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POLLUTION OF COASTAL WATERS OFF CHICAGO BY SINKING PLUMES FROM THE INDIANA HARBOR CANAL

by

W. Harrison, D. L. McCown,
L. A. Raphaelian, and K. D. Saunders

Great Lakes Project

ARGONNE NATIONAL LABORATORY

ENERGY AND ENVIRONMENTAL SYSTEMS DIVISION

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ABSTRACT

On March 2, 1977, during sinking-plume conditions, a portion of the water of the Indiana Harbor Canal (IHC) was injected with samarium and rhodamine-dye tags and a section of the IHC's surface was covered with simulated oily waste tagged with dysprosium. Water samples were taken downcurrent, over a 54-hr period, from a vessel and from the raw-water streams from the intakes at Chicago's South Water Filtration Plant (SWFP). Bottom currents and water temperatures were measured almost continuously at four Lake Michigan stations located between the IHC and the SWFP.

Unequivocal evidence is presented for transport of the tagged IHC water and oily waste to the SWFP's intakes. Organic contaminants from the IHC were present in trace concentrations in the SWFP's raw water. A model for the transport and mixing of the entire IHC effluent, for the environmental conditions during the experiment, indicates a minimum dilution of 4 in the plume offshore of the SWFP and, for the assumed plume trajectory, values of 5×10^2 and 10^5 at the shore and crib intakes, respectively. A similar model applied to the experimental situation of tagged effluent showed reasonable agreement with measurements. Analysis of historical data indicates that the worst-case pollution event that might be experienced at the SWFP, assuming constant pollutant loading in the IHC, would be due to 24 hr of northwest wind followed by a 3.0-in. (7.6 cm), 24-hr rainfall that coincides with 3.0×10^6 m of total wind movement from the southerly quadrants.

EXECUTIVE SUMMARY

This report presents the results of research conducted by Argonne National Laboratory for the Institute for Environmental Quality, State of Illinois. The most significant pollution episodes at Chicago's potable-water intakes in Lake Michigan occur during winter months. Plumes of sinking effluent from the Indiana Harbor Canal were thought to be the cause. The Argonne study was designed to investigate this possibility. The following items were emphasized and the following conclusions drawn.

a) Tagging and tracing of Indiana Harbor Canal (IHC) water and associated oily waste from Indiana Harbor to the intakes of Chicago's South Water Filtration Plant (SWFP)

Efficient methods were developed for 1) tagging canal effluent and oily waste, 2) tracking and over-water sampling of tagged effluent and oily waste, and 3) analyzing for tracer concentrations. Dysprosium (Dy), used to tag the oily waste, and samarium (Sm), used to tag the IHC water, occur naturally in Lake Michigan waters in concentrations below the limits of detection of the analytical method. In the March, 1977, field study, the Sm and Dy tags were sampled in dye-tagged IHC effluent as it moved northwestward from the Indiana Harbor release point toward the SWFP. Water samples from the SWFP's shore and crib raw-water streams indicated the presence of the Sm and Dy tags during an intensive sampling period conducted 35-50 hr after tracer release. Significantly more Sm (the water tracer) entered the crib intake. The Sm tracer reflects the behavior of sinking-plume water following the lake's bottom contour from the entrance of Indiana Harbor to the crib. The Dy tracer path described the route followed by a primarily wind-driven surface film and associated near-surface water.

b) Development of a simple model for northwestward transport and dilution of IHC effluent

Data from three current meters were used to provide a representation of the near-bottom velocity field on March 3, the period of maximum current during the tracer experiment. This representation indicates the potential for transport of the IHC effluent into the nearshore region between Calumet and Indiana Harbors and then return of the effluent to deeper lake waters and continued northwestward transport parallel to shore. Observations of effluent transport during the study suggest that this representation of advection is reasonable. A simple turbulent diffusion model was coupled with this advection representation to predict dilution ratios for the entire IHC effluent plume. In the vicinity of the SWFP's intakes, that model indicates that minimum (centerline) plume dilution ratios are about 4 and that, for the plume trajectory assumed, dilution ratios at the shore and crib intakes are 5×10^2 and 10^5 , respectively. Since only a small portion of the IHC effluent plume was tagged in the field experiment, experimentally determined dilution ratios are not comparable to model predictions for the entire plume.

However, a similar turbulent diffusion model was applied for the experimental conditions, and it yielded dilutions of about the same order of magnitude as those inferred from measurements at the SWFP's intakes.

c) Characterization of the trace organic contaminants associated with a sinking plume

Trace organic contaminants present in water samples taken from Indiana Harbor, the lake, and the raw-water streams at the SWFP during the sinking-plume experiment were investigated by capillary-column gas chromatography/mass spectrometry (GC/MS). No polychlorinated biphenols (PCBs), polynuclear aromatics (PNAs), pesticides or other pollutants of interest could be detected in any of the water samples at the 100-1000 parts per trillion level. Alkane hydrocarbons were detectable in the water samples, however, and an attempt was made to determine the presence of the simulated oily waste released in the field experiment by identifying specific organic components isolated from water samples. This approach proved successful over only a short distance downcurrent because background hydrocarbon concentrations in the lake water were too similar to the GC/MS signature of the experiment's simulated oily waste. In fact, the background hydrocarbons detected in the lake-water samples appeared to be essentially dilutions of those found in the IHC effluent.

d) Delineation of the environmental determinants for the worst-case scenario for pollution by IHC effluent at Chicago's SWFP intakes

Historical data on the intensity and duration of hydrocarbon odors in the raw-water streams at the SWFP's shore and crib intakes were compared to wind-velocity data from Midway Airport,* rainfall data from the SWFP's gage, and water-level data for Calumet Harbor. Significant pollution episodes at the SWFP were found to be related to persistent southerly winds, especially when immediately preceded by a period of northwesterly winds. (Such a sequence may assist in flushing polluted IHC water into the nearshore water prism, owing to initial setup and then rapid setdown of that prism by NW and SW winds, respectively.) Rainfall of more than 1/4 in. (6.4 mm) in 24 hr also adds polluted water to the lake by causing some combined sewers in the IHC watershed to overflow. The worst-case pollution event was judged to be

*Midway Airport is approximately 14.5 km inland from the SWFP.

24 hr of NW wind, followed by 3.0×10^6 m of total wind movement from the southerly quadrants, during which time there coincided a (maximum-expectable) 24-hr rainfall of 3.0 in. (7.6 cm). Due to the short time series of relevant wind and rainfall data, the return period of such an event could not be estimated.

1 INTRODUCTION

1.1 PURPOSE AND SCOPE OF STUDY

A comprehensive background report (Snow, 1974) was prepared by the Illinois Institute of Technology Research Institute (IITRI) for the U.S. EPA (Region V) on the water-pollution situation in southwestern Lake Michigan as it relates to effluent from the Indiana Harbor Canal (Fig. 1.1). The IITRI report did not treat the sinking-plume condition that develops during winter, however, and did not present unequivocal evidence of the presence of Indiana Harbor Canal (IHC) effluent at Chicago's South Water Filtration Plant (SWFP). Nor were any data presented by the IITRI on the organic contaminants found in a plume emanating from the IHC. Because the most significant pollution of the SWFP's raw water was thought to be caused by sinking plumes in winter, and due to the increased interest in organic contaminants in municipal water supplies, the Illinois Institute of Environmental Quality commissioned the present study.

The objectives of this study were

- a) to tag and follow effluent from the Indiana Harbor Canal to the intakes of Chicago's South Water Filtration Plant under a winter, sinking-plume condition,
- b) to tag and follow a quantity of simulated oily waste from the Indiana Harbor Canal (IHC) to the intakes of Chicago's South Water Filtration Plant (SWFP) under a winter, sinking-plume condition,
- c) to characterize the organic compounds in a sinking plume
 - 1) at the mouth of Indiana Harbor, 2) in the lake, and
 - 3) in the raw-water streams for the shore and crib supplies at the SWFP, and
- d) to determine worst-case scenarios for IHC pollution at Chicago's SWFP as based upon analysis of historical meteorological and SWFP water-quality data.

Due to the difficulties of conducting midwinter operations on southern Lake Michigan and to the expense of the technique used for tracing IHC effluent, this study was limited to two field experiments. The first field study, in February 1976, was undertaken to test the over-water procedures (McCown, Harrison, Orvosh, 1976); the second, in March 1977, was a full-scale effort, the results of which form a significant part of this report. Laboratory work on canal and lake-water samples consisted of neutron-activation analysis (NAA)

Fig. 1.1. Location Map for Study Area and Current-Meter Positions (I-IV) in Southwestern Lake Michigan.

for rare-earth tracers, and gas-chromatographic/mass-spectrometric (GC/MS) analysis for trace organic compounds. Other work consisted of the analysis of historical meteorological data as related to raw-water odor episodes at the SWFP.

1.2 RESEARCH APPROACH

1.2.1 Tagging and Tracing IHC Water and Associated Oily Waste

It is important to distinguish between the dynamics of waste-receiving waters and the motions of the associated oily wastes within and upon these waters. Adequate understanding of these separate but complementary motions is essential for the development of predictive models. Accordingly, a method was developed for the simultaneous tagging and tracing of oil and water, by means of which concentrations of tags as low as 10^{-10} g/sample could be determined. Traditionally, two classes of substances have been used to tag water or pollutants for tracing: fluorescent dyes and radionuclides. Fluorescent dyes have several drawbacks. Some fluorescent dyes bleach in the sunlight. Others that do not bleach may become adsorbed onto suspended particles, which then settle out of the water column. Radionuclides have several advantages for water and contaminant tracing, but have an unacceptably high radiation hazard for all but very short-term studies.

The approach to tracing in the present study uses stable-element tags and neutron-activation analysis (NAA). Among the advantages of this method are the following:

- 1) there is no radiation hazard to the environment,
- 2) detection is possible to 10^{-10} g/sample of rare-earth concentration in the tagged water,
- 3) there is negligible tracer loss to suspended matter and sediments, and
- 4) the stable-element tags themselves can be chosen to be non-toxic to the environment.

Certain rare-earth elements (REEs), such as dysprosium, samarium, lanthanum, europium, and ytterbium suggested themselves as likely candidates for tags. The availability of a high-flux reactor and of superior radiation-counting equipment at Argonne, and the existence of precision boat-positioning equipment within the Water Resources Research Program at ANL, made it possible

to design a relatively sophisticated experiment for studying the transport of polluted IHC water and simulated oily waste to Chicago's water intakes.

Among the REEs mentioned above, dysprosium (Dy) and samarium (Sm) were chosen as the most suitable for the present study because

- 1) they have high detectability (see Sec. 2.1.1) and short half-lives, and
- 2) their natural occurrence in Lake Michigan is at concentrations below the limits of detectability provided by the methods used in the present study. Thus, any Dy or Sm detected by the Argonne methodology (Sec. 2.1.4) would represent the presence of the artificial tags.

With regard to point 2 note that, prior to tagging, 24 samples of water were taken from each of the shore and crib intakes of the SWFP and analyzed for their natural Dy and Sm content. No Dy or Sm was detected in the 48 samples that were used to determine background concentrations. Minimum detectabilities are 6×10^{-10} g for Dy, and 2×10^{-8} g for Sm, using the Argonne method.

1.2.2 Characterization of Organic Contaminants

As of this writing, the health hazards of minute quantities of organic chemicals in drinking water have not been resolved (Wade, 1977), nor is there a standard for organic-chemical contamination in the regulations promulgated from the Safe Drinking Water Act of December 1974. It is of importance, however, to obtain data on the concentrations of organic compounds in drinking-water sources whenever significant pollution events occur. This report pays special attention to hydrocarbons (including polyaromatics) because these are typically found in effluents from energy-intensive industries. Owing to the small concentrations expected and lack of information on the specific compounds that might be present, it was decided to identify the organic compounds isolated from water samples by capillary-column GC/MS. Liquid-liquid extractions, and separations into the acid, base, and neutral fractions, were deemed adequate and standards were used for precise identifications of the major compounds present in the water samples.

1.2.3 Documentation of Lake Currents

Three current meters were deployed in a close array directly off the SWFP during the initial feasibility study (McCown et al., 1976). Data from

these meters revealed unexpected current patterns between the mouth of the Indiana Harbor and the SWFP. Therefore, a more open deployment of four current meters was made along the line of expected plume flow from the mouth of the Indiana Harbor to the Dunne Crib (Fig. 1.1), during the winter 1977 study.

1.2.4 Determination of Worst-Case Pollution Scenarios

Historical lake temperature, wind, and rainfall data were related to the incidence and magnitude of "hydrocarbon odors" at the SWFP in an attempt to discern those meteorological conditions conducive to pollution at the intakes for the SWFP. By combining these meteorological conditions with insights from the field measurements made for the present study, and with probability statements for specific worst-case meteorological conditions (such as very persistent southerly winds and associated rain in January), it was hoped that extreme pollution scenarios for the SWFP could be developed.

1.3 PREVIOUS WORK

The Great Lakes Project in Argonne's Energy and Environmental Systems Division assisted the IITRI in field and analytical studies of the dispersion of the IHC effluent for the floating-plume condition. Snow (1974, v. 1, p. 129) listed the following mechanisms of transport and dispersion from the canal into the lake:

- 1) turbulent vertical mixing of IHC water in the canal with intruding lake water,
- 2) inertial jet flow near the canal mouth,
- 3) gravity spreading of canal water moving into the lake,
- 4) vertical mixing of the plume due to turbulent eddies in the lake,
- 5) plume transport by ambient lake currents,
- 6) mixing of plume margins by turbulent eddies in the lake, and
- 7) shearing and dispersion of the plume by lake currents.

Lake currents in winter occasionally flow northward, just off the IHC. There is some evidence (P. A. Reed, 1975, personal communication) that, when conditions are right for developing a sinking plume, plume-borne pollutants may be transported as far north as the City of Chicago's Central Water Filtration Plant (CWFP),* which draws its water from the Dever Crib, located 3.2 km

*Recently renamed the James W. Jardine Water Purification Plant.

NE of CWFP (Fig. 1.1). According to Reed, plume water is commonly transported as far as the intake crib for Chicago's South Water Filtration Plant (SWFP) during winter months. During January 1975, for example, the SWFP experienced a two-week period of hydrocarbon odors in its raw water. The severity of the odors was greater in the SWFP's raw water from its shore supply than in the raw water from its crib (Fig. 1.1). The hydrocarbon odors were accompanied by elevated concentrations of ammonia-nitrogen, and there can be little doubt that a significant percentage of the hydrocarbon odors originated from waters of the IHC. According to permit data (Snow, 1974, v. 1, p. 200), for example, the ARCO refinery, Inland Steel, Youngstown Sheet and Tube, and others contribute up to 22,680 kg/day (50,000 lb/day) of oil and grease to the IHC. If the lake temperature is appropriate (less than about 2°C), development of a pronounced sinking plume occurs when

- a) there is significant rainfall in the area (0.64 cm [0.25 in] of rain in a day will cause overflowing of some combined sewers that enter the IHC), and
- b) there are brisk winds from southerly quadrants.

Modern studies of currents off Chicago began with two surveys by the U.S. Public Health Service (1963a, 1963b). The first of these used Geodyne Savonius-rotor current meters at three stations off the coast of Chicago. Two of these stations provided current information for the period December 18, 1962 - March 22, 1963. Of these two stations, only station 3 (42°01.7' N, 87°31' W) was near enough to shore (9 km) to be considered useful for coastal current delineation. The prevailing direction of the currents for January 31 - March 22, 1963, was about 150°, with a minor peak at about 340°. The third station (41°50.2' N, 87°29.7' W) was in operation for 6 days during March 1963. These data are interesting and important as they represent the first long-term time series of current measurements in Lake Michigan in the winter. They are, however, not particularly useful in the context of this study, as the current meters were located too far lakeward to resolve the nearshore currents and too far north to be representative of the currents near the Indiana Harbor-Calumet Harbor region.

The second study by the U.S. Public Health Service (1963b) used drogues to measure lake currents in the nearshore zone. This study took place on April 11-12, 1963, and was of too short a duration to make any available estimates of nearshore currents.

Saylor (1966) reported on the current patterns in Calumet Harbor under various wind conditions. The current patterns were determined from a combination of current meter, drogue and dye measurements. He found that, under southerly winds, the currents from the south did not penetrate into the harbor and were deflected around the end of the breakwater (Fig. 2.1). There was little flow through the opening in the breakwater under these conditions. During periods of northerly winds, a significant current is seen through the breakwater opening with little flow around the end of the breakwater into Calumet Harbor. He concluded that currents due to seiche modes were relatively weak, but important for the flushing of stagnant water in the upper reaches of the harbor.

The next study of currents in the southwestern region of Lake Michigan was performed by Dan Frye and L. S. Van Loon of Argonne National Laboratory (Snow, 1974, pp. 17-126). Three Braincon 381 histogram-recording Savonius-rotor current meters were deployed, one adjacent to the 68th St. Crib at a depth of 5.2 m and the other two off the Inland Steel landfill at depths of 3 and 6 m. The currents were measured from November 8 to December 8, 1973. The investigators found a cyclical variation of current speed with the speed minima corresponding to shifts in the current direction. The current directions were generally shore-parallel, and the currents at the crib and off the landfill were similar in direction. This study produced the first moderately long time series of current velocities in the Indiana Harbor-Calumet Harbor region under a period of low stratification, but it suffered from the twofold drawbacks of limited time and the use of Savonius-rotor current meters in a wave field.

Monahan and Pilgrim (1975) made current-meter measurements of currents off Chicago from July to October 1974. They found generally northward-flowing currents during this period. This study was inadequate for assessing currents in the Calumet Region, as the stations were located too far north and east ($42^{\circ}00' \text{ N}$, $87^{\circ}30.0' \text{ W}$ and $41^{\circ}55.5' \text{ N}$, $87^{\circ}33.5' \text{ W}$), the current meters used were Savonius-rotor meters, the lengths of the time series were too short, and the measurements were taken during periods of strong stratification of the lake.

Saunders and Van Loon (1976) obtained current measurements for June-December 1975, using ducted-impeller current meters. The current meters were

located at middepth about 3 km SE of the Dunne Crib. Although the time series was long, and the current meters did not suffer from wave-enhanced speeds, the data are still unsuitable for the present study, as most were obtained under periods of strong stratification. Such data cannot be extrapolated to winter conditions when the lake is well mixed.

Although the above measurements give some insight into lake currents in the area of interest, they do not reflect conditions occurring at the time of sinking-plume activity. For this reason, the special measurements described in Sec. 2.3.2 were made.

Channell (1971) used rare-earth elements and neutron-activation analysis for tagging and tracing estuarine water. To our knowledge, however, the present study is the first published work of its kind for fresh coastal waters.

We have been unable to find published data on the concentrations of specific organic contaminants in the raw-water supplies to the SWFP during a winter pollution event. J. C. Means et al. (1977, p. 211) reported "low concentrations" of base-extractable organics at "unpolluted Lake Michigan sites" near the Central and South Water Filtration Plants and stated that "some of the hydrocarbons, alkylphenols, and phthalates found to be discharged into Lake Michigan by the Calumet River at Indiana Harbor may have been the ones detected in the filtration plant water." Risley and Fuller (1966) found average phenol concentrations of 3.1 $\mu\text{g}/\ell$ in 1962-1963 in the lake adjacent to Indiana Harbor and said these relatively high levels were due to waste discharges from the heavily industrialized Calumet District. During 1965-1976, 20 percent of the water samples collected at the SWFP had phenol concentrations exceeding 3 $\mu\text{g}/\ell$, the single-value limit for Illinois at that time, but in 1971 only 11 percent of the samples exceeded the limit (Vaughn and Reed, 1973).

R. A. Schacht (1974) reported on pesticides in the Illinois waters of Lake Michigan, stating that, in 1970, "six crib samples from water treatment plants and 3 open water samples showed concentrations of DDT, heptachlor epoxide and dieldrin all below 1 ppt" (part per trillion).

2 EXPERIMENTAL PROCEDURES

2.1 PLUME-TRACING METHODOLOGY

2.1.1 Tagging Agents

Dysprosium (Dy) was the agent chosen to tag the simulated oily waste, and samarium (Sm) was selected to tag the IHC water. (The neutron-activation characteristics of Dy and Sm are shown in Table 2.1.)

A third agent, the fluorescent dye rhodamine-WT, was used to tag the canal water so that, in conjunction with a pump and fluorometer, the tagged water mass could be followed by the sampling boat.

2.1.2 Tagging Procedures2.1.2.1 IHC Water Tag (Sm)

Waters of the IHC are turbid and highly polluted. Introduction of a REE tag into the IHC water column in the ionic form would hazard removal of the REE from solution by any of several mechanisms. Two examples are:

Table 2.1. Neutron-Activation Characteristics of Dysprosium and Samarium (from Lederer, 1967)

Reaction	^{164}Dy (n, γ) ^{165m}Dy	^{154}Sm (n, γ) ^{155}Sm
Half-life ($T_{1/2}$)	75 s	22.5 min
Thermal neutron-capture cross section (σ)	2000 barns ^a	5 barns
Isotopic abundance	28%	23%
Major gamma energy ^b	0.1082 MeV	0.1043 MeV
Sensitivity as determined by experiment	6×10^{-10} g ^c	2×10^{-8} g ^c

^abarn = 10^{-24} cm²

^bFrom Bowman, 1974

^cIrradiation time: 90 s; delay to count: 30 s; count: 90 s.

- 1) the formation of insoluble compounds by reaction with some of the many species in solution in the IHC or on the bottom of the canal, and
- 2) removal from solution by adsorption on suspended solids.

Channell (1971) showed that the persistence of lanthanum in waters that are in contact with bottom sediment is almost twice that for lanthanum complexed with EDTA* than for lanthanum dissolved in acid. Channell suggested that chelation would be advantageous for an injection into an area where suspended solids were flocculating or where the water depth would allow significant contact of the tagged water mass with bottom sediments. IHC waters contain an abundance of suspended solids, and, in a sinking plume, this water remains in contact with bottom sediments. Chelation of REE tags, by complexing with DTPA,** was therefore considered necessary.

IHC water was tagged in-situ with 13.6 kg (30 lb) of samarium that had been complexed with DTPA, and with 7.5 kg of rhodamine WT dye.[†] The samarium/DTPA/Rh-Wt tag was dispersed in IHC water by pumping the tag through a pipe with small holes drilled along one side. The pipe was lowered over the rail of the boat and the samarium solution was pumped into the pipe and dispersed at various depths between the surface and -1.0 m through the holes in the pipe. The dispersion process required 10 min and occurred at the "REE tagging location" (Fig. 2.1). On March 2, 1977, the tagging location was approximately 900 m upflow from the point where the canal water was sinking. The zone of convergence of canal and lake water was easily determined with a temperature probe and is indicated in Fig. 2.1 by "surface temperature convergence." As the survey vessel NEPTUNE proceeded lakeward, the surface water temperature dropped from 7.5 to 1.8°C within a few meters. Canalward of the sinking zone, the water temperature was vertically isothermal. Just lakeward of the sinking zone, however, the temperature profile showed warm ($\approx 4.0^\circ$) water near the bottom, overlain by colder ($\approx 1.8^\circ\text{C}$) water.

*EDTA is Ethylenediaminetetraacetic acid

**DTPA is Diethylenetriamine-pentaacetic acid

[†]Volumes released were 114 l (30 gal) of samarium/DTPA solution and 38 l (10 gal) of rhodamine WT solution, respectively.

Fig. 2.1. Location of REE Tagging Location, Temperature-Convergence Zone, and Positions of Sampling Transects.

2.1.2.2 Oily-Waste Tag (Dy)

Numerous bench tests were conducted to determine how well the simulated refinery/steel-mill oily waste retained the Dy tag. The simulated waste was made up from equal parts of 30-W motor oil, #2 diesel fuel, and engine drain oil. The results of the bench testing are discussed in detail, in the Argonne National Laboratory Report ANL/WR-76-4 (McCown, Harrison, and Orvosh, 1976). In summary, the tests showed that a maximum of 0.001% of the Dy migrated from the oil into the water over a five-day time span.

The Dy-tagged, simulated oily waste was poured on the surface of the IHC effluent at the same time and in the same location that the in-situ water tag (Sm) was injected. The oily-waste and tracer consisted of 170 l of the waste mixed with 1.4 kg (3 lb) of Dy. The Dy had been dissolved in a 50% acetic acid solution.

2.1.3 Sampling Procedures

2.1.3.1 Boat Samples

Documentation of transport and dispersion in a sinking plume requires many data points. This requirement dictates the removal of water samples from several depths and at many locations in the lake. In addition, it is of great importance to know to a high degree of accuracy the position of the boat when samples are being taken. Clearly, electronic boat-positioning equipment and an underway sampling system are required if an area of interest such as that of Fig. 2.1 is to be covered in a reasonable period of time.

Argonne National Laboratory (ANL) has developed a towed-depressor/thermistor array (Frigo, Paddock, and McCown, 1975), and the knowledge gained from ANL's research and development efforts was used to design a three-dimensional water-sampling system. The sampling system (Fig. 2.2) includes:

- 1) a Motorola Mini-Ranger electronic positioning system interfaced with an x-y plotter for real-time positioning,
- 2) a fluorometer, pump, and hoses to follow the dye patch,
- 3) a dynamically depressed faired cable with small tubes attached which extend to the four depths to be sampled and one large tube to draw bottom-water samples (Fig. 2.3), and
- 4) a bottom-water sampler.

UNDERWAY SAMPLING SYSTEM

Fig. 2.2. Schematic of the Three-Dimensional Underway Water-Sampling System.

- A - 6.4 mm (1/4") STEEL CABLE
- B - 6.4 mm (1/4") HOLLOW NYLON TUBE
- C - 13 mm (1/2") HOLLOW NYLON TUBE
- D - 1.6 mm (1/16") STEEL CABLE
- E - PLASTIC ELECTRIC CABLE TIE

Fig. 2.3. Cross-Sectional View of the Sampling Chains in Fig. 2.2.

The intermediate-depth water samples are pumped onboard, through 6.4 mm (0.25-in.)-O.D. [4.7-mm I.D.] nylon tubes, by a Masterflex multichannel tubing pump. The flow rate, through ≈ 20 m of tube, is ≈ 100 ml/min. This relatively low flow rate is sufficient because each sample is only 15 ml volume. The tubes are length-compensated; that is, they are all the same length, so that sample-removal delay times are all equal. The major retarding force in the tube is not hydrostatic head, but friction with the tube sidewalls.

The bottom sample is drawn through a 9.6-mm I.D. nylon tube (Fig. 2.3), which is connected to the faired cable at a point 1 m above the depressor fin (Fig. 2.2). The end of the bottom-sampler tube is connected to a 7.3 kg (16 lb) shot that trails the depressor fin by ≈ 12 m so that the shot is dragging the bottom. The bottom sampler has a relatively high flow rate, 7.5 l/min and it is driven by a positive-displacement 12-V DC "puppy" pump. Water from the bottom is fed directly to the fluorometer; however, a valved-tee (Fig. 2.4) at the fluorometer inlet directs a small portion (≈ 200 ml/min) of the water to the sampling manifold (Fig. 2.4) to be sampled for subsequent NAA at Argonne. All the samples for NAA were drawn in new, 15-ml polyvials.

In addition to the sampling equipment described above, a surface-skimming water sampler was built; however, no acceptable means could be determined to calibrate the surface-skimmer. Samples drawn by the surface-skimmer were collected in the field, but the results of the samples collected by the skimmer are presented in only one instance, Fig. 3.1. The surface-skimmer results are not quantitative and can only be an indication of tracer presence or absence.

In the course of tracking and sampling the plume, ≈ 1000 polyvial samples were collected onboard the NEPTUNE. Pertinent water-sampling parameters such as time, date, and depth are shown in Table 2.2, and sampling transects are plotted on Fig. 2.1.

2.1.3.2 Water-Intake Samples

Water samples were drawn at the SWFP from the raw-water streams for the shore and crib intakes. These 15-ml samples were drawn every 10 min for almost all the period between 2200 hr on March 3, to 1240 hr on March 4, 1977.

Fig. 2.4. Schematic of Onboard Sampling Manifold and Fluorometer.

Table 2.2. Log for Shipboard Activities, Winter Sinking-Plume Study, 1977

Day	Date	Time (hr CST)	Activity	Sampling Depths (meters below surface)	No. Stations in Transect
Wed.	2 Mar.	1300-1310	Tracer dumped		
"	"	1806-1823	IHC Transect A ^a	0,1,4,7,B ^b	18
"	"	2015-2025	" " B	0,1,4,7,B	11
"	"	2226-2040	" " C	0,1,4,7,B	13
Thurs.	3 Mar.	0408-0424	Cal. Hbr. " D	0,1/2,3-1/2,6-1/2,B	7
"	"	0424-0426	" " " E	" " " " "	7
"	"	0430-0447	" " " F	" " " " "	17
"	"	0449-0455	" " " G	" " " " "	6
"	"	0505-0508	" " " H	" " " " "	3
"	"	0509-0528	" " " I	" " " " "	17
"	"	1246-1316	" " " J	" " " " "	15
"	"	1345-1401	" " " K	" " " " "	17
Fri.	4 Mar.	1057-1127	" " " L	0,1,4,7,B	28
"	"	1214-1228	" " " M	0,1/2,3-1/2,6-1/2,B	17
"	"	1504-1516	" " " N	0,1,4,7,B	6
"	"	1516-1556	" " " O	0,1,4,7,B	17
"	"	1652-1706	" " " P	0,1,4,7,B	7

^aSee Fig. 2.1 for location of transects^bB-Bottom

From 1240 hr to 1600 hr March 4, 1977, samples were drawn every 20 minutes. (See Table 2.3 for precise sampling schedule.) Water-intake samples were drawn in the same type of 15-ml polyvials that were used for the shipboard samples. All polyvials used for sampling were new.

2.1.4 Analytical Procedures

2.1.4.1 Sample Preparation, Irradiation, and Counting

Lake water in the polyvial samples was evaporated by placing three trays of ≈ 104 polyvials each into an oven, set at 80°C , for about 48 hours. Evaporation of the water eliminates ^{19}O gamma interference, the polyvials do not have to be sealed before insertion into the reactor, and no allowance is needed for sample expansion or hydrolysis during irradiation.

Immediately before irradiation, the outside of each polyvial was washed several times with alcohol to remove NaCl or other surface contamination. The polyvial was then filled with helium, packed into the "rabbit" capsule for insertion into the reactor, and irradiated for 90 s (timed by stopwatch) in a flux of $2.5 \times 10^{13} \text{ n}/(\text{cm}^2 \cdot \text{s}^{-1})$. During the 30 s that elapsed between the end of irradiation and the start of counting, two steps were performed: (1) the rabbit capsule was removed from the rabbit tube and taken to a hood where the polyvial was extracted, and (2) the polyvial was placed in a sample holder for counting. All samples were counted for 90 s, and counting started 120 s after insertion of the sample into the reactor flux.

Making the time interval for irradiation, delay, and counting the same for all samples permitted direct comparison of peak areas of particular gammas with the peak areas of calibration samples. This simplified quantification of the amount of Sm and/or Dy in the lake-water samples. Because the time intervals were of equal duration, the ratio of the number of counts (N_c) in a calibration sample's peak to the amount of element (W_c) contained was equal to the ratio of the number of counts in the unknown peak (N_u) to the amount of unknown element (W_u) contained in the sample, or

$$\left(\frac{N_c}{W_c} = \frac{N_u}{W_u} , \text{ or } W_u = \frac{N_u W_c}{N_c} \right).$$

(When time intervals are not equal, the radioactive delay must be accounted for with an exponential decay term and the calculation becomes more difficult.)

Table 2.3. Sampling Times at SWFP Crib and
Shore Raw Water Intakes, 1977

Date	Time, hr	Sampling Interval
3 Mar.	2200-2350	Every 10 min
4 Mar.	0000-0220	Every 10 min
"	0230-0330	Every 10 min
"	0340-0420	Every 10 min
"	0430-0520	Every 10 min
"	0530-0620	Every 10 min
"	0630-0730	Every 10 min, except samples not taken @ 0650
"	0740-0750	Every 10 min
"	0810-0900	Every 10 min, except no polyvial sample @ 0830 & 0850
"	0910	Every 10 min
"	0930-1030	Every 10 min, except no polyvial taken @ 0940, 0950, & 1000, no gallon segment taken @ 1000
"	1040-1130	Every 10 min
"	1140-1230	Every 10 min, except no polyvials taken @ 1230
"	1240-1600	Every 20 min

The irradiated samples were counted with an Ortec, solid-state lithium drifted germanium [Ge(li)], low-energy, photon spectrometer (LEPS) with an energy dispersion of 120 eV/channel and a resolution of approximately 250 eV. This detector (Model #8013-25400) had an active surface area of 500 mm². The signal from the detector was fed into a Canberra (Model #1468) live-time corrector and then to an Ortec (Model #452) spectroscopy amplifier for pulse shaping. Finally, the signal went to a Nuclear Data (Model #560), 4096-channel, multichannel analyzer that had a CRT display and a teletype for hard copy. The CRT display had two line markers that could be moved independently through the spectrum for bracketing any particular area of interest.

A hard-copy output could be extracted in two modes. The first mode was a totalizing function that averaged the number of counts in the two channels designated by the markers, then subtracted that average from each channel between the markers. The hard copy in this first mode gave a total number of counts between the markers and a net number of counts. The second mode of output was a channel-by-channel printout of the number of counts in each channel between the markers.

The data were extracted by totaling three equal areas: one area on each side of the peak for background, and the area containing the Sm or Dy peak. The net number of counts due to the peak was calculated by

$$N = T - (2/3)B_N - (1/3)B_F,$$

where

N = net number of counts in the peak,

T = total number of counts in the peak region* (Fig. 2.5),

B_N = total number of counts in the near background (Fig. 2.5),

and

B_F = total number of counts in the far background (Fig. 2.5).

The above-described method of using the total counts and not the net counts to sum the counts under the Sm or Dy peak was superior to using the machine's net calculation. For small peaks, the error, when using the machine calculation, could be quite large because only two channels are used to determine background.

*Total number of counts in any region (peak or background) is the number of counts in the first channel, plus the number of counts in the second channel, ..., plus the number of counts in the last channel.

Fig. 2.5. Schematic of CRT Display from Multichannel Analyzer Indicating the Locations of the Sm and Dy Peaks and the Regions Used to Determine Background.

The NAA procedure allowed analysis of about 15 samples per hour because it was possible to irradiate one sample while the previous one was still being counted.

2.1.4.2 Error Analysis

Flux variation. The neutron flux in Argonne's CP-5 reactor was controlled automatically to vary no more than $\pm 0.5\%$. Repeated irradiations of a single calibration sample indicated that the actual variance was $< \pm 0.5\%$.

Sample-volume variation. Ten water samples taken in the field were selected at random and weighed to determine volume variation. The volume variation error (1σ) was found to be $< 3\%$ by weight. The weight variation of empty polyvials was $< 0.3\%$.

Counting statistics. The statistical counting error is generally accepted as

$$e = \sqrt{N} = \sigma$$

with

e = error,

N = number of counts,

and

σ = one standard deviation.

This error reflects the Poisson distribution related to the random nature of radioactive decay. For a detailed analysis, the reader is referred to Livesey's textbook (1966, p. 146-149). The summation of counts under a peak is subject to two statistical errors. The first is the error in determination of the total number of counts in the peak (T). The second error is in the determination of the number of counts in the background [$B = (2/3)B_N + (1/3)B_F$] that must be subtracted from T to obtain the net number of counts (N) in the peak. That is,

$$N = T - (2/3)B_N - (1/3)B_F.$$

The error in N is due to the error in T , denoted by ϵ_T , and the error in determining B , denoted by $\epsilon_B = \sqrt{[(2/3)\epsilon_N]^2 + [(1/3)\epsilon_F]^2}$. The percent total error in N , e_N , is

$$e_N = \frac{\sqrt{(\epsilon_T)^2 + (\epsilon_B)^2}}{N} \times 100 = \frac{\sqrt{(\epsilon_T)^2 + (1/9)(4\epsilon_N^2 + \epsilon_F^2)}}{N} \times 100.$$

The statistical error increases with decreasing elemental concentration (lower peaks) and, generally, only becomes a significant factor, considering other errors, when elemental concentrations are approaching the minimum detectable amounts.

Counting geometry. The geometric counting error can be the largest error in activation analysis and one of the most difficult to quantify. This error occurs because the REE, upon drying, becomes distributed in places other than the center of the bottom of the polyvial. The geometric error was measured by making a number of 1-ml calibration samples with precisely the same amount of Sm. Then some of the calibration samples were filled with distilled water, capped, and shaken by hand. The 1-ml and the full samples were dried in the oven, irradiated, and counted to determine if a significant difference in the number of counts could be detected. The results for 24 low-concentration full samples were:

$$\begin{aligned}\text{mean} &= \bar{\mu}_F = 397 \text{ counts} \\ 1\sigma &= 32.2 \text{ counts} \\ \frac{\sigma}{\bar{\mu}_F} \times 100 &= 8.1\%\end{aligned}$$

and the results for ten 1-ml (same concentration) samples were:

$$\begin{aligned}\text{mean} &= \bar{\mu}_1 = 426 \text{ counts} \\ 1\sigma &= 21.5 \text{ counts} \\ \frac{\sigma}{\bar{\mu}_1} \times 100 &= 5.0\%.\end{aligned}$$

But the statistical error for a typical 1-ml sample that had 429 counts ($\approx \bar{\mu}_1$) was 6.0%, and the statistical error for a full sample with 395 counts ($\approx \bar{\mu}_F$) was 6.5%. Consequently, for these samples, with amounts of Sm approaching the minimum detectable number of counts (100 cts), the geometric variability is of the same order as the statistical error. To be conservative, we will add 7.3% (% difference of $\bar{\mu}_F$ and $\bar{\mu}_1$) to the counts of each sample.

Sampling procedures. Undoubtedly, errors are associated with the sampling procedure; however, no way is known of putting a numerical value on these errors. The method of tagging in no way ensures a homogeneous mixture, although with time the mixture should become more homogeneous, so that samples taken in close proximity can differ markedly from each other and not be indicative of the average concentration in the general area. This type of

error is inherent in any type of tracing experiment and is usually neglected, not because it does not exist, but because it generally cannot be quantified.

Error summary. Of the six types of errors discussed above, three are relatively minor, one is basically undetermined, one increases with decreasing tracer concentration, and one (the geometric error) is treated as constant. For the purpose of reporting results, the errors due to calibration solution, sample volume, and flux variation will be considered insignificant compared to the other errors, and results will be reported as follows:

sample weight (g) + 7.3% (from geometry) $\pm$ statistical counting error (e_N).

Normally, there would also be some error due to the preparation and counting statistics of the calibration sample; however, we have mixed, irradiated, and counted hundreds of calibration samples, and constructed a calibration curve so that these errors are insignificant.

2.2 ORGANIC-CONTAMINANTS ASSESSMENT

2.2.1 Sampling Procedures

Three different procedures were used to obtain water samples (Table 2.4) for analysis of trace-level organic compounds. For sampling at the tagging point, a 1-gal sample jug was lowered on a rope into the water and allowed to fill. Samples taken aboard the NEPTUNE, in Calumet Harbor and Lake Michigan, were drawn by filling the jugs from the fluorometer drain (Fig. 2.4). Lake water drawn into the South Water Filtration Plant was sampled in the plant's water-chemistry laboratory where taps are provided that connect with the water tunnels leading to the shore and crib intakes.

Sampling of shore-intake water began at 0230 hr and ended at 1320 hr on March 4, 1977. Five 1-gal samples were drawn (Table 2.4), each consisting of six or seven 10-min subsamples composited over a 50- or 60-min period. One grab sample of crib water (No. 11, Table 2.4) was taken on March 10. Sample jugs had been precleaned with methylene chloride. Each was immediately capped and refrigerated within 58 hr of being taken.

Table 2.4. Water Samples Taken for GC/MS Analysis

Sample number	Date (1977)	Time (hr CST)	Location
1	Mar 2	1245	REE tagging location (Fig. 2.1)
2	Mar 2	2230	Transect C, Indiana Harbor (Fig. 2.1) most concentration
3	Mar 3	0430	Transect F, Indiana Harbor (Fig. 2.1)
4	Mar 3	1240	Transect J, Calumet Harbor (Fig. 2.1)
5	Mar 4	0230-0330	SWFP, shore intake (Fig. 1.1)
6	Mar 4	0430-0520	SWFP, shore intake (Fig. 1.1)
7	Mar 4	0630-0730	SWFP, shore intake (Fig. 1.1)
8	Mar 4	1040-1130	SWFP, shore intake (Fig. 1.1)
9	Mar 4	1300-1320	SWFP, shore intake (Fig. 1.1)
10	Mar 4	1500	Transect O, Calumet Harbor (Fig. 2.1)
11	Mar 10	1415	SWFP, crib intake (Fig. 1.1, "Dunne Crib")

2.2.2 Analytical Procedures

Each of two 2000-ml portions of a water sample were buffered to pH 7 with a phosphate buffer and extracted with two 100-ml portions of methylene chloride and one 100-ml portion of 15% ether in petroleum ether. The extracts were combined and extracted with two 100-ml portions of 0.1 N sodium hydroxide to separate the acidic compounds from the basic and neutral compounds.

The aqueous phases were combined, acidified to pH 2 with 0.1 N hydrochloric acid and extracted with two 50-ml portions of methylene chloride and one 50-ml portion of 15% ether in petroleum ether. The organic phases were combined and dried over anhydrous sodium sulfate, evaporated to dryness, and taken up in 50 μ l of methylene chloride to give the acid fraction.

The organic phase, containing the basic and neutral compounds, was extracted with two 100-ml portions of 0.1 N hydrochloric acid. The aqueous phases, containing the basic compounds, were combined, neutralized with 0.1 N sodium hydroxide, and extracted with two 50-ml portions of methylene chloride and one 50-ml portion of 15% ether in petroleum ether. The organic phases were combined and dried over anhydrous sodium sulfate, evaporated to dryness, and taken up in 50 μ l of methylene chloride to give the base fraction.

The organic phase which had been extracted with 0.1 N hydrochloric acid was dried over anhydrous sodium sulfate, evaporated to dryness, and taken up in 50 μl of methylene chloride to give the neutral fraction. Blank fractions were similarly prepared by extraction of 1000-ml of distilled water.

The remaining extracts, from which the acid and base fractions had been removed, were dried over anhydrous sodium sulfate, evaporated to dryness, and taken up in 50 μl of methylene chloride to give the neutral fraction. A blank was prepared with 1000 ml of distilled water.

To each fraction, 1 μl of anthracene- d_{10} (2000 ppm in methylene chloride) was added just before injection into the gas chromatograph to serve as a reference.

Analyses of the acid, base, and neutral fractions of each water sample (Table 2.4) were conducted using a Hewlett-Packard Gas Chromatograph/Mass Spectrometer (GC/MS) equipped with a data system.

Capillary columns were used in the gas chromatograph. These columns allow considerably greater separation and resolution of the organic components in a fraction than do standard packed columns. Capillary columns also provide increased sensitivity and drastically reduced background from column bleed in the mass spectra.

A capillary column with an internal diameter of about 0.35 mm, coated with SE-30 was used. The chromatographic conditions were as follows: starting temperature 20°C, 2-min hold, 4°C/min to 300°C, and hold for a total run time of 90 min. As opposed to typical GC/MS operation, no separator was used to remove the carrier gas. The outlet of the capillary column was connected directly to the source of the mass spectrometer, and, therefore, there could be no discrimination in the amount of each component reaching the mass spectrometer. That is, assuming that the individual components in the mixture are not lost in the column, the amount of these components reaching the source of the mass spectrometer is a true representation of the mixture injected on the column.

Finally, a Grob-type injection system was used in place of the inlet splitters typically used with capillary columns. The Grob system avoids the loss of large amounts of samples and the discrimination, typically found in split systems, of components of the mixture. It permits the analysis of minute concentrations of the specific organics present.

2.3 ANCILLARY ENVIRONMENTAL DATA ACQUISITION

2.3.1 Meteorological Data

Of primary interest to this study were 1) wind data, for comparisons with measured currents and pollution events at the SWFP, and 2) rainfall data, for the relevance of rainfall magnitude to the initiation of combined-sewer overflow into the waters leading to the IHC. The closest National Weather Service reporting meteorological station to the study area was at Midway Airport, Chicago. Wind data were generally obtained from the Midway Airport records because the quality of the wind data was slightly better than that which could be obtained at the SWFP and the Midway wind data were available in magnetic-tape format.* Rainfall data, however, were obtained from the SWFP's rainfall records because of the SWFP's closer proximity to the study area. A tipping-bucket rain gage is used to collect rainfall data at the SWFP.

2.3.2 Lake Currents and Water Temperatures

Lake-current and water-temperature data were gathered at the four stations (I-IV) shown on Fig. 1.1. A Bendix Q-15R current-meter sensor was positioned 1.5 m above the bottom at each station; at Station I, a second meter was positioned 5 m above the bottom in order to obtain information on the vertical structure of the currents. The designs of the moorings are shown in Figs. 2.6 and 2.7. Two thermistors and an Argonne current-recording package (Saunders et al., 1976) were also placed on each mooring. The sampling rate was one observation of current speed every 8 min, where the averaging period for speed was 8 min. Current directions were sampled four times during each 8-min period, and the temperature was sampled once every 8 min. The current meters were calibrated before deployment, and the observed currents were corrected for nonlinearity (Saunders, 1978). All data were recorded on a cassette magnetic tape for later reduction by computer. The data reduction scheme has been described in Saunders and Van Loon (1976).

*We have not made an intercomparison of Midway and SWFP wind data as this would be a study in itself. For the lake-circulation scale of interest, the driving winds will be of sufficient speed to be of essentially the same direction at both Midway Airport and the SWFP.

Fig. 2.6. Schematic Design of the Winter 1977 Moorings for the Near-Bottom Current Meters and Thermographs (Stations II, III, and IV).

Fig. 2.7. Schematic Design of the Winter 1977 Mooring for the Current Meter and Thermograph at Station I.

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3 RESULTS

3.1 FIELD AND LABORATORY STUDIES

3.1.1 IHC Plume Tracking (Field Study)

3.1.1.1 Shipboard Tracking in Calumet Harbor

About 1000 water samples were collected in polyvials aboard the NEPTUNE while tracking the dye that was used to tag the IHC effluent. Of the 1000, approximately 200 were collected in Transects A, B, and C (Fig. 2.1) in the canal-entrance and near-entrance areas. All 200 were analyzed by NAA for their Dy and Sm concentrations. Of the remaining 800 samples collected in the Calumet Harbor area, 350 were analyzed* and only ten of those indicated the presence of Sm (canal water); however, many of the samples from Calumet Harbor indicated the presence of Dy (simulated oily waste).

In Figs. 3.1-3.6, the sampling stations are numbered in ascending order corresponding to the direction of boat travel. The transect locations are plotted on Fig. 2.1. Each transect (on Fig. 2.1) has an arrow indicating the direction of boat travel and the ends of each transect correspond to the first or last sampling station. The distance between sampling stations varies slightly but is ≈ 100 m.

Contour values for Dy in Figs. 3.1-3.6 are in nanograms per liter (ng/l); that is, 10^{-9} g/l. The Dy-concentration contour interval is based upon a two-standard-deviation spread (statistically, the 96% confidence level) in the net number of counts in the peak. This spread is close to 100 counts. Thus, each ng/l contour interval on Figs. 3.1-3.6 reflects a 100-count interval in the raw data. Owing to rounding, and significant-digit considerations, the conversions from counts to ng/l may give nonuniform differences in contour values. Note that 100 counts corresponds to the minimum detectable amount of Dy or Sm.

Figures 3.2-3.6 show, in addition to the Dy concentration, the near-bottom dye concentration. The dye was used merely to indicate the presence

*That is, every other or every third sample along a transect was analyzed (unless a high value was observed, in which case samples on either side were analyzed).

Fig. 3.1. Transect A: Dy Concentrations. (Concentrations in ng/l. All 90 samples collected were analyzed. The dashed contours indicate how the figure would look if concentration values for the surface samples could have been considered.)

Fig. 3.2. Transect F: Dy Concentrations and Near-Bottom Dye Concentrations (dot indicates sample analyzed at that point, Dy concentrations in ng/l).

Fig. 3.3. Transect I: Dy Concentrations and Near-Bottom Dye Concentration: (dot indicates sample analyzed at that point, Dy concentrations in ng/l).

Fig. 3.4. Transect K: Dy Concentrations and Near-Bottom Dye Concentrations (dot indicates sample analyzed at that point, Dy concentrations in ng/l).

Fig. 3.5. Transect L: Dye Concentrations and Near-Bottom Dye Concentrations (dot indicates sample analyzed at that point, Dy concentrations in ng/l).

Fig. 3.6. Transect N: Dy Concentrations and Near-Bottom Dye Concentrations. (dot indicates sample analyzed at that point, Dy concentrations in ng/l).

Fig. 3.7. Relative Amount of Sm or Dy in the Samples Collected at the SWFP as a Function of Time. (Dashed line indicates the minimum detectable amount; two dots at a sample indicate the sample was irradiated twice and shows the value of each irradiation.)

of IHC effluent and exact correspondence between the Dy and dye should not be expected. The Dy values on Figs. 3.2-3.6 represent "instantaneous" values, inasmuch as they were determined from 15-ml grab samples. The dye values represent integrated averages over a much larger volume of water (≈ 125 ml/s) and a much longer time period. The purpose of monitoring the dye was to indicate water masses to be sampled for Dy and Sm.

Figure 3.1 is a plot of the Dy concentrations (oily-waste tag) with depth as found in Transect A (Fig. 2.1). Transect A passed directly through the strong surface-temperature gradient at the mouth of the IHC, and Fig. 3.1 clearly shows a zone of sinking Dy (between Stations 1 and 6) and a region of high Dy concentration near the bottom. Thus, Fig. 3.1 shows the sinking of the simulated oily waste; however, the dashed contours, which indicate how the raw data would have been contoured if the results of the uncalibrated surface sampler (Sec. 2.1.3.1) were considered, show that some of the oily waste does cross the subduction zone and does not sink.

Figure 3.2, for Transect F (Fig. 2.1), shows both the Dy concentrations through the water column and the dye concentration near the bottom. Along this transect, the simulated oily waste and its Dy tag seem to be relatively well mixed with depth. There is one sample point with a very high Dy concentration; the high value may be due to an unusually large drop of oil drawn through the sampling tubes. These singular spots of high concentration occur in many transects.

Figure 3.3, for Transect I, shows a relatively high concentration of Dy at the lakeward end of the transect. Again, the Dy/oily-waste appears to be relatively well mixed, as in Transect F. A peculiar occurrence in Transect I is that the dye does not reflect the increasing Dy/oily-waste concentration at the lakeward end of the transect.

Transect K data (Fig. 3.4) reveal the close proximity of the effluent to the shore. Figure 2.1 shows that the NEPTUNE steamed obliquely into and then away from shore. The region of highest concentration was only about 500 m from shore. Concentrations may have been higher further inshore, but, because of the shallow depth, the NEPTUNE could not sample there.

Transect L (Fig. 2.1) was made by steaming southeastward along the centerline of the dredged ship channel, which runs parallel with the Calumet

Park Breakwater. Concentrations (Fig. 3.5) along this transect show that the Dy/oily waste, and the dye, made a clockwise circuit of the Calumet Harbor, because no dye had been detected in the channel on the previous day.

Transect N (Fig. 2.1) was made by steaming out of the Calumet River, starting about 900 m upstream of the river entrance. The Dy data (Fig. 3.6) indicate that some of the effluent from the IHC entered the Calumet River. Stations 1-4 (Station 4 is at the river entrance) were in the river, and there were detectable amounts of Dy at those stations.

3.1.1.2 Tracer Concentrations at the SWFP

Some 240 polyvial water samples were drawn at the SWFP from the raw water streams of the shore and crib intakes. NAA analyzed all 240 samples, and concentration data for the samples that contained Sm and/or Dy are shown in Tables 3.1 and 3.2. For all the samples that contained detectable Sm and/or Dy, Fig. 3.7 gives relative amounts as a function of time for each raw-water intake. Relative amount is computed as the amount of a given REE found in a polyvial sample divided by the quantity of that REE that was released in the IHC effluent times 100.

3.1.2 Organic Contaminants in IHC Plumes

A GC/MS analysis was performed on the simulated refinery/steel-mill oily waste that had been tagged with the Dy tracer. Particular attention was paid to the presence or absence of aliphatic and aromatic hydrocarbons, indanes, tetralins, phenol, cresols, and xylenols. Table 3.3 shows ions that are characteristic of these types of compounds. Figure 3.8 shows a scan of these ions, along with the total-ion spectrum, for the oily waste. Several aliphatic hydrocarbons (alkanes) are present, whereas there is a noticeable lack of aromatic hydrocarbons, indanes, tetralins, phenol, cresols, and xylenols.

It might be expected that those compounds found in the oily waste would be present also in the Transect C (Fig. 2.1) water sample, which was taken at the location of greatest dye concentration (March 2nd, 2230 hr). This water sample was taken 9-3/4 hr after the initial tagging of the Indiana Harbor Canal effluent. In the GC/MS analysis of the Transect C sample, there was again a noticeable lack of aromatic hydrocarbons, indanes, tetralins, phenol,

Table 3.1. Sm Concentrations of Samples
Collected at the SWFP

Date	Time, CDT	Concentration, ^a μg/ℓ	% error
<u>Crib Samples</u>			
3 Mar.	2220	61.0 ^b	2.0
"	2310	7.7 ^b	8.3
4 Mar.	0030	2.8 ^b	23
"	0300	6.7 ^b	9.6
"	0430	102.1 ^b	1.4
"	0450	6.1 ^b	10
"	0720	2.4 ^b	24
"	1040	5.0 ^b	13
"	1200	2.1 ^b	27
"	1220	5.1 ^b	12
"	1520	1.6	34
<u>Shore Samples</u>			
3 Mar.	2200	2.9 ^b	22
"	2250	1.6	42
"	2340	4.0 ^b	18
4 Mar.	0300	1.6	46
"	0450	1.6	41
"	0710	2.7 ^b	25
"	1100	1.8	34
"	1200	1.9	32

^a Minimum detectable amount, Sm - 100 counts =
1.4 μg/ℓ

^b Indicates average of two irradiations.

Table 3.2. Dy Concentration of Samples
Collected at the SWFP

Date	Time, CDT	Concentration, ^a ng/l	% error
<u>Crib Samples</u>			
3 Mar.	2210	54	29
"	2230	82	20
"	2310	54 ^b	29
"	2320	61 ^b	27
"	2340	55 ^b	30
"	2350	70 ^b	24
"	2400	47	33
4 Mar.	0020	57	26
"	0030	60 ^b	26
"	0050	43	36
"	0100	43	39
"	0110	43	37
"	0140	48	34
"	0400	51 ^b	32
"	0710	45	33
<u>Shore Samples</u>			
3 Mar.	2200	74 ^b	21
"	2230	158 ^b	14
"	2250	45	44
"	2300	48	39
"	2350	62	31
4 Mar.	0020	45	43
"	0050	74 ^b	29
"	0100	46 ^b	45
"	0120	64	32
"	0130	58	31
"	0220	48	40
"	0230	71	26
"	0250	67	29
"	0300	74	28

Table 3.2 (Contd.)

Date	Time, CDT	Concentration, ^a ng/ℓ	% error
<u>Shore Samples</u>			
4 Mar.	0330	43	45
"	0410	52	36
"	0420	47	40
"	0430	69	27
"	0550	55	32
"	0630	49	36
"	0720	68	26
"	0730	55	31
"	0840	45	40
"	1010	64	28
"	1050	50	35
"	1100	62	28
"	1110	56	35
"	1240	49	36
"	1320	47 ^b	35
"	1500	45	37
"	1520	62	27

^a Minimum detectable amount, Dy - 100 counts =
43 ng/ℓ

^b Indicates average of two irradiations.

Fig. 3.8. Total-Ion Chromatogram and Single-Ion Chromatograms of 57, 91, 131, 94, 108, and 122 Ions for Simulated Oily Waste

Table 3.3. Characteristic Compounds and Ions Expected in Simulated Oily Waste

Type of Compound(s)	Characteristic Ion (AMU)
Aliphatic hydrocarbons	57
Aromatic hydrocarbons	91
Indanes, tetralins	131
Phenol	94
Cresols	108
Xylenols	122

cresols, and xylenols (Fig. 3.9), and the patterns of the 57-ion spectrum for the oily waste and the Transect C samples appear similar (Fig. 3.10).

A plot of the relative concentration (as measured by peak-area units) of n-alkanes versus the number of carbon atoms in the n-alkanes shows that the relative concentration of n-alkanes appears to vary with the number of carbon atoms in the same way as for the alkanes, C₁₇ through C₂₁, for the oily waste and the Transect-C samples (Fig. 3.11).^{*} However, there appears to be a marked decrease in the concentration of lower n-alkanes, C₁₂ through C₁₆, possibly due to the 9-3/4 hr of "weathering" during which time the lower n-alkanes would readily vaporize.

Further decreases are seen (Fig. 3.11) in the relative concentrations of n-alkanes from Transect C (9-3/4-hr sample) to Transect F (15-3/4-hr sample), to Transect O (50-1/4-hr sample). The relative concentrations of n-alkanes in Transect J (24-hr sample) are not in step with this progression, because the plume could not be sampled in its zone of maximum concentration when Transect J was run. The plume was hugging the shore at that time, and the water was too shallow to permit the NEPTUNE to run closer to shore over most of the length of Transect J (Fig. 2.1).

Similar changes in relative concentration, due apparently to weathering and dilution, are present in the data for the raw-water samples drawn at

^{*}Probably, n-alkanes higher than C₂₁ are present in the oily-waste sample, but, relative to the lower n-alkanes, the higher n-alkanes are present in considerably lower concentrations. If one were to increase the concentration of the sample to look at these higher n-alkanes, column overload would take place and resolution of the peaks would be poor.

Fig. 3.9. Total-Ion Chromatogram and Single-Ion Chromatograms of 57, 91, 131, 94, 108, and 122 Tons for Transect C Sample.

Fig. 3.10. Single-Ion Chromatograms for Ion 57 of Transect-C and Simulated-Oily-Waste Samples; n-Alkanes C₁₂ through C₃₀ are labeled.

Fig. 3.11. Relative Concentration of *n*-Alkanes as a Function of Number of Carbon Atoms in Oily-Waste, Release-Point, and Transect C, F, O, and J Samples (Table 2.4, Samples 2, 3, 4, and 10).

Fig. 3.12. Relative Concentration of *n*-Alkanes as a Function of Number of Carbon Atoms in Raw-Water Samples (Table 2.4) from the SWFP's Shore (Nos. 5, 6, 7, 8, 9) and Crib (No. 11) Intakes.

the SWFP. These data (Fig. 3.12) show an even greater decrease in relative-concentration values for the lower n-alkanes, but the data plots have the same patterns as the transect samples (Fig. 3.11). The GC/MS scan of the IHC-effluent sample taken at the REE tagging point was also run and found to contain predominantly n-alkanes (Fig. 3.11). Remember that this sample was taken before release of the simulated oily waste.

Of the total organic extract from a given water sample, 6% or 3 μl of the total 50- μl extract was injected on the column. The detection limit of the GC/MS typically ranges from 10 to 100 mg/ μl for each individual component, depending upon the specific component. This corresponds to a 100- 1000 parts per trillion detection limit for the individual components based on the extraction of a 4-l water sample. Unfortunately, at these levels of detection, no positive identification could be made for individual PCBs, PNAs, or pesticides. Some phthalates were present, but this is not unusual for these types of samples.

3.1.3 Lake Currents and Water Temperatures

Table 3.4 shows the data return from the current-meter/thermograph moorings discussed in Sec. 2.3.2. The intermittent speeds at Station II were caused by a corroded electrical connector. Recorded speeds showed good agreement with those at the other stations, but the periods over which good speed data exist are too short to permit useful comparisons with the other records. The errors in the temperature data are probably the result of water leaking

Table 3.4. Quality of Data Return, Winter Current-Meter Moorings, 1977

Station	Height above bottom, m	Current speed	Current direction	Thermistors	
				T1	T2
I	5	Good (occasional spikes)	Good	Sporadic errors	Good
I	1.5	Good	Good	None	None
II	1.5	Intermittent	Good	None	Good
III	1.5	Good	Good	None	Good
IV	1.5	Good	Good	Good	None

through cracks in the insulation or the protective cases around the thermistors.

3.1.3.1 General Features of the Observed Current

For 4 January 1977 - 26 March 1977, the major features of the observed currents may be summarized as follows:

- 1) the mean flow was toward the southeast;
- 2) the average speed was about 0.015 m/s;
- 3) the rms speed was about 0.074 m/s;
- 4) there were four major reversals of the generally southeastward flow during the recording period;
- 5) the currents parallel to the depth contours were relatively uniform at the three stations that returned usable data;
- 6) the vertical variation of the current was small at Station I;
- 7) most of the energy of the currents was in the low frequency region of the spectrum, between 1×10^{-6} Hz and 1.4×10^{-5} Hz (0.004 hr^{-1} - 0.05 hr^{-1}); and
- 8) the coherence between the currents at different stations was generally high at frequencies below 0.050 hr^{-1} and low above that (with the exceptions of the frequency bands near 0.12 hr^{-1} and 0.454 hr^{-1}).

These observations will be discussed in detail.

The observed currents

The speeds and directions of the near-bottom currents at Stations I, III, and IV are plotted in Figs. 3.13-3.15, respectively, and the progressive-vector diagrams* for these stations in Figs. 3.16-3.18, respectively. From these last, one can see that all stations showed a general drift toward the south. Table 3.5 lists the mean speeds and directions, as well as the rms velocity. Four major reversals, as seen in the progressive-vector diagrams, occurred during Feb. 21-24, March 2-4, March 11-13, and March 24-26. The last reversal is not completely documented as it was in progress when the capacity of the data tape was reached. In general, the reversals were characterized by the following properties:

*The progressive-vector plot is a form of graphical representation of current-meter or anemometer data that is generated by sequentially plotting each equal-time-interval velocity vector "head to tail." The plot is useful for assessing total water or wind motions, as well as patterns of motions over time.

Fig. 3.13. Current Speeds and Direction, Station I (Near Bottom) from January 4 to March 26, 1977. [The time is in days from the beginning of 1977 (January 1, 1977 = day 1).]

Fig. 3.14. Current Speeds and Directions, Station III (Near Bottom), from January 4 to March 26, 1977. [The time is in days from the beginning of 1977 (January 1, 1977 = day 1).]

Fig. 3.15. Current Speeds and Directions, Station IV (Near Bottom), from January 4 to March 26, 1977. [The time is in days from the beginning of 1977 (January 1, 1977 = day 1).]

Fig. 3.16. Progressive-Vector Diagram for Currents Observed at Station I.

Fig. 3.17. Progressive-Vector Diagram for Currents Observed at Station III.

Fig. 3.18. Progressive-Vector Diagram for Currents Observed at Station IV.

Table 3.5. Statistics of the Currents at Stations I, III and IV

Station	Average Speed, m/s	Average Direction, deg.	RMS Velocity, m/s
I top	0.013	179.8	0.070
bottom	0.015	199.2	0.061
III	0.015	162.7	0.074
IV	0.022	164.6	0.060

- 1) after southeastward flow, the direction of the current vector rotated clockwise toward the west-northwest;
- 2) the current speed was a minimum at the time the direction changed;
- 3) during a reversal, the speed would then increase to a maximum of about 0.15 m/s and then decrease, the total period lasting about 48 hr;
- 4) the direction of the current vector would then rotate counterclockwise back toward the southeast.

This description indicates that the event of February 21-24 really consisted of two events of which the second occurred before the southeastward flow had been reestablished. There is also an anomalous period lasting from March 8 to March 10 which, while not a real reversal, was also not characterized by the general southward flow.

In general, when the currents had a northward component, they followed a direction that was nearer an east-west line than when they had a southerly component. (For example, the most probable northerly-flowing current at Station III was on a bearing of 335° , whereas the most probable direction for southerly flow was on a bearing of 135° --see Fig. 3.19.)

Spatial structure of the currents

Although based upon only sparse sampling, the flow field seems to have been rather uniform over the region of interest. The currents at the three good stations were resolved into components, parallel and perpendicular to the major axis of the current fluctuations. The inclination of the major axis was defined as the angle at which the cross correlation of the two

Fig. 3.19. Histogram of Current Directions at Station III for January 4 - March 26, 1977.

components of the velocity at a given station became zero. Cross correlations were then made between the major and minor components of all the useful records, using a sample of 4000 points. The correlation coefficients are shown in Table 3.6, the letter *u* denoting the major component of the current, *v* the minor component, and the subscripts the station and vertical position. The principal direction of the major axis, measured clockwise from north is also given. This indicates that the major components of the currents are well correlated, but that the minor components are not so well correlated.

The spatial correlation function for this area and time period may be estimated by plotting the values of the cross-correlation coefficient as a function of separation distance between the current meters (Fig. 3.20). The cross-correlation coefficients between the major components appear to fall off as an approximately linear function of distance; the cross-correlation coefficients of the transverse components fall off as a steeper curve (possibly exponential?). If the linear trend of the major component correlation coefficients is extrapolated to the point of zero correlation, we obtain 28 km as the estimate of the longshore scale over which the principal velocity components may be expected to be well correlated. This estimate may be in error as it was determined from an extrapolation of data covering only

Fig. 3.20. Correlation Coefficients for the Principal and Transverse Components of the Current between Stations as a Function of Distance between Stations. [These are defined as

$$r_{u_i u_j} = \frac{\langle u_i' u_j' \rangle}{(\langle u_i'^2 \rangle \langle u_j'^2 \rangle)^{1/2}}$$

and $r_{v_i v_j}$ similarly. The notations u and v denote the principal and transverse components of the current, respectively, and the subscripts refer to the station. The circles (o) denote data from the 1977 winter moorings. The correlation coefficients from the summer 1976 moorings (denoted by Δ) are plotted for comparison.]

Table 3.6. Cross Correlations between Current-Meter Records

i	j	$r_{ui\ uj}$	$r_{vi\ vj}$	$r_{ui\ vj}$	θ_i
I_T	I_B	0.795	0.427	0.126	-50°
I_B	III_B	0.892	0.569	0.005	-61°
IV_B	I_B	0.746	0.302	0.232	-51°
III_B	IV_B	0.819	0.427	0.086	-45°

7.5 km. Further experiments with current meters placed at larger intervals along the shore should provide better estimates of the correlation distance.

Temporal structure of the currents

The temporal structure of the currents can be studied by representing them by their Fourier transforms. The variance spectral density, $S(f)$, is defined as the sum of the squared amplitudes of the Fourier transforms of both components of the current. Therefore, the kinetic energy per unit volume in any frequency band $f_1 \leq f \leq f_2$ is given by

$$E(f_1 \leq f \leq f_2) = \frac{\rho}{2} \int_{f_1}^{f_2} S(f) df.$$

It is convenient in plotting to use the logarithm of the frequency, rather than the frequency itself. Therefore, if we rewrite the integral in terms of $\ln f$, we get

$$E(f_1 \leq f \leq f_2) = \frac{\rho}{2} \int_{f_1}^{f_2} f S(f) d(\ln f),$$

so that if $fS(f)$ is plotted against $\ln f$, the area under the curve between any two frequencies will be proportional to the kinetic energy in that frequency band.

The spectral-density estimates have been obtained with the aid of the program BMDX92, developed at UCLA (Dixon, 1969). The low-frequency spectra were computed after decimating a low-pass filtered record of the current.

The low-frequency spectrum for the currents at Station I is plotted in Fig. 3.21. Most of the kinetic energy in the currents is seen to be

Fig. 3.21. Frequency-Weighted, Low Frequency Autospectrum of the Current Variance at Station I. (The units of the ordinate are mm^2/s^2 , and those of the abscissa are cycles per hour.)

concentrated at frequencies below about $3 \times 10^{-2} \text{ hr}^{-1}$. The major peaks in the spectrum are found at 5.85×10^{-3} , 1.46×10^{-2} , 2.05×10^{-2} , and $2.64 \times 10^{-2} \text{ hr}^{-1}$ corresponding to periods of 171, 68.3, 48.8, and 37.9 hr, respectively. There is also a small peak near the diurnal frequency ($4.16 \times 10^{-2} \text{ hr}^{-1}$). The high-frequency spectrum (Fig. 3.22) has little energy content, but there is a broad band in the range $0.1\text{--}1.0 \text{ hr}^{-1}$, where significant energy is to be found, with a major peak at 0.454 hr^{-1} .

Cross-spectral analysis shows large coherence (0.8 or higher) between the longshore components of the currents at frequencies below 0.05 hr^{-1} . There are some high values at frequencies between 0.9 and 1.3 hr^{-1} . Except for the lowest frequencies, the coherences between the transverse components of the velocity at different locations are much lower.

For the two current meters at Station I, the above description remains true regarding the longshore components of the currents, but the transverse components showed much higher coherences between the upper and lower meters.

The coherence and phase plots for the bottom currents at Stations I and III are shown in Fig. 3.23, and the same quantities for the upper and lower current meters at Station I are shown in Fig. 3.24.

3.1.3.2 Interpretation of the Currents

As seen in the previous section, when the general flow was toward the north, the currents had an onshore component that was larger than the corresponding offshore component when the flow tended southward. Thus, during an episode of northerly flow, the currents nearer the shore should be more parallel to the shore and be stronger than those currents farther offshore and along the contour where the current meters were located. This inference will be valid if the current velocities do not vary significantly in the vertical. Such an assumption is supported by the comparison of the currents at Station I but, as no current meters were located near the surface, cannot be regarded as being proven.

Under this assumption, the currents inshore should increase with distance north along the shoreline over the region of interest. The current speed does increase between Stations IV and III during the second episode. The current direction at Station III during this episode was about 334° . The

Fig. 3.22. High-Frequency Portion of the Current-Variance Auto-spectrum for Station I. (The units are the same as in the previous figure, though the scale on the ordinate is expanded.)

Fig. 3.23. Low-Frequency Phase and Coherence Spectra between the Principal Components of the Near-Bottom Currents at Stations I and III.

Fig. 3.24. Low-Frequency Phase and Coherence Spectra between the Principal Components of the Near-Bottom and Mid-depth Currents at Station I.

average shoreline direction for this region is about 328° , so at Station III the current had a slight offshore component. This is reflected in a slight decrease in speed between Stations III and I. The relations occurred similarly for the other three current-reversal episodes.

Following the northward-flowing episodes, the current flowed westerly for a short time and then southerly along the shore. The offshore movements were less than the previous onshore movements, acting to trap the water brought into shore during the previous period. If a tracer were carried onshore and advected north of a sampling point along the shore during the northerly-flowing episode, one should expect to see the same tracer during the period immediately following the episode.

The progressive-vector diagrams (Figs. 3.16-3.18) indicated that there were no major reversals during January and early February. During this period the lake was subject to an abnormally extensive ice cover that could have been expected to decrease the coupling between the wind and the lake. This is the most likely cause for the small motion experienced during this period.

As introduced in the previous section, the spectrum of the currents exhibits two or three major frequency bands, accounting for most of the fluctuating energy in the currents. The first band is centered at about 0.006 hr^{-1} (period ~ 7 days). The currents in this frequency range are probably the result of direct coupling of the winds to the near-shore waters, the current-spectral peak coinciding with the peak in the wind spectrum.

The second band contains two major and one minor peak at about 0.015 hr^{-1} (67 hr), 0.02 hr^{-1} (50 hr), and 0.027 hr^{-1} (37 hr), respectively. In their study of the currents in the Straits of Mackinac, Saylor and Sloss (1976) identified a coherence peak in the cross-spectrum of the currents at the Straits and the Goderich water levels in the range of 56.9-49.6 hr. They also noted coherence peaks in the Milwaukee water level and Straits current cross-spectrum at 53 hr and 61.5 hr. These coherence peaks were identified with the co-oscillation of Lakes Michigan and Huron. Powers and Ayers (1960) and Rockwell (1966) computed the period of the co-oscillation as 51 and 48 hr, respectively. This agrees quite well with our observation of a peak at about 50 hr. The 50-hr peak probably represents the co-oscillation of the two lakes.

Saylor and Sloss (1976) report a peak in the cross-spectrum for the Milwaukee-water-level/Straits-current cross-spectrum at 38.4 hr. This is close to our peak at 37 hr and is probably related. The physical process responsible for this peak is not known. If the source of the peak were due to second-class motions in the lake, particularly in the southern basin, treating the basin as a circular paraboloid would lead to an expected period of about $7T_{\text{inertial}} \approx 124$ hr (see Lamb, 1945, § 212). If the southern basin is treated as an elliptical paraboloid (Ball, 1965) with a shape parameter $a = 0.38$, we would expect a period of about 132 hr. For a more elliptical lake, the period is even longer. This indicates the source of the 37-hr motions are probably not second-class oscillations. They may, however, be important in the motions related to the lowest frequency peak. [This peak can also be identified in some of the spectra of Mortimer and Fee (1976), henceforth denoted as MF, at the Calumet Harbor (MF, p. 12, record A), Mackinaw City and Lakeport (MF, p. 16, record E).]

The third band appears about a frequency of 0.04 hr^{-1} and most likely results from the diurnal forcing of the lake by coastal winds.

There is little energy at higher frequencies, but the high-frequency spectra do contain some features of interest. The peaks at about 0.2 and 0.32 hr^{-1} are near and probably forced by the second and fourth longitudinal seiche modes of the lake which have frequencies of 0.198 and 0.319 hr^{-1} (Mortimer and Fee, 1976). The prominent peak at 0.47 hr^{-1} corresponds to the first transverse seiche, with a period of 0.457 hr^{-1} (Mortimer and Fee, 1976). The other peaks at higher frequencies are probably due to higher seiche modes.

If the logarithm of spectral density is plotted against the logarithm of the frequency (Fig. 3.25), for frequencies below about 0.1 hr^{-1} and above 0.8 hr^{-1} the spectral density varies as the negative second power of the frequency. This is the expected form of the spectrum in the frequency domain when energy is neither added nor removed in a given frequency band and viscous dissipation is not active in that band (see Monin and Yaglom, 1975, p. 361 and Saunders et al., 1976, Appendix III). The flattening between 0.1 and 0.8 hr^{-1} indicates that energy is being added in this band, probably by the forcing of surface seiches by atmospheric pressure fluctuations.

Fig. 3.25. High-Frequency Autospectrum of the Current Variance at Station I, Plotted on a Log-Log Scale.

3.1.3.3 Temperature Observations

The major purpose of making the temperature measurements near the bottom was to observe the passage of a sinking plume, if such existed. During the first episode, a jump in temperature was observed first at Station IV and then at Station III on February 23 (Fig. 3.26). The maxima at Stations IV and III were reached at 1409 and 1913 hr, respectively. If this were the result of simple advection of a single parcel of warm water, it would imply an average current speed of about 0.24 m/s. Such a speed is significantly higher than any observed during this period. Also, the temperature at Station III was warmer than that at Station IV, both before and during the temperature rise, indicating water of greater density at Station III.

During the second current-reversal episode, the only rise in temperature was observed at Station IV, on March 4. No corresponding rise was observed at Station III.

On March 8, a rise in temperature was observed at Station IV, followed several hours later by a much sharper rise at Station III. The temperature of the water after the initial rise was between 2.9 and 5.7°C at both stations.

The temperature of the water never dropped below about 2°C after this period, and a strong sinking plume probably could not have existed.

3.1.3.4 Discussion of the Temperature Observations

None of the observations show any evidence of a 4°C sinking plume. There is some evidence that warmer water near the bottom may be associated with the episodes of northward current reversal, but this is very weak, as it only appears in three instances.

The differences in temperature at the two stations during the February 21-24 episode may be due to Station IV being on the edge of the sinking plume while Station III was nearer the center of the plume.

During the March 2-4 episode, Station IV was near the plume but Station III was missed by the plume. This could have occurred if the plume was advected offshore of Station III and then later on shore. Such flow would be consistent with the directions of the currents observed at Stations I, III, and IV.

Fig. 3.26. Plot of Temperature vs. Time at Stations III and IV for February 19 - March 26, 1977.

The temperature rises on March 8 and 9 are much more difficult to explain in terms of a sinking plume. During this period, the bottom currents at Stations III and IV were directed almost exactly toward the west. This should have precluded IHC sinking-plume water from reaching them. The source of warm water may not have been the IHC effluent, but some other source.

3.1.4 IHC Plume Water at Chicago's SWFP Intakes

It is instructive to examine data from the SWFP's Water Laboratory for a typical IHC-related pollution event at the SWFP and to compare the laboratory data with concurrent data for winds and lake-water temperatures. An IHC-effluent pollution event at the SWFP is marked by hydrocarbon odors (Table 3.7, "Ch") and by elevated concentrations of ammonia-nitrogen in the raw water supplied by the shore and crib intakes. During January 1975, such conditions lasted about 2 weeks. Table 3.7 (P. A. Reed, 1975, personal communication) gives daily averages of at least six separate samplings for the variables of interest. The severity of hydrocarbon odors was greater (Table 3.7) at the shore supply than at the crib, as is common during these occurrences (P. A. Reed, 1975).

Table 3.7 shows that the odors were accompanied by elevated concentrations of ammonia-nitrogen, but that the peaks of ammonia-nitrogen occurred at different times. These differences are due to the basically different origins for the hydrocarbon odors and ammonia-nitrogen levels. Hydrocarbon odors are due primarily to quasi-steady-state waste loadings from steel mills, the petroleum refinery, and the bulk petroleum terminals on the IHC. Elevated ammonia-nitrogen levels, however, are primarily due to combined sewer overflows into the Grand Calumet River/IHC system. These overflows are related to rainfall events. P. A. Reed (personal communication, 1975) suggests that "0.25 inches of rain in a day will bring some combined sewers in this area to the point where they start to overflow." As shown in Table 3.7, the rain gage at the SWFP registered 34.3 mm (1.35 in.) of precipitation (as rain) on January 10, 1975. Some 8.64 mm (0.34 in.) of rain were registered between 0200 and 0300 hr alone. The significant elevations of ammonia nitrogen at the SWFP on the following several days (Table 3.7) can only be the result of combined-sewer overflow flushing quantities of ammonia nitrogen into the IHC. The hydraulic head caused by the rainfall runoff undoubtedly generated a

Table 3.7. Average Values for January, 1975, Pollution Event at Shore and Crib Intakes for Chicago's SWFP

Date (Jan)	Wind (Measured at SWFP)			Raw Water Odor and NH ₃ -N				Precipitation at SWFP gage (in.) (mm)		Average raw-water temperature (°F) (°C)	
	direction (quadrant from)	speed (mph) (m/s)		Odor*		NH ₃ -N (mg/l)					
				Shore	Crib	Shore	Crib				
5	SE	15	6.7	2Ch	2E	0.00	0.02			36	2
6	SW	16	7.2	2Ds	2M	0.03	0.00			36	2
7	SW	14	6.3	3Ch	3M	0.03	0.00	0.10	2.5	37	3
8	W	12	5.4	4Ch	3Ch	0.04	0.02	0.02	0.5	37	3
9	SE	15	6.7	3Ch	2Ch	0.03	0.00			37	3
10	SE	21	9.4	5Ch	3Ch	0.02	0.00	1.35	34.3	38	3
11	W	26	11.6	5Ch ^a	3Ch ^a	0.20 ^c	0.23 ^d	0.02	0.5	39	4
12	SW	18	8.1	3Ch	4Ch	0.08	0.26 ^e			36	2
13	SW	14	6.3	4Ch ^a	4Ch ^b	0.12	0.16			35	2
14	SW	12	5.4	4Ch	3Ch	0.13	0.07			35	2
15	W	12	5.4	4Ch	3Ch	0.09	0.09			35	2
16	W	15	6.7	5Ch	3Ch	0.08	0.06			35	2
17	SW	16	7.2	4Ch	2Ch	0.11	0.04			35	2
18	SW	19	8.5	3Ch	2M	0.07	0.04			35	2
19	N	21	9.4	3Ds	3E	0.06	0.01			35	2
20	S	21	9.4	3Ds	3E	0.05	0.00			35	2

^a maximum: 6Ch

^b maximum: 10Ch

^c maximum: 0.38 mg/ℓ

^d maximum: 0.30 mg/ℓ

^e maximum: 0.34 mg/ℓ

*Ch = "hydrocarbon" odor; Ds = "septic" odor; M = "musty" odor; E = "earthy" odor (American Public Health Association, 1965, Table 18).

strong sinking plume, which was then advected northward to the SWFP's intake by northward-flowing lake currents (set up by winds blowing primarily from southern quadrants).

The period of hydrocarbon odors conformed to a wind and water temperature pattern that has been observed frequently during past episodes of marked odors. Beginning on January 5 (Table 3.7), the ambient lake-water temperature was about 36°F (2°C) and winds were predominantly from the south-east. These conditions permit the formation of a sinking plume of IHC water and its advection north to the SWFP's intakes. From January 7 through 14, a southerly wind component was present nearly all the time. January 8 and 11 seem to be exceptions (Table 3.7), but on January 8 the wind was from the southwest for 10 hours out of 24. Winds were relatively light as well. On January 11, the wind blew from the southwest for 8 hours at a speed slightly greater than that of the west wind, which was present for the remaining 16 hours.

On January 15, the wind changed from southwest to west, with occasional periods of southwest wind and a decrease in speed. On January 16, the wind was from the west all day. A shift to westerly winds characteristically results in a decrease in hydrocarbon odors at the SWFP as the lake currents that drive the sinking plume turn from northwesterly to more southeasterly in their flow. After the shift to westerly winds on January 15, the hydrocarbon odors began to decrease in intensity and the odor period ended on January 18.

A final bit of evidence for IHC water at the SWFP's intakes comes from the average temperature of the raw water (Table 3.7) being pumped by the SWFP. The temperature of the IHC water is strongly influenced by the release into the IHC of quantities of heated industrial process waters. Typically, then, during an IHC pollution event at the SWFP, the temperature of the raw water will rise to a peak during the height of a pollution event and then decline. Such a pattern is seen in Table 3.7.

The presence of IHC water at Chicago's SWFP is marked by hydrocarbon odors and slightly elevated temperatures of the raw water. If sufficient rainfall has occurred to cause combined-sewer overflow into the IHC's watershed, then elevated levels of ammonia nitrogen may occur as well. Conditions required for transport of IHC water to the SWFP's intakes include 1) winds from the southerly quadrants and 2) ambient lake-water temperatures of less than 4°C, which will permit formation of water of maximum density (a "sinking

plume") when heated IHC water mixes with near-freezing lake water. (Prediction of the onset, duration, and intensity of an IHC pollution event will require additional correlations between water-plant and environmental data, however. Further insights are sought in the historical reconstruction of plume-pollutional events and environmental data given in the next section.

3.2 HISTORICAL RECONSTRUCTIONS OF PLUME-POLLUTION EVENTS AND RELATED ENVIRONMENTAL DATA

3.2.1 Methodology

Log sheets for the SWFP's Water Laboratory were studied for January, for 1970 through 1976. Clear-cut pollution episodes, as evidenced by hydrocarbon odors and elevated raw-water temperatures, were catalogued. January is known to be the month most given to pollution episodes.

The SWFP pollution-episode data were compared with wind data taken at Midway Airport and with rainfall data as measured by a recording rain gage at the SWFP. Comparisons were made by preparing a series of charts (Figs. 3-27-3.33) that show the pollution episodes and rainfall events superimposed upon progressive-vector diagrams for Midway winds. It may be useful to examine the chart for January 1975 (Fig. 3.32) which covers the SWFP pollution episode described in detail in the section immediately above.

Each vector on Fig. 3.32 represents an 8-hour average wind speed and direction for wind data from Midway Airport. It will be recalled (Table 3.7) that the IHC pollution episode that covered January 5-18, 1975, began after 24 hours of southeasterly winds on January 5 and 6 (Fig. 3.32). Note that small discrepancies are to be expected in comparing the wind data from Midway Airport with those from the SWFP. The durations of the 34.3-mm (1.35-in.) rainfall event and of the 14-day SWFP pollution episode are both recorded on the progressive-vector chart. Thus, Figs. 3.27-3.33 permit rapid visual comparisons between significant SWFP pollution episodes and the meteorological variables that produced them. Fig. 3.33 covers the experimental study.

3.2.2 Interpretations

The first mechanism that must be understood when discussing the transport of polluted IHC water to the SWFP's intakes is the initial flushing of

Fig. 3.27. Eight-Hour Progressive-Vector Diagrams for January 1970 Midway Airport Winds and Hydrocarbon-Odor Values for Raw Water from the SWFP's Shore Intake (Numbers above Vectors) and Crib Intake (Numbers below Vectors). Units for each abscissa and ordinate on this and subsequent (to Fig. 3.32) diagrams are 10^6 m.

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Fig. 3.30. Eight-Hour Progressive-Vector Diagrams for January 1973 Midway Airport Winds and Hydrocarbon-Odor Values for Raw Water from the SWFP's Shore Intake (Numbers above Vectors) and Crib Intake (Numbers below Vectors).

Fig. 3.31. Eight-Hour Progressive-Vector Diagrams for January 1974 Midway Airport Winds and Hydrocarbon-Odor Values for Raw Water from the SWFP's Shore Intake (Numbers above Vectors) and Crib Intake (Numbers below Vectors).

Fig. 3.32. Eight-Hour Progressive-Vector Diagrams for January 1975 Midway Airport Winds and Hydrocarbon-Odor Values for Raw Water from the SWFP's Shore Intake (Numbers above Vectors) and Crib Intake (Numbers below Vectors).

Fig. 3.33. Progressive-Vector Diagrams for March 1-4, 1977, Midway Airport Winds, and March 1-5, 1977, Lake Michigan Bottom Currents at Station III (Fig. 1.1).

quantities of canal water into the lake. A suitable hydraulic head in the IHC is required for this flushing. The head may be achieved by

- a) sufficient rainfall runoff entering the Grand Calumet River/IHC system,
- b) transport of lake water up-canal, due to setup of the near-shore lake-water prism by northwest winds, followed by relatively rapid relaxation of the setup, or
- c) setdown of the nearshore water prism by persistent winds from the southerly quadrants.

When mechanism a operates nearly simultaneously with either mechanism b or c, an especially strong hydraulic head may be generated for flushing IHC water into the lake.

Rainfall greater than or equal to 0.64 cm (1/4-in.) in 24 hours will be assumed to be sufficient to develop a hydraulic head that will flush significant quantities of water into the lake. (As mentioned earlier, this amount of rainfall is sufficient also to cause combined-sewer overflows into the Grand Calumet River/IHC system.) Such rainfall events are noted on Figs. 3.30-3.32, which show that the rainfall was a prelude to the relatively long-term presence of polluted IHC water (as indicated by hydrocarbon-odor levels) at the SWFP's intakes.

As for the flushing of IHC water into the lake due to relaxation of the setup in the coastal-water prism, this is believed well shown on Fig. 3.27. Persistent shore-parallel winds from the NW, on January 17 and 18, 1970, set up the nearshore water prism. This is evidenced by the National Ocean Survey's water-level gage at Calumet Harbor. The water level there rose from an elevation of 176.30 m (578.50 ft) at 2300 hr on January 16 to 176.60 m (579.39 ft) at 0900 hr on the 18th. It then fell rapidly to a low of 176.40 m (578.74 ft) at 0600 hr on January 19th. This drop, at about 0.009 m/hr (0.031 ft/hr), probably permitted the flushing of IHC water into the lake, IHC water that showed up two days later at the SWFP's shore intake when a daily average of 6 hydrocarbon odor units were noted (Fig. 3.27) in the raw water.

The plan area of the IHC system that may be set up by NW winds is of the order of 2.35 km². This is the area bounded by a line across the Indiana harbor entrance channel (at the limit of the Inland Steel land fill) and includes Indiana Harbor proper, the IHC, the entire east branch of the Grand

Calumet River, and the west branch from the IHC to the Indiana/Illinois stat line. There is a (lagged) linear relationship between water levels in Calumet Harbor and those in the Grand Calumet River at Kennedy Avenue (T. P. Chang, 1977, oral communication). Thus, given sufficiently rapid relaxation of coastal-water setup, the hydraulic head in the IHC system will probably be able to inject polluted water into Lake Michigan. The fall in the Calumet Harbor water level cited above (0.20 m) permitted a change in water volume of about $470,000 \text{ m}^3$, for an average flow rate of $6.22 \text{ m}^3/\text{s}$ (220 cfs) over and above that induced by industrial wastewater contributions and other natural flow.

Snow (1974, p. 11) reviewed six months of mean-monthly flow data taken by the U.S. Geological Survey (USGS) for the Grand Calumet River; U.S. EPA flow measurements taken on 28 days in 1971 and 1972 for the Grand Calumet River and IHC; the October 1-4, 1973, flow survey conducted by Combinatorics in the east and west branches of the Grand Calumet River and the IHC; and the three-day survey Snow himself made at the mouth of the IHC. The USGS recorded monthly mean flow values of 31.90 and $41.06 \text{ m}^3/\text{s}$ (1128 and 1450 cfs) in March 1956 and 1964, respectively, at Dickey Road on the IHC. This location is upstream of the part of the IHC subjected to the large industrial flows from Inland and Youngstown Steel and upstream of the "estuarine" portion of the IHC, where lakewater inflow influences the total flow volumes. Thus, the $6.22\text{-m}^3/\text{s}$ (220-cfs) flow mentioned above as being possible due to setup and relaxation in Calumet Harbor would represent about 17% of the flow in the IHC as gaged by the USGS at Dickey Road.

Snow (1974, p. 19) cites Winters and Bowden as saying that "changes of water level as much as 3 ft.... occur occasionally." He says that such changes could flush a slug of polluted water into the lake "and produce concentrations higher than the usual plume." The evidence of this study would suggest that drops of water level of as little as 0.7 ft (0.2 m) in 24 hours, following several hours of relatively high water in the coastal-water prism, could contribute a sufficient volume of polluted IHC water to the mouth of the IHC so that, under conditions of sinking-plume formation, the polluted water could find its way quickly into the coastal waters of Lake Michigan.

Wind patterns (Fig. 3.29) for January 3-12, 1972, were similar to those cited immediately above, but the IHC water, as evidenced by hydrocarbon odors,

took longer to reach the SWFP intakes. This may in part be due to the fact that warm air was blowing over cold water during January 7-12, 1972, a situation that leads to poor coupling between atmosphere and water. (The reverse was true for January 17-23, 1970, when the air was colder than the lake water.) Thus, the development of a sufficient hydraulic head in the IHC to flush quantities of water into the lake may not have been engendered by either the relaxation of the N/NW wind stress of January 3, 4 (1972) or by the magnitude of the setdown of the nearshore water prism due to the warm southerly airflow of January 7-12. Unfortunately, the Calumet Harbor water-level gage was inoperative during January 1972, and it is not possible to check this hypothesis.

That relatively strong southerly winds may set down the nearshore water prism and cause a hydraulic head sufficient to flush quantities of IHC water into the lake seems demonstrated by the data for January 16-17, 1972 (Fig. 3.29). Air temperatures were below lake temperatures for about 42 hours of this 48-hour period of relatively strong (24-28 mph) southwesterly winds. The significantly strong hydrocarbon-odor episode of January 18-21 is directly related to the quantities of IHC water flushed into the lake.

Once initiated, pollution events at the SWFP's intakes may persist for several days under light winds from the southwest, west, or even northwesterly quadrants, but mainly at the shore rather than the crib intakes. That there can be exceptions to this rule may be seen for January 8-10, 1971 (Fig. 3.28), where only crib hydrocarbon odors resulted from two days of nearly due south winds. This pattern is nearly repeated (Fig. 3.28) on January 20, with one day of due south wind followed by several days of SW and SSW winds. Note, however, that the strong pollution of January 21-25 was preceded not only by roughly 20 hours of due-south wind on January 20, but by roughly 60 hours of NW wind on January 17-19.

Again, the approximately shore-parallel NW wind caused a setup of the water surface in the IHC and tributaries such that, following a sudden shift in the wind to the south (January 20, 1971; Fig. 3.28), with air temperature less than water temperature producing good air/water coupling, there was a sudden relaxation in the setup, followed by an equally sudden setdown, of the coastal-water prism. This is borne out by the Calumet Harbor water-level record, which went from a high value of 176.63 m (579.49 ft); at 0900 hr on

January 19, to 176.08 m (577.70 ft), at 2300 hr on January 20, 1971. The greatest rate-of-fall of water level during this period was 0.02 m/hr (0.057 ft/hr), from 1800 hr on January 19th to 1700 hr on the 20th. The pollution event initiated by the winds of January 18-20, 1971, persisted for about six days under southwesterly winds (averaging 16-19 mph at the SWFP during January 22-25).

Having dealt with the mechanisms for flushing polluted IHC water into the lake, we must now treat the transport of sinking plumes of polluted IHC water from the mouth of the IHC to the SWFP's shore and crib intakes. Inferences that follow, about the correlation of wind vectors with the motion of sinking plumes, must be recognized as speculations. Very little is known about the operation of the wind and coastal-current regime along the Illinois/Indiana shoreline.

With one trivial exception, IHC pollution at the crib intake is always preceded by wind from the due south (primarily) or southeast (secondarily). The relationship between wind direction and pollution at the SWFP's shore intakes is not at all clearcut.

4 DISCUSSION

4.1 INTRODUCTION

In this part of the report we examine and extend certain aspects of the above work. The results of the field experiment are summarized and employed to provide descriptions of the sinking plume behavior of the IHC effluent. Then, based on the characteristics of lake currents during the study period, a simple model is proposed to estimate the mixing by turbulent diffusion of the entire IHC effluent as it moves northwestward. Results of the tracer experiment, in which a portion of the IHC effluent was tagged, are compared with estimates of dilution using a similar turbulent-diffusion model to gain some understanding of the applicability of such models in the study region. The characteristics of organic contaminants in the IHC, the lake, and the SWFP's raw water are discussed, and a scenario is developed for environmental factors that could produce a "worst-case" pollution episode at the SWFP.

4.2 CHARACTERISTICS OF IHC EFFLUENT PLUME FOR JANUARY 4 - MARCH 26, 1977

The South Water Filtration Plant's intakes are located at the shore near the plant, and at the Dunne Crib (Fig. 1.1). These intakes lie on a northwesterly bearing from the IHC. In order that the effluent from the IHC reach the SWFP's intakes, it must be advected by the nearshore currents in the lake. This section discusses the advection of the effluent and the dilution of the effluent as based on the random motions of the observed currents. This discussion is limited to the period January 4 - March 26, 1977. It should be remembered that the ice-cover observed during this period may not apply to other years, as this winter was the severest on record. The advection and dispersion physics, on the other hand, are generally applicable and may be used to deduce the expected transport and mixing of IHC effluent under similar wind and ice-cover conditions.

If the IHC effluent is to reach the intakes, a northward current along the shore is a necessary but not completely sufficient condition. The current must be of sufficient magnitude and persistence for the water to move the distance between the IHC and one or the other of the intakes. During the winter of 1977 such events were not common -- only four occurred. Each of these was

delineated by elevated levels of hydrocarbon odors in the raw water drawn in from the SWFP's intakes.

There were also several northward current episodes of lesser magnitude. Weak hydrocarbon odors were detected during these periods, but they were not significant. (The maximum level observed during one of these episodes was 4 Ch.)

During March 8-10 an episode of generally westward flow occurred. The hydrocarbon-odor levels, generally low during the preceding days, were most likely the remnants of the March 2-4 episode. On March 9, a maximum hydrocarbon odor level of 7 Ch was reached at the shore intakes and on March 10 an odor level of 10 Ch was reached at the Dunne Crib.

Generally, hydrocarbon odors are not observed at the SWFP until northward-flowing currents have continued for about a day. Hydrocarbon odors then persist even after the current has reversed direction. From the description of these episodes in Sections 3.1.3.1 and 3.1.3.2, this is the expected behavior. The structure of the currents both before and after the northward-current episodes indicates that any tracer in the IHC effluent will tend to be confined to the shore region by the current field. Also, mixing will likely occur only slowly and will be due to advection of the surface waters offshore by wind along with the slow replacement by deeper water from the lake.

4.3 SIMPLE MODEL FOR NORTHWESTWARD TRANSPORT AND DILUTION OF IHC EFFLUENT

4.3.1 Representation of Average Current Field

A representation of the average current field has been constructed from the current-meter records for March 3, 1977 (Fig. 4.1) as an aid in determining the path of the IHC effluent. This day was chosen because it coincides with the period of maximum current during the tracer experiment. The streamlines of Fig. 4.1 were estimated as follows. Streamline directions were drawn at the locations of the current meters and computed to be the average direction of the current at each meter during the episode. The spacing of the streamlines was computed to be inversely proportional to the observed average speeds. The current field was modified in the vicinity of the mouth of the IHC by taking the flow out of the IHC into account. Any

Fig. 4.1. Schematic Reconstruction of the Velocity Field of the Near-Bottom Water on March 3, 1977.

reconstruction such as Fig. 4.1, based only on three data points in the entire field, is certainly subjective and the details of the field may be criticized on many grounds. In spite of the shortcomings, it is the best estimate of the near-bottom velocity field that can be made with the existing data.

Several important features may be deduced from the representation of the velocity field. First, the turning of the current after passing the Inland Steel Breakwater will advect the IHC effluent into the nearshore region between the IHC and Calumet Harbor. This is both a shallow region and one subject to a great deal of wave action due to reflection and interference of surface wave trains. These factors act to create a large effective vertical diffusivity which acts to mix the effluent in the vertical. If a strong sinking plume were leaving the IHC, the strong mixing in this region would act to weaken or destroy the sinking plume. Second, the IHC effluent advected into the region between Calumet and Indiana Harbors must also return to the lake. The only return paths are through the break in the Calumet Harbor Breakwater or around the end of the breakwater (Fig. 1.1). Observations aboard the NEPTUNE indicated that the major area of return is around the end of the breakwater. Third, the IHC effluent would, if there were no mixing across the streamlines, be confined to a very narrow region near the shore as it passed the South Water Filtration Plant.

The path deduced by this schematic reconstruction explains why no temperature jump was observed at Station III (Fig. 1.1) and indicates that the temperature jump at Station IV was probably not due to IHC effluent. It does not explain why hydrocarbon odors were observed at the Dunne Crib or how the samarium reached the crib.

4.3.2. Dilution Estimate for IHC Effluent Plume

In order to explain these observations, it is necessary to consider turbulent mixing of the IHC effluent plume with the lake waters. In a turbulent fluid, such as the lake, the transport of a passive scalar tracer (denote the concentration thereof by ϕ) is governed by the turbulent advection-diffusion equation:

$$\frac{\partial \phi}{\partial t} + \vec{u} \cdot \nabla \phi = \nabla \cdot (D \nabla \phi)$$

where $\bar{u}$ and ϕ are the velocity vector and concentration, respectively, averaged over turbulent time scales and D is the turbulent diffusivity or mixing-coefficient tensor.

If, in the case of the IHC plume, the following assumptions are made

- the plume is formed by a steady, continuous source at the IHC,
- the mixing is in steady state,
- the velocity vector, $\bar{u} = U\hat{i}$, is uniform in time and space, where the x coordinate is locally parallel to a streamline, and
- the longitudinal and vertical gradients of concentration are negligible relative to lateral gradients,

the advection-diffusion equation becomes

$$U \frac{\partial \phi}{\partial x} = \frac{\partial}{\partial y} \left(D_H \frac{\partial \phi}{\partial y} \right)$$

for lateral spreading. The y -coordinate is locally perpendicular to a streamline, and D_H is the lateral or horizontal mixing coefficient.

Experimental observations of mixing in the Great Lakes (Csanady, 1972; Huang 1971) and the oceans (Okubo, 1971) have indicated that D_H may not be constant, but rather increases as the scale or width of the plume increases. Relationships for these observations take the form:

$$D_H = k s_y^n$$

where

s_y = the standard deviation of the lateral concentration distribution,
and

k, n = experimental constants.

Values of n vary from 0 - 1.5 and, for the purpose of the example calculation for the IHC plume, $n = 4/3$ (so-called 4/3's law) and $k = 0.000463$ have been used (Okubo 1971). The use of the "4/3's law" results in more rapid lateral spreading relative to smaller values of n and, hence, that choice may represent a "conservative" approach to mixing of the IHC plume. Effects of buoyancy, vertical velocity shear, and vertical concentration gradients have not been explicitly included in D_H .

The advection-diffusion equation can be solved with the 4/3's law relation and the definition that the initial width of the plume is $b = 12^{1/2} s_y(o)$ to yield (Brooks, 1960)

$$\frac{\phi(x,y)}{\phi_o} = \frac{1}{2} \left[\operatorname{erf} \left(\frac{b/2 - y}{\sqrt{2(s_y^2(x) - s_y^2(o))}} \right) + \operatorname{erf} \left(\frac{b/2 + y}{\sqrt{2(s_y^2(x) - s_y^2(o))}} \right) \right]$$

where

$\phi(x,y)$ = concentration at any point in the plume,

ϕ_o = initial plume concentration at $x = 0$,

ϕ/ϕ_o = concentration ratio,

erf = error function, and

$$s_y(x) = \left[\left(\frac{b}{\sqrt{12}} \right)^{2/3} + \frac{2kx}{3U} \right]^{3/2}.$$

The dilution ratio is defined as $\left(\frac{\phi(x,y)}{\phi_o} \right)^{-1}$.

This simplified model for plume mixing was applied to the entire IHC plume in the region between the IHC and the SWFP. The centerline of the plume (x coordinate) was assumed to follow the streamline in Fig. 4.1 which is nearest to shore. The plume was assumed to begin ($x = 0$) on that streamline opposite the IHC entrance and to have an initial width of 300 m, approximately the width of the IHC entrance.

Lateral concentration distributions, in terms of concentration ratios, ϕ/ϕ_o , for $x = 6, 8$, and 12 km from the IHC are plotted in Fig. 4.2. The effects of the shoreline have been included but are minor. At 12 km, in the vicinity of the shore and crib intakes, the centerline (minimum) dilution-ratio is about 4.4 . If it is assumed that the plume centerline coincides with the streamline nearest shore in Fig. 4.1, the dilution ratio at the shore intake is about 5×10^2 and at the crib is about 10^5 . Figure 4.3 depicts the contours of 0.1 and 0.01 concentration ratio (dilution ratios of 10 and 100 , respectively) determined by the model for the conditions stated above. These results provide only an approximate description of the mixing of the IHC plume under a specific set of inferred currents and plume trajectory. Although this type of model may have some validity for the case studied, as indicated in Section 4.4.2, the effects of vertical mixing of the unsteady nature of the currents, of interactions with harbor structures, and of transport along other streamlines could act either to increase or decrease dilution ratios at the crib or shore intake.

Fig. 4.2. Dilution Ratios vs. Transverse Distance for a Pollutant at 6, 8, and 12 km Downflow from a Line Source. (The parameters for these curves are: $K_0 = 0.10 \text{ m}^2/\text{s}$, $b = 150 \text{ m}$, $U = 0.08 \text{ m/s}$.)

Fig. 4.3 Schematic Representation of the Expected Dilution Ratios in the Nearshore Waters of Southwestern Lake Michigan on March 3, 1977, Based on the Data in Figs. 4.1 and 4.2. The cross hatching represents dilution ratios in the range 10-100; solid black represents dilution ratios in the range 1-10. (Current structure in the embayment between Calumet Harbor and Indiana Harbor is too complex to allow estimation of the dilution ratios there, as based on the simple theory in the text.)

Finally, the information gathered on the current structure can be used to estimate a bound on the average dilution ratio that may be expected should the IHC effluent mix uniformly with the nearshore lake waters. The volume flux out of the IHC during the study was about $120 \text{ m}^3/\text{s}$. The average speed of the lake water was about 0.08 m/s . If we assume that all of the water within 4 km of shore mixes with the IHC effluent, for an average depth of 10 m, a volume flux of about $3200 \text{ m}^3/\text{s}$ of lake water mixes with the IHC effluent. This results in an average dilution ratio of about 27.

In summary, for the set of environmental conditions studied, it appears that uniform mixing of the entire IHC effluent with nearshore lake waters produces a dilution of 27. In the more likely event that the IHC effluent moves northwestward as a plume, the minimum dilution ratio estimate on the plume centerline is about 4. Larger dilution ratios are found at the shore and crib intakes, if the plume centerline does not cross them. The values of those dilution ratios depend on the particular trajectory of the plume relative to the intakes. For the conditions assumed above, dilution ratios of about 5×10^2 , and 10^5 , were found for the shore and crib intakes, respectively. Since the field experiment did not involve tagging the entire IHC effluent for a continuous period, the experimental tracer data cannot be used directly to evaluate the model proposed above. However, the "instantaneous" tagging of a portion of the IHC effluent can be modeled in a similar fashion for comparison with experimental dilution data to investigate the applicability of the turbulent-diffusion-model approach. The results of the tagging experiment and dilution estimates are discussed in the following section.

4.4 TRANSPORT AND DILUTION OF TAGGED IHC EFFLUENT AND OILY WASTE AS BASED UPON TRACER DATA

4.4.1 Interpretation of Experimental Observations

Results of the plume-tracking field study (Sec. 3.1.1) show that the effluent from the IHC enters the City of Chicago's water-purification system at the SWFP's Dunne Crib and shore intakes. Unfortunately, a detailed picture of the effluent's path to the crib or shore intake cannot be established from the tracer data. However, two paths may exist for transport of IHC effluent to the SWFP's water intakes. Each path is governed by the nature of entry of IHC effluent into the lake, incompletely mixed near-surface water taking one path and well-mixed, 4°C bottom water taking the other.

During the development of a sinking plume, when the IHC waters mix with Lake Michigan waters at the subduction zone, not all the IHC water sinks to the bottom. If all the IHC water sank to the bottom, then the near-surface temperatures immediately lakeward of the convergence zone would be the same as ambient Lake Michigan water. But temperature profiles immediately lakeward of the convergence zone show the near-surface water to be 1-1.5°C, not near 0°C as is typical for ambient Lake Michigan water. Therefore, some portion of IHC water stays near the surface and moves toward the shore due to the action of winds blowing from the southerly quadrants. This is the portion of the IHC effluent that was tracked by the NEPTUNE, and it typically follows a path along the shoreline.

The other path, followed by the portion of IHC water that sinks to the bottom, roughly parallels the 9.1-m (30-ft) depth contour (Fig. 2.1). This isobath coincides with the lakeward terminus of the IHC entrance channel. Such bottom water from the IHC would move directly into the lake and then northeastward along the coast, missing the area enclosed behind the Calumet Harbor Breakwater. This sinking-plume portion of the IHC effluent would follow the second path to travel directly to the SWFP. Topographically, the depths of the crib intake and of the IHC entrance channel are about the same, 9.1 m (30 ft). Effluent flowing out of the IHC along the bottom would tend to remain near the 9.1-m (30-ft) contour as it moved northwestward parallel to shore, and this path would carry it directly to the crib intake. Further evidence of the existence of a direct lakeward path is found in the high concentrations of Sm detected in the crib samples and the fact that these samples were drawn at the same time that the NEPTUNE was drawing water samples in Calumet Harbor, water samples that contained Dy (oily waste) but virtually no Sm (canal water).

The results from Transect I (Figs. 2.1 and 3.3), which ends near the 9.1-m (30-ft) isobath, indicate an increasing concentration of Dy in a lakeward direction, but no corresponding increase in dye. In approaching the 9.1-m (30-ft) isobath, the NEPTUNE may have entered a segment of the plume moving northwestward along the bottom. However, the fact that the dye concentrations do not reflect the increasing Dy concentrations is puzzling. Because the Dy-tagged oil spread over the surface of the canal much faster than the Sm- and dye-tagged water spread beneath the surface, the Dy-tagged oily

waste reached the subduction zone first. Transect I may have reached the leading edge of the tagged oily waste that had been admixed into the sinking plume before the Sm and dye became admixed.

Table 3.1 shows the Sm concentrations in the raw-water samples collected at the SWFP. Seven of the eleven crib samples contained higher concentrations of Sm than any of the eight shore samples. Two of the crib samples (March 3 at 2220 hr and March 4 at 0430 hr) contained very high concentrations of Sm. In contrast, fourteen of the crib samples contained Dy and all but two of these were in a three-hour-and-ten-minute span (2210-0120). Thirty-one of the shore samples contained Dy, however, and these were fairly equally spaced throughout the entire 17-hour sampling interval at the SWFP.

These results indicate that significantly more Sm (the water tracer) went to the crib intake than to the shore intake. Also, significantly more Dy (the oil tracer) went to the shore intake than to the crib intake. This appears reasonable, because a large portion of the oily waste (Dy) would tend to remain on the surface and thus would be blown toward the shore by the SE winds that occurred during the experiment. Therefore, the oily waste would have had a higher probability of interacting with the shore intake. The water (Sm tracer), however, would be more likely to sink at the subduction zone and be carried along the 9.1-m (30-ft) isobath with the prevailing northwesterly directed current (Fig. 3.33) to pass over the crib's bottom water intake. As mentioned above, further evidence of this partitioning of the oily waste and IHC water is found in the fact that so little Sm (the water tag) was seen in the Calumet Harbor area.

4.4.2 Comparison of Simple-Model Dilution Estimates with Measurements

Turbulent diffusion models of the type employed in Sec. 4.3.2, to estimate the degree of mixing and dilution of the entire IHC effluent plume as it moves toward the SWFP intakes, can be used to estimate the mixing of the water tag (Sm) during the experiment. The limited Sm data at the shore and crib intakes and the possible partitioning of the tag described above, however, do not permit validation of even the simple model proposed. Nevertheless, a general comparison between model predictions and measured dilution ratios may provide some basis for turbulent diffusion model capability.

Table 4.1 presents dilution ratios for the Sm samples collected during the experiment at the SWFP's crib and shore intakes. The dilution ratio is defined as the ratio of the initial concentration in the water at the tagging location to the concentration in the collected samples. Initially, 13.62 kg of Sm were mixed in the IHC waters over a patch about 24 m x 2 m in area and 1 m in depth, yielding an initial concentration of 0.284 g/l.

The mixing of the tagged portion of the IHC effluent was modeled in two steps. The dilution ratio due to mixing as the patch moved from the tagging location out into the lake was modeled first, and then it was combined with the dilution ratio due to mixing in the lake as the patch moved to the vicinity of the SWFP's shore and crib intakes.

A model was used for determination of the mixing of the tagged water from the point of tagging to a location in the lake outside the harbor. The model is similar to that described in Sec. 4.3.2 except that it is for an instantaneous source of finite size and uses a constant horizontal mixing coefficient. On March 2, 1977, the average velocity in the canal was about 0.04 m/s. We estimate the horizontal mixing coefficient for this condition to be about 0.01 m²/s. Model computations indicate that in the lake, about 2 km from the tagging point, the tagged patch will have nominal dimensions of about 100 m on a side. The dilution ratio based on the maximum concentration at the center of the patch is about 137.

The mixing of the patch in the lake, as mixing takes place in transport from the location outside the harbor to the vicinity of the SWFP's intakes, can be estimated by means of models accounting for variable horizontal mixing coefficients as suggested in Sec. 4.3.2. For the tagged patch approximately 100 m x 100 m, lake current of 0.08 m/s, and transport 12 km north toward the SWFP's intakes, two calculations were made. First, a model employing 4/3's-law mixing ($n = 4/3$, $k = 0.00463 \text{ m}^{2/3}/\text{s}$) was used. It produced a patch nominally 1440 m in diameter in the vicinity of the intakes with a dilution ratio based on the maximum concentration at the center of the patch of about 109. Together with the dilution due to mixing in the canal, the dilution ratio based on the initial tagged water concentration is $(109)(137) \approx 1.5 \times 10^4$. Second, a model employing linear mixing ($n = 1$, $k = 0.00142 \text{ m/s}$) was used. It produced a patch nominally 840 m in diameter in the vicinity of the intakes with a dilution ratio based on the maximum concentration at the

Table 4.1. Dilution Ratios for Samarium Samples
Collected at the SWFP

Date	Time CDT	C_F , $\mu\text{g}/\ell$	Dilution Ratio, $\frac{C_I}{C_F}$
<u>Crib Samples</u>			
3 Mar.	2220	61.0	4.7×10^3
"	2310	7.7	3.7×10^4
4 Mar.	0030	2.8	1.0×10^5
"	0300	6.7	4.2×10^4
"	0430	102.1	2.8×10^3
"	0450	6.1	4.7×10^4
"	0720	2.4	1.2×10^5
"	1040	5.0	5.7×10^4
"	1200	2.1	1.4×10^5
"	1220	5.1	5.6×10^4
"	1520	1.6	1.8×10^5
<u>Shore Samples</u>			
3 Mar.	2200	2.9	9.8×10^4
"	2250	1.6	1.8×10^5
"	2340	4.0	7.1×10^4
4 Mar.	0300	1.6	1.8×10^5
"	0450	1.6	1.8×10^5
"	0710	2.7	1.1×10^5
"	1100	1.8	1.6×10^5
"	1200	1.9	1.5×10^5

Note: Initial concentration (C_I) = 0.284 g/ ℓ .
 C_F = final concentration.

center of the patch of about 37. Together with the dilution due to mixing in the canal, the dilution ratio based on the initial tagged water concentration is $(37)(137) \approx 5.1 \times 10^3$. Note that these dilution ratios, 1.5×10^4 and 5.1×10^3 , are for the center of the patch and are thus minimum values for the patch. The exact location of the patch relative to the intakes is unknown as no measurements of the patch were made in that area. However, the dilution ratios calculated for the center of the patch are of about the order of magnitude (Table 4.1) of those determined from sampling at the crib and shore intakes.

The results of these comparisons should be viewed with some caution. Models with alternate mixing laws and assumptions about the trajectory of the patch might give reasonable results as well. The small amount of tagged IHC water may not have moved as a single discrete patch toward the intakes but rather in several patches. What can be stated is that the application to the tracer experiment of a turbulent diffusion model similar to that model employed in Sec. 4.3.2 to estimate mixing of the entire IHC effluent yielded dilution results which were not vastly different from dilutions inferred from measurements. Clearly, verification of even the simple model proposed in Sec. 4.3.2 for the IHC effluent requires more detailed velocity data and tracer measurements in the tagged patch, and better estimates of mixing and transport of the IHC effluent require the use of more complicated circulation modeling.

4.5 ORGANIC CONTAMINANTS PRESENT IN IHC, LAKE, AND SWFP WATERS DURING THE FIELD EXPERIMENT

As mentioned in Sec. 1.1, one objective of this study was to characterize the organic compounds in a sinking plume 1) at the mouth of Indiana Harbor, 2) in the lake, and 3) at the SWFP. As explained in Sec. 3.1.2, the concentration of PCBs, PNAs, pesticides, and other organic pollutants of interest must be below the 100- to 1000-parts per trillion level if at all present in the IHC, lake, and SWFP raw-water samples.

With regard to the hydrocarbons detected (Figs. 3.11 and 3.12), these reflect 1) hydrocarbons already present, that is, background, and 2) the hydrocarbons common to the simulated oily waste used in the experiment.

The simulated oily waste emanating from Indiana Harbor was largely in the form of a slick on the surface of the water. As shown in the previous section (4.2), due to SE winds that occurred during the experiment, most of the simulated oily waste was blown toward the shore, rather than finding its way to the lake bottom in the sinking plume. This conclusion is supported by the fact that the concentrations of n-alkanes in the transect samples (Fig. 3.11) are about 5-10 times as great as those in the crib sample (Fig. 3.12), although somewhat greater dilution at the crib might be expected due to the longer travel distance. The concentration of n-alkanes in the shore samples, however, is of the same order of magnitude as that of the crib sample. In light of the Dy/oil-tracer work, the organic contaminants we are seeing in the SWFP shore and crib samples are primarily pre-existing contaminants and do not reflect compounds common to the simulated oily waste. The simulated oily waste is probably similar enough to the background in the lake so that the tracing of the simulated oily waste by GC/MS alone is not possible.

Relative concentration values for Transect C, F, J (Fig. 3.11) and SWFP (Fig. 3.12) samples do, however, reflect a progressive decrease in overall concentration of organic contaminants, as represented by n-alkanes, in the effluent from Indiana Harbor as it proceeds northward into the coastal waters off Chicago.

4.6 WORST-CASE POLLUTION EPISODE TO BE EXPECTED

The following discussion addresses only the environmental determinants of the worst-case pollution episode that could be expected at the SWFP. It will be assumed that the pollution loading of the IHC has been and will be constant. Although this assumption is patently wrong, we mean here to address only the environmental factors that can converge to produce the possibility for a severe pollution event.

To develop an estimate of the worst-case pollution episode that one might expect at the SWFP, we shall examine historical data for winds at Midway Airport for January, the month when the frequency of pollution episodes is characteristically greatest. Eight-hour, progressive-vector diagrams are presented in Appendix A (Figs. A1-A6) for 22 successive Januarys, from 1948 through 1969. These diagrams are constructed in the same fashion as the six figures (Figs. 3.22-3.27) for Januarys 1970-1975 explained in Sec. 3.2. Also

presented in Appendix A are progressive-vector diagrams (Figs. A7-A9) for Midway Airport winds for 10 months of March (1965-1974). These are presented largely to see if there are significant differences between January and March winds. (January and March essentially begin and end the sinking-plume season in southwestern Lake Michigan.)

Each of the 28 progressive-vector plots for Januarys 1948-1975, and Marches 1965-1974, was examined for periods of steady wind from the southerly quadrants. Each such period found was ranked according to the length of the total vector for wind from the southerly quadrants. The sum of all the 8-hour vectors from the SE, SSE, S, SSW, or SW points of the compass gave the total-vector length. Only small departures from these vectors were tolerated when attempting to identify a coherent total vector.

The results of the above analysis are given in Table 4.2. Only those periods with a total-wind-vector length of $>2.5 \times 10^6$ m are listed. The results of the ranking indicate that a vector length corresponding to a total wind movement of about 3×10^6 m from the southerly quadrants may be taken as the upper bound for the worst-case wind event.

With regard to the maximum expectable rainfall in the Grand Calumet River/IHC watershed, we turn to Huff and Vogel's (1976) historical study of heavy rainstorms in Chicago and northeastern Illinois. Data for outstanding

Table 4.2. Ranking of Most Significant Periods of Southerly Winds for Januarys (1948-1975) and Marches (1965-1974)

Rank	Duration of Period	Text figure	Vector length (10^6 m)	Wind duration (hr)	Dominant wind direction(s) (from)
1	March 14-19, 1968 ^a	A7	3.0	144	S,SSW
2	January 13-18, 1973	3.30	2.8	144	S,SSW
3	March 8-10, 1967	A7	2.7	56	SSW
4	January 2-11, 1975	3.32	2.6	195	SW,S,SE

^aVaughn (1970, Table 5) noted that the period March 16-21, 1968, was a period of maximum use of activated carbon at the SWFP. A total of 297,524 lbs (134,954 kg) were used. The maximum threshold odor of 25 Ch occurred on March 19.

24-hour rainstorms were tabularized. The rainfall data for January 12, 1960, and March 25, 1954 (Huff and Vogel, 1976, Table 12), suggest that a maximum of about 3.00 in. (76 mm) of rain could be expected in the watershed during a 24-hour period falling within the critical January-March, three-month span. (Huff and Vogel [1976, Table 15] found zero frequency of occurrence of heavy 1-day rainstorms in February in the historical storm series [1949-1974] that they studied.)

Mean lake level is the final limnological/meteorological parameter of significance to this study that can be investigated for its historical variation. Clearly, however, the proper evaluation of the degree of importance of this variable to such considerations as 1) the effect of lake level on IHC-pollutant dilution ratios, 2) the speed of IHC-effluent discharge, or 3) the velocity of alongshore currents is not something that can be treated in a limited investigation such as the present one. We merely note in passing, therefore, that

- a) historical data (U.S. Dept. of Commerce, 1971) on the elevation of the Lake Huron/Lake Michigan system show that over 1860-1970 the maximum expectable difference between average monthly high and low values is 6.6 ft (2.0 m),
- b) the maximum expectable difference for January, for historical data (U.S. Dept. of the Army, 1977) covering the 1900-1976 period, is 4.5 ft (1.37 m), and
- c) the mean lake level, during the March 1977 field effort reported here, was at 578.0 ft (176.2 m), or 0.3 ft (0.09 m) above the 1900-1976 average lake level for the Lake Michigan/Lake Huron system.

Clearly, the convergence of strong southerly winds and significant rainfall over the IHC watershed will produce the optimum conditions for a worst-case pollution event at the SWFP. Unfortunately, the historical time series for wind and rainfall data are too short to permit statistical estimates of the probabilities or return periods of specific wind/rainfall-correlation events. In fact, only two such correlations may be examined here. The ≈ 3.0 -in. (7.6-cm) rainfall event of January 12, 1960, correlates with 24 hr of SE wind (Fig. A4), followed by 16 hr of SW wind, for a total wind movement of about 850,000 m from the southerly quadrants. The ≈ 2.5 -in. (6.4-cm) rainfall of March 25, 1954, correlates with 13 hr of SE, S, and SW wind, although 2.5 hr of E or NE wind occurred midway throughout the series. Total wind movement from the southerly quadrants was approximately 445,000 m during and immediately after the heavy rain of March 24-25, 1954.

If the most historically unfavorable wind and rainfall events are combined, the following worst-case scenario emerges for a sinking-plume pollution episode at the SWFP: 24 hr of wind from the NW,* followed by 24 hr or more of wind from the southerly quadrants (up to a maximum of 3.0×10^6 m of total wind movement), during which time a 3.0-in. (7.6-cm) rainfall occurs. Unfortunately, the historical time series upon which this scenario is based is too short to permit an estimate of its probability of occurrence or return period.

*Such NW wind causes setup of the coastal water prism that produces an hydraulic head in the IHC and tributaries (Sec. 3.2.2); this facilitates flushing of IHC effluent into the coastal water prism when the wind shifts rapidly to the southerly quadrants and the setup is relaxed or becomes a setdown.

5 RECOMMENDATIONS FOR FUTURE RESEARCH

Continued improvement in the quality of the IHC effluent is expected in the future as a result of implementation of recent state and federal water-quality laws. This lessens somewhat the urgency for additional research on the transport and dispersion of IHC effluent in southwestern Lake Michigan. At the same time, the threat of large to catastrophic spills of toxic substances into the IHC, Indiana Harbor, Calumet Harbor, or Burns Ditch remains in effect *vis-a-vis* Chicago's South Water Filtration Plant. Of highest research priority is the development of a simple model for predicting the rate of travel of a toxic-pollutant cloud from point of release to the SWFP's shore and crib intakes, together with an estimate of the dilution ratio at each intake and duration of impact. The on-duty manager of the SWFP would use such a simple model immediately upon notification of the time, place, and quantity of material in the toxic spill. Model output would be invaluable for taking special water-treatment precautionary measures or for providing public warnings, if needed.

The development of a model simple enough to be operated quickly by an individual without special equipment would itself require the formulation and verification of a rather sophisticated computer model. Such a sophisticated model would permit the running of a number of cases for different wind conditions. The model output for the various cases would then be synthesized into the simple model needed by the water-plant supervisor. One such sophisticated computer model is now under development (see Schwab, Katz, and Saunders, 1977).

Verification of the model would require a network of current meters in the southwestern Lake Michigan nearshore region to define the spatial as well as the temporal structure of the currents. This network would be associated with at least one open-lake meteorological station to obtain wind, temperature, and humidity data representative of open-lake conditions. Multiple thermal surveys would also be required in the region covered by the current meters.

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APPENDIX A

Progressive-Vector Diagrams for Januarys 1948-1969
and Marches 1965-1974

Fig. A1. Eight-Hour Progressive-Vector Diagrams, for Januarys 1948-1951, for Midway Airport winds. Distances along axes are in 10^5 or 10^6 meters (as indicated).

Fig. A2. Eight-Hour Progressive-Vector Diagrams, for Januarys 1952-1955, for Midway Airport Winds. Distances along axes are in 10^5 or 10^6 meters (as indicated).

Fig. A3. Eight-Hour Progressive-Vector Diagrams, for Januarys 1956-1959, for Midway Airport Winds. Distances along axes are in 10^5 or 10^6 meters (as indicated).

Fig. A4. Eight-Hour Progressive-Vector Diagrams, for Januarys 1960-1963, for Midway Airport Winds. Distances along axes are in 10^5 or 10^6 meters (as indicated).

Fig. A5. Eight-Hour Progressive-Vector Diagrams, for Januarys 1964-1967, for Midway Airport Winds. Distances along axes are in 10^5 or 10^6 meters (as indicated).

Fig. A6. Eight-Hour Progressive-Vector Diagrams, for Januarys 1968-1969, for Midway Airport Winds. Distances along axes are in 10^5 or 10^6 meters (as indicated).

Fig. A7. Eight-Hour Progressive-Vector Diagrams, for Marches 1965-1968, for Midway Airport Winds. distances along axes are in 10^5 or 10^6 meters (as indicated).

Fig. A8. Eight-Hour Progressive-Vector Diagrams, for Marches 1969–1972, for Midway Airport Winds. Distances along axes are in 10^5 or 10^6 meters (as indicated).

Fig. A9. Eight-Hour Progressive-Vector Diagrams, for Marches 1973-1974, for Midway Airport Winds. Distances along axes are in 10^5 or 10^6 meters (as indicated).

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