-Surface	216	8	0.03	0.011	0.29	0.38	--	16	11.0	7
Bottom	258	7	0.05	0.022	0.44	0.49	--	25	10.0	7
6-Surface	174	5	0.02	0.005	0.24	0.28	--	9	12.4	5
Bottom	210	30	0.03	0.005	0.24	0.29	--	9	12.0	5
7-Surface	160	0	0.01	0.005	0.15	0.25	4	8	12.0	3
Bottom	164	0	0.02	0.005	0.21	0.26	4	8	12.0	3
14-Surface	152	1	0.01	0.003	0.12	0.24	--	8	--	3
Bottom	158	2	0.01	0.003	0.23	0.24	--	8	--	3
					SOUTHEAST**					
11-Surface	322	4	0.09	0.039	0.58	0.66	--	41	9.8	9
Bottom	310	6	0.09	0.033	0.57	0.61	--	39	9.5	8
12-Surface	224	7	0.04	0.015	0.39	0.44	--	20	11.2	7
Bottom	288	7	0.08	0.029	0.44	0.59	--	33	10.4	7
13-Surface	186	8	0.03	0.005	0.23	0.31	--	10	12.0	7
Bottom	198	10	0.03	0.006	0.22	0.33	--	13	11.4	6
					NORTHEAST**					
8-Surface	262	5	0.05	0.022	0.43	0.51	--	26	10.5	7
Bottom	260	10	0.07	0.022	0.37	0.50	--	27	10.0	7
9-Surface	238	15	0.05	0.016	0.29	0.43	--	20	10.6	8
Bottom	264	14	0.06	0.022	0.50	0.49	--	26	9.0	8
10-Surface	182	14	0.03	0.005	0.21	0.28	--	10	13.0	6
Bottom	188	19	0.03	0.005	0.14	0.28	--	8	13.0	6
15-Surface	152	0	0.01	0.003	0.29	0.24	--	8	--	3
Bottom	152	1	0.01	0.003	0.11	0.26	--	8	--	3

*Bottom samples were taken 7 to 10 m below surface.

**Stations 1, 2 and 3 also are included in these transects. See EAST transect for data.

Table 14. Metal concentrations* in µg/L for three plume transects on 4/8/1976. See Fig. 4A for station locations

Station No. and depth**	Cr	Pb	Zn	Cu	Fe
		EAST			
1-Surface	4	8	20	30	1000
Bottom	7	8	30	30	600
2-Surface	8	5	40	22	620
Bottom	11	10	<20	17	120
3-Surface	10	12	30	12	960
Bottom	8	6	20	12	780
4-Surface	7	5	30	30	520
Bottom	6	5	40	12	640
5-Surface	<3	4	30	44	100
Bottom	4	3	20	6	360
6-Surface	<3	3	<20	30	280
Bottom	<3	5	<20	20	980
7-Surface	<3	5	30	25	100
Bottom	<3	8	20	36	100
14-Surface	<3	<3	<20	3	--
Bottom	<3	<3	<20	<3	--
		SOUTHEAST***			
11-Surface	6	4	20	16	420
Bottom	6	3	20	13	500
12-Surface	3	<3	<20	11	360
Bottom	6	4	20	19	480
13-Surface	<3	3	<20	17	360
Bottom	<3	<3	20	8	400
		NORTHEAST***			
8-Surface	<3	3	<20	7	520
Bottom	5	4	<20	11	520
9-Surface	4	<3	<20	11	780
Bottom	3	4	<20	21	780
10-Surface	<3	<3	<20	13	840
Bottom	<3	7	<20	30	700
15-Surface	<3	<3	<20	3	--
Bottom	<3	<3	<20	<3	--

*Cd levels were <0.2 or 0.2 µg/L.

**Bottom samples were taken 7 to 10 m below surface.

***Stations 1,2 and 3 also are included in these transects. See EAST transect for data.

Table 15. Baseflow measurements of water quality at harbor stations

Time, hr	Depth, m	Suspended solids, mg/L	P, mg/L Total	P, mg/L Soluble	Conductivity, μmho	DO, mg/L	Temperature, °C	Secchi disc, m	Current Velocity, kmph	Current Direction, degrees
				STATION NO. 1* - 13th STREET BRIDGE - 5/11/1977						
1045	0	6	0.22	0.093	720	3.5	20	--	--	--
	4	5	0.24	0.108	760	2.3	19		--	--
	8	94	0.38	0.092	690	0.6	16		--	--
1335	0	6	0.22	0.092	730	4.2	21	--	--	--
	4	6	0.24	0.115	750	2.4	19		--	--
	8	138	0.51	0.092	730	0.2	17		--	--
				STATION NO. 2* - 2nd STREET BRIDGE - 5/11/1977						
1115	0	8	0.19	0.091	710	2.5	22	--	--	--
	4	10	0.14	0.050	490	4.8	14		--	--
	8	14	0.14	0.045	420	6.0	12		--	--
1440	0	82	0.36	0.066	610	3.2	18	--	--	--
	4	195	0.65	0.059	610	3.7	17		--	--
	8	153	0.54	0.057	580	4.0	16		--	--
				STATION NO. 3* - BROADWAY BRIDGE - 5/11/1977						
1225	0	15	0.16	0.051	500	5.1	15	--	--	--
	4	19	0.16	0.039	510	6.4	12		--	--
	8	27	0.14	0.024	330	7.2	11		--	--
1355	0	96	0.36	0.045	490	5.4	15	--	--	--
	4	93	0.35	0.044	450	5.2	14		--	--
	8	100	0.37	0.042	430	6.0	13		--	--
				STATION NO. 6** - BREAKWATER CENTRAL OPENING - 5/19/1977						
1205	0	4	0.08	0.021	--	8.0	15	1.75	0.28	90
1210	7	3	0.02	<0.004	--	11.8	10		0.28	255
1340	0	5	0.05	<0.004	--	8.9	15	1.65	0.28	320
1345	7	4	0.06	<0.004	--	8.5	12		0.37	263
1540	0	4	0.06	0.006	--	9.1	14	1.70	0.28	85
1545	7	4	0.06	0.008	--	12.4	8		0.37	270
				STATION NO. 7** - HARBOR MOUTH - 5/19/1977						
1135	0	3	0.12	0.066	--	5.2	17	--	0.37	115
1140	7	4	0.04	0.005	--	10.2	9		0.28	270
1420	0	3	0.12	0.063	--	5.6	17	1.5	0.18	170
1425	7	4	0.07	0.014	--	8.9	10		0.18	105
1625	0	5	0.12	0.068	--	5.2	18	1.5	0.28	130
1630	7	4	0.07	0.011	--	7.1	11		0.28	95
				STATION NO. 1** - BROADWAY BRIDGE - 5/19/1977						
1305	0	9	0.16	0.087	--	4.6	20	1.5	0.37	150
1308	7	6	0.09	0.018	--	8.0	10		0.46	340
1455	0	14	0.16	0.068	--	5.5	19	1.9	0.18	125
1500	7	14	0.17	0.072	--	6.7	13		0.18	345
				STATION NO. 2** - 1.6 km EAST OF BREAKWATER - 5/19/1977						
1525	0	2	<0.02	<0.004	--	13.1	--	3.2	--	--
1530	10	2	0.02	<0.004	--	12.9	--		--	--
				STATION NO. 3** - 13th STREET BRIDGE - 5/19/1977						
0940	0	3	0.22	0.116	700	1.5	23	--	--	--
0945	7	78	0.31	0.049	500	3.2	15		--	--
1030	0	4	0.20	0.110	--	3.5	18	--	0.18	285
1035	5	40	0.21	0.055	--	3.0	15		0.18	310
1045	0	4	0.20	0.110	690	1.8	23	--	--	--
1050	7	40	0.21	0.055	480	--	--		--	--
1135	0	2	0.20	0.105	690	2.1	23	--	--	--
1140	7	112	0.35	0.034	480	2.9	16		--	--
1235	0	3	0.20	0.110	690	2.4	23	--	--	--
1240	7	20	0.18	0.064	490	3.2	16		--	--
1342	0	56	0.30	0.073	690	2.4	23	--	--	--
1347	7	87	0.36	0.065	510	2.5	16		--	--
				STATION NO. 4** - JONES ISLAND OUTFALL - 5/19/1977						
1600	0	49	0.75	0.024	--	--	--	--	--	--
				STATION NO. 5** - 2nd STREET BRIDGE - 5/19/1977						
1005	0	2	0.17	0.096	610	2.4	22	--	--	--
1010	7	8	0.12	0.046	390	6.2	13		--	--
1110	0	3	0.17	0.088	610	3.4	23	--	--	--
1115	7	13	0.11	0.033	350	6.7	12		--	--
1200	0	37	0.16	0.077	610	3.5	23	--	--	--
1205	7	7	0.10	0.032	330	6.9	12		--	--
1300	0	3	0.16	0.080	610	3.4	23	--	--	--
1305	7	6	0.12	0.043	400	7.4	11		--	--
1405	0	3	0.19	0.105	530	3.6	20	--	--	--
1410	7	233	0.20	0.069	510	3.9	19		--	--

*See Fig. 4B for station locations.

**See Fig 4C for station locations.

Table 16. Averages and ranges of baseflow water quality data in mg/L at three harbor sites

	Solids		P		N		
	Total	Suspended	Total	Soluble	Total organic	(NO_3+NO_2)	Cl
				INNER HARBOR*			
Spring							
Average	420	17	0.15	0.06	0.78	0.85	52
Range	350 to 510	6 to 22	0.13 to 0.18	0.032 to 0.011	0.71 to 0.95	0.73 to 1.84	28 to 110
Summer							
Average	300	10	0.18	0.04	0.76	0.20	34
Range	270 to 380	5 to 14	0.12 to 0.23	0.020 to 0.056	0.56 to 0.98	0.14 to 0.32	25 to 42
				INSHORE ZONE**			
Average	175	2	0.014	0.004	0.21	0.25	12
Range	155 to 180	3 to 18	0.008 to 0.032	0.003 to 0.005	0.01 to 0.70	0.10 to 0.29	8 to 16
				OFFSHORE ZONE**			
Average	155	1	0.009	0.001	0.19	0.19	7

*Baseflow samples obtained at Broadway bridge during 1976.
**Based on data from other studies summarized (1) and baseflow survey from this study.

Table 17. Water temperatures and current velocities and directions at harbor stations on 5/19/1977. See Fig. 4C for station locations

	Samples taken at depth, m of																				
	0			5			10			15			20			25			28		
Time, hr	T	V	D	T	V	D	T	V	D	T	V	D	T	V	D	T	V	D	T	V	D
STATION NO. 1 -- BROADWAY BRDIGE																					
1300	20	0.37	160	19	0.28	145	15	0.18	185	12	0.28	310	10	0.46	340	-	--	--	-	--	--
1305	--	--	105	--	--	105	--	--	330	--	--	335	--	--	--	-	--	--	-	--	--
STATION NO. 7 -- HARBOR MOUTH																					
1235	17	0.37	115	17	0.28	105	12	0.18	65	9	0.28	250	9	0.28	250	8	0.28	260	-	--	--
1400	17	0.18	30	15	0.18	225	13	0.18	290	11	0.18	235	10	0.18	265	-	--	--	-	--	--
1405	--	--	170	--	--	115	--	--	70	--	--	270	--	--	105	-	--	--	-	--	--
1410	--	--	290	--	--	75	--	--	80	--	--	90	--	--	--	-	--	--	-	--	--
1415	--	--	50	--	--	65	--	--	80	--	--	100	--	--	--	-	--	--	-	--	--
1620	18	0.18	50	17	0.46	80	16	0.46	80	13	0.37	110	11	0.28	130	-	--	--	-	--	--
1625	--	--	130	--	--	80	--	--	80	--	--	100	--	--	95	-	--	--	-	--	--
STATION NO. 6 -- BREAKWATER CENTRAL OPENING																					
1120	18	0.28	70	--	--	--	13	0.18	85	--	--	--	9	0.28	250	-	--	--	-	--	--
1125	--	--	150	--	--	--	--	--	150	--	--	--	--	--	--	-	--	--	-	--	--
1200	15	0.28	90	15	0.28	95	12	0.28	100	9	0.28	235	9	0.28	255	-	--	--	6	0.28	300
1325	14	0.28	350	14	0.28	240	11	0.28	300	9	0.28	270	8	0.37	260	7	0.37	240	-	--	--
1330	--	--	290	--	--	300	--	--	270	--	--	250	--	--	265	-	--	--	-	--	--
1540	14	0.28	270	14	0.18	260	10	0.18	270	9	0.28	275	7	0.37	275	7	0.37	235	-	--	--
1545	--	--	85	--	--	75	--	--	235	--	--	285	--	--	265	-	--	260	-	--	--
1550	--	--	--	--	--	110	--	--	100	--	--	140	--	--	300	-	--	--	-	--	--

T is temperature in °C, V and D are current velocity in kmph and direction in degrees, respectively.

Table 18. Water temperatures and current velocities and directions at harbor stations. See Fig. 3B for station locations

	Samples taken at depth, m of																				
	0			5			10			15			20			25			28		
Time, hr	T	V	D	T	V	D	T	V	D	T	V	D	T	V	D	T	V	D	T	V	D
							STATION NO. 1 -- HARBOR MOUTH - 6/28/1977														
1430	19	0.37	85	20	0.28	75	16	0.18	200	14	0.28	165	12	0.28	315	---	----	---	-	----	---
1440	--	----	---	18	0.46	130	16	0.28	85	14	0.28	350	13	0.28	350	---	----	---	-	----	---
1450	20	1.30	100	20	1.20	85	17	0.46	70	--	----	---	--	----	---	---	----	---	-	----	---
1625	20	1.39	65	18	0.74	70	15	0.28	335	13	0.28	75	12	0.37	160	---	----	---	-	----	---
1635	20	0.74	80	20	0.37	65	16	0.56	195	14	0.56	235	12	0.56	285	---	----	---	-	----	---
1645	20	0.74	40	20	0.65	40	16	0.56	15	14	0.83	240	--	----	---	---	----	---	-	----	---
1650	--	----	---	--	----	---	16	0.93	215	--	----	---	--	----	---	---	----	---	-	----	---
1815	19	0.46	65	17	0.37	160	15	0.65	270	14	0.46	315	11	0.46	310	---	----	---	-	----	---
1825	18	0.37	70	18	0.18	155	16	0.65	210	14	0.28	320	12	0.37	310	---	----	---	-	----	---
1900	18	0.74	70	17	0.37	65	16	0.18	345	14	1.02	220	10	0.56	250	---	----	---	-	----	---
1910	18	0.56	65	18	0.56	45	16	0.18	50	14	0.28	330	12	0.93	210	---	----	---	-	----	---
1925	18	0.46	75	16	0.37	75	15	0.28	330	14	0.18	290	12	0.46	265	---	----	---	-	----	---
							STATION NO. 2 -- BREAKWATER CENTRAL OPENING - 6/28/1977														
1530	16	0.93	90	16	0.74	105	16	0.56	105	16	0.74	135	14	0.56	135	121	0.37	120	9	0.28	180
1540	16	0.93	45	16	1.11	90	16	0.56	45	16	0.74	150	13	0.74	135	10	0.46	315	-	----	---
1715	17	0.93	120	16	0.37	100	16	0.46	85	14	0.28	170	10	0.37	305	8	0.56	270	-	----	---
1725	17	0.37	140	16	0.37	145	9	0.18	315	8	0.93	345	8	0.46	250	8	0.37	300	-	----	---
1735	17	0.93	155	16	0.56	135	9	0.74	225	--	----	---	--	----	---	---	----	---	-	----	---
1840	16	0.93	120	16	0.56	90	16	0.93	55	16	0.56	150	10	0.37	140	8	0.28	50	-	----	---
1850	16	0.65	130	16	0.93	40	16	0.37	100	15	0.18	120	9	0.56	345	8	0.46	310	-	----	---
1930	16	0.83	115	16	0.83	115	16	0.93	40	12	0.56	150	8	0.28	140	8	0.56	345	-	----	---
1940	16	0.65	80	16	0.83	40	16	0.74	155	12	0.18	120	8	0.28	200	8	0.28	280	-	----	---
1950	16	0.37	70	16	0.37	35	16	0.28	75	10	0.28	165	8	0.28	220	8	0.28	195	-	----	---
2000	16	0.37	45	16	0.46	30	14	0.18	85	8	0.46	185	8	0.37	190	8	0.37	190	-	----	---
							STATION NO. 1 -- HARBOR MOUTH - 6/30/1977														
1530	16	0.56	277	14	0.93	270	14	0.93	285	14	1.11	270	13	1.30	268	13	0.56	240	-	----	---
1540	15	1.11	53	15	1.11	88	15	1.39	83	14	1.20	74	14	1.30	83	---	----	---	-	----	---
1550	18	2.26	74	18	1.67	75	17	1.39	83	16	1.11	90	16	0.74	85	---	----	---	-	----	---
1700	18	1.20	90	16	0.74	97	16	0.83	57	16	0.93	172	16	0.28	247	---	----	---	-	----	---
1710	17	0.18	208	17	0.56	251	16	0.46	251	14	0.93	228	14	0.65	203	---	----	---	-	----	---
1715	--	----	---	--	----	---	13	0.74	233	14	0.65	223	--	----	---	---	----	---	-	----	---
1900	17	0.74	37	16	0.28	5	15	0.74	218	14	0.56	337	14	0.46	320	13	0.30	218	-	----	---
1930	17	2.22	77	16	2.22	83	16	2.22	80	15	1.85	80	14	1.57	80	---	----	---	-	----	---
							STATION NO. 2. -- BREAKWATER CENTRAL OPENING - 6/30/1977														
1615	10	0.37	283	10	1.39	248	10	1.20	256	11	1.48	268	11	1.57	256	---	----	---	-	----	---
1625	10	2.26	232	10	1.85	223	10	1.67	226	10	1.85	232	10	1.57	227	---	----	---	-	----	---
1730	10	0.74	158	11	0.93	137	12	1.20	113	12	0.93	75	11	0.83	88	10	0.46	113	-	----	---
1740	10	0.37	138	10	0.18	138	10	0.37	46	10	0.46	360	10	0.46	293	10	0.83	345	-	----	---
1750	12	0.37	271	12	0.28	45	12	0.65	337	11	0.74	242	10	0.83	320	10	0.94	14	-	----	---
1800	13	2.78	87	13	1.85	97	13	2.22	93	13	1.76	82	12	1.30	53	12	1.20	17	-	----	---
1810	10	1.57	227	11	2.22	255	12	2.59	218	12	0.93	352	12	1.30	315	12	1.67	262	-	----	---
1825	11	2.96	278	11	2.41	286	11	1.85	286	11	1.67	285	11	1.76	285	---	----	---	-	----	---
1840	12	0.65	104	12	0.46	72	12	0.65	145	12	0.46	80	13	0.37	82	12	0.46	172	-	----	---

T is temperature in °C, V and D are current velocity in kmph and direction in degrees, repectively.

Table 19. Water temperatures and current velocities and directions at harbor stations on 7/28/1977. See Fig. 3C for station locations

	Samples taken at depth, m of																	
	0			5			10			15			20			25		
Time, hr	T	V	D	T	V	D	T	V	D	T	V	D	T	V	D	T	V	D
STATION NO. 1 -- HARBOR MOUTH																		
1315	24	0.93	65	22	0.83	80	19	0.83	90	15	0.46	75	14	0.37	90	--	----	---
1325	24	1.11	90	23	0.93	80	21	0.83	90	17	0.56	75	14	0.37	70	--	----	---
1350	24	0.65	75	23	0.37	95	21	0.28	115	16	0.28	345	13	0.46	270	--	----	---
1400	23	0.93	75	23	0.83	80	22	0.56	80	18	0.46	75	14	0.18	25	--	----	---
1415	24	0.74	80	23	0.56	80	20	0.37	85	19	0.28	50	15	0.18	265	--	----	---
STATION NO. 2 -- BREAKWATER CENTRAL OPENING																		
1445	20	0.56	120	19	1.11	125	14	0.74	165	11	0.46	240	10	0.83	290	--	----	---
1450	20	0.74	125	19	0.74	135	12	0.46	160	12	0.37	220	10	0.46	185	--	----	---
1500	20	0.37	150	17	0.46	185	13	0.74	240	13	0.83	240	10	0.83	190	--	----	---
1505	20	2.78	345	15	0.65	215	14	0.65	220	12	0.65	230	10	0.56	240	20	0.74	70
1705	20	0.65	100	20	0.65	105	13	0.37	140	12	0.56	165	--	----	---	--	----	---
1710	19	0.46	70	19	0.46	115	15	0.46	315	13	0.74	240	10	0.93	240	--	----	---
1715	19	0.46	330	16	0.83	290	13	0.65	240	10	0.93	230	8	0.93	250	--	----	---
1730	20	0.56	105	18	0.56	125	14	0.46	165	10	0.28	215	10	0.28	235	9	0.37	285
1735	20	0.56	105	20	0.65	110	16	0.37	115	14	0.28	125	10	0.18	225	10	0.37	330
1740	20	1.11	95	19	1.39	95	19	1.48	90	18	1.30	80	15	1.20	90	12	1.39	115
1745	20	0.65	5	19	0.46	15	17	0.46	110	11	0.46	140	11	0.28	225	10	0.56	255
1750	19	0.74	110	19	0.65	110	17	0.65	340	13	0.37	325	12	0.28	180	12	0.28	180
1800	19	0.28	330	14	0.74	250	14	0.74	250	12	1.02	235	9	1.02	245	9	0.83	260
1815	20	1.11	105	20	0.83	140	18	0.74	175	14	0.46	140	12	0.56	75	12	0.65	70
1820	20	1.39	85	20	1.20	95	20	1.11	90	20	1.20	80	15	1.39	100	12	1.39	105
1830	--	----	---	14	0.74	140	14	0.37	180	--	----	---	--	----	---	--	----	---
1835	16	0.46	250	15	0.28	205	15	0.46	225	14	0.74	240	12	1.02	230	12	0.83	220
1900	19	0.74	90	19	0.65	125	19	0.56	170	14	0.37	135	11	0.56	175	10	0.37	195

T is temperature in °C, V and D are current velocity in kmph and direction in degrees, respectively.

Determination of the degree of water quality impairment in the harbor and inshore zones during runoff events was dependent on defining the ranges of pollutant concentrations during baseflow. The mean and ranges of several parameters at the surface for the inshore zone near Milwaukee (Table 16) were obtained from the literature (1). For the purpose of this report the eastern boundary of the inshore zone is 5 km from the breakwater. Surface concentration observed during background surveys on May 19, 1977 and April 8, 1976 also were used. Inner harbor surface water quality data collected over a 2-yr period in the Menomonee River Pilot Watershed Project were used to estimate average baseflow pollutant levels for the inner harbor area. The inner harbor trends were assumed to hold true for the outer harbor, since insufficient baseflow data were available. Most baseflow surface water quality values for inshore and harbor zones contained considerable variability; because of this and the fact that different laboratories analyzed the inshore zone samples emphasizes the need for caution in examining the results. In contrast, most of the offshore zone surface concentrations obtained from the literature (1) and this study, showed less variability (Table 16). Baseflow water quality data for the various zones showed that not only were the harbor zones always impaired relative to the inshore and offshore zones but that the inshore zone was always impaired relative to the offshore zone.

A comparison of the above baseflow values with event surface water quality in the inner harbor indicates that the water quality of the harbor was usually degraded during runoff events (Tables 3 to 19). During an event the levels of total and suspended solids and total organic N were usually elevated whereas total- and soluble-P levels were seldom increased. In contrast to water quality in the harbor zones, the inshore zone usually was not lowered during an event (Tables 3 to 16). Noticeable exceptions to this trend in the inshore zone occurred on February 25, and September 9, 1976 at two sampling sites (sites 5 and 7 in Figs. 2B and 3A) and July 18, 1977 for suspended solids and chlorides. Although the levels of these parameters were within the range for background values, the values were significantly higher than the means. The event values for these two parameters and the other three parameters were usually close to the mean of the baseflow values for all event surveys in the inshore zone. The two stations with higher values on September 9, 1976 were just outside the south breakwater opening and represented a very small area of contamination in the inshore zone. The higher levels of suspended solids were expected on July 18, 1977 because of the appearance of large areas of turbid water in the inshore zone. The February 25, 1976 values were probably a result of an extended period of high flow during a snowmelt. The trend for the inshore zone obviously indicates that the offshore zone usually was not affected during runoff events.

Although water quality in the harbor was affected during runoff events, the inshore zone was rarely altered significantly. Only the July 18, 1977 event with relative high flows [85 cms (3000 cfs) at 70th Street] and rainfall (5 cm) impaired the water quality for a large area of the inshore zone. All the other events were considered more normal with peak flows <42 cms (<1500 cfs) at 70th Street and <2.5 cm rainfall. However, water quality in the inshore zone was definitely degraded relative to the offshore zone.

Thus, the data indicate that the input from the harbor was affecting the inshore zone, but this was not noticeable during high flow periods of a commonly occurring event. Transport of event-related pollutants to the inshore zone appears to be controlled by the physical confinement of the harbor and current movement in the harbor.

Current and Dispersion Patterns

Transport mechanism of pollutants from the inner to outer harbor and through the central breakwater opening to the inshore zone was investigated by observing the direction and velocity of currents during runoff events (Tables 17 to 19). A current direction of approximately 270 degrees indicated that the direction of flow was to the harbor and 90 degrees indicated flow was towards the lake. Currents were observed to reverse direction and stratified flows were recorded for most of the sampling days. The reversal of current direction has been observed as far as 3.2 km above the end of the inner harbor. The current velocity usually varied considerably during a sampling day and represented brief intervals of flow ranging from 62 to 620 cms (2,200 to 22,000 cfs) at the central breakwater opening; and current measurements for events on June 28 and July 18, 1977, indicated that there were periods of stratified flow at each end of the inner harbor and the central breakwater opening. The surface 3 m was observed to have more periods of outward flow than the lower depths. The current direction changed significantly at least once during the brief sampling period for depths below 5 m. A reversal of current direction resulted in a change in water temperature.

Lake water coming into the harbor significantly lowered the temperature in the upper layers. Pollutant concentrations were higher in the strata flowing towards the lake for both stations on June 28 and July 18 (Tables 18 and 19). Current velocities ranged from 0.28 to 2.8 kmph and usually were higher in the upper 3 m of the water column. The flow was not stratified on June 30, 1977 and the whole water column reversed direction frequently during the period of record (Table 18). Current velocities on this date were generally higher than on other sampling dates. The entire water column at the breakwater opening reflected the temperature of the hypolimnetic water of the inshore zone. Flows were stratified and reversed direction during the period of measurement at both stations for the low flow survey on May 19, 1977 (Table 17); current velocities were consistently low and ranged from 0.18 to 0.37 kmph (0.1 to 0.2 knots). The data from all the sampling days demonstrated the variability in current movement from day to day, however insufficient flow measurements were recorded to predict any long term trends in current direction and velocities.

The results of the current measurements suggest that the current pattern in the harbor controls the transport of pollutants to the inshore zone during runoff events. The lake and harbor seiches were probably responsible for the observed current patterns. The pattern of reversing current directions at the central breakwater opening could alternate the discharge of harbor water to the inshore zone with lake water coming into the harbor.

Pollutants discharged to the harbor during events could have entered the inshore zone in plugs during the event and for some time afterwards with the size and frequency of the plugs probably varying considerably throughout the year. Some portion of the event loading was discharged to the inshore zone after a residence time in the harbor but the relative portion of the event loading that reached the inshore zone during the brief period of high flows was probably small and the amount reaching the inshore zone during most events was insufficient to alter noticeably water quality. An exceptionally large event, such as the one on July 18, 1977, immediately lowered water quality of the inshore zone because a portion of the river water flowed along the surface and reached the inshore zone during the event. The results indicate that the effect of event flows was modified by the harbor current pattern and harbor structures, and the degradation of the inshore zone was probably a more gradual process.

The dispersion pattern of the pollutants reaching the inshore zone was difficult to assess in the study, since the only surface plume observed was on July 18, 1977. This plume had dispersed sufficiently in about a day or so as to extend approximately 5 km into the inshore zone from the center breakwater opening (Fig. 6). The plume dispersed symmetrically on either side of an east-west axis. The plumes emerging from the north and south breakwater openings were much smaller in size. The long term dispersion pattern of the plume will not be known until remote sensing data from the two WDNR DC-3 overflights and the LANDSAT satellite have been interpreted. The dispersion of pollutants from the other events surveyed was only visible in the form of small islands of turbid water in the inshore zone or a narrow line of turbid water along the outside edge of the breakwater, however, those conditions existed during baseflow. The dispersion pattern can vary from day to day because of the significant effect of wind on the direction of the surface currents in the inshore zone. Past investigations of the inshore currents in the Milwaukee area indicated that the general flow in spring and summer is highly variable and that small residual flows exist to the south at this time. During the fall and winter, the flow is north past the Milwaukee area with minimum variability.

Annual Lake Loading Estimate

The results of this study indicate that the transport of pollutants to the inshore zone was modified by harbor currents and structures and therefore the water discharged to the harbor had an undetermined residence time. The pollutant load in the discharge waters was probably reduced by settling processes during residence. Enough of the river inputs have been deposited annually to require dredging to maintain shipping canals. The question remains to determine how much of the annual harbor loadings from events and baseflow were retained in the harbor zones. Determination of the retention of pollutants from individual events was not attempted from the available data.

A mass balance relationship was used to estimate annual inputs to the inshore area from the rivers and the Jones Island STP. The relationship was based on comparing the inputs to the inner or outer harbor for an

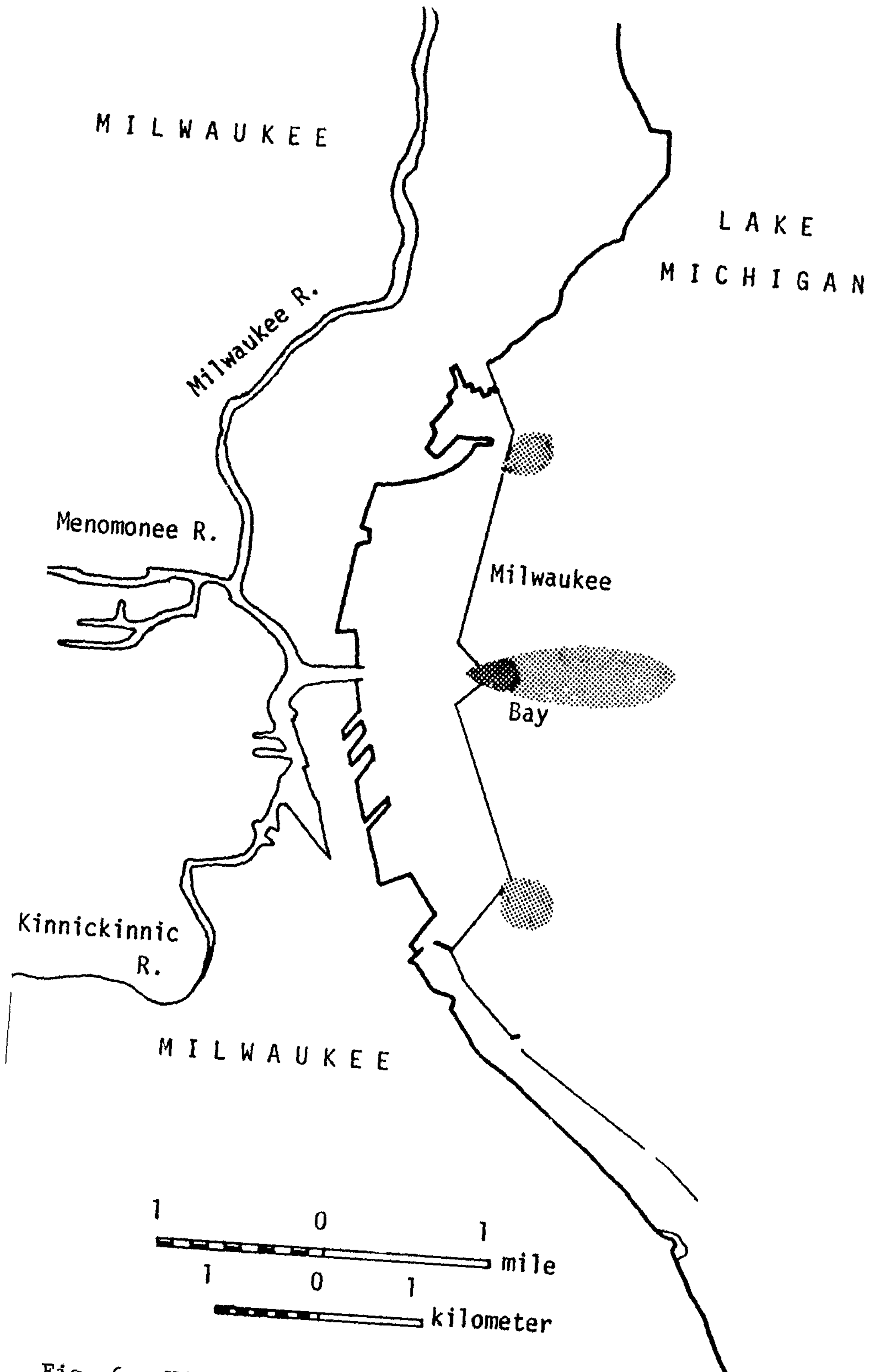

Fig. 6. Visible plumes following 7/18/1977 event.

average residence time with the average mass of a pollutant present in those areas. If the amounts of a nonconservative pollutant (e.g., total P) in the inner or outer harbors was exceeded by the inputs for the residence time, part of the nonconservative pollutant was considered to have been retained in these areas. The residence time for the inner and outer harbors was calculated using the concentration gradients of chloride in a residence time equation (Eq. (3)) developed for coastal regions (8).

$$t = \frac{V}{Q_D} \frac{(C_{SS}-C_L)}{(C_D-C_L)} \qquad \text{Eq. (3)}$$

where
- V = volume in the coastal zone
- Q_D = volumetric flow from rivers and discharges
- C_{SS} = mean concentrations in the coastal zone
- C_D = concentration in the river and discharges
- C_L = concentration in the outer lake
- t = residence time

Equation (3) states that the coastal residence time is the mean mass excess divided by the total discharged mass excess. Chloride was used for the calculation of residence times because its mass was assumed to be conserved during transport. The residence time of the harbor areas calculated with the chloride concentrations was used in the mass balance equation for determining retention of nonconservative pollutants.

The inner harbor was the coastal zone when the outer harbor was considered to be the lake. The concentration values for the terms C_{SS} and C_L used for the inner harbor residence time calculations were averages from available data sources from this study and the Menomonee River Watershed Project (Table 20). Since the inner harbor was not a well-mixed area, the mean concentration of chloride and other parameters were weighted for different areas in the inner harbor. The mean river concentrations of chloride and the other pollutants were obtained by dividing the combined yearly loadings by the combined yearly volume of water discharged (Table 20). Long term water discharges were obtained from the USGS to determine total water loadings for the river. The residence time of the inner harbor was estimated to be 4.6 days using Eq.(3). The natural residence time of the inner harbor was determined to be 5.2 days; natural residence time being determined by dividing the volume of the harbor by the tributary flow. The estimated residence time represents an average of all possible conditions and probably varies with significant changes in river flows and current movement. The similarity in the natural and estimated residence times probably means a significant increase in discharge to the inner harbor substantially reduces the residence time for a portion of the pollutants. The inner harbor was determined to be flushed 79 times/yr.

The outer harbor was the coastal zone when the inshore area was the lake in Eq. (3). The inner harbor was considered to discharge to the outer harbor at a higher rate than the combined river flows. The rate of 1.3×10^6 cms/day was determined by increasing the combined river rates by the ratio of the inner harbor residence time. This rate could be highly

Table 20. Mean annual surface concentrations of pollutants in mg/L in the harbor region*

Region or tributary	Mean flow, cms	Solids		P		(NO_3+NO_2)-N	Cl
		Total	Suspended	Total	Soluble		
Inner Harbor	--	405	19	0.17	0.070	0.70	54
Outer Harbor	--	245	9	0.06	0.016	0.40	31
Inshore Zone	--	180	3	0.02	0.003	0.22	8
Menomonee River	2.5	780	190	0.35	0.15	1.7	160
Milwaukee River	11.3	460	40	0.21	0.15	1.0	33
Combined Rivers**	14.4	510	67	0.24	0.15	1.1	56
Jones Island STP	6.2	840	40	0.66	0.15	--	200

*Means include values from this study and the literature.

**Combined Menomonee, Milwaukee and Kinnickinnic Rivers.

variable and was the best available estimate for an average rate. Discharges from Jones Island STP were included as inputs to the outer harbor. The values used to solve Eq. (3) were mean values of data obtained from this study and the literature (Table 20). The mean concentrations for chloride and other parameters in the inshore zone were obtained by combining historical data with results of this study. The residence time calculated for the outer harbor was 5.2 days, which was adjusted to 6 days to allow the chloride inputs and outputs to balance. This adjustment resulted from the need to average chloride concentrations that were highly variable with time and location in the outer harbor. Ideally the residence times should have been calculated for a specific time period like a season for both harbor zones instead of an average residence time throughout the year. Data were not available for such an estimate. The natural residence time of the outer harbor was determined to be 20 days. The higher natural residence time indicates that the current pattern of the breakwater openings increased the transport of water out of the outer harbor. The outer harbor was determined to be flushed 61 times/yr.

The percentage of the annual inputs retained in the inner and outer harbors was calculated using the mass balance equation (Eq. (4)).

$$\% \text{ Retained} = \left(\frac{(Q_D \times C_D \times t) - (V \times C_{SS})}{Q_D \times C_D \times t}\right) 100 \qquad \text{Eq. (4)}$$

The terms have the same definitions as in Eq. (3).

Equation (4) states that the percentage of material entering the harbor area that is retained depends on the difference between the amount of material input during the residence time and the average amount of material present in the harbor area.

The concentration values used for the nonconservative parameters are shown in Table 20. From Eq. (4) the annual river inputs retained in the inner harbor were 70, 22, 52 and 35% for suspended solids, total- and soluble-P and $(NO_3 + NO_2)$-N, respectively; annual inputs from the inner harbor and from Jones Island STP retained in the outer harbor were 1, 33 and 43% for suspended solids and total- and soluble-P, respectively. The 1% value for suspended solids is probably low and represents the sensitivity of the equation to inaccurate estimates of concentrations. The mass balance results from the inner and outer harbors were used to calculate the total amount of all the harbor inputs entering the inshore area/yr. The quantities and percentages of suspended solids, total- and soluble-P discharged annually from the river and STP that enter the inshore area/yr were 17×10^6 (45%), 144×10^3 (61%), and 35×10^3 (35%) kg, respectively. Although the numbers represent gross estimates, the percentages indicate that a significant portion of the pollutants entering the harbor area did not reach the inshore area. The most obvious mechanism of retention of the particulate pollutants is deposition during their residence time in the harbor. Soluble pollutants such as soluble-P might be sorbed onto particulate matter or incorporated in the biomass in the harbor.

The percentage of suspended solids entering the inshore zone/yr was compared to the suspended solids in the inshore plume of July 18, 1977. A concentration of 6 mg/L of suspended solids was assumed over the entire surface area of the plume to the bottom of the thermocline at 10 m. An estimate of 850,000 kg was calculated which was 5% of the annual suspended solids loading to the inshore zone. The amount of suspended solids in the plume was small relative to the total input/yr. The size of the input during one of the only events at which a plume was observed, supports the conclusion that only a small portion of the event loading enters the inshore zone during the brief period of high river flows.

Preliminary results from the Menomonee River Watershed Project have shown the annual event loading of suspended solids, total- and soluble-P to be roughly 80, 50 and 50% respectively, of the total annual Menomonee River loadings. Thus, a significant portion of the total annual inputs from these three rivers that were retained in the harbor could have originated from runoff events. Without a great deal of information to verify the adequacy of Eq. (4), it must be assumed that the 70% value calculated is a reasonable estimate of suspended solids retention in the inner harbor. Data from the Menomonee River Watershed would indicate that approximately 80% of the total suspended solids loadings arises during events and without evidence to the contrary it must be assumed that retention in the inner harbor is the same for events and baseflow. Based on these calculations, 8 to 9 x 10^6 kg of suspended solids was retained in the inner harbor and 3 to 4 x 10^6 kg entered the outer harbor. Similar calculations could be made with total- and soluble-P with lesser degree of certainty that the estimates are reasonable because of the possible effect of suspended solids concentration on P transformations and most of the P retained in the inner harbor did not arise from annual event loadings. Although the mass balance results indicate that a small amount of suspended solids was retained in the outer harbor, any calculation of event pollutant loading retained in the outer harbor is considered difficult because of the significant contribution from the Jones Island STP. For example, differences in the characteristics of the suspended solids in the sewage effluent and the river make it difficult to assume that the percentage of total inputs are the same for both sources. The above estimates of the amount of the annual event loading retained in the inner harbor are only gross estimates. The numbers demonstrate that loading estimates to the lake from land use activities should be significantly reduced.

Bottom sediments

Bottom sediment survey data indicate that pollutants from the rivers are retained in the harbor area (Tables 21 and 22). Total-P, total-N and metal concentrations were higher in the harbor than in the river and lake sediments. All but one of the sediment samples consisted mostly of sand and silt size fractions. Stations 11H and 12H to the south of the main channel in the outer harbor had lower pollutant values than other harbor stations. A large portion of the pollutants discharged must have been deposited in the main channel and a lesser amount was transported

Table 21. Sediment analyses (% of oven-dried weight) for Menomonee River, Milwaukee Harbor and Lake Michigan. See Fig. 5 for station locations

Station No.	Sand	Silt	Clay	Total N	Total P
413008*	46	46	8	0.07	0.05
413006*	91	9	0	0.03	0.04
413004*	60	34	6	0.16	0.06
2H**	54	40	6	0.21	0.19
3H	28	66	6	0.25	0.30
4H	20	72	8	0.20	0.34
8H	16	76	8	0.12	0.27
11H	6	80	14	0.13	0.18
12H**	34	56	10	0.12	0.08
4LM	39	56	5	0.03	0.06
2LM	0	30	70	0.03	0.09
5LM	32	50	18	0.10	0.09
6LM**	60	32	8	0.04	0.04

* Mainstem monitoring stations on the Menomonee River.

**Pesticide concentrations were below detection limits at these. stations. PCB concentrations were 1.6 and 8.3 mg/kg at stations 12H and 6LM, respectively.

Table 22. Metal concentrations in mg/kg in sediments of Menomonee River, Milwaukee Harbor and Lake Michigan. See Fig. 5 for station locations

Station No.	Cd	Cr	Pb	Zn	Cu	Fe	Ni
413008	1.2	11	83	180	18	30,000	20
413062	1.4	32	62	75	18	15,000	20
413004	10	110	690	510	18	40,000	33
2H	8.4	124	440	370	63	--	--
3H	17	1240	380	470	108	40,000	45
4H	23	1420	330	600	125	40,000	43
8H	18	880	250	570	104	40,000	39
11H	14	790	210	430	73	40,000	41
12H	5.8	175	66	150	30	30,000	21
4LM	1.5	15	30	42	8	7,000	12
2LM	2.0	37	30	52	25	19,000	37
5LM	1.0	27	33	86	23	50,000	36
6LM	0.2	6	7	21	5	20,000	7

to parts of the outer harbor. Pollutants associated with the particulates discharged during events were probably responsible for the observed enrichment of pollutants in the harbor bottom sediments.

Resuspension

Aerial photographs obtained by NASA during the overflight on April 8, 1976 confirmed the presence of a narrow band of turbid water along the shoreline extending a number of miles north of the Milwaukee embayment (6). The embayment includes the area between the Linwood Water Purification Plant just north of the outer harbor to Sheridan Park just south of the outer harbor. The turbidity extended further into the lake north of Milwaukee and the suspended material was entering the outer harbor through the north opening. There also was a band of turbidity along the outside edge of the breakwater wall. The suspended material was not discharged into the lake from a runoff event because a significant amount of rainfall had not occurred for almost 2 weeks. Instead, the suspended material may have originated from shoreline erosion and/or resuspension of bottom sediments. Areas of active erosion have been identified just north of the Milwaukee embayment and inshore currents could have transported the suspended material to the breakwater. Resuspension was also a possibility, since the inshore area was not stratified. On April 8, 1976 an easterly wind was recorded and the highest turbidity was in relatively shallow (2 to 6 m) water.

Concentrations of suspended solids in the areas of turbid water (Station Nos. 10, 6 and 13) were higher than baseflow averages for the inshore zone and areas of low turbidity on April 8, 1976 (Table 13). Some of the concentrations of total-P and total-solids were higher at Stations 10, 6, and 13 than at Station 7 in a low turbidity area. The total-P and total-solids concentration, however, did not usually exceed baseflow averages. The concentration gradients of suspended solids mapped by NASA (6) for April 8, 1976 were used to estimate the amount of suspended solids in the turbid water inside the Milwaukee embayment. Approximately 1.8×10^6 kg of suspended solids were found in the turbid water, which represents about 4.5% of the total annual loading of suspended solids to the harbor or about 12% of the total annual loading leaving the harbor. This amount of suspended solids was about twice as much as suspended solids observed in the July 18, 1977 runoff event plume in the inshore area. The suspended solids concentration was also higher on April 8, 1976 than on July 18, 1977. The annual contribution of suspended solids to the inshore area from a combination of resuspension and shoreline erosion could be significant when compared with the annual input to the inshore area from the Milwaukee harbor. Shoreline erosion or resuspension did not appear to degrade water quality in the inshore zone.

REFERENCES

1. Torrey, M. S. Chemistry of Lake Michigan, Vol. 3, Environmental Status of the Lake Michigan Region, Argonne National Laboratory/ES-40, 1976. 418 pp.

2. Ayers, J. C. and J. C. K. Huang. Studies of Milwaukee Harbor and Embayment. In: Studies on the Environment and Eutrophication of Lake Michigan, J. C. Ayers and D. C. Chandler, (eds.). Special Report No. 30, Great Lakes Research Division, University of Michigan, Ann Arbor, Michigan, 1967. 415 pp.

3. Envirex, Inc. Compilation, Analysis and Interpretation of Selected Lake Michigan Water Quality Data. Envirex, Inc., Environmental Science Division, 1974. 286 pp.

4. American Public Health Assoc. R. C. Rand, A. E. Greenberg, and T. J. Taras (eds.). Standard Methods for the Examination of Water and Wastewater, 14th ed. Washington, D. C., 1975.

5. U. S. Environmental Protection Agency. Manual of Methods for Chemical Analysis of Water and Wastes, 2nd ed. EPA 625/6-76-003A, U.S. Environmental Protection Agency, 1976. 317 pp.

6. Raquet, C. A., J. A. Salzman, T. A. Coney, R. V. Svehla, D. F. Shook and R. T. Gedney. Coordinated Aircraft/Ship Surveys for Determining the Impact of River Inputs on Great Lakes Water--Remote Sensing Results. NASA Lewis Research Center, 1977.

7. Bannerman, R., J. G. Konrad, D. Becker and G. V. Simsiman. Surface Water Monitoring Data. Part I: Quality of Runoff from Mixed Land Uses. Final Report of the Menomonee River Pilot Watershed Study, Vol. 3, U.S. Environmental Protection Agency, 1979.

8. Palmer, M. D. Coastal Region Residence Time Estimates from Concentration Gradients. J. Great Lakes Research 1:130-141, 1975.

TECHNICAL REPORT DATA *(Please read Instructions on the reverse before completing)*		
1. REPORT NO. EPA-904/79-029-J	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE Effects of Tributary Inputs on Lake Michigan During High Flows-Volume 10		5. REPORT DATE December 1979 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) R. Bannerman, J. G. Konrad and D. Becker		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Wisconsin Department of Natural Resources Post Office Box 7921 Madison, Wisconsin 53707		10. PROGRAM ELEMENT NO. A42B2A 11. CONTRACT/GRANT NO. R005142
12. SPONSORING AGENCY NAME AND ADDRESS U.S. Environmental Protection Agency Great Lakes National Program Office 536 South Clark Street, Room 932 Chicago, Illinois 60605		13. TYPE OF REPORT AND PERIOD COVERED Final Report 1974-1978 14. SPONSORING AGENCY CODE U.S. EPA-GLNP
15. SUPPLEMENTARY NOTES University of Wisconsin-Water Resources Center and Southeastern Wisconsin Regional Planning Commission assisted.		

16. ABSTRACT

This study was in part of TASK D of the Pollution from Land Use Activities Reference Group (PLUARG) objective to diagnose the degree of impairment of Great Lakes water quality. The overall objective of this study was to determine the effects of input from the Milwaukee, Menomonee and Kinnickinnic Rivers.

17. KEY WORDS AND DOCUMENT ANALYSIS		
a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Metal Water Quality Data Sediment Pollutants Organic Total-phosphorus Soluble phosphorus		
18. DISTRIBUTION STATEMENT Document available to the public through the National Technical Information Service, Springfield, VA. 22161	19. SECURITY CLASS *(This Report)* 20. SECURITY CLASS *(This page)*	21. NO. OF PAGES 56 22. PRICE

EPA Form 2220-1 (9-73)

☆ U. S. Government Printing Office 1981 750-809