United States
Environmental Protection
Agency

Environmental Research
Laboratory
Duluth MN 55804

EPA-600/3-80-007
January 1980

Research and Development

EPA

Sources and Transports of Coal in the Duluth-Superior Harbor

RESEARCH REPORTING SERIES

Research reports of the Office of Research and Development, U.S. Environmental Protection Agency, have been grouped into nine series. These nine broad categories were established to facilitate further development and application of environmental technology. Elimination of traditional grouping was consciously planned to foster technology transfer and a maximum interface in related fields. The nine series are:

1. Environmental Health Effects Research
2. Environmental Protection Technology
3. Ecological Research
4. Environmental Monitoring
5. Socioeconomic Environmental Studies
6. Scientific and Technical Assessment Reports (STAR)
7. Interagency Energy-Environment Research and Development
8. "Special" Reports
9. Miscellaneous Reports

This report has been assigned to the ECOLOGICAL RESEARCH series. This series describes research on the effects of pollution on humans, plant and animal species, and materials. Problems are assessed for their long- and short-term influences. Investigations include formation, transport, and pathway studies to determine the fate of pollutants and their effects. This work provides the technical basis for setting standards to minimize undesirable changes in living organisms in the aquatic, terrestrial, and atmospheric environments.

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

EPA-600/3-80-007
January 1980

SOURCES AND TRANSPORTS OF COAL IN THE DULUTH-SUPERIOR HARBOR

by

Michael Sydor
Kirby Stortz
Department of Physics
University of Minnesota, Duluth
Duluth, Minnesota 55812

Grant No. R-803952

Project Officer

Douglas W. Kuehl
Environmental Research Laboratory
Duluth, Minnesota 55804

ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
DULUTH, MINNESOTA 55804

DISCLAIMER

This report has been reviewed by the Environmental Research Laboratory - Duluth, U.S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the U.S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

FOREWORD

As the dependence of the United States upon coal as a major source of energy increases, so shall the problems associated with the mining, transport and storage of coal. These problems include the adverse effects coal particulates can have upon the ecosystem.

The Duluth-Superior Harbor on the western end of Lake Superior is rapidly becoming a major shipping port for coal from the western states. Concern for the water quality of the harbor has resulted in an effort to evaluate the distribution of coal particulates in the harbor and subsequently evaluate the effects of the coal particulates upon water quality.

This report describes the distribution of coal particulates throughout the harbor as released from selected sites and measured by experimental data. In addition the report describes a mathematical model developed to predict distribution of coal from spills.

J. David Yount
Deputy Director
Environmental Research Laboratory-Duluth

ABSTRACT

Dispersion of particulates from ORTRAN coal transshipment facility was investigated to estimate the input of coal dust into Duluth harbor and to determine the transport of coal particulates to Lake Superior. A numerical model was used to discuss dispersal of contaminants and determine the residence time of pollutants in the waterway. The model was verified using measurements of water levels, currents, and water quality parameters.

The relative magnitudes of dust sources due to ship loading and coal pile maintenance were obtained from particulate concentrations movements in air and measurement of particle deposition rates. The deposition rates were established from analysis of material trapped in collection buckets and directional measurements of dust deposited on slides. The overall magnitudes of the dust sources as a function of winds were estimated using a Gaussian plume model.

Resuspension by ship traffic acting as a secondary source of particulates was investigated through measurement of suspended solids and turbidities in the resuspension plumes. The numerical model for the harbor was subsequently used to estimate the transport of the resuspended material to Lake Superior.

Remote sensing data correlated with measurements of dustfall and snow reflectivity were used to identify the major dust sources in the harbor.

This report was submitted in fulfillment of Grant No. R-803952 by the Environmental Research Laboratory - Duluth under sponsorship of the U.S. Environmental Protection Agency. The report covers a period from July, 1975 to June, 1978, and was completed as of April, 1979.

CONTENTS

FIGURES

TABLES

ACKNOWLEDGMENTS

The work of Dr. Thomas F. Jordan, Physics Department, University of Minnesota, Duluth, on harbor dynamics is gratefully acknowledged. We wish to thank our co-workers Steve R. Diehl, Gordon J. Oman, David T. Smith, and John A. Sorensen for their help in computations and reduction and analysis of data.

We are indebted to Mr. Nelson Thomas, U.S. E.P.A. Grosse Ile, Michigan, for some of the particle size analysis and to Mr. Thomas M. Biele, Lakewood Filtration Plant, for use of Hiac PC 320 particle size counter.

Our thanks to Dr. Philip M. Cook, U.S. E.P.A., Duluth, for discussion of particle size work and for advice and help on electron microscopy work. We are indebted to our former colleague Mr. Duane W. Long, now with Western Lake Superior Sanitary District, for chemical analysis of the samples.

Our sincere thanks to Mr. Courtland L. Mueller Jr. and Mr. Howard J. Schwartz of the U.S. Army Corps of Engineers for information on the harbor sedimentation and use of their facilities in field work.

SECTION 1

INTRODUCTION

This study is part of a continuing program designed to determine some of the environmental effects resulting from the Nation's increased usage of coal. The purpose of this study was to investigate the input, dispersion, and transport of coal contaminants within the Duluth-Superior harbor and Lake Superior. Coal contaminants studied were those resulting from operation of the new Orba Rice Transshipment Company (ORTRAN) coal transshipment facility located in Superior, Wisconsin.

To determine the characteristics of the particulate dispersal in the harbor, it was necessary to predict mass transport in the entire waterway. This required extensive measurements and the use of hydrodynamic and water quality models. Similarly, description of the manner and magnitude of the input of particulates into the harbor required measurements of particulate concentration in the air and their deposition rates under various meteorological conditions. This data was extended through numerical modeling to assess the total magnitude of dust sources.

McElroy and Chiu (1974) proposed a mathematical model for water quality in the St. Louis River from Lake Superior to Brookston, Minnesota. Their model was based on the Columbia River Model developed by Callaway, et al. (1970) and documented by Feigner and Harris (1970). The Columbia River Model has been used successfully in other investigations (Churchill 1976). McElroy recommended that the 1974 St. Louis River Model be ammended to include the effects of the Lake Superior seiche. The seiche is a complex periodic oscillation of the lake's water level caused by meteorological factors such as winds and air pressure variations over the lake. Following McElroy's suggestion, a network of water level and current meters was installed during 1975 and 1976 to measure seiche oscillations and determine the effect of seiche on mass transport in the harbor. This data was necessary for model verification. At the same time, the Columbia River Model was modified to include the seiche. By the time ORTRAN became fully operational in late 1976, the water quality model was extensively tested and verified.

However, in the short time since ORTRAN has been fully operational, it has been impossible to determine accurately the distribution and seasonal variation of dust sources as a function of maintenance practices, and all of the various meteorological factors such as winds, precipitation, and humidity. For this report, a few specific meteorological events were monitored and modeled. These results were then extended using yearly wind distributions and ship traffic data to roughly estimate the annual input of particulate into the harbor and to determine the transport of the particulate to Lake Superior. Although these annual estimates are crude, they do provide reasonable estimates of the relative significance of various mechanisms for input of particulate into the harbor and lake.

SECTION 2

CONCLUSIONS

Duluth-Superior harbor is a freshwater estuary. The dominant force driving mass transport in the harbor is the Lake Superior seiche, which acts on the harbor through two inlets. The seiche ranges in amplitude from 3 to 25 cm and reverses the flow in the St. Louis River up to Fond du Lac, the site of the first river dam. For high seiche many of the main shipping channels show oscillatory currents which exceed 20 cm/sec, a threshold sufficient for resuspension of unconsolidated sediment.

Windblown dust from the ORTRAN coal transshipment facility is the major source of coal particulates for the harbor. Some of this dust comes directly from wind action on the coal pile, however, much of it is caused by grooming of the pile by large caterpillar tractors. Generally, the windblown material from ORTRAN deposits over land occupied by railways and other industrial sites. However, for southerly and easterly winds dust from the facility falls out over parts of the harbor, including the fish spawning and recreational areas near the Arrowhead Bridge. During one day of 6.8 m/sec (15 mph) northeast wind, 287 kg of coal particulates were deposited in the waterway southwest of the pile. Annually about 20 metric tons of coal particulates are deposited in the harbor, and about 1.5 tons fall out directly over Lake Superior. The most significant input of coal particulate from the facility into the lake comes from the springtime transport to the lake of about 4 tons coal dust which accumulates in the harbor ice cover.

The ship loading operation is a major source of coarse particulates. During this process, coal is moved via a conveyor system from a large outdoor storage pile to large lake carriers, which transport the coal to Detroit. Depending on wind conditions, between 20 and 260 kg of coal particulates are deposited in the channel where the ships are tied up during loading. The dust originates from the loading chute and the associated conveyor system. This material is further dispersed by resuspension due to ship traffic.

Concentrations of coal particulates in the harbor waterway range from 1 mg/ℓ in the channels near the loading dock to 1 μg/ℓ in the channel where chlorinated effluents are put out by the Duluth sewage plant. Generally the concentration of coal particulate in the shipping channels ranges between 1 μg/ℓ and 20 μg/ℓ, roughly 0.1% of the average concentration of suspended solids in the harbor. Less than 1% of the coal input into the harbor water (mostly the fine particulates between 1 and 6 μ in diameter) is transported to Lake Superior. This amounts to an annual input of 50 to

250 kg of coal into the lake. This input is small when compared to the direct fallout of particulate over the lake.

A momentary spill of dissolved pollutant distributed uniformly throughout the channel adjacent to the coal dock would take from 8 to 21 days to reach Lake Superior at peak concentration. Depending on seiche amplitude, the peak concentration of pollutant at the lake entries would range from 0.05 to 0.1% of the initial concentration in the loading channel. At 0.1% concentration level, the spill would extend over 30% of the harbor. The contaminant would reach areas of the harbor extending from the Burlington Railway Bridge, which is 2.5 km upriver from the coal dock, to the lake entries, and would remain in the harbor at concentration levels above 0.01% for 30 to 40 days.

Sedimentation of ORTRAN coal particulates in the harbor affects primarily areas downriver from the Burlington Northern Railway Bridge. Sedimentation levels of coal for one year range from 0.2 g/m^2 for areas 3 km from the source to 100 g/m^2 near the coal dock.

Resuspension of bottom sediments by ship traffic is an important secondary source of harbor turbidity. Suspended solids in ship resuspension plumes range from 10 to 50 mg/ℓ, five times the usual concentration of suspended solids in the harbor. An estimated 10^5 kg of material is resuspended per passage of a coal ship. The resuspended material is coarse and settles rapidly, thus the output of resuspended material into Lake Superior is negligible. Most of the material resuspended by ship traffic is redistributed to the low turbulence areas within the transit channels.

During the winter, remote sensing data can be used to identify major dustfall sources in the harbor. Remote sensing data coupled with snow albedo measurements indicate that the input of dust from the C. Reiss Inland Dock and the Hallet Storage Facility may exceed the input from the ORTRAN coal transshipment facility. This is largely due to the prevailing wind directions, and various maintenance practices at the bulk material storage piles. The proximity of these old coal piles to the waterline is also a factor.

SECTION 3

RECOMMENDATIONS

Although the ORTRAN coal transshipment facility is located so as to reduce the input of coal into the harbor and lake and appears relatively clean in comparison to other storage facilities, the terminal is still a substantial source of coal dust. A more detailed investigation of this facility should be conducted to determine accurately the input of coal particulates into the harbor and lake as a function of climatological factors such as temperature, humidity, and winds. The effects of grooming of the coal pile by large caterpillar tractors should be examined closely. In particular the design of the caterpillar fans should be changed to minimize the blowing of coal particles into air. The effectiveness of current dust abatement procedures such as spraying of the pile should be examined throughout the seasons and an effort should be made to determine what additional measures could help diminish the dust source.

If the input of coal dust into the harbor and the lake is deemed significant in terms of toxic pollutants, the prevailing winds and the proximity of the populated areas should be considered as first priority when locations of future coal facilities are planned. To reduce the concentration of coal particulates in the harbor and the lake, future coal shipping facilities should be located on main channels, preferably in the inner harbor. Presence of adjoining slips should be avoided, and the coal piles should be placed as far from the water line as possible.

The older coal storage facilities common in many Great Lakes' harbors should be examined as sources of coal dust. Because these old facilities are often located at the water line and generally do not have dust abatement facilities, they are significant sources of coal particulates in the harbors. Use of remote sensing is feasible as a means of identification and surveillance of dust sources from bulk storage piles.

SECTION 4

WATER LEVELS - HARBOR DYNAMICS

To examine how water moves in the harbor, the forcing terms and the geometry of the harbor need to be examined from the standpoint of wave propagation and resonance characteristics. A bay or a harbor on the Great Lakes acts like an estuary where water movement is driven by lake level oscillations and the harbor geometry (Freeman, Hamblin, and Murty 1974). For instance, a harbor inlet can be considered as an oscillating plug of water coupling the harbor (or bay) with the lake (Defant 1961, Miles 1974, Ippen and Goday 1963). The geometry of the inlet and the bay reservoir could select certain frequencies for mass movement, thus acting as a kind of mechanical filter (Hwang and Tuck 1970, Carrier et al. 1971). A single very small inlet would select only the long period water level oscillations (Carrier et al. 1971). On the other hand, if more than one inlet is present, the inlets could act in unison as coupled oscillators selecting certain forcing terms and causing anomalous water transports in parts of the harbor. These anomalous transports could be significant in resuspension of sediment and in dispersal of pollutants (Bennett 1974).

The Duluth-Superior harbor is typical of Great Lakes harbors. The waterway forms the mouth of the St. Louis River (Figure 1). It includes some 50 km of shipping channels, whose depth generally ranges from 5 to 10 meters with an average depth of 8.5 meters. The harbor is subject to a lake seiche which usually ranges in amplitude between 3 and 15 cm, but may exceed 25 cm during severe storms. Table 1 shows the pertinent geometrical properties of the harbor and inlets, and some flow characteristics derived from numerical modeling and physical measurements.

To examine the harbor for resonance frequencies, note that there are two lake entries or inlets to the Duluth-Superior harbor. There is also one major harbor constriction under the Blatnik Bridge which separates the inner harbor from the outer harbor. If these inlets and the constriction are considered as a system of coupled oscillators, the following solution is found for the angular frequency ω representing the Helmholtz resonances for the harbor:

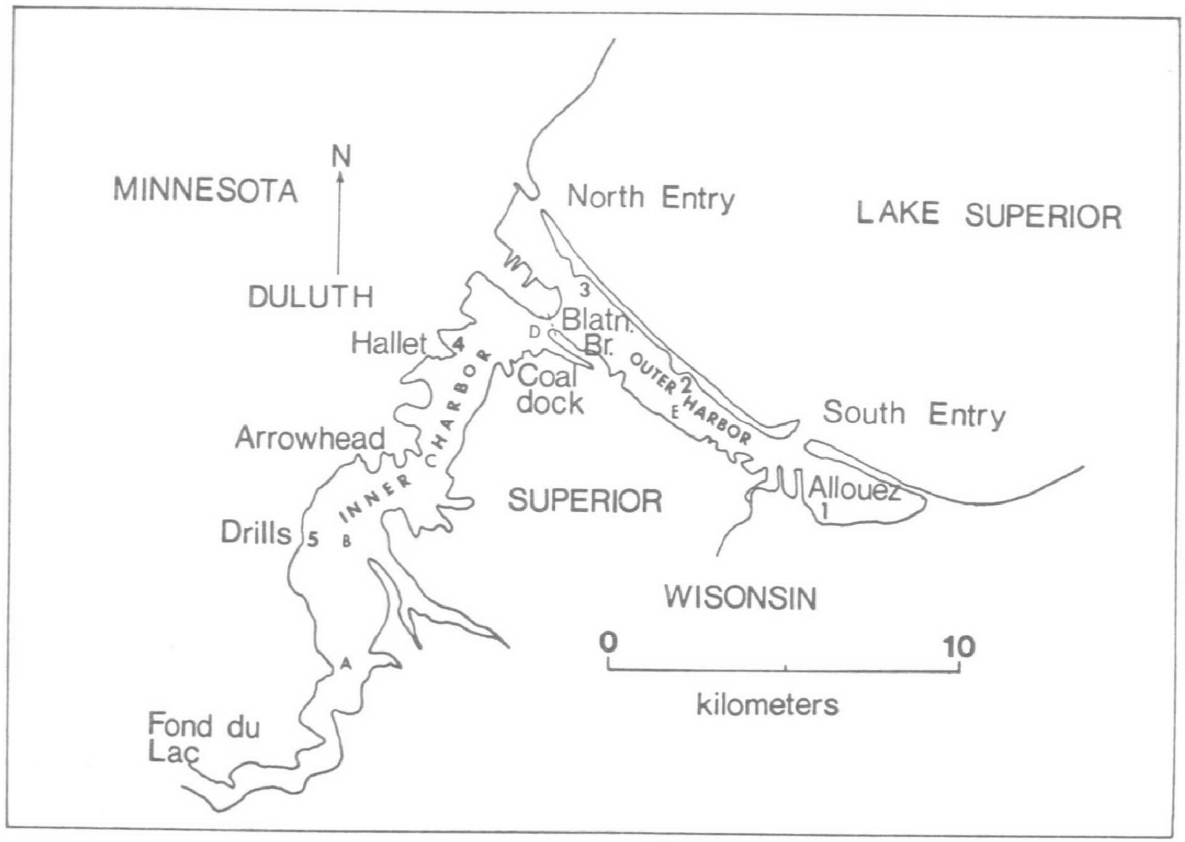


Figure 1. Duluth-Superior harbor. Water level stations are indicated by numbers, current meter stations by letters.

$$\omega^2 = \frac{1}{2}\frac{g}{A}\left(\frac{S_1}{L_1} + \frac{S_2}{L_2} + \frac{S_3}{L_3} + \frac{A}{A'}\frac{S_3}{L_3}\right) \pm$$

$$\left[\frac{g^2}{4A^2}\left(\frac{S_1}{L_1} + \frac{S_2}{L_2} + \frac{S_3}{L_3} + \frac{A}{A'}\frac{S_3}{L_3}\right)^2 - \frac{g}{A'}\frac{S_3}{L_3}\frac{g}{A}\left(\frac{S_1}{L_1} + \frac{S_2}{L_2}\right)\right]^{\frac{1}{2}} \qquad (1)$$

where A = area of outer harbor, A´ = area of the inner harbor, S_1, S_2, S_3, L_1, L_2, L_3 are the cross-sectional areas and lengths of the north entry, south entry, and inner harbor entry respectively, and g = 9.8 m/sec^2.

TABLE 1. GEOMETRICAL AND FLOW PROPERTIES OF THE DULUTH-SUPERIOR HARBOR

Total Surface Area	45×10^6 m^2
Outer Harbor Surface Area (A) (east of Blatnik Bridge)	16×10^6 m^2
Inner Harbor Surface Area (A´) (west of Blatnik Bridge)	29×10^6 m^2
Surface Area in Shipping Channels	9.6×10^6 m^2
Total Volume	0.17×10^9 m^3
Volume in Shipping Channels	$.073 \times 10^9$ m^3
North Entry Cross-sectional Area (S_1)	796 m^2
South Entry Cross-sectional Area (S_2)	1300 m^2
Inner Harbor Inlet Cross-sectional Area (S_3)	972 m^2
North Inlet Length (L_1)	480 m
South Inlet Length (L_2)	900 m
Inner Harbor Inlet Length (L_3)	126 m
% Flow in Dredged Channels	80%
Discharge at North Entry (% of total)	60%
Discharge at South Entry (% of total)	40%
% of Total Harbor Volume Exchanged Per Day for Average Seiche	6%
% of Total Harbor Volume From Daily Outflow of St. Louis River	2%
Average Discharge Rate of St. Louis River	30 m^3/sec

Table 2 gives the periods of Helmholtz frequencies for various assump-

TABLE 2. HELMHOLTZ FREQUENCIES FOR VARIOUS COUPLING OF INLETS AS A SYSTEM OF OSCILLATORS

Coupling Scheme			Period in Hours
Three inlets acting as a coupled system of oscillators			2.3
The north and south inlets acting as a coupled oscillator		$A_{bay} = 45 \times 10^6\ m^2$	2.1
Single inlet acting as an oscillator connecting the bay and the lake			
	North inlet	$A_{bay} = 45 \times 10^6\ m^2$	2.9
	South inlet	$A_{bay} = 45 \times 10^6\ m^2$	3.1
Single inlet mode			
	North inlet	$A_{bay} = 16 \times 10^6\ m^2$	1.7
	South inlet	$A_{bay} = 16 \times 10^6\ m^2$	1.9

tions on the effective harbor area, A_{bay}, and oscillator coupling schemes. It takes on the order of 30 minutes for a disturbance to propagate between the entries. Periods shorter than 1 hour are damped out. Thus, the important Helmholtz oscillation periods range from 1 hour to 3 hours.

Spectral analysis of the daily water level measurements shows oscillation peaks at 1.5, 1.9, 2.3, 2.8, 3.3, and 3.8 hours at the Allouez Bay Station near the south entry to the lake, and 1.9, 2.3, 2.8, 3.3, and 3.8 hours at the Drills Marina Station well inside the inner harbor. The observed periods shorter than 3 hours could be considered in terms of the possible Helmholtz oscillation modes given in Table 2 since all of the above periods at Allouez and Drills appear correlated over times on the order of one day. The observed 2.3 hour harbor oscillation corresponds, perhaps fortuitously, with the period produced by three coupled oscillators (Table 2).

To examine for possible Helmholtz modes due to the action of a single inlet, the results of Seeling and Sorensen (1977), who propose a Helmholtz period of 1.4 hours for the north and the south inlet of the Duluth harbor, were considered. The observed period of 1.5 hours at Allouez could correspond to this value. However, Seeling and Sorensen took the reservoir area for the oscillator as an area somewhat smaller than the outer harbor area which may not be justified. The above authors define a frictionless inlet-bay Helmholtz period as:

$$T = 2\pi[(L+L')A_{bay}/(gA_c)]^{\frac{1}{2}}$$

where T is the frictionless inlet-bay Helmholtz period and

$$L' = -(B/\pi)\ln[\pi B/(gdT^2)^{\frac{1}{2}}]$$

where d is the height of water above equilibrium at the entry, and B, L, and A_c are respectively the width, length, and cross-sectional area of the inlet. This equation for T reduces to the single oscillator solution given by ω in equation (1) if L' is neglected. L' is small for the Duluth-Superior Harbor.

Using equation (1), the calculated period for a single inlet oscillator is 1.7 and 1.9 hours for the north and the south inlets respectively, if the effective bay reservoir area is taken as the area of the outer harbor alone. However, it is more likely that the harbor inlets act as an oscillator together. The coupled mode for the two inlets is 2.1 hours. It will be seen later that this period is much closer to an observed long term 2 hour oscillation predominating in the harbor. On the other hand if the two lake inlets acting as coupled oscillators are considered with A_{bay} equal to the outer harbor area alone rather than the entire harbor, equation (1) yields a period of 1.3 hours, which is reasonably close to the 1.5 hour period observed in spectral analysis of a daily water record for the outer harbor. This period appears to damp out farther into the harbor.

To determine if indeed the Helmholtz oscillations have a dominant effect on mass movement in the harbor or merely produce short term distortion of lake level oscillations, long term water level fluctuations in the harbor were examined and compared to the seiche periods of Lake Superior. The spectral analysis on a continuous water level record of 5 weeks, a time comparable to flushing time for the harbor (Section 11), would bring out the persistent frequencies while the short term resonances would average out to relatively low values. The results from the analysis of long term water level records are shown in Figure 2. The long duration periods in Figure 2 show highly correlated peaks at 2.0, 3.8, 4.8, and the fundamental 7.9 hour

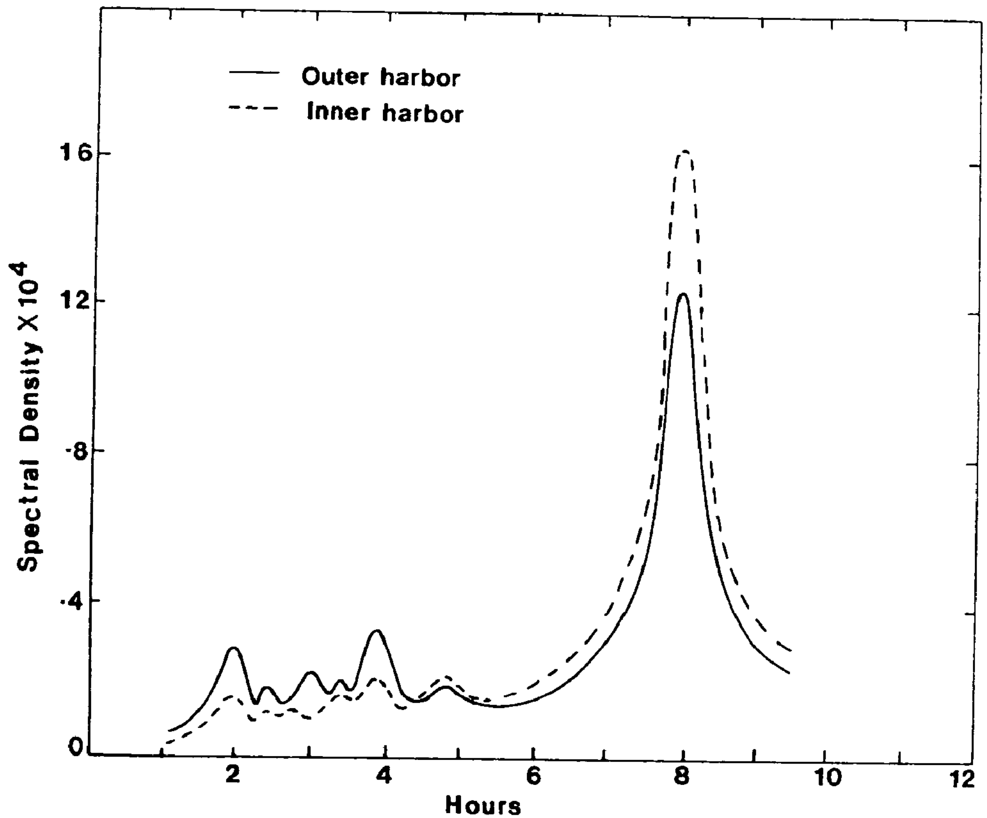


Figure 2. Fourier analysis of water level data showing the long term oscillation periods in the harbor and Lake Superior.

frequency. These periods correspond closely to the lake level oscillation modes found by Mortimer and Fee (1976). It therefore appears that the persistent oscillations in the harbor and therefore the long term transports are largely due to lake level fluctuations, with persistent sympathetic ringing apparent at the two hour period, which does not damp out sufficiently fast and contributes appreciably to the flushing exchange for the harbor.

The relative strength of the oscillation peaks shown in Figure 2 depends on the action of the harbor as a filter and the selective excitation of Helmholtz frequencies by the lake level fluctuations of similar periods. To examine which of the calculated Helmholtz frequencies are allowed, the fact that the water levels at the lake inlets oscillate in-phase (to within 5 minute resolution) can be used as a condition on the excitability. Such calculations are outside of the interest here, however, it is pointed out that the eigen vectors for the Helmholtz frequencies with periods larger than one hour all satisfy the in-phase condition at the lake entries.

SECTION 5

HYDRODYNAMIC MODEL

A numerical model of transports provides a useful tool in assessing relative changes in dispersion of pollutants under a variety of seiche conditions. Here a hydrodynamic model is developed and verified. This model will subsequently serve as the basis for development of a water quality model and discussion of dispersal of contaminants.

For this project transports for representative seiche conditions were calculated. Since there are no pronounced effects on transports due to factors other than river through-flow and the lake level oscillations, representative conditions for the harbor could be simulated by running of the model for a few specific data periods when water level fluctuations were characteristic of the usual ranges of seiche amplitudes. The actual water levels at the lake inlets and the St. Louis River discharge rate served as the boundary conditions for the hydrodynamic model. The numerical grid for the model consisted of junctions connected by straight channels, which averaged about 600 meters in length, Figure 3. The channels covered the dredged and shallow areas of the entire harbor from Lake Superior to Fond du Lac. In a sense the grid, consisting of one-dimensional channels, provided a pseudo two-dimensional model, where interaction between channels was allowed at the junctions. The channels and junctions were numbered consecutively following the scheme of McElroy and Chiu (1974). The hydrodynamic model was based on the Columbia River Model proposed by Callaway, Bryan, and Dittsworth (1970). The basic equations are the equations of motion (2) and continuity (3) given by

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + g\frac{\partial h}{\partial x} + k|u|u = 0 \qquad (2)$$

$$\frac{\partial h}{\partial t} + \frac{1}{b}\frac{\partial q}{\partial x} = 0, \quad q = Au \qquad (3)$$

where x = distance along the longitudinal axis of the river

t = time

u(x,t) = velocity in x direction

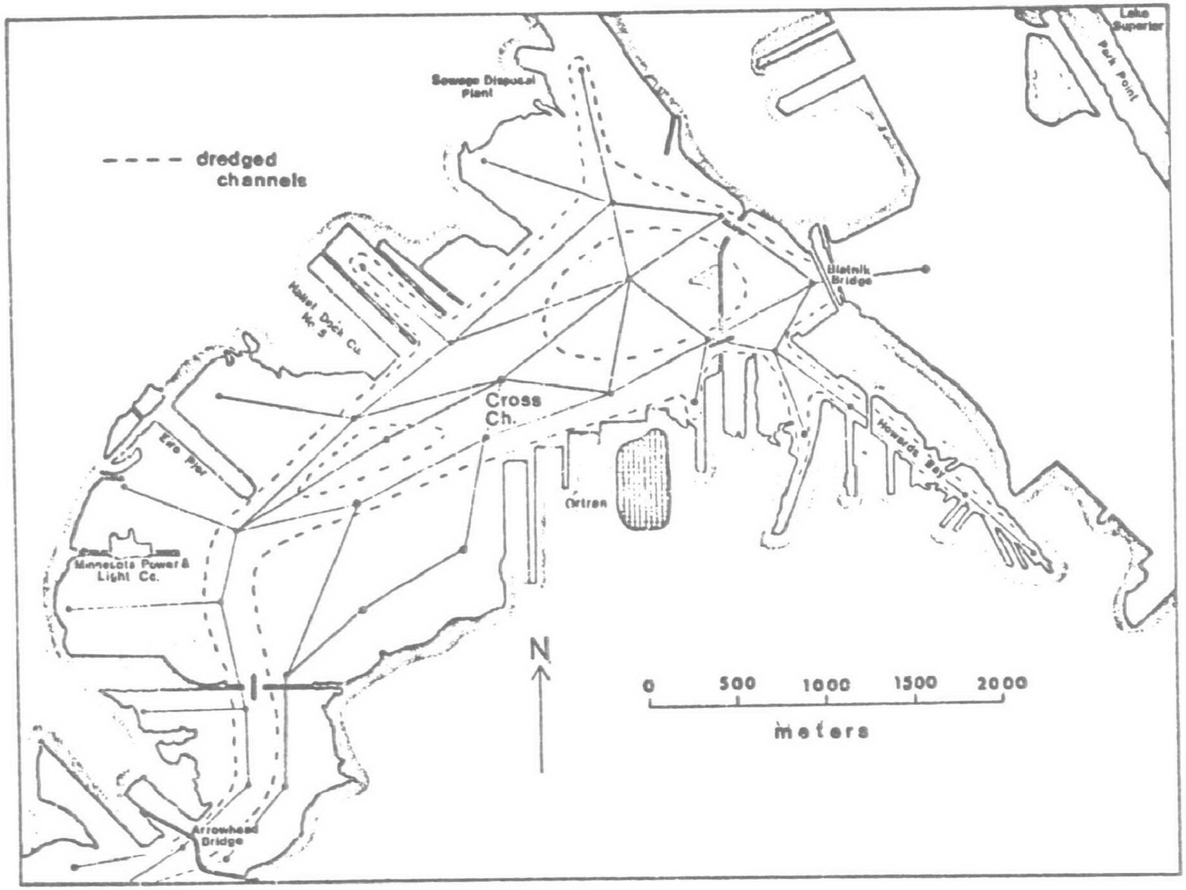


Figure 3. Hydrodynamic model grid for the inner harbor.

$h(x,t)$ = water stage

g = gravitational constant

k = frictional constant

b = width of river

q = river flow

A = cross sectional area of river

Equations (2) and (3) are written in a finite difference form, the river is schematized, i.e. depths, areas (A), widths (b), roughness coefficients (k) are determined, initial conditions are specified and u and h are solved for by the "leapfrog" method. In the leapfrog method, the initial conditions of velocity and stage are read into the computer along with boundary conditions. Velocity and flow are computed from the momentum equation. The computed flow is substituted into the continuity equation to obtain a new stage elevation which is then used in place of the initial condition to obtain new velocity and flow values. The new flow obtained is again substituted into the continuity equation and the process "leapfrogs" until the cycle is complete.

When the equations are applied to the network, the following assumptions are made:

1. Acceleration and momentum transfer normal to the flow direction is negligible.
2. Wavelength is at least twice the channel depth.
3. Coriolis and wind forces are negligible.
4. Each channel is straight and has a constant cross sectional area and depth.

In a finite difference form, equation (2) becomes:

$$\frac{\Delta V_i}{\Delta t} = - V_i \left[\frac{\Delta V}{\Delta X}\right]_i - K_i |V_i| V_i - g \frac{\Delta H_i}{L_i} \tag{4}$$

where V_i = i^{th} channel velocity

Δt = time step

$$\left[\frac{\Delta V}{\Delta X}\right]_i = \text{velocity gradient in channel } i$$

$$= -\frac{B_i}{A_i}\left[\frac{\Delta H_i}{\Delta t} - V_i \frac{\Delta H_i}{L_i}\right]$$

B_i = channel width

A_i = channel cross sectional area

L_i = channel length

ΔH_i = difference in stage between ends of channel

K_i = frictional resistance coefficient

$$= \frac{gn^2}{R^{4/3}}$$

n = Manning roughness coefficient

R = hydraulic radius

Equation (3) becomes

$$\frac{\Delta H_j}{\Delta t} = \frac{Q_j}{A_j} \qquad (5)$$

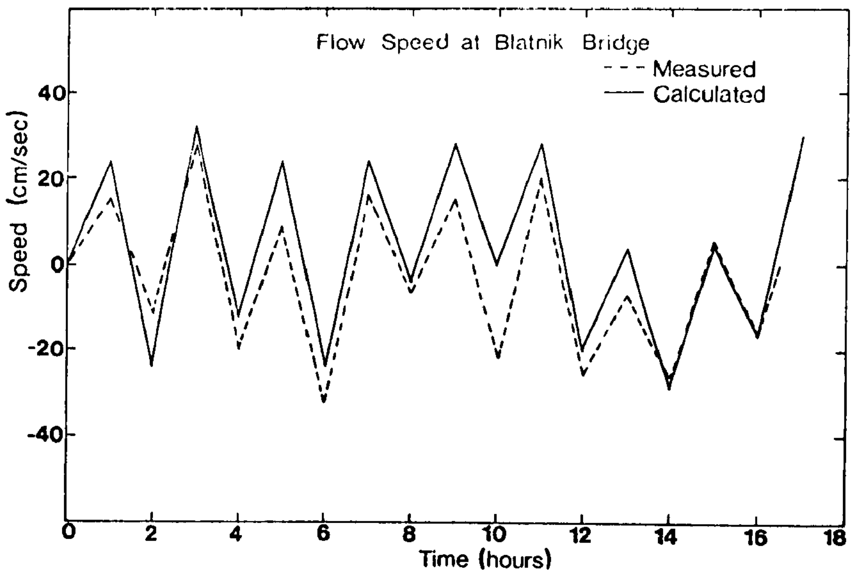
where ΔH_j = head of junction j

Q_j = net flow into j during a time step

A_j = junction surface area (constant)

Equations (4) and (5) are then solved using a two step Runge-Kutta integration method. Manning's coefficient, n, was adjusted to give the best agreement between measured and calculated values of velocity and stage. The value of n ranged between 0.020 and 0.080, with the larger values found in the area east of the Blatnik Bridge, where the channel structure was most complex and flow rates in the shallower parts of the system were more important because of the harbor configuration and the relative abundance of the shallow areas. The time step was chosen to satisfy the Courant Condition for numerical stability. Applying this condition yielded a step of about 55 seconds. When the time step in the model was varied from 10 to 60 seconds there was no significant difference in the results for transports. For steps larger than 60 seconds the model became unstable.

A comparison of calculated and measured water currents and water levels from 11AUG76 are shown in Figures 4 and 5 for three of the locations marked



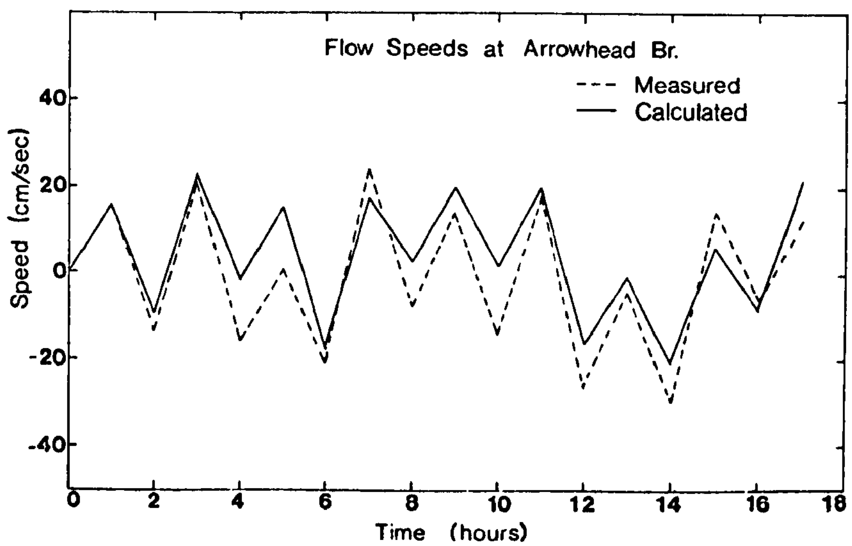


Figure 4. Calculated and measured currents up and down river from the ORTRAN coal dock.

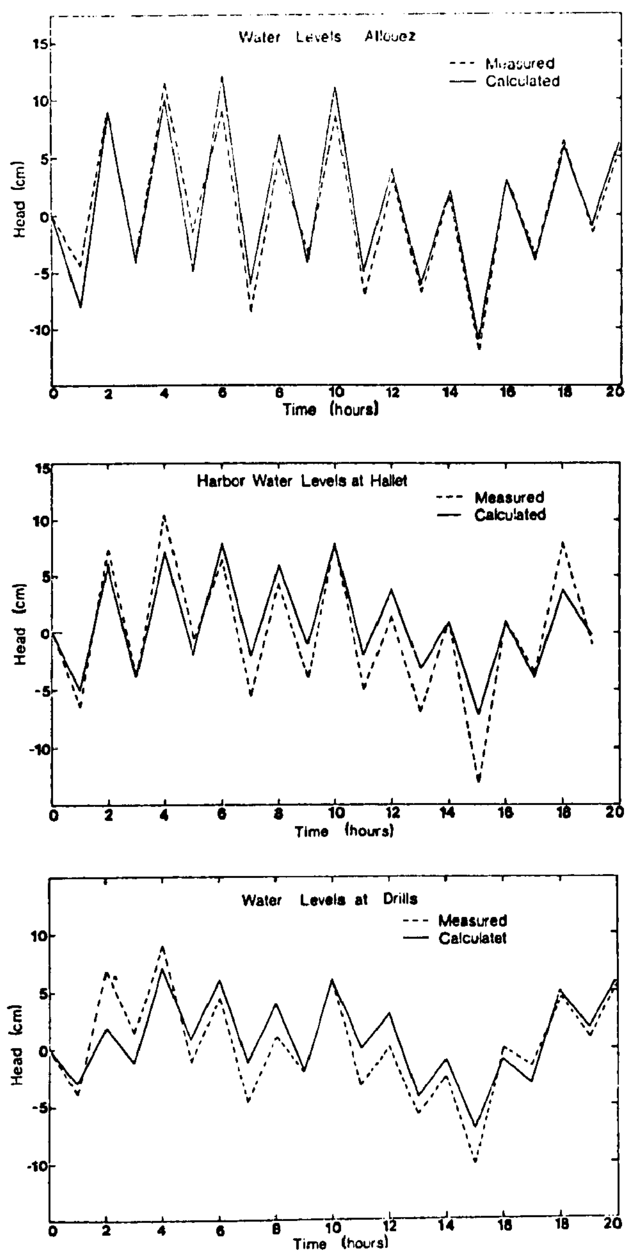


Figure 5. Comparison of measured and calculated water levels.

in Figure 1. As expected the measured and calculated values for water level follow each other closely at Allouez Bay which is located near Lake Superior and is the water level reference point. The values depart somewhat as one moves into the harbor. The calculated and measured currents and water levels have the same phase and are generally within 20% of each other in magnitude. Table 3 shows some typical flow rates for various channels of interest. It

TABLE 3. CALCULATED CURRENTS FOR VARIOUS CHANNELS OF INTEREST

Absolute Minimum, Average, and Maximum Speeds (cm/sec)						
	3.0 cm Seiche			15.0 cm Seiche		
Location	Min	Av	Max	Min	Av	Max
Superior Entry *	-7.9	2.0	11.5	-30.4	1.9	34.6
Duluth Entry *	-16.6	1.9	19.4	-41.9	2.5	45.8
Superior Front Channel *	-3.0	1.1	5.0	-11.8	1.2	14.1
Duluth Harbor Basin	-2.1	0.4	2.7	-5.3	0.5	6.1
Blatnik Bridge *	-17.1	3.4	22.3	-45.4	3.7	50.0
Sewage Plant	-15.6	3.2	20.5	-42.0	3.4	45.7
Coal Dock	-7.7	1.6	10.0	-20.6	1.6	22.1
Cross Channel	-0.9	-0.0	0.8	-1.9	0.0	1.8
North Channel *	-9.0	1.9	11.8	-24.4	2.0	25.7
South Channel	-5.1	2.1	8.8	-19.0	1.8	20.8
Arrowhead Bridge *	-8.4	2.7	12.6	-26.5	2.5	28.2
Drills*	-6.4	3.0	11.3	-23.2	2.6	24.7
Oliver Bridge	-1.5	2.7	6.5	-8.9	2.7	11.9
Fond du Lac *	14.3	15.6	16.7	11.9	15.5	18.5

* Insitu current measurements made in channel.

can be seen that for high seiche conditions currents exceeding 20 cm/sec occur in many channels. Currents in excess of 15 cm/sec are of interest in consideration of resuspension and transports of suspended solids (Sundborg 1956).

The numerical model predicts currents in all channels as a function of Lake Superior seiche height and St. Louis River flow rate. This information is necessary in the study and simulation of the dispersion of particulates from the coal dock.

SECTION 6

WATER QUALITY MODEL

In constructing the model for transport of suspended solids, each channel in the hydraulic model is subdivided longitudinally into 20 equal sections in which complete mixing is assumed during each integration time step of the sediment transport model. This subdivision of the channels is necessary to obtain realistic approximation to actual mixing processes (Csanady 1973, Galloway and Vakil 1977).

In the water quality model the results from the hydrodynamic model are used to predict the spatial distribution of a substance with time. The general differential equation which describes the mass transport is:

$$\frac{\partial C}{\partial t} = D_L \frac{\partial^2 C}{\partial x^2} - U \frac{\partial C}{\partial x} \pm \Sigma S \qquad (6)$$

where C = concentration of the substance

U = velocity of the stream flow

D_L = longitudinal dispersion coefficient

t = time

x = distance along the longitudinal axis of the stream

S = sources or sinks of the substance being modeled

The first term on the right represents the mass transport due to longitudinal dispersion or diffusion, and the second term represents the transport due to advection. For a conservative substance, there are no sources or sinks other than inflow or diversions. Since there are no diversions, the transport of a conservative substance can be represented as:

$$\frac{\partial C}{\partial t} = - U \frac{\partial C}{\partial x} + D_L \frac{\partial^2 C}{\partial x^2} + \text{input} \qquad (7)$$

The mass transported into junction j from junction j+1 through channel i due to each of these three processes, advection, diffusion, and input, can be represented in finite difference form by equations (8), (10), and (11).

$$\Delta M_a = - U_i A_i \Delta t C_a \qquad (8)$$

where ΔM_a = mass transported by advection

U_i = speed in channel i

A_i = cross sectional area of channel i

C_a = concentration of advected substance, chosen to be the concentration in junction j+1, which is the upstream concentration.

$$\Delta M_d = - D_L A_i \Delta t (C_{j+1} - C_j)/x_i \qquad (9)$$

where ΔM_d = mass transported by diffusion

C_j = concentration in junction j

x_i = length of channel i

Using an expression for the dispersion coefficient derived by Orlob (1959) the equation becomes

$$\Delta M_d = K|Q_i|R_i \; \Delta t \; (C_{j+1} - C_j)/x_i \qquad (10)$$

where K = diffusion constant

Q_i = flow in channel i

R_i = hydraulic radius of channel i

The absolute value of the flow is used in order to insure that the mass will be diffused from the junction with the higher concentration to the junction with the lower concentration. From several test runs it was determined that the advective transport is the dominant transport process. A value of 10.0 was chosen for K, which gives average values of D_L that are comparable to those found by Orlob (1959). Finally,

$$\Delta M_t = C_{in} QIN_j \; \Delta t \qquad (11)$$

where M_t = mass transport through inflow

C_{in} = concentration of inflow

QIN_j = flow rate of inflow to junction j

Thus for each time interval Δt, the mass change for any junction j can be written

$$\Delta M_j = \sum_i (\Delta M_a + \Delta M_d + \Delta M_t)_i$$

$$= \sum_i [U_i A_i C_a \Delta t + C|Q_i| R_i (C_{j+1} - C_j)/x_i] \qquad (12)$$

$$+ C_{in} QIN_j \Delta t$$

where the sum over i indicates the sum over all the channels connected to junction j.

The concentration of a substance in each junction can then be found by dividing the mass in that junction by the junction volume, which is defined as the sum of the volumes of the channels connected to it.

The solution technique for the water quality model is as follows.

1. Initial and boundary conditions are specified for the system.
2. Average hydraulic parameters, which were obtained from the hydrodynamic model, are specified. These parameters include channel speed and flow as well as junction head.
3. Mass transfers due to advection and diffusion are made between all the junctions.
4. If the substance is not conservative the mass in each junction is decayed using an appropriate decay coefficient. The only decay process that was considered is settling. Resuspension of bottom sediments is also accounted for at this time.
5. Mass due to inflow is added to each junction where it occurs.
6. The volume of each junction is adjusted according to the surface elevation or head change from the hydraulic input data.

7. The concentration in each junction is found by dividing the total mass by the new volume of the junction.

8. Results are stored for future analysis.

9. Steps 2 through 8 are repeated for each time step until the model time period is completed.

The time step Δt in the water quality model was chosen to meet the following conditions.

1. Δt is an integral multiple of the time step for the hydraulic model, which was 60 seconds, so that the hydraulic input data for each quality time step would be an average of an integral number of hydraulic cycles.

2. Δt is an integral division of the 8 hour seiche mode, which is the dominant driving force in the model.

3. Δt is the largest time period which would not allow water to completely travel the length of any channel during a single time step.

The values of Δt for each seiche amplitude modeled are shown in Table 4.

TABLE 4. TIME STEPS FOR VARIOUS SEICHE AMPLITUDES USED IN WATER QUALITY MODEL

Seiche Amplitude (cm)	Time Step (sec)
0.0	3600
3.0	1800
6.0	1200
15.0	900

Boundary conditions which had to be determined were: the concentrations of each modeled substance in Lake Superior at both the Duluth and Superior entries, and the concentration at U.S. Highway 23 in Fond du Lac, the upstream end of the model grid. An initial distribution of concentrations throughout the harbor also had to be determined for each modeled parameter. This data was obtained from sampling cruises.

To ensure that the water quality model was realistic, a conservative parameter was modeled in time. Specific conductance was ideal for this purpose because it is a quickly measureable conservative parameter. The specific conductance is normally a factor of two higher in the harbor than it is in Lake Superior. Thus, influx of lake water into the harbor can be easily detected in the conductance measurements. Furthermore, since the conductance has substantial variations over the harbor due to known input sources, the parameter serves well for verification of the water quality model in time and for verification of the simulation of dispersion processes from a point source.

Continuous measurement of specific conductance near the Blatnik Bridge is performed routinely by the Western Lake Superior Sanitary District (WLSSD). As a test of the water quality model, conductance was modeled at the Blatnik Bridge over a fifteen day period from 03JUN77 to 18JUN77. The results from the model were compared with the WLSSD conductivity data.

The boundary value and the initial condition for conductance distribution were derived from data obtained during shipboard sampling of the entire system. Measurements were taken at three depths and the actual conductivity distribution for the model was obtained from the depth averaged distribution of the in situ measurements. Sewage treatment plant discharges are the major sources of conductivity in the harbor. To determine the magnitude of these sources, the discharge rates of the sewage treatment plants in the harbor were obtained from WLSSD records. Figure 6 shows the daily variation in the discharge rate at the main treatment plant located near the Blatnik Bridge. The daily flow rates of the St. Louis River for the model period were obtained from Minnesota Power and Light Company data.

A comparison of the actual and simulated conductivity near the Blatnik Bridge is shown in Figure 7. The modeled data was plotted for a 6 hour average, short enough to resolve the fluctuation in the Duluth sewage plant output. The transport time from the sewage plant to the monitoring station is on the order of one day, thus the fluctuation in specific conductance at the Blatnik Bridge due to the sewage plant output was small because of dispersion. Good agreement was obtained between the measured and simulated conductances with an average error less than 8%. Precipitation during the model period, Table 5, accounts for some of the wider departures between the modeled and measured values.

The water quality model was constructed primarily for examination of the dispersion of contaminants arising from the operation of the ORTRAN coal facility. For further model verification, simulations were made of the Duluth sewage plant output for parameters such as dissolved solids and phosphates. Chemical analysis (performed by others associated with this program) attempted to identify a leachate which would be modeled so as to study the effects of the coal facility on the environment. It appeared, however, that leachates were a minor environmental problem. As a result,

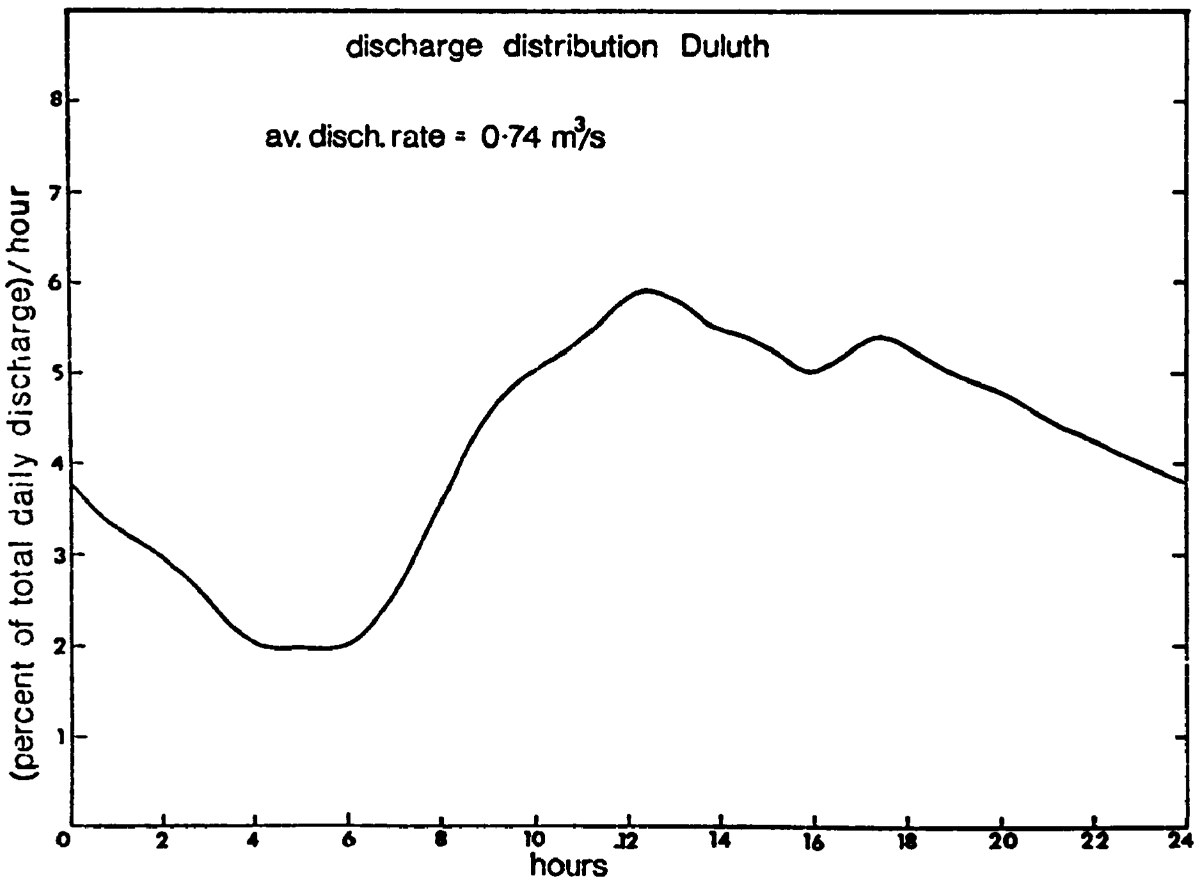


Figure 6. Daily variation in Duluth Sewage Plant discharge rate.

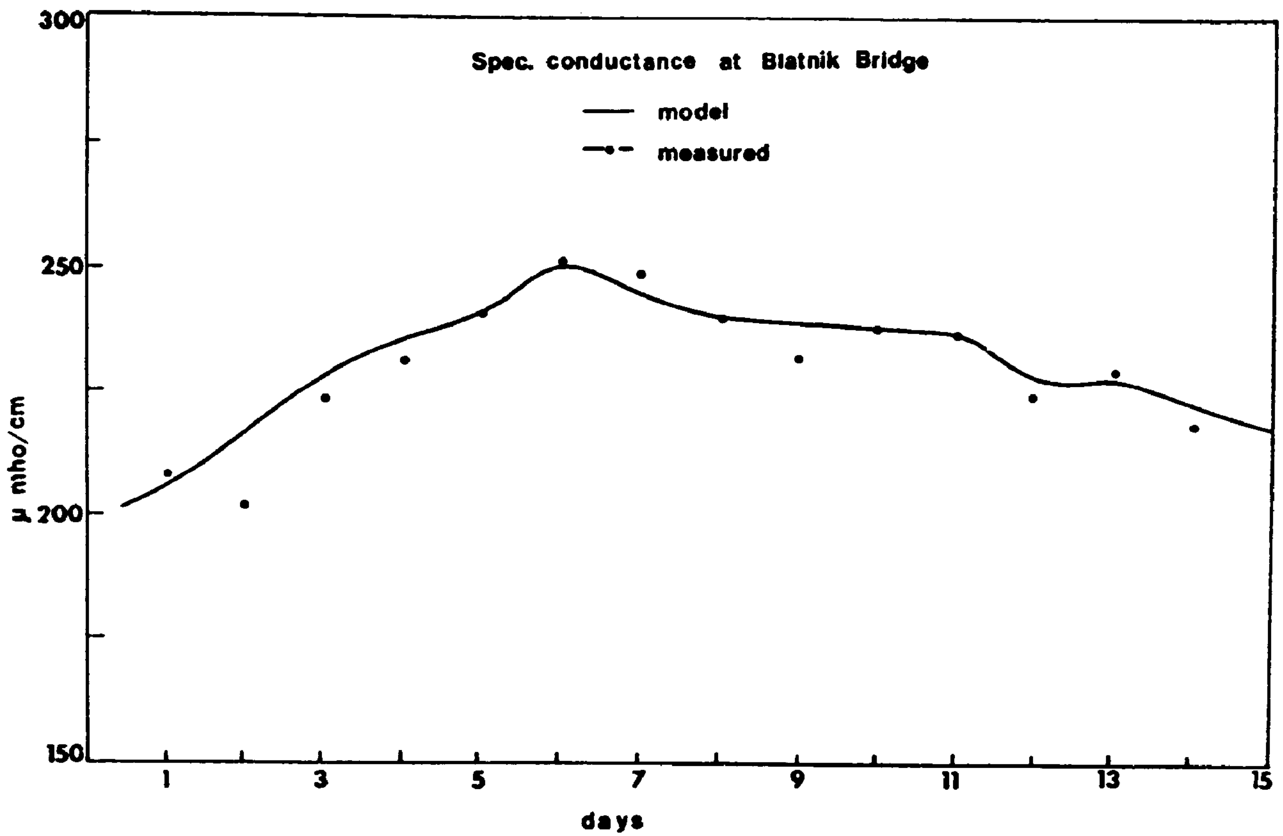


Figure 7. Calculated and measured specific conductance at west Blatnik Bridge junction.

TABLE 5. PRECIPITATION RECORDED DURING WATER QUALITY SIMULATION PERIOD

Model Day	Airport Precipitation (cm)
1	1.12
2	0.0
3	0.51
4	Trace
5	1.75
6	0.13
7	0.0
8	0.30
9	0.0
10	0.0
11	0.0
12	Trace
13	Trace
14	0.38
15	0.28

the dispersal of a hypothetical conservative leachate from the coal dock was modeled to determine contaminant residence time and the dispersion characteristics for the harbor. These results will be discussed later.

With apparent absence of a leachate problem, attention was turned to the investigation of the direct contamination of harbor by coal particulates. It was evident that fine particulates are a contaminant which is directly put into the harbor, at least at ship loading. The dispersal of particulates could be modeled without detailed apriori knowledge of their chemical behavior or environmental impact. The spillage at ship loading could be treated as a point source of particles. However, the windblown material from the pile constituted a broad source whose distribution would have to be determined as a boundary condition for modeling purposes. At the outset of the research program it was generally believed that windblown dust from the coal pile would be negligible because of dust abatement practices which would be undertaken in the operation of the coal storage facility. However, soon after the facility came into full operation it was evident that the windblown dust from the coal pile was a significant source of particulate contaminant. It was also learned from the leachate studies part of the research program that the fine particulate appeared actually to be the most significant form of coal related pollutant to fish (Carlson and Caple 1978). Thus, the choice to focus on the dispersion of particulates as an obvious source of coal related contaminant appeared well justified. However, before dispersion of coal particulates in the harbor could be simulated, the nature of the sources and the settling rates had to be examined.

SECTION 7

WINDBLOWN COAL DUST

In the process of acquiring coal particulate data, a number of interesting observations were noted concerning conditions which effect the windblown dust source. One of the most surprising was the fact that downwind concentrations generated by the dumping of coal from the overhead conveyor to the coal pile were usually less significant than the amount of coal particulates resulting from grooming the coal pile with caterpillar tractors. Particularly noticeable were the large dust plumes generated by either the caterpillar tractors or the earth-movers maneuvering near the base of the pile. Since two caterpillars were at work nearly every time the coal pile was observed, the caterpillar operation appeared to be the most consistant source of particulates. When the caterpillar tractors ceased operation, the particulate level would usually fall below one-fourth its previous value but would not completely drop to the background particulate level upwind from the facility. Thus the coal pile appeared to put out particulates at low levels on almost a continuous basis. Besides the grooming of the pile, sudden changes in wind direction also gave rise to visually dense dust plumes.

After a rain the dust count would stay quite low for one to two days. However, specific measurements on the behavior of the source as a function of climatological factors such as isolation and humidity were not made. Continuous monitoring and surveillance is necessary to describe the source accurately on an annual basis. The source as a function of winds only was examined in order to estimate roughly the annual magnitude and distribution of the source.

In considering particulate dispersion as a function of winds, first the concentrations and the deposition of particulates for a specific wind event was considered. The northeasterly wind was chosen for the purpose of detailed study because such wind produced coal dust plumes over a flat empty terrain where extensive measurements could be made and where access to good sampling sites was not limited by private property restrictions. Furthermore northeast winds carried the windblown material over environmentally significant parts of the harbor where recreational areas and fish spawning areas are located and where the windblown particulates would constitute a major direct input of coal related pollutants into the harbor.

To establish the magnitude of the windblown dust source, measurements were made on the particle concentrations in the air, particle size distributions in air and water, and the rate at which particles deposited in collection buckets, on slides, and in water-filled cuvettes. The contents of catch buckets were analyzed for total particulate and chemical composition. Taconite dust and grain dust for samples near the grain elevator were the major background material. The slides were examined microscopically for particle size distribution, while the cuvettes were analyzed optically for particle size, concentration, and identity based on light scattering (Diehl 1978). The collection buckets provided a measure of the long term accumulation of coal dust. The slide and cuvette sampling was performed during visible dust plumes in conjunction with measurement of winds. The cuvettes were used in relatively short duration measurements where the distribution of sampling points was adjusted in the field to measure quickly the distribution of coal dust concentration in air and its fallout on a water surface.

To estimate the total input of particulates into the harbor it was necessary to extend the measurements made at the sampling stations to the entire area. For this purpose the dust plume was modeled numerically.

The basis for most mathematical treatments of dust dispersion was the familiar steady state diffusion equation given by

$$u \frac{\partial C}{\partial x} = \frac{\partial}{\partial y}\left[K_y \frac{\partial C}{\partial y}\right] + \frac{\partial}{\partial z}\left[K_z \frac{\partial C}{\partial z}\right]$$

where C is the concentration, u is the wind speed, and K_y, K_z are the horizontal and vertical eddy diffusivities respectively. The coördinate system is chosen so that the x-axis extends horizontally in the downwind direction and the z-axis extends vertically from the earth's surface. Both the source and the horizontal wind field are assumed to be time independent and diffusion in the direction of the wind is ignored.

One of the most widely used solutions of this equation is the Gaussian plume formulation for a point source, commonly expressed as

$$C = \frac{Q}{2\pi\mu\sigma_y\sigma_z}\left[\exp[-\tfrac{1}{2}(\frac{y}{\sigma_y})^2]\right]\left[\exp[-\tfrac{1}{2}(\frac{z-H}{\sigma_z})^2] + \exp[-\tfrac{1}{2}(\frac{z+H}{\sigma_z})^2]\right] \qquad (13)$$

where the diffusion parameters are usually written as

$$\sigma_z = ax^b \text{ and } \sigma_y = cx^d$$

and where Q is the source intensity and H is the height of the source above the earth's surface defined at z = 0. The solution assumes a spatially independent wind speed and the eddy diffusivities are only allowed to vary as powers of the downwind distance. For a single point source, the diffusion in the crosswind and vertical directions produces a Gaussian concentration profile about the plume centerline. For sources which cannot be realistically represented by a point source, multiple point sources can be employed and their contributions summed to yield a close approximation to the actual source configuration.

One of the major advantages of air quality models based on this solution is that only a few input parameters are required. Furthermore, since a large number of investigators have used such models, the diffusion parameters, σ_y and σ_z, have been studied and empirically determined under a variety of conditions including the various classes of atmospheric stability (Pasquill 1962, McElroy 1968, Koch 1971, 1973, 1976, Turner 1970, and Busse and Zimmerman 1973).

In its most widely used form the Gaussian plume model assumes total reflection of the plume at the earth's surface. In other words, the loss of pollutants due to deposition or reaction at the surface is neglected. Since this assumption is difficult to justify for particulate dispersion, the diffusion equation was solved again using for a boundary condition that the deposition at the surface is proportional to the concentration at the surface,

$$\text{Surface Flux} = -K_z \left.\frac{\partial C}{\partial z}\right|_{z=o} = -K_z \, \alpha C(z=o)$$

where α is the constant of proportionality. For the case of constant eddy diffusivities, K_y and K_z, the correct solution can thus be shown to be

$$C = \frac{Q}{2\pi x\sqrt{K_y K_z}} \exp\left[-\frac{u}{4x}\frac{y^2}{K_y}\right] \left\{\exp\left[-\frac{u(z-H)^2}{4K_z x}\right] + \exp\left[-\frac{u(z+H)^2}{4K_z x}\right] - 2\alpha\int_0^\infty \exp\left[-\frac{\alpha\lambda+(z+H+\lambda)^2}{4K_z x}\right]d\lambda\right\}. \tag{14}$$

Although the equation is now further complicated by the deposition term, the additional integral can be readily evaluated by computer using a series approximation. When the source is located on the ground, H = 0, this solution reduces to that given by Smith (1962) for one-dimensional case along the z axis. Good fits to observed particulate deposition rates were obtained using this solution.

Figure 8 shows a contour plot of predicted deposition rates downwind from the coal pile for a 6.8 m/sec (15 mph) northeast wind on 17APR78. The model was calibrated with in-the-field measurements of particulate concentrations in air including the upwind observations used to estimate and extract the background concentration. Dry-fall sampler measurements analyzed microscopically were used to correlate the air dust concentration in air with the mass deposition rates. The rates predicted by the model were then scaled to yield the observed mass deposition rates. The results of the model

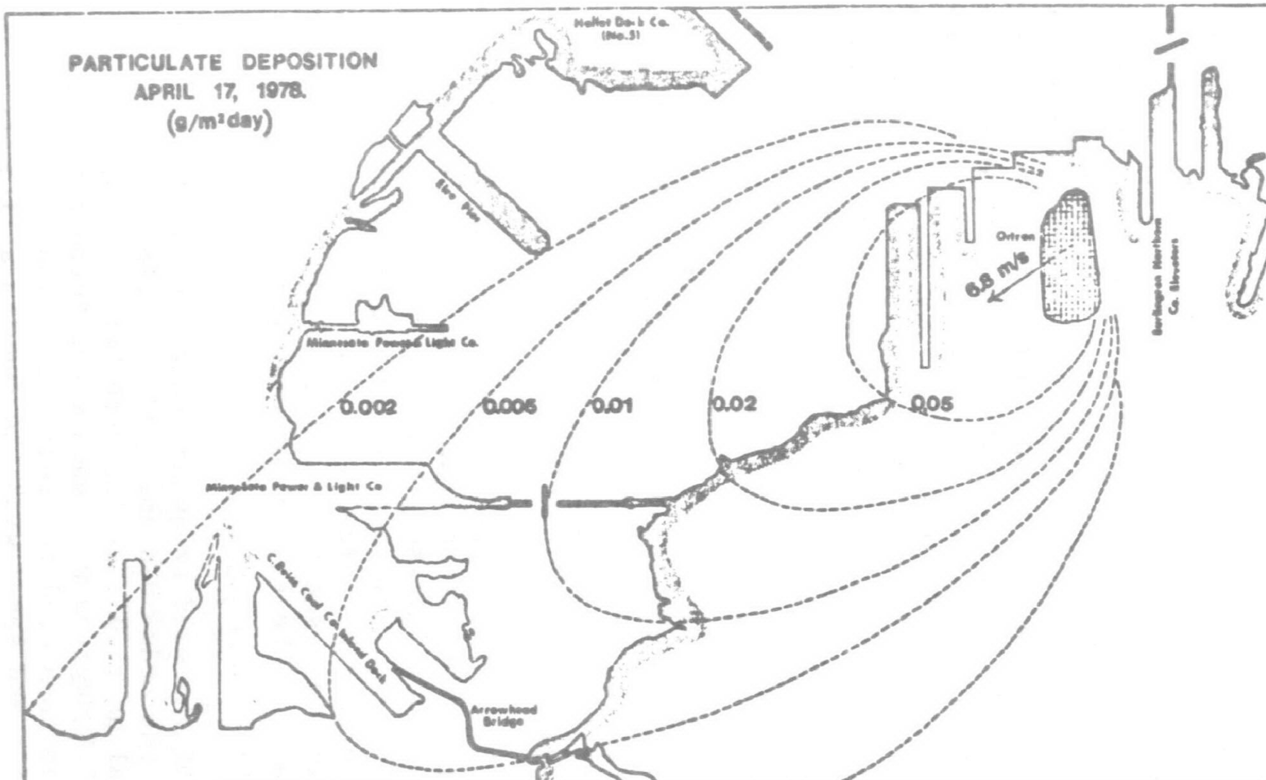


Figure 8. Distribution of coal dust fallout after 1 day of 6.8 m/s northeasterly winds.

yielded distribution of dust fallout and the deposition constant α quite close to the observed dust deposition rates at sampling stations.

It should be pointed out, however, that dust deposition rates over harbor water may differ from the deposition over flat field where most of the calibration measurements were taken. For instance, placement of collectors at various heights and near obstacles appeared to produce significant variations. Furthermore, the solution to the diffusion equation which was used to model coal particulate dispersion is based on a few questionable assumptions. For example, in order to extract a solution, both the wind speed and vertical eddy diffusivity K_z were held constant, yet both are actually functions of altitude. However, as pointed out by Smith (1962), little error is introduced by using a constant wind velocity except perhaps at short range. The vertical eddy diffusivity K_z is difficult to represent mathematically and no general solution of the diffusion equation has yet been found. Depending on weather conditions, K_z usually increases linearly from the ground, levels off, and then decreases at large heights or near a temperature inversion (Moore 1975). Smith actually suggests that a constant vertical eddy diffusivity K_z is a reasonable approximation for the case of downwind distances greater than a few hundred meters but less than the distance needed for the plume to reach an inversion layer. Fortunately, most of the areas of interest around the coal facility fall within this downwind range.

Since the model assumes a point source surrounded by uniform terrain, various model improvements to account for the effects of turbulence due to the coal pile itself and large nearby structures such as grain elevators are currently being investigated. It may be necessary to change to a numerical model employing a finite-difference scheme.

Another imperfection of the present model is that no allowance was made for the increased deposition rate of the larger particles (> 20 μ) simply due to their increased mass. These particles are less important in terms of the long range transport but some improvement might be also realized in the future by breaking the particle size distribution into various categories which could be handled independently. The results thus far, however, provide a good estimate of the fallout of coal particulates from a dust plume over the harbor.

By application of the wind frequency data for the Duluth harbor shown in Figures 9 and 10, the model was employed to estimate roughly the total yearly loading of coal particulates into the harbor. The winds were grouped by direction every 22.5 degrees with each group further divided into three speeds. The model was then used to predict downwind deposition for each separate wind direction and speed with the results scaled according to the frequency of occurrence of each wind subdivision. Finally, the individual model results were overlayed to produce the contour map of Figure 11, showing yearly deposition in the vicinity of the coal facility. A solution where the source was taken proportional to wind velocity was also considered. The results are shown in Figure 12 and appear to be quite similar to the constant source solution giving the results in Figure 11.

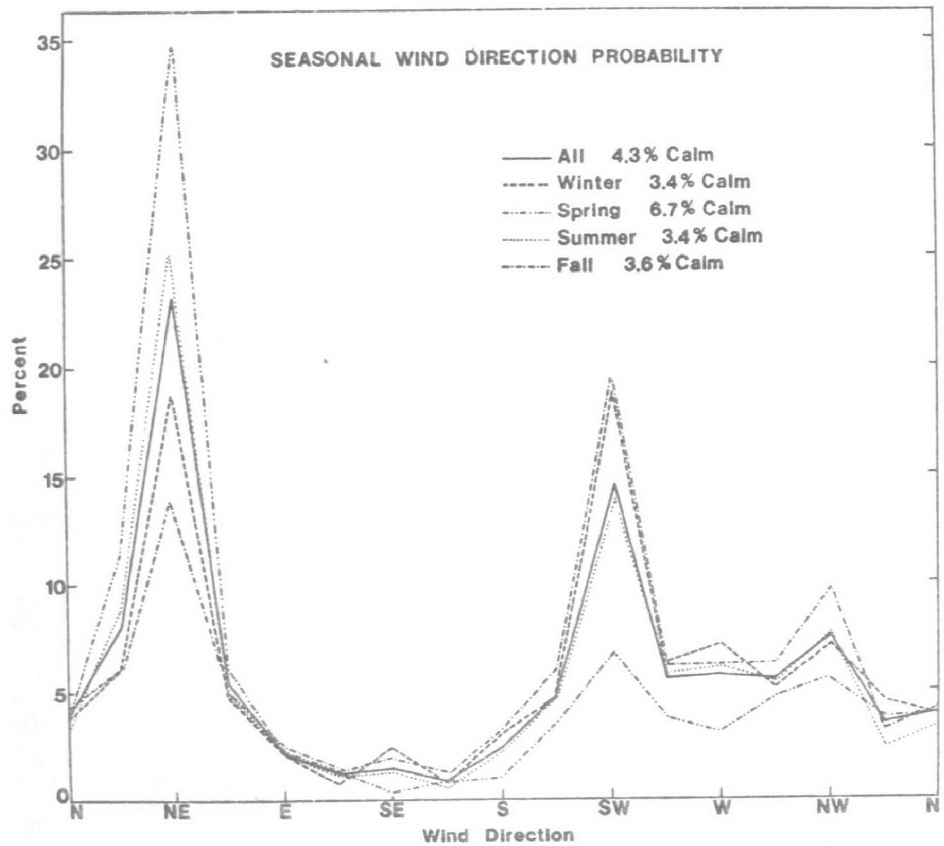


Figure 9. Distribution of wind directions for the Duluth-Superior harbor (4 year average).

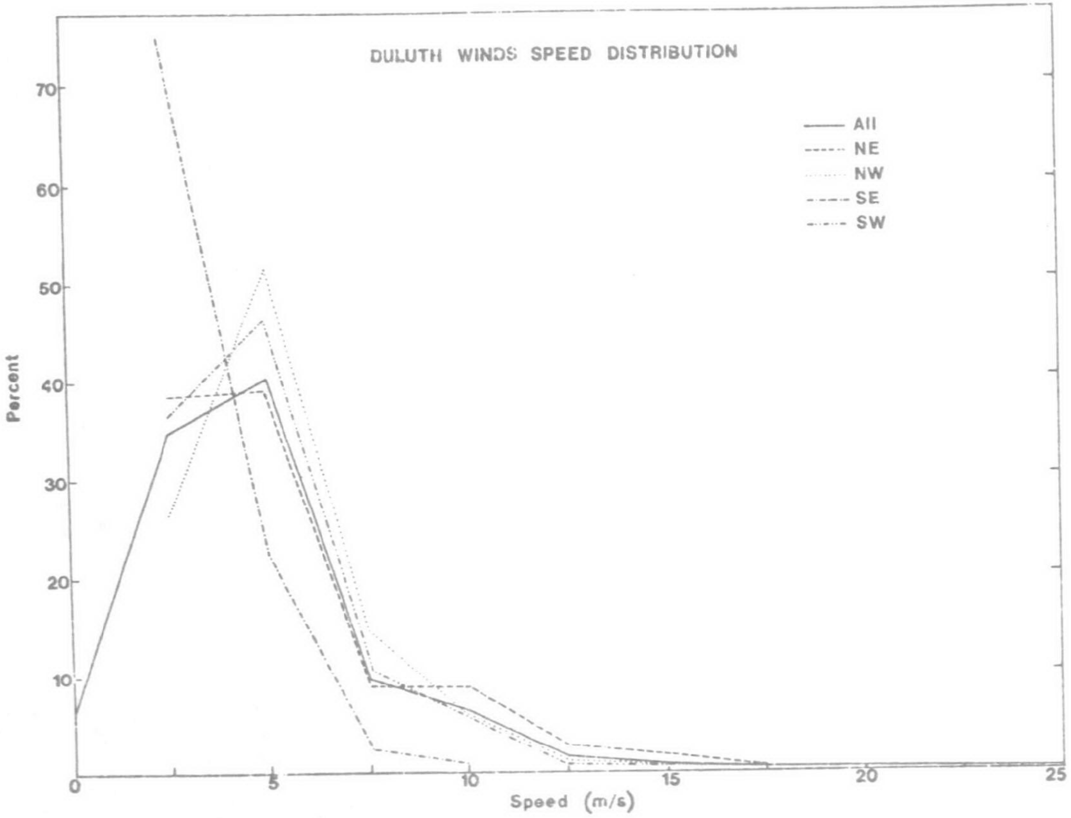


Figure 10. Distribution of wind speeds for the Duluth-Superior harbor (4 year average).

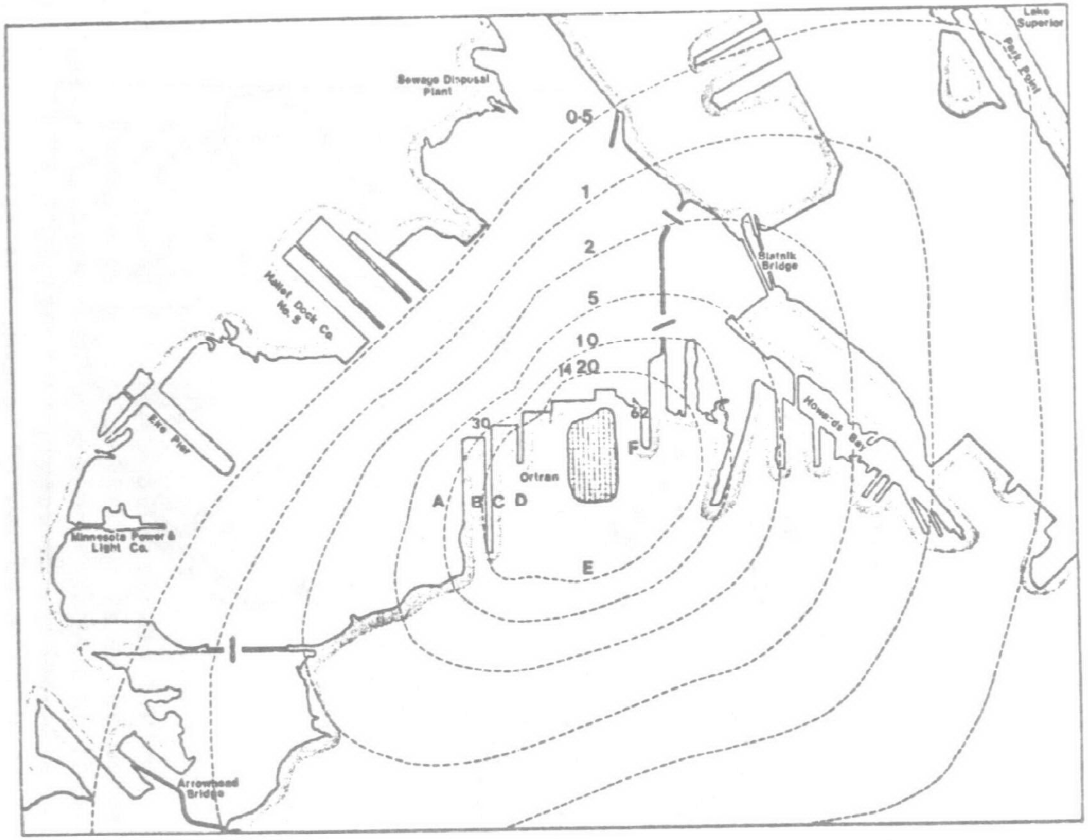


Figure 11. Estimated annual distribution of coal dust fallout based on a Gaussian plume model with constant dust source. Contour numbers represent fallout in g/m^2. Sampling stations are shown by letters. Accumulation of dust in ice cover is shown by small numbers (values extended to yearly basis).

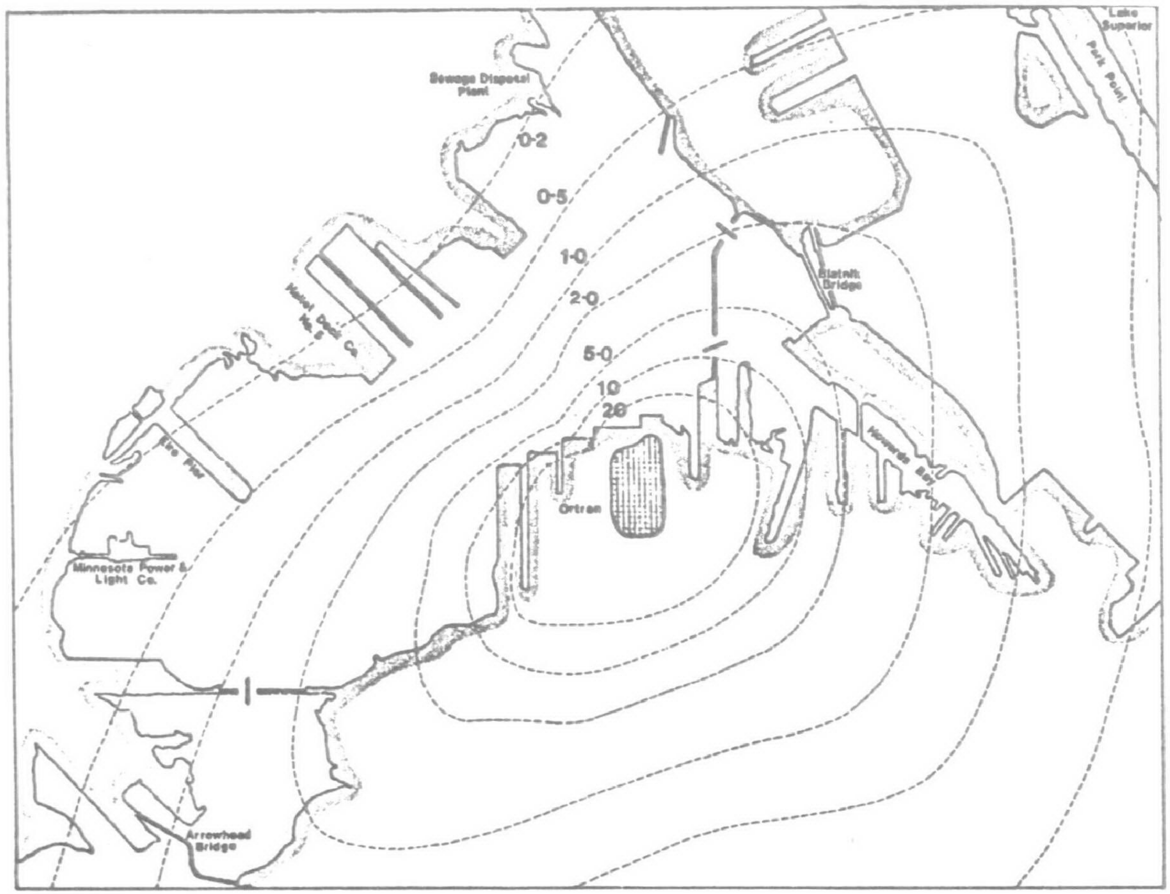


Figure 12. Estimated annual distribution of coal dust (g/m^2) based on a Gaussian plume model with dust source proportional to wind speed.

The source intensity for the yearly dustfall estimate was checked using deposition rates determined from collection containers placed at six locations around the coal facility between 01MAR78 and 17MAR78. The wind frequency data for this 17-day period was applied to the model and the fallout was found for these six locations. The deposition rate at each sampling location, indicated on the contour plot of Figure 11, can be seen in Table 6

TABLE 6. COAL PARTICULATE FALLOUT (10^{-2}g/m^{2}/day)

Location	Collection Containers March 1 - 17, 1978	Model predictions Applied Winds: March 1 - 17, 1978	Slide Samplers Average of 9 days in Jan. - Mar., 1978
A	1.1	1.2	-
B	3.1	3.6	5.5
C	2.9	3.8	6.5
D	11.0	6.2	15.5
E	3.5	6.3	10.0
F	56.0	48.9	92.2

along with the model results from this calibration period. The sensitivity of the collection containers to local terrain features makes comparison difficult. Glass-slide samplers were also deployed at these same locations on selected days in the winter. Particles which deposited on the slides were categorized by size and counted by use of a microscope. The results from glass slides, which represent a total of about 9 days, are also shown in Table 6. Although the slide deposition rates are higher than those obtained by the collection containers, the slide results tend to be biased toward downwind samples. Also shown in Figure 11 are the locations and results of three ice samples. The ice samples were cut out of the harbor ice sheet in late March. Yearly deposition rates were determined by estimating the number of days since the ice had formed and scaling the average daily mass of coal found in the ice-snow surface accordingly. Ice sample data north and northeast of the pile agree quite well with the model predictions. The value northwest of the pile is too high, due to the contribution of coal dust from piles located at the Hallet Storage Facility across the harbor. The influence of this source will be discussed later in the section on snow albedo.

The model predicts that annually about 20 metric tons of coal are carried from the ORTRAN coal facility into the harbor waters, and roughly 1.5 metric tons are deposited directly into Lake Superior. The water area receiving the highest level of contamination is the slip located on the northeast side of the coal pile adjoining the Burlington Northern elevators, where nearly 3 metric tons of coal is deposited yearly. Due to both insufficient data and a few weak assumptions inherent in the model, these estimates could be in error by a factor of two. But even the rough estimate of windblown source shows it to be the dominant source of input of coal particulate into the harbor and the lake. Many additional measurements need to be made. For example, the source intensity was estimated in the model from data taken in the late winter. The source may differ from season to season. The changing effects of precipitation, humidity, wind, and temperature may be considerable. Operating procedures at the coal facility are also known to be changing. In the winter, for instance, the sprinkling system used to reduce dust from the conveyors appears to be shutdown possibly due to freezing problems. As a result, large dust plumes are visible at times from the overhead conveyors.

SECTION 8

DISPERSAL OF COAL DUST FALLOUT IN THE HARBOR WATERWAY

The transport of coal particulates in the harbor can be examined through use of the water quality model. The deposition rate shown in Figure 8 corresponds to a total input of 287 kg of coal particulate into the harbor per day. By using this deposition rate as the only input source to the water quality model, the fate of the particulates once they enter the water could be determined if their settling rates in the waterway were known. The settling rates for coal dust have to be approximated.

It is difficult to trace coal particulates in water and determine their settling rates since the windblown dust is deposited over broad areas of the harbor and the coal particulate concentrations are low in comparison to the background suspended load. Furthermore, other coal sources contribute to the input of coal particulates upstream from the transshipment facility. However, a realistic limit on settling rates for coal particulates can be obtained by examining the particle size distributions and settling rates for natural turbidity in the harbor and Lake Superior. Particle sizes for samples collected in the field were measured optically using a forward scattering technique. The optical method is preferable to measurements made with electrolyte counters because forward scattering is independent of particle shape (Kerker 1969). Figure 13 shows the size distribution for suspended solids in the harbor, Lake Superior, material resuspended by ship traffic, and coal dust fallout from windblown material. Coal dust fallout and the suspended particulates in the harbor both show a break at a diameter of 4 μ. A similar observation has been made by McCave (1975). It can be seen that the coal dust particles are coarse compared to the suspended solids in the harbor, thus, the settling rates in the harbor provide a lower limit on the settling rate for the coal particulate.

Estimates of settling rates for in situ conditions were based on sampling measurements and mass balance for suspended load in the harbor channels. The distribution of suspended solids in the harbor was obtained from rapid sampling at the stations shown in Figure 14. Samples were taken at 50 cm below the surface, mid-depth, and 50 cm off the bottom. Sampling stations were grouped to cover the three main sections of the harbor: Fond du Lac to Blatnik Bridge, Blatnik Bridge to the Duluth entry, and Superior front channel to the Superior entry. The stations within each section were sampled at three stages of the 8 hour fundamental seiche cycle. The inner harbor inlet at Blatnik Bridge always showed well-mixed conditions. The stations on each side of the inlet served as reference stations and were overlapped in each sampling scheme. Some stratification in the suspended solids and

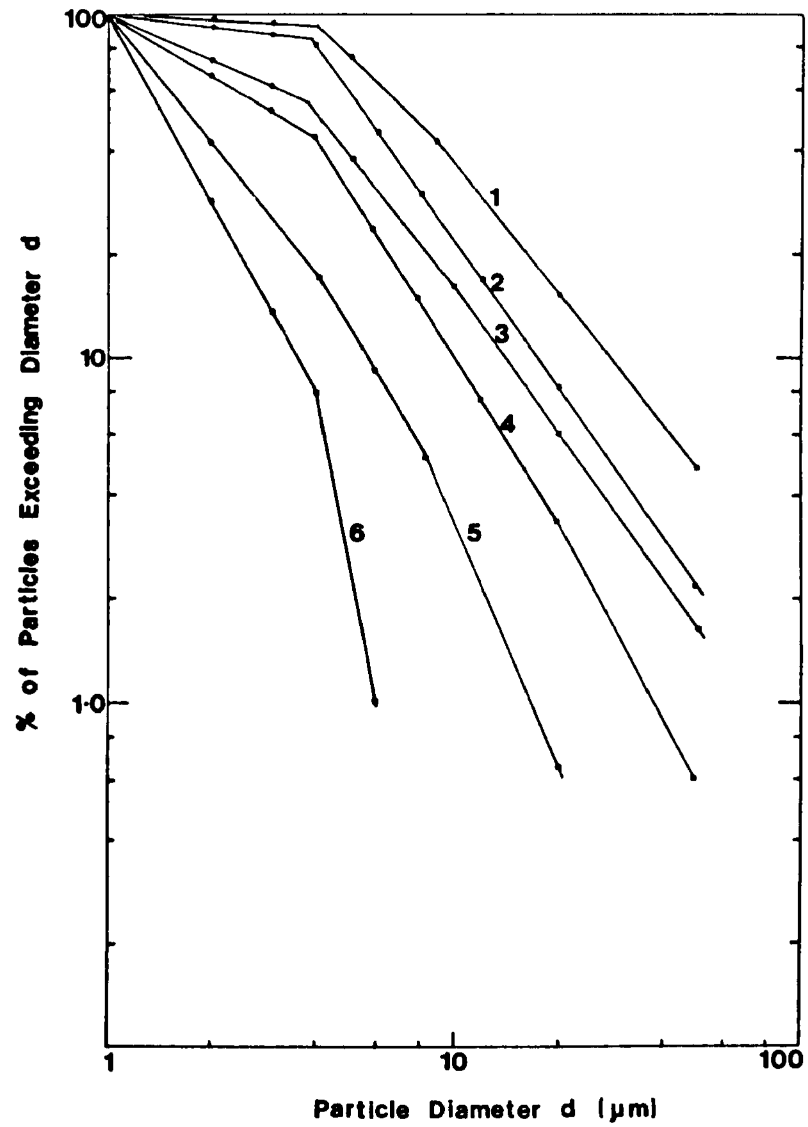


Figure 13. Particle size distribution:

1 - Dustfall at ship loading for southerly winds,
2 - Ship traffic resuspension plume,
3 - Windblown dustfall from coal pile at 0.6 - 0.7 km and dustfall from ship loading for northerly winds,
4 - Suspended solids in St. Louis River near runoff sources at Pokegema and Nemadji,
5 - St. Louis River plume in Lake Superior,
6 - Suspended solids in Lake Superior near Duluth.

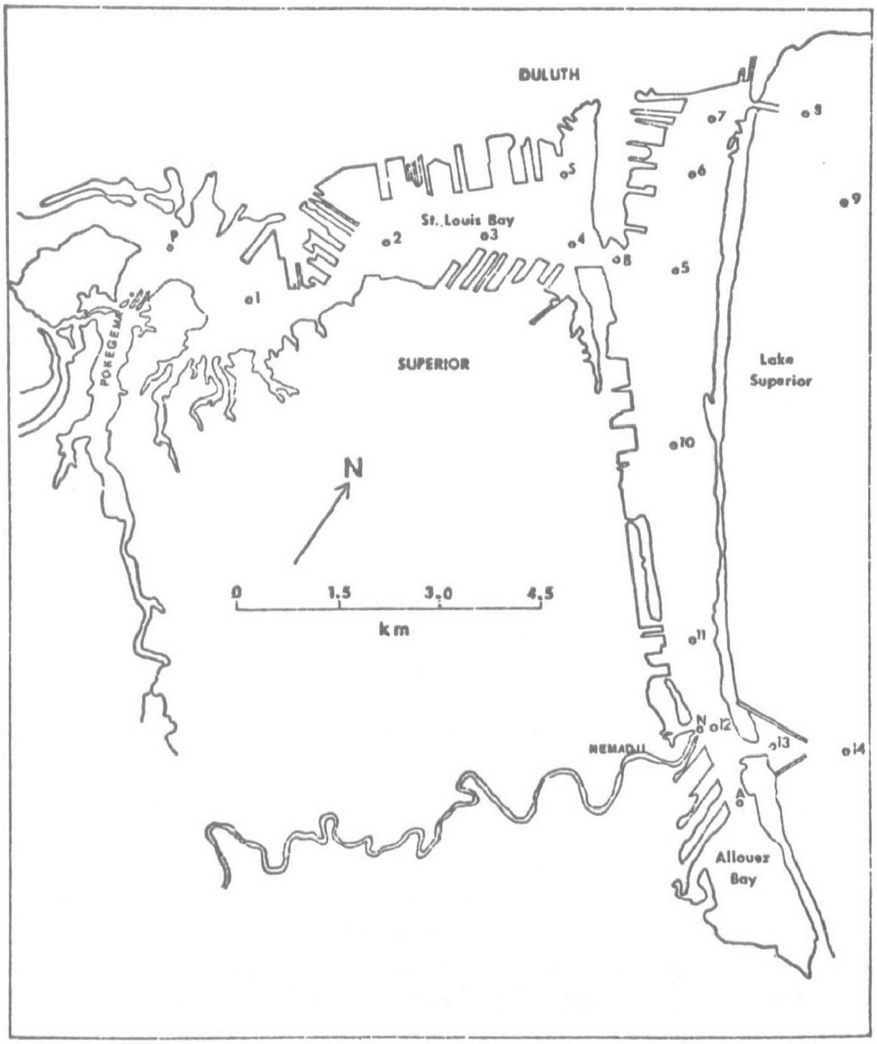


Figure 14. Sampling stations for water quality parameters. The letters indicate particulate source stations.

chemical parameters was evident, but generally the variation in chemical parameters with depth indicated well-mixed conditions (U.S. E.P.A. 1976). In the mass balance calculations, suspended solids averaged over the three depths were used as initial values in the model. The settling rate was varied in the model to give the best agreement between the calculated and measured suspended solids values. The calculated settling rate for suspended solids in the inner harbor, Figure 15, is largely due to settling of suspended load from the Pokegema River. Dispersion accounts for most of the variations in suspended solids well away from the particulate sources. Nemadji River input near the Superior entry shows about 60% load deposition in the Superior harbor basin. It should be noted that the settling rate in Figure 15 is not a settling rate in the usual sense since no stratification of suspended material is allowed, although it is taken into account by the depth averages of the sampling measurements. In the model the suspended solids are remixed every integration step, which was chosen on the basis of previous realistic simulations of conservative parameters.

To examine how realistically the results in Figure 15 approximate the actual settling processes, other settling rates based on in situ measurements were considered. Figure 16 shows the average removal rate of suspended solids along the shore zone of Lake Superior. The results are based on depth integrated values of suspended solids and turbidity measurements for several days along transects perpendicular to an erosion bank of Lake Superior. This erosion bank is essentially a uniform 40 km line source of red clay (Stortz 1976). After a storm, a zone of highly turbid water runs along the entire bank. The transports are parallel to the shore, thus much of the loss of suspended solids integrated over a cross sectional area of the shore zone comes from settling. The uniformity of the turbid bank along the shore can be checked from remote sensing data (Hess 1973, Sydor 1976). Comparison of Figure 15 and Figure 16 shows that the settling rates are similar. The settling rate for the inner harbor is slower in the first three days, that is in the large size range. This discrepancy may be somewhat accounted for by the fact that the inner harbor has an organic component as well as red clay from Pokegema. Thus, the effective density for the inner harbor material is lower for particulates exceeding the 4 μ size. Over a seven-day period, the large particles settle out, thus, the tail of the curves where they overlap closely would be determined by the small particulates which are red clay in both cases. The agreement at the tail of the curves in Figures 15 and 16 is good because concentrations of low size particulates can be accurately determined, and the well-mixed conditions are applicable. The depth and average flow speeds in the river and the lake are also comparable, however, it should be pointed out that the purpose of comparison here is only to consider the general magnitude of the settling rates for in situ conditions to determine if the calculated rate for the St. Louis River is reasonable. It is seen that the settling rate estimated from the model is realistic.

In considering the settling rate for coal particulates, note that the coal fallout has a relatively high fraction of large size particles. The coarse fraction determines the mass distribution and the settling rate. Particles exceeding 25 μ contain 50 - 85 percent of the total mass. To examine further the settling rates, Stokes velocities (McCave 1975) were

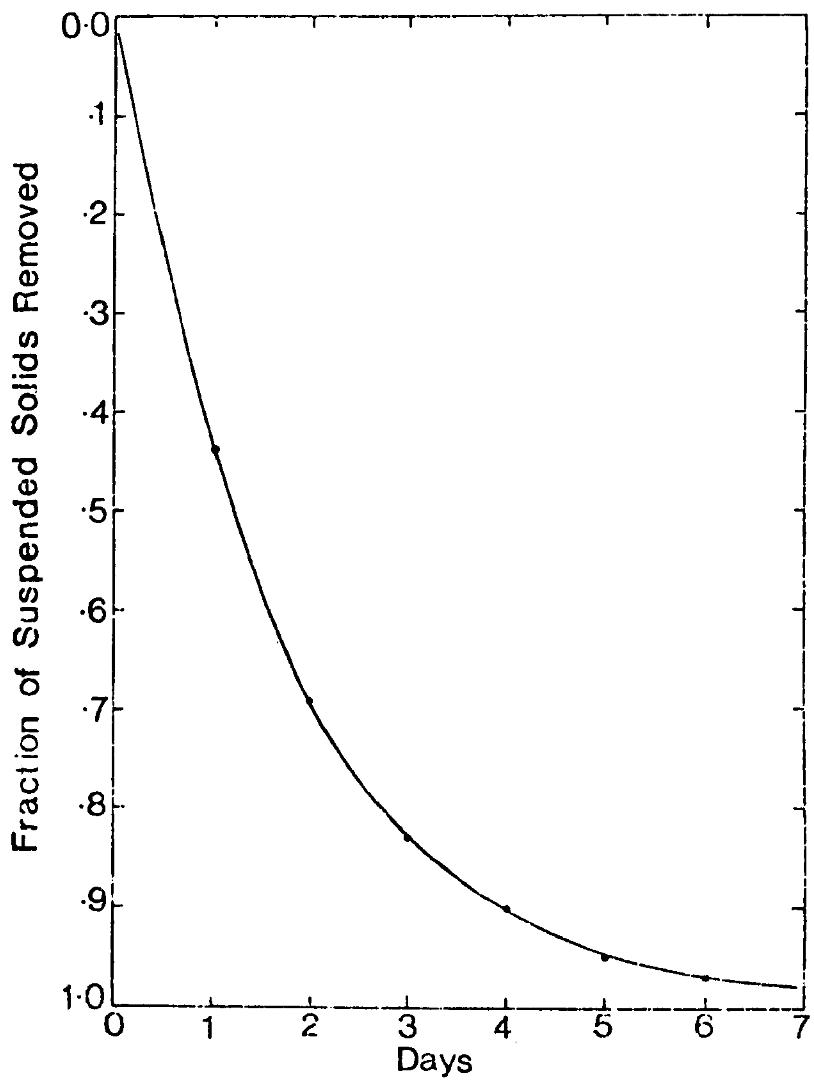


Figure 15. Calculated settling rate for St. Louis River particulate.

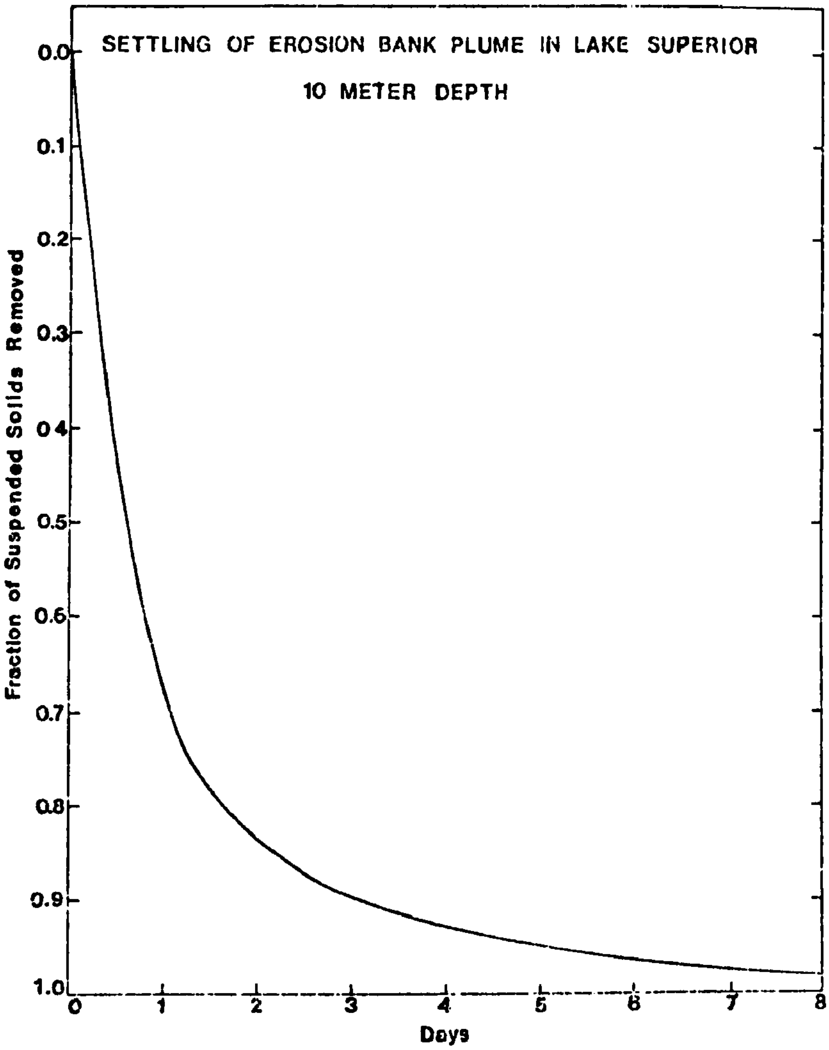


Figure 16. Measured settling rate for red clay in Lake Superior shore zone.

considered. Figure 17 shows the Stokes settling rate for the Duluth harbor particulates. The rate was obtained by assigning an average density of 1.4 (McCave 1975) to the particles in the St. Louis River, where 30% of suspended load is organic. The resulting settling rate is a factor of two slower than the rate previously determined from mass balance in the harbor. The discrepancy arises from a variety of factors including turbulence, clumping, and particle shapes. For coarser particles typical of coal fallout and the resuspended material, the Stokes settling rate would well approximate actual settling. Thus, Figures 18 and 19 are taken respectively as the settling rates for coal particulates and resuspended material in the harbor.

Before proceeding to model particulate dispersal using the above settling rates, it is of interest to consider for a moment the fine component of particulate contaminants. Coal particles smaller than 5 μ appear to constitute the important fraction of the suspended material so far as toxic effects on fish are concerned (Carlson, Caple 1978). The settling rates for the fine material can either be neglected and treated as conservative matter for which Stokes law cannot be applied (Brun-Cottan, 1976), or the settling rate of fine particulates can be measured in the laboratory to provide a lower limit on the actual settling rates. The rate measured in the laboratory for samples of St. Louis River plume consisting largely of the fine particulate (see Figure 13) is shown in Figure 20. It is seen that the settling rate for particles less than 4 μ is low. Thus coal particulates in this size range would be transported to Lake Superior much like dissolved material since this fraction constitutes less than one percent of the total coal particulate fallout in the harbor, one would expect a model to yield a comparable figure for the amount of coal transport from the harbor to the lake.

Simulation of particle dispersal in the harbor waterway was obtained by applying the settling rates given in Figure 18 to the water quality model. Concentration of all discharges into the harbor and the particulate concentration in the lake was set at zero. Initially all junction concentrations were also set at zero. The model was then run for two days, during which time the atmospheric deposition rate for each junction was based on Figure 8. The input for each junction was distributed uniformly over the junction area, and was put in at a constant rate during these first two days. The total input into the harbor was 574 kg. No settling of particulates was allowed during the two input days since the northeasterly winds caused a high seiche and produced enough turbulence to prevent settling. The high seiche usually damps out after one or two days. After the two days, the atmospheric input, Figure 21, was stopped and the model was run with settling allowed in all channels where flow speeds were less than 15 cm/sec (Sundborg 1956). The model was run typically for three weeks. AT the end of that time most of the particulate either settled to the bottom or was transported to Lake Superior where it was completely removed at either the Duluth or the Superior entry. The resulting distribution of coal sediment, due to fallout of dust over the harbor for the northeasterly wind, is shown in Figure 22. If after the first two days of input, settling was allowed in all channels at all times, a sediment distribution shown in Figure 23 was calculated. It can be seen from Figures 22 and 23 that for high seiche conditions an accumulation of sediment occurs in the Cross Channel in excess

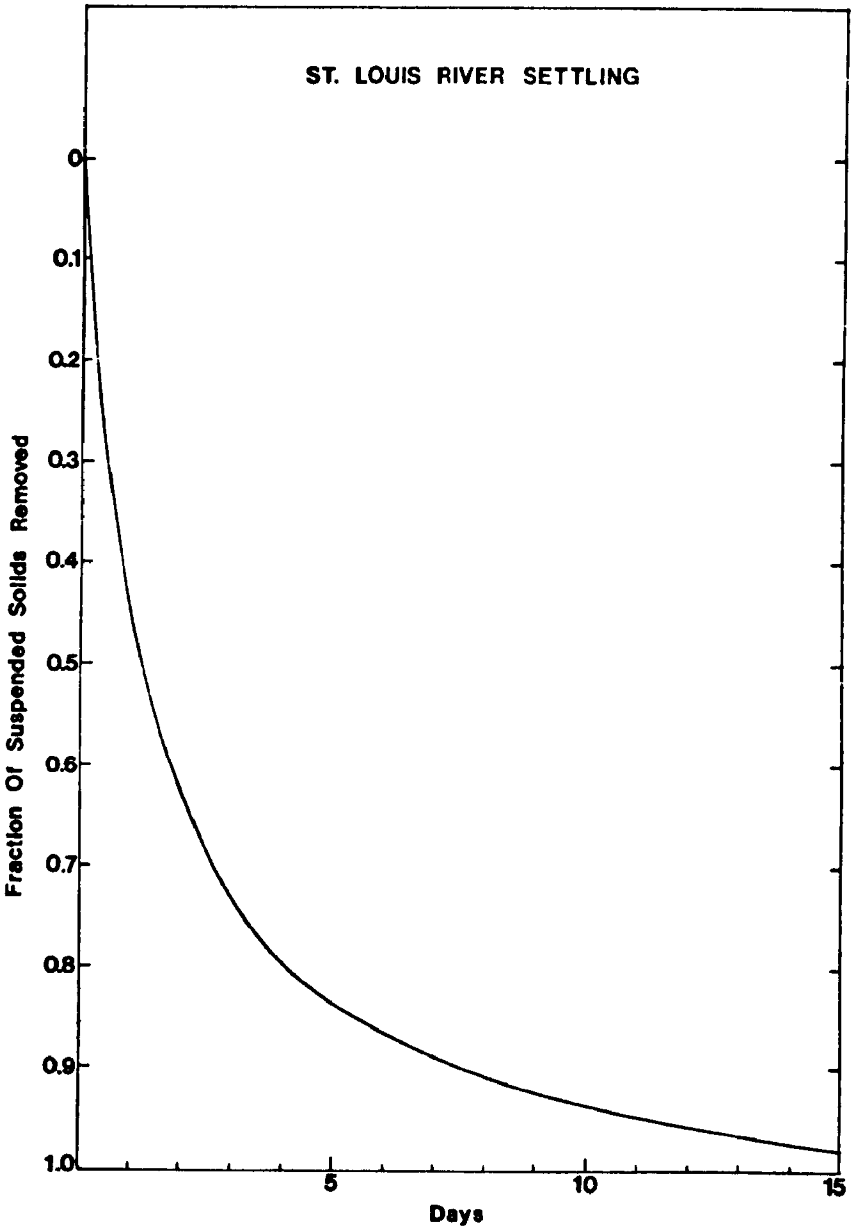


Figure 17. Stokes settling for St. Louis River particulate.

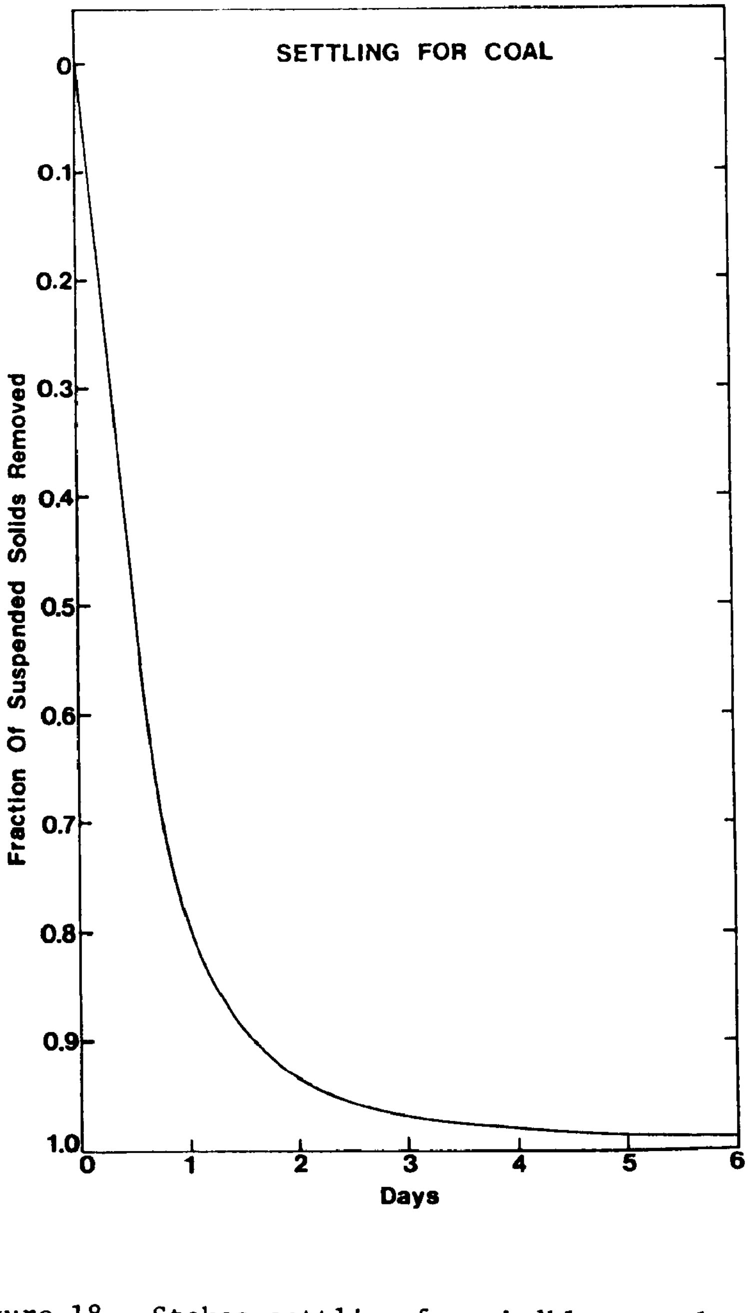


Figure 18. Stokes settling for windblown coal dust from the pile and at ship loading for northerly winds.

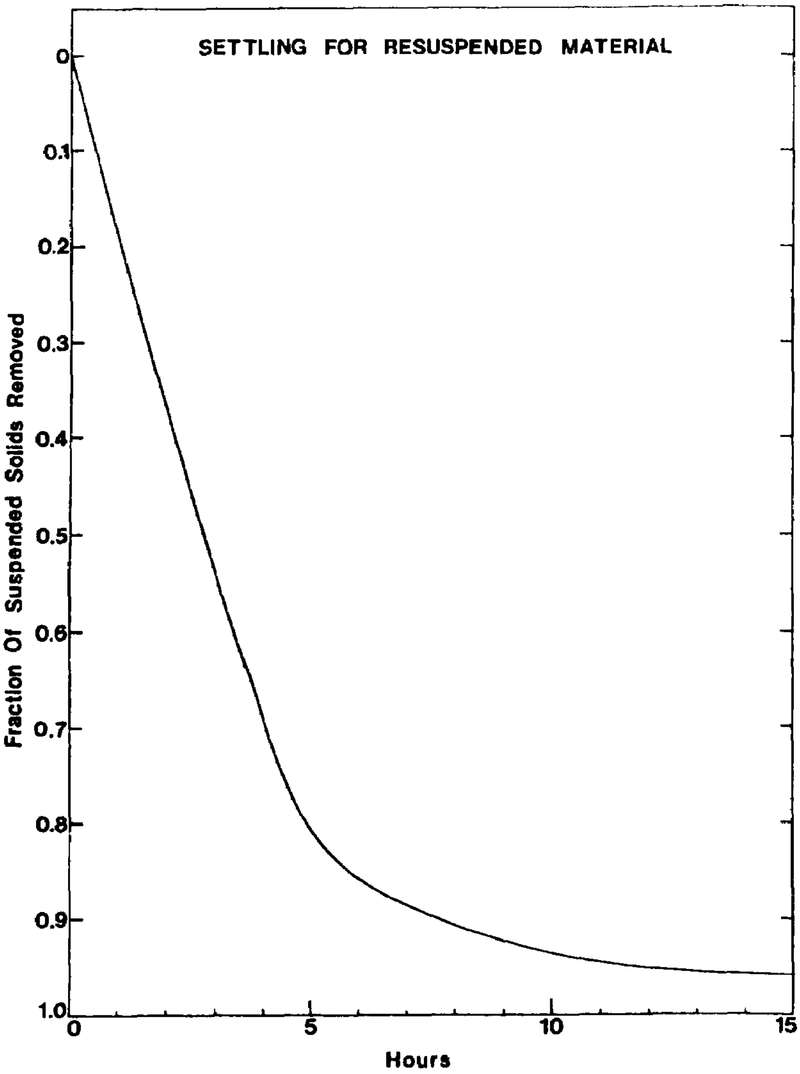


Figure 19. Estimated Stokes settling for resuspended material.

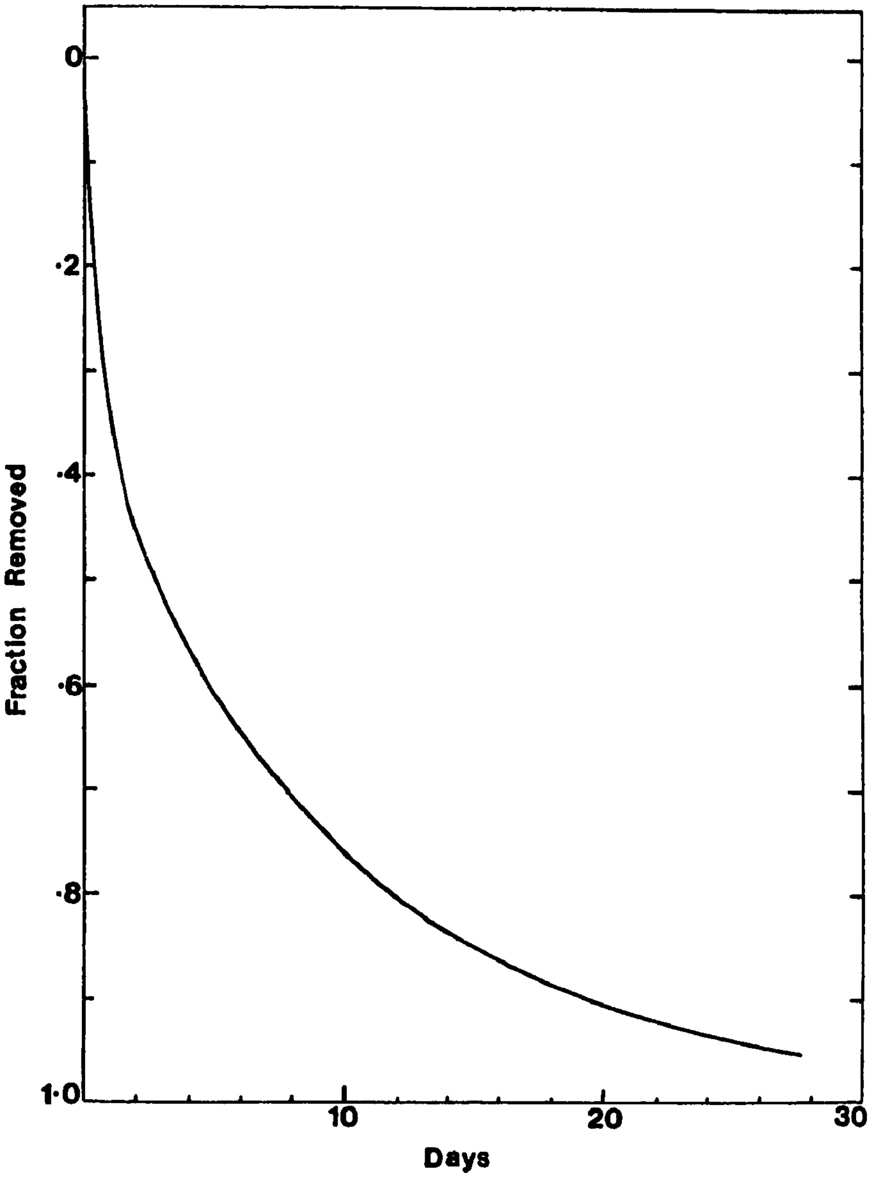


Figure 20. Settling in column of St. Louis River plume particulates.

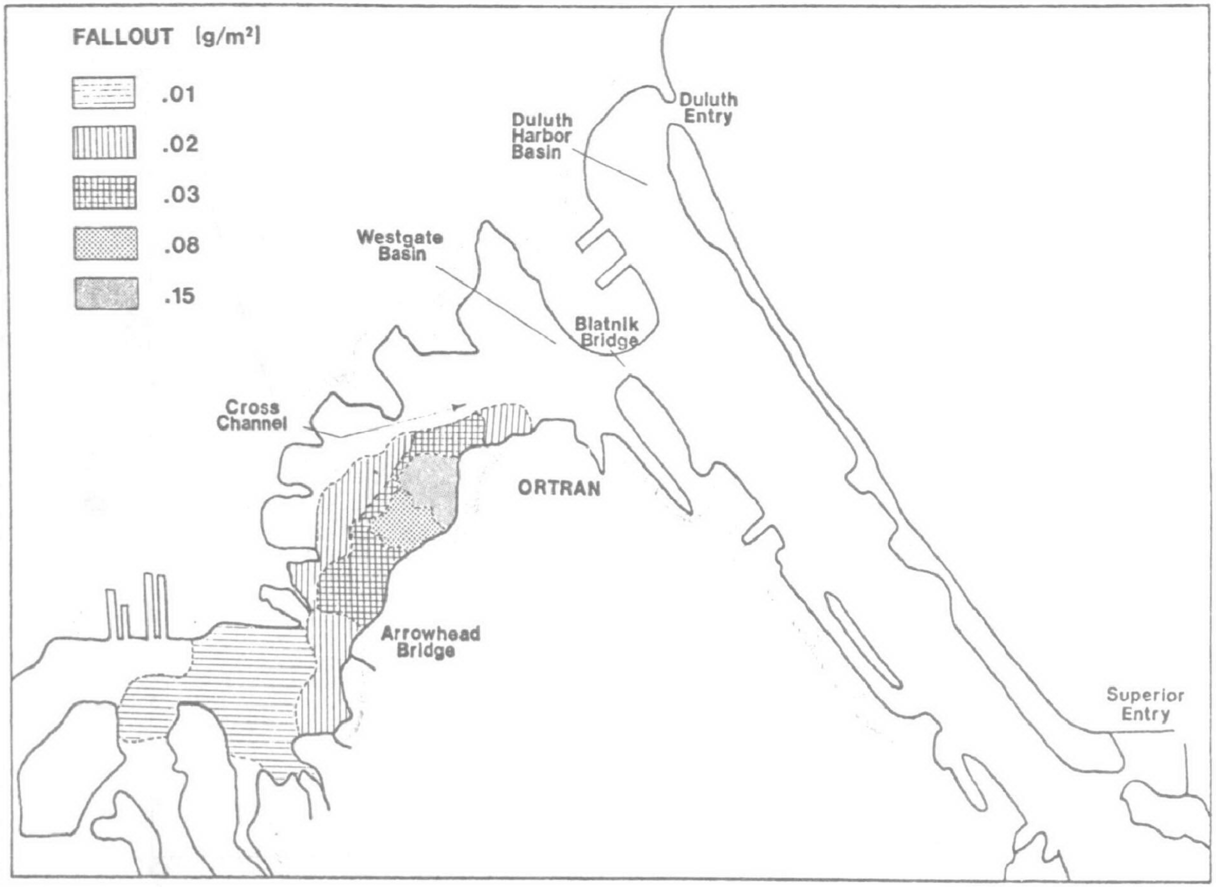


Figure 21. Fallout from the coal pile after 2 days of 6.8 m/s northeasterly winds.

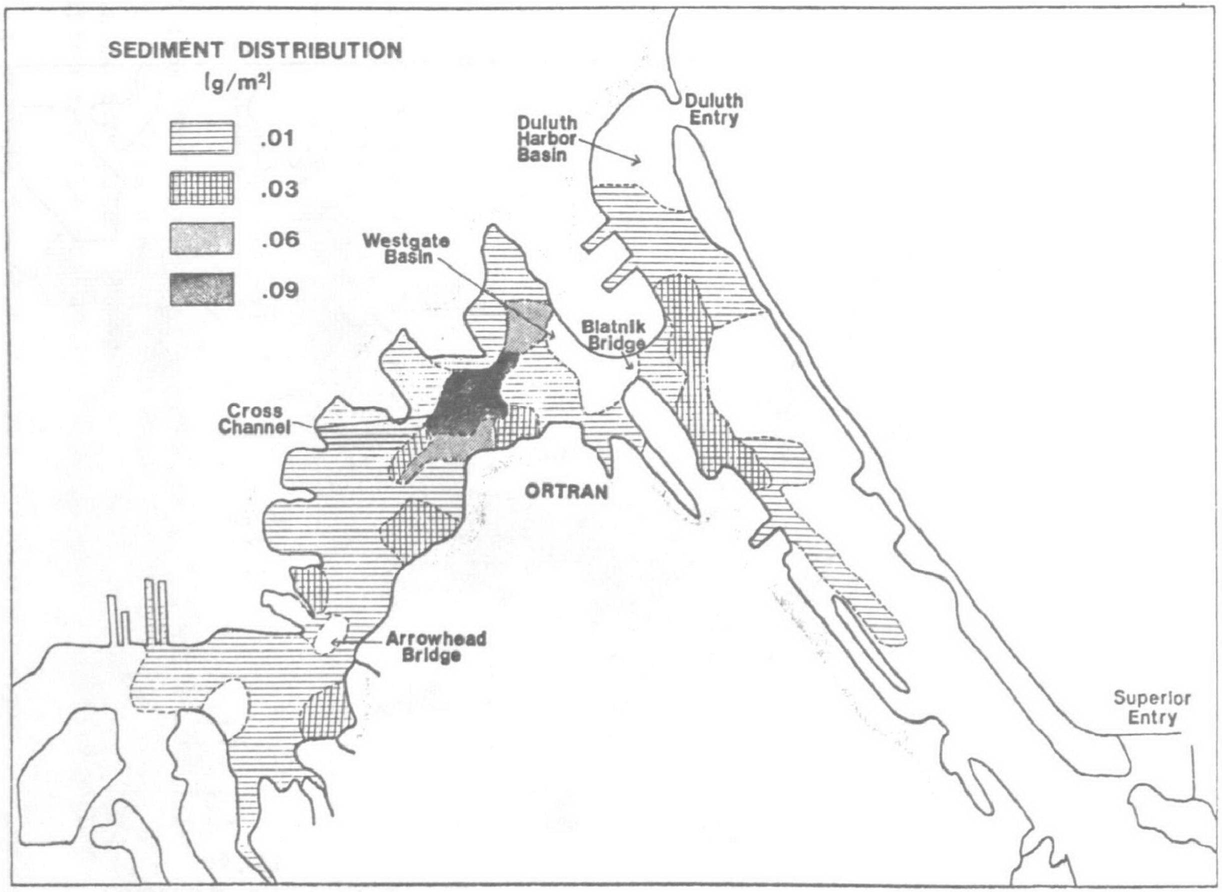


Figure 22. Sediment distribution from 2 day fallout during northeasterly winds. The distribution was calculated for transports due to 15 cm seiche and no settling in high flow zones.

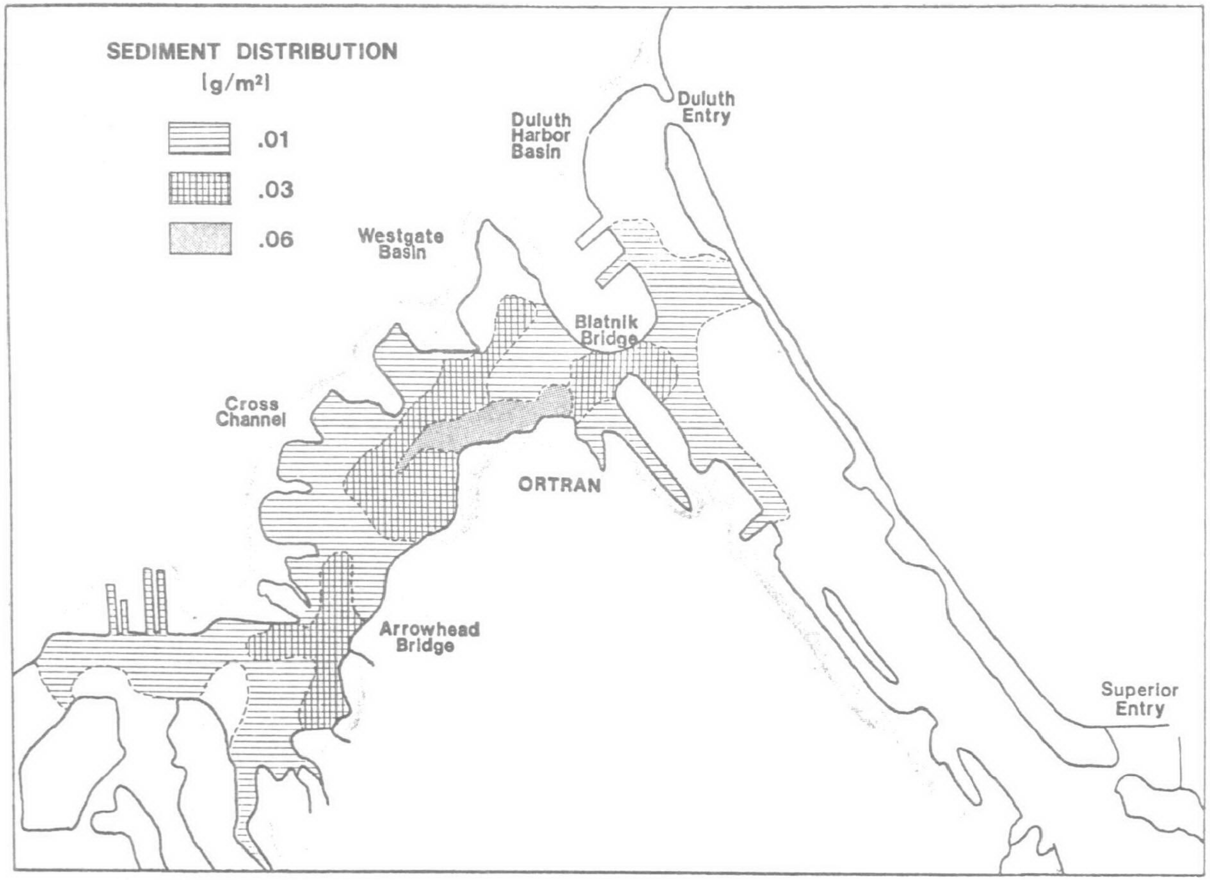


Figure 23. Sediment distribution from 2 day fallout during northeasterly winds. The distribution was calculated for 15 cm seiche and settling in all channels.

of 0.1 g/m^2. The high seiche tends to deposit material in low flow and shallow areas, giving the sediment distribution a patchy appearance. A similar patchy appearance is often observed in remote sensing data for suspended solids during the spring runoff, when red clay from the Pokegema River appears distinct in the St. Louis River (Sydor 1978). Deposition of coal in main channels is prevalent for low seiche conditions as shown in Figure 24. The main channels are subsequently scoured by ship traffic. The amount of material transported to the lake under various boundary conditions is shown in Table 7. The maximum output to the lake is 2.6% of the total

TABLE 7. KG OF COAL PARTICULATES DEPOSITED IN LAKE SUPERIOR FROM A 574 KG FALLOUT OVER THE HARBOR

	Duluth Entry	Superior Entry
3.0 cm seiche, settling everywhere	2.2	0.02
3.0 cm seiche, settling in low flow channels	3.2	0.12
15.0 cm seiche, settling everywhere	12.4	0.024
15.0 cm seiche, settling in low flow channels	15.2	6.88

load. A typical output to the lake is 0.5% of the total input, indicating that particles less than 6 μ in size constitute the bulk of the material taken out to the lake. This fact is also reflected in the particle size distribution for the St. Louis River plumes in Lake Superior, Figure 13.

It is evident from the results of this and the preceeding section that the windblown source constributes a large input of particulate into the harbor and affects areas of the harbor well upstream from the coal dock. For instance, the area around the Arrowhead Bridge, a recreational fishing spot, is directly subject to coal dust fallout. On the other hand, the output of the coal dust from the harbor to Lake Superior is quite low as seen from Table 7. This suggests that the harbor is a long term sink of coal fallout. Extension of the results in Table 7 by using the yearly estimate of fallout of coal in the harbor as the total input of particulate in the model

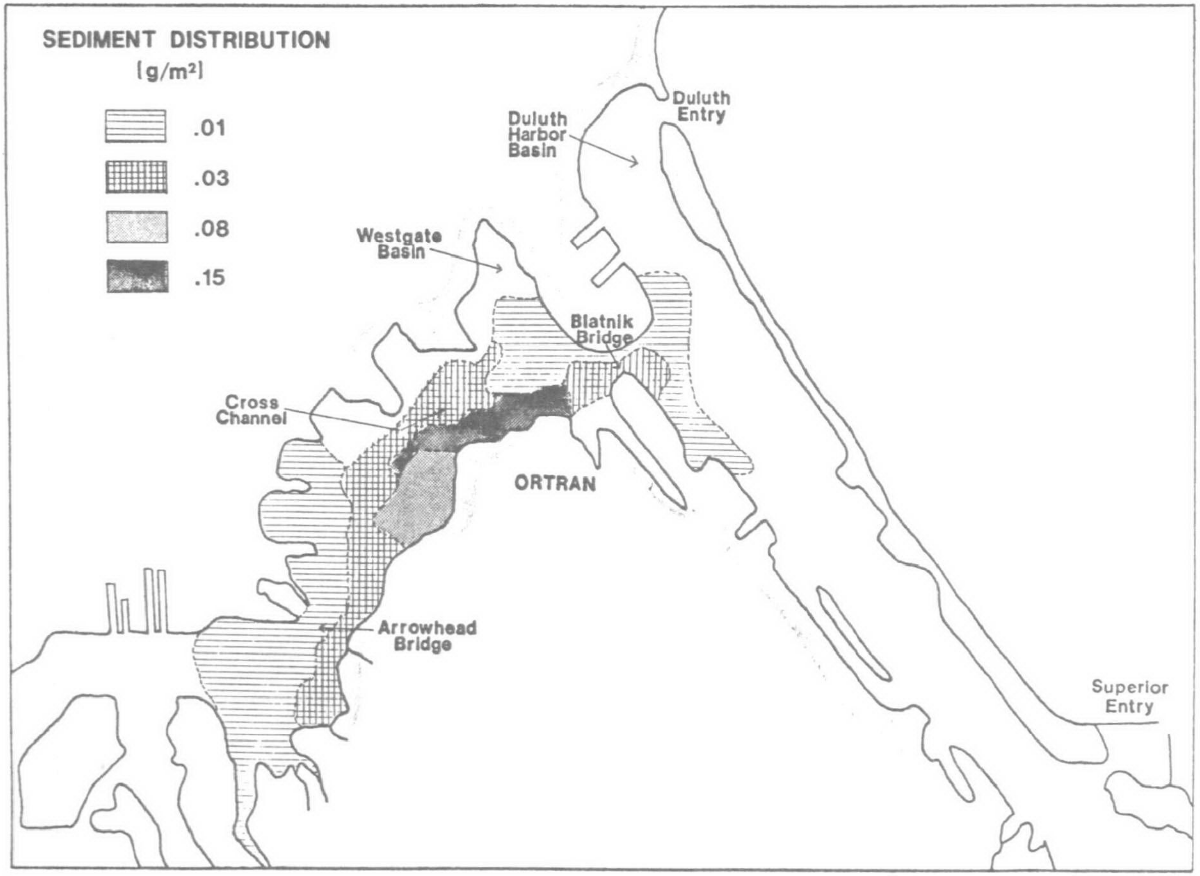


Figure 24. Sediment distribution from 2 days of fallout for northeasterly winds. Distribution calculated for transports due to 3 cm seiche.

indicates that 50 - 250 kg of coal are transported to the lake annually. This contribution of coal dust to the lake comes largely from the fraction of fine particulate within the 12,500 kg annual input of coal dust into the harbor during the open water season. The transport of these particles to the lake provides input a factor of 10 lower than the direct annual coal dust fallout over the lake of 1.5 metric tons.

SECTION 9

PARTICULATE INPUT DURING SHIP LOADING

Each year about 100 cargoes of coal, averaging 45,000 metric tons each, are loaded by ORTRAN into ships which dock in the channel along the north end of the facility. During the loading process some coal is released into the air from the loading chute and the associated conveyor, which together constitute a point source of windblown material close to the water.

A series of measurements were made to determine the average coal input into the harbor from ship loading. The measurements were made from a boat which moved along the dock and the ship during the loading operation. Samples were taken two hours before ship loading, during the ship loading, and one hour after ship loading. Dustfall samples were collected on slides, water-filled cuvettes, and water-filled buckets. The samples were analyzed for particle size distribution and fallout rate. Concentrations of particles in the air were also measured using a portable air sampler. From the average size distribution for the particulates around the coal carrier at loading shown in Figure 13, it is seen that the particles are coarse. The average fallout into the harbor is estimated at 120 kg per loading. This estimate was based on a Gaussian plume for a point source with input scaled to correspond to the measured fallout rates. The input varied from 20 kg - 260 kg and was highly dependent on particle size distribution and wind direction. During a loading under southwest winds, a slick of coal 2 - 3 meters wide and 150 meters long was observed around the ship. The concentration of particles in the slick after 2 hours of loading was estimated at 2 mg/cm^2. After the loading stopped, the slick dispersed within 10 minutes, and concentration of suspended solids near the ship dropped to within 0.5 mg/ℓ of the background.

To simulate the dispersion of particulates during the loading of a ship, 20 kg of fine material (with particle size distribution comparable to the windblown material from the coal pile) was distributed over the channel adjacent to the coal dock. The input was spread uniformly in time over 8 hours, a time comparable to the duration of ship loading. The settling rates were taken according to Figure 18.

Figures 25 and 26 show the sediment distribution in the harbor resulting from application of the water quality model to a single ship loading and then extending these results to 100 ship loadings. It is seen that high seiche and no settling conditions in the turbulent channels (Figure 25) produce dispersal of the particulates to the adjacent channels and the entire West Gate Basin area. The amount of material reaching Lake Superior from ship

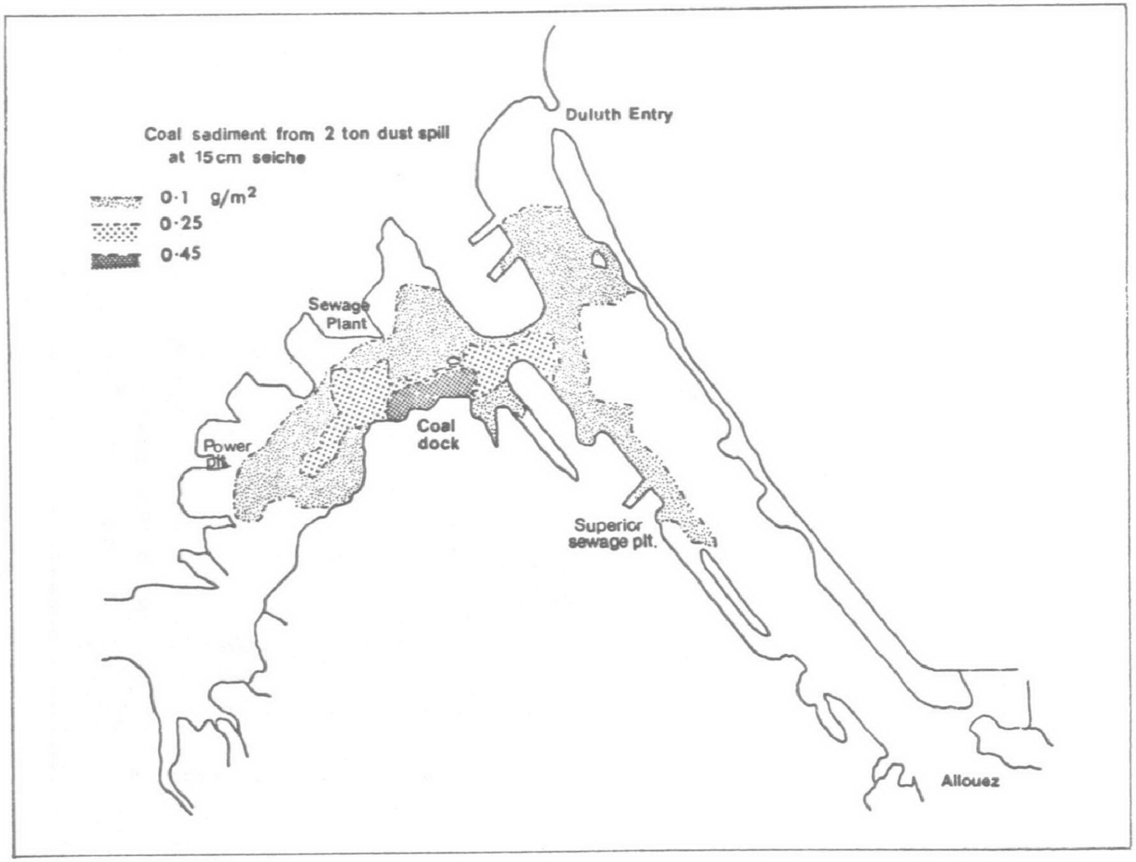


Figure 25. Sediment distribution resulting from yearly input of windblown fines during ship loading - based on 15 cm seiche transports.

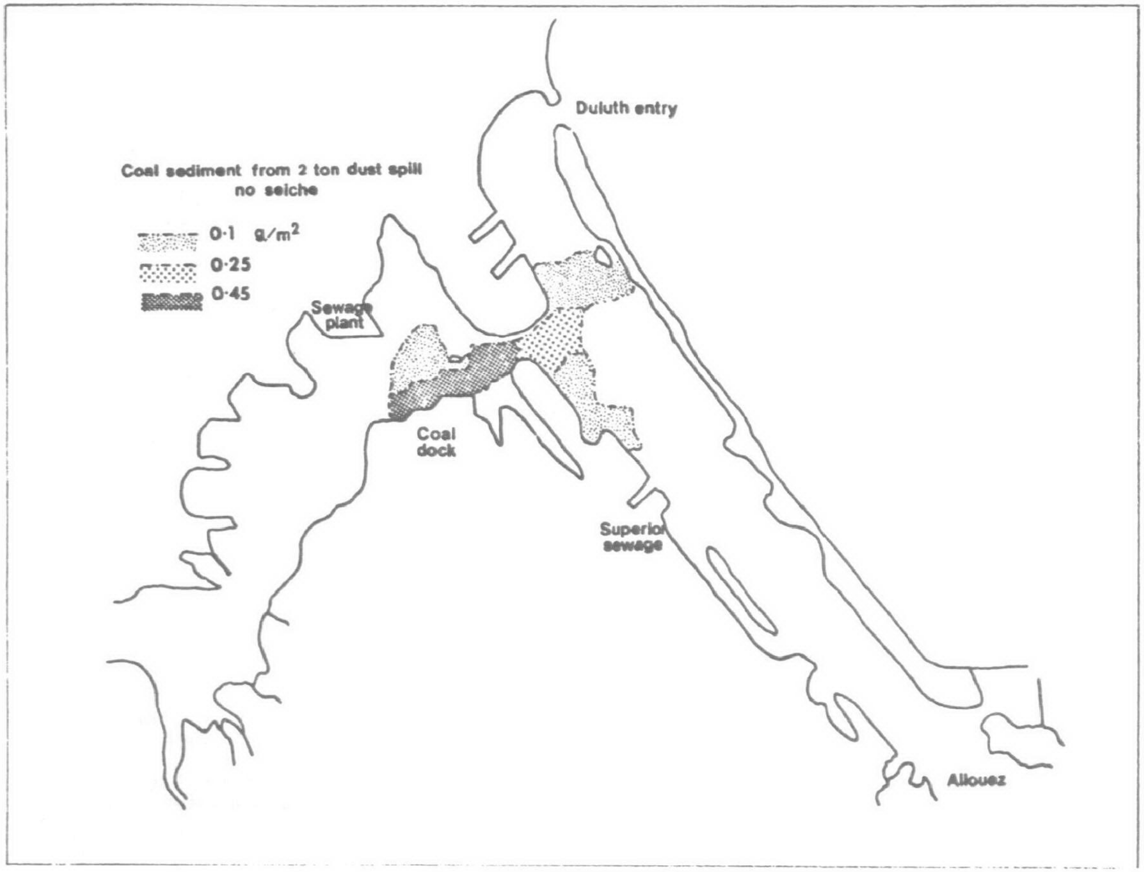


Figure 26. Sediment distribution resulting from yearly input of windblown fines during ship loading - based on 3 cm seiche transports.

loading operation ranges from 0.04% of the spilled load for a low seiche to 0.26% of the load for a high seiche. A summary of the results for the transport of this material is shown in Table 8.

TABLE 8. TRANSPORT OF PARTICULATES FROM THE COAL DOCK TO LAKE SUPERIOR

Percent of Particulates Entering Lake Superior		
Seiche Amplitude (cm)	Settling in all Channels	Settling in Low Flow (15 cm/sec or less)
0.0	0.00	0.00
3.0	0.01	0.02
6.0	0.04	0.07
15.0	0.13	0.26

The concentrations of coal particles in the harbor waterway and in the lake attributable to ship loading are low in comparison to the windblown material. However, the source from carrier loading is important locally since it could produce high particulate concentrations in the loading channel over short periods of time. The input of coarse material from accidental spill and runoff over the deck could also produce high contaminant concentration in the loading channel. However, such sources cannot be evaluated here. In the short run, an accidental spill would be localized to the dock area. Eventually, however, the material would be transported to the other channels by resuspension from ship traffic.

SECTION 10

RESUSPENSION DUE TO SHIP TRAFFIC

In order to examine the long term transport of sediment in the harbor, especially of the coarser material, measurement of resuspension due to ship traffic was considered and estimates of the transport of the resuspended material to Lake Superior were made.

Measurements of resuspension due to ship traffic were made by sampling of the water column for suspended solids and turbidity at 50 cm and 4 m depths and 50 cm from the bottom. Sampling was performed in conjunction with water level and current measurements. The samples were taken just before ship passage, one minute after the ship passage, every two minutes thereafter for 30 minutes, and every 15 minutes for the next 2.5 hours. Turbidity above background was averaged over the cross sectional area of the channel. The resulting settling rate determined from decrease of the suspended solids and average turbidity in the channel is shown in Figure 27. Extension of this curve beyond 3 hours was based on an exponential fit. The result in Figure 27 is comparable to the settling velocity given by Ariathurai et al. (1977) for shoal material, and by Koh and Chang (1973) for dredged material from the Great Lakes. Interpretation of the sampling results for measurement of resuspension required measurement of water levels and knowledge of the direction of water movement. Rapid sampling over the shipping channel was essential.

It was difficult to estimate particle size distributions of the resuspended material because samples contained background material which could not be separated from the actual resuspended material. The necessity for dilution of samples for particle size analysis also presented problems because coarser material settles quickly, making it difficult to estimate accurately the percent of the total mass in the few large particles. Figure 13 shows the estimated size distribution of resuspended solids in the St. Louis River. The corresponding settling rate calculated using Stokes Law is shown in Figure 19. Both Figures 27 and 19 indicate settling of the material within hours of resuspension. This result is largely due to the coarseness of the particulates. The two settling curves provide a range of settling rates for the resuspended material. The in situ measurements are likely to overestimate the actual settling rate because it was difficult to detect remnants of the well-dispersed resuspension plume obscured by fluctuations in background suspended load. The Stokes settling rate based on particle size distribution is likely to be an underestimate of the actual settling rate because the coarser fraction was probably missed in particle size analysis, even though precautions were taken to minimize the problem.

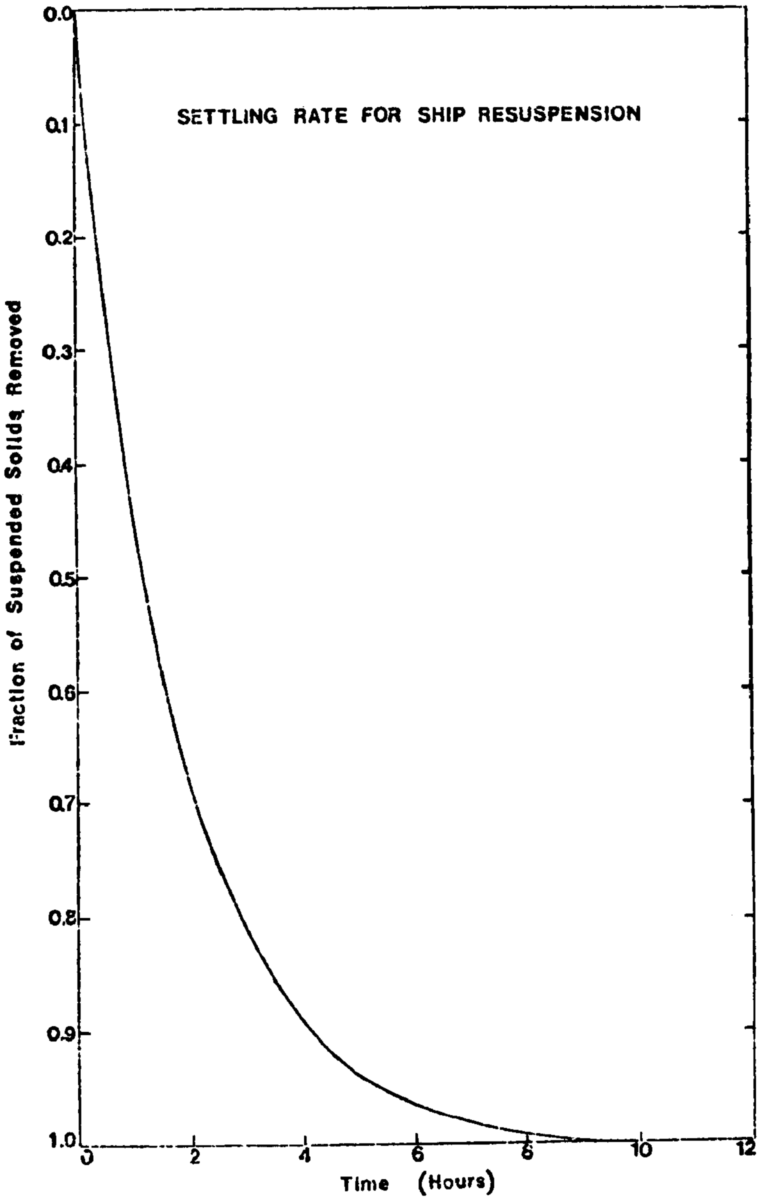


Figure 27. Settling rate for resuspended material. The curve was extended beyond 3 hours by applying an exponential fit to the data.

The water quality model was used to study the transport of the resuspended material. From sampling it was determined that a ship resuspends sufficient material to produce an average concentration of 10 - 15 mg/ℓ of resuspended particulates in the numerical grid channels corresponding to the track traversed by the ship. Since the time required for a ship to travel through the harbor to the coal dock is short compared to the oscillation periods for the harbor, in modeling of the transport of the resuspended material the initial suspended solids concentrations were set at 10 mg/ℓ in all junctions that the ship would traverse. The concentration in all other junctions was set at 0. The concentration of all inflow was also set at 0, and the settling rate was taken according to Figure 27. Since the settling rate was determined on the basis of actual concentration of suspended solids in the harbor, the above boundary condition is realistic. Two dispersion cases were tested, one where the ship entered the harbor through the Duluth entry, and the second case where the ship entered the harbor through the Superior entry. Generally, most ships enter through the Duluth entry, however, since the Superior entry is used occasionally, both cases were run. Each case was simulated for two seiche levels, a low seiche of 3.0 cm amplitude, and a high seiche 15.0 cm in amplitude. The distribution of resuspended material after ship passage is shown in Figure 28. The resulting sediment distribution is shown in Figure 29. The material remains largely in the original channels where it was resuspended and usually accumulates at the edges of the channels where it is less likely to be resuspended again. The smaller particulates are transported outside of the resuspension channels and accumulate in the low flow and low traffic areas.

How realistic is the simulation of resuspension? The analysis of the harbor sediments and the associated input of contaminants into the water column due to resuspension by ship traffic has been dealt with by Van Tassell and Moore (1976), U.S. E.P.A. (1976), and Winslow et al. of M.P.C.A. (1976). The M.P.C.A. report addresses itself to the actual resuspension of sediments by ship traffic. Remote sensing data shows the presence of resuspension in the Duluth Harbor Basin where the M.P.C.A. tests were made. The U.S. E.P.A. found polluted sediments in parts of the harbor. In the U.S. E.P.A. investigation the polluted sediments were found to be associated with fine particulates and were found at the edges of Duluth and Superior harbor basins where dredged channels broaden, the flows are low, and traffic is infrequent. The contaminated sediment accumulation areas correspond well to the results shown in Figure 29 where the new sediment areas correspond to the area of polluted sediment identified by the U.S. E.P.A.

An estimated 10^5 kg of material is resuspended by passage of a vessel. 100 kg of the resuspended material (Table 9) flows into the lake, the remainder settles out to be resuspended again. The fine resuspended material entering the lake disperses throughout the lake. The coarser fraction, exceeding 20 μ, will be transported by the lakeshore currents to the public beaches along Minnesota Point (Keillor 1976). Total output to the lake by ship traffic resuspension amounts roughly to 100 metric tons of sediment per year. This estimate was based on a traffic of 1000 large ships visiting the harbor per year; about 10% of this traffic is due to coal carriers visiting the transshipment facility. Presently less than 0.01% of this material is coal particulate. The fraction of coal particulate will increase over the

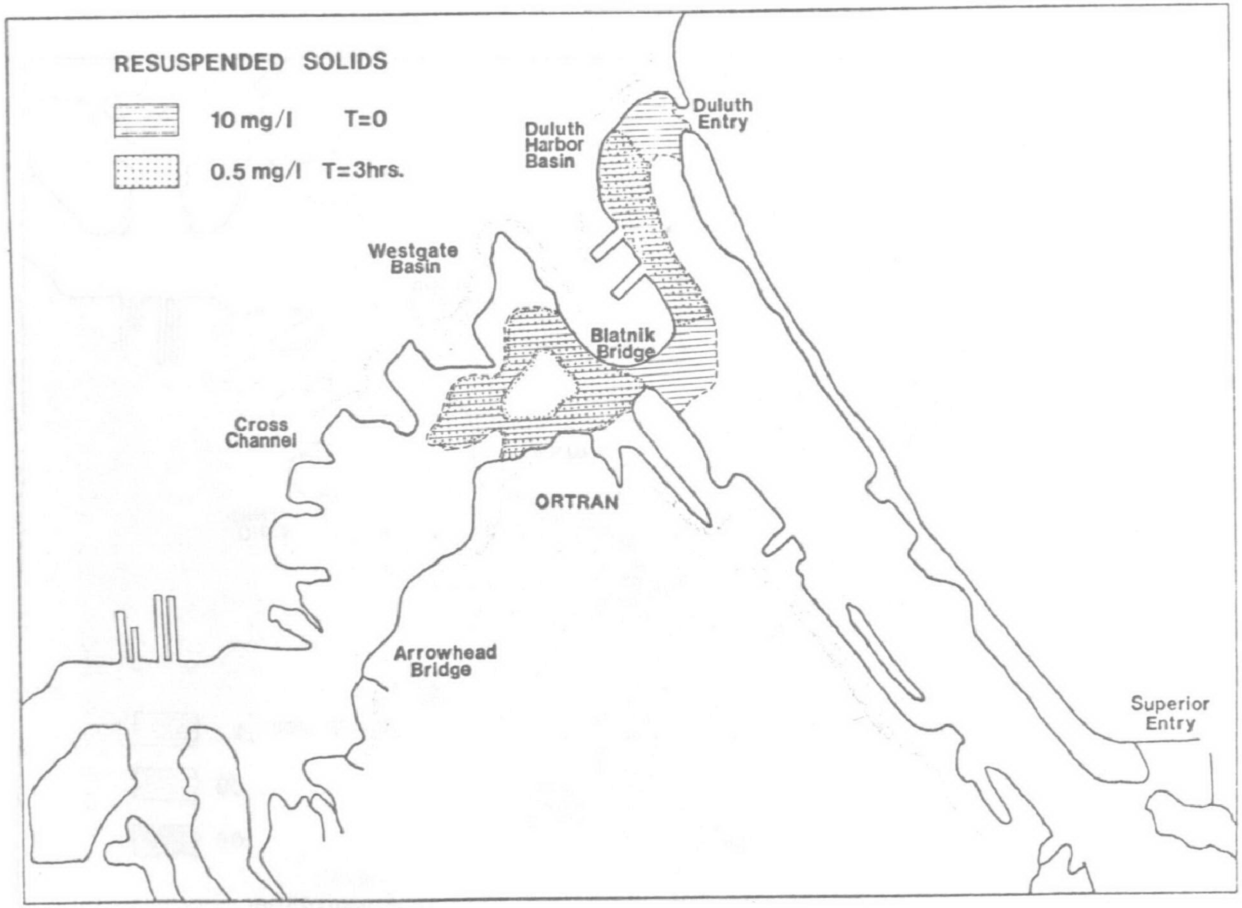


Figure 28. Suspended solids track for coal carrier entering the harbor through Duluth entry. T is time after ship's passage.

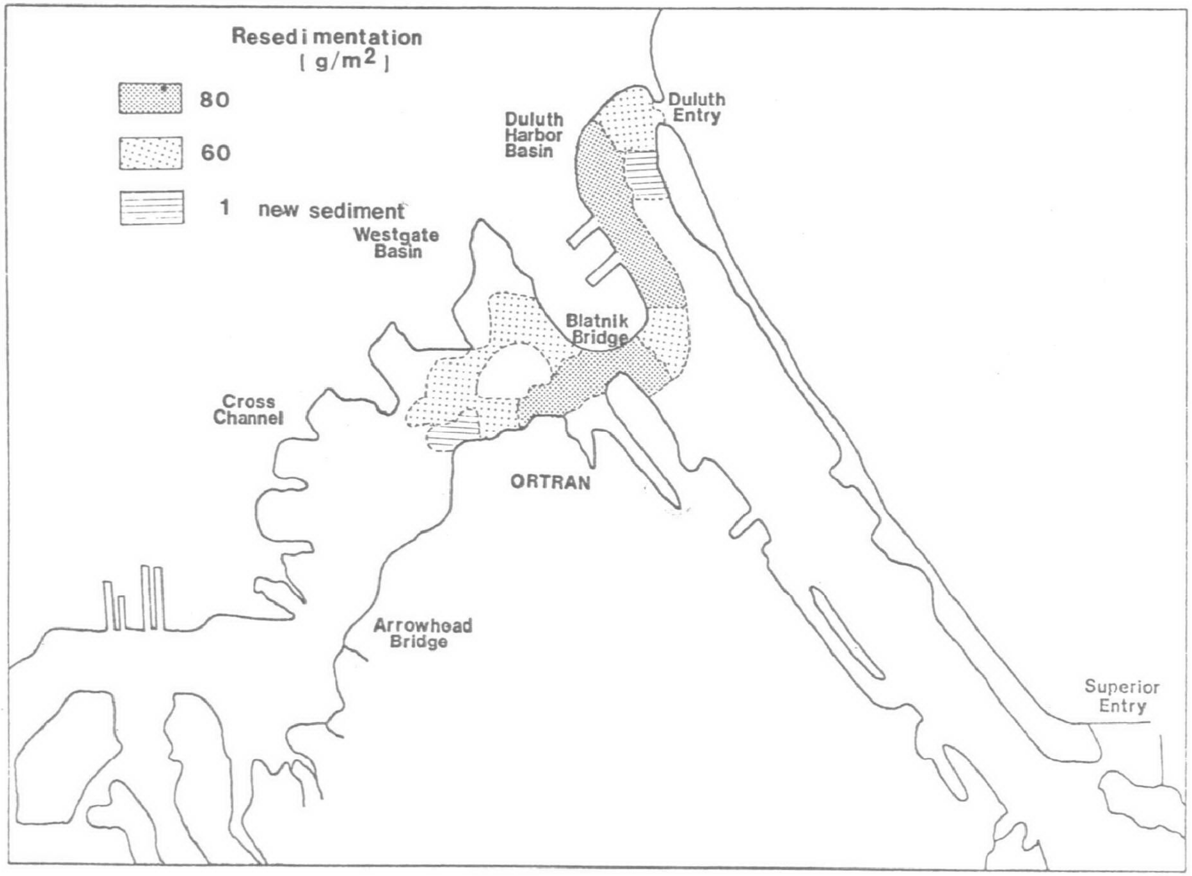


Figure 29. Redistribution of sediment after resuspension from a ship's passage.

years by about 2% (based on the annual input) until an equilibrium ratio between the coal particles and other sediment in the harbor is reached.

TABLE 9. PERCENT OF TOTAL LOAD RESUSPENDED DUE TO SHIP TRAFFIC WHICH IS CARRIED TO LAKE SUPERIOR

	Output at Duluth Entry	Output at Superior Entry
Ship enters Duluth entry 3.0 cm seiche	0.11	0.00
Ship enters Duluth entry 15.0 cm seiche	0.18	0.00
Ship enters Superior entry 3.0 cm seiche	0.00	0.0003
Ship enters Superior entry 15.0 cm seiche	0.00	0.0025

SECTION 11

POLLUTANT RESIDENCE TIME IN THE HARBOR

Examination of the dispersal of particulates indicated that extensive areas of the harbor are affected upstream from a contaminant input source. The contaminants appear to reside in the harbor for a prolonged time. To determine the residence or flushing time of a pollutant in the harbor, a simulation was made for the dispersion of 200 kg of conservative material put in at a uniform rate along the coal dock over an 8-hour period. The concentrations of this hypothetical substance with time was determined through use of the water quality model. The results for two seiche amplitudes are shown in Figures 30 and 31.

It is seen that the peak concentration of contaminant arrives at the Duluth entry in 5 to 8 days and at the Superior entry in 9 to 17 days. The peak concentration at the entries is 0.05% of the initial concentration in the input channel. The concentration peak is spread out in time over two to three weeks depending on the seiche amplitude. Flushing of the contaminant into the lake is shown in Figure 32. It was assumed that once the contaminant reached the lake it was quickly swept away from the entry by currents. This is a reasonable boundary condition in light of the investigation of pollutant transports in the lake by Oman and Sydor (1978). From Figure 32 it is seen that the residence time of a conservative contaminant in the harbor is 30 - 40 days.

It is of interest to estimate roughly the fate of fine particulate entering the lake from the harbor. The fine particulates may affect fish life or the water quality at the municipal water intakes. If the laboratory measurements of settling rates shown in Figure 20 are considered, roughly 30 percent of the fine material injected into the inner harbor would enter the lake. Based on results of transport models for Lake Superior it is estimated that the particles could subsequently end up at the Duluth and the Cloquet water intakes, where their concentration would range from 10^{-9} to 10^{-10} of the average concentration at the input channel (Oman and Sydor 1978).

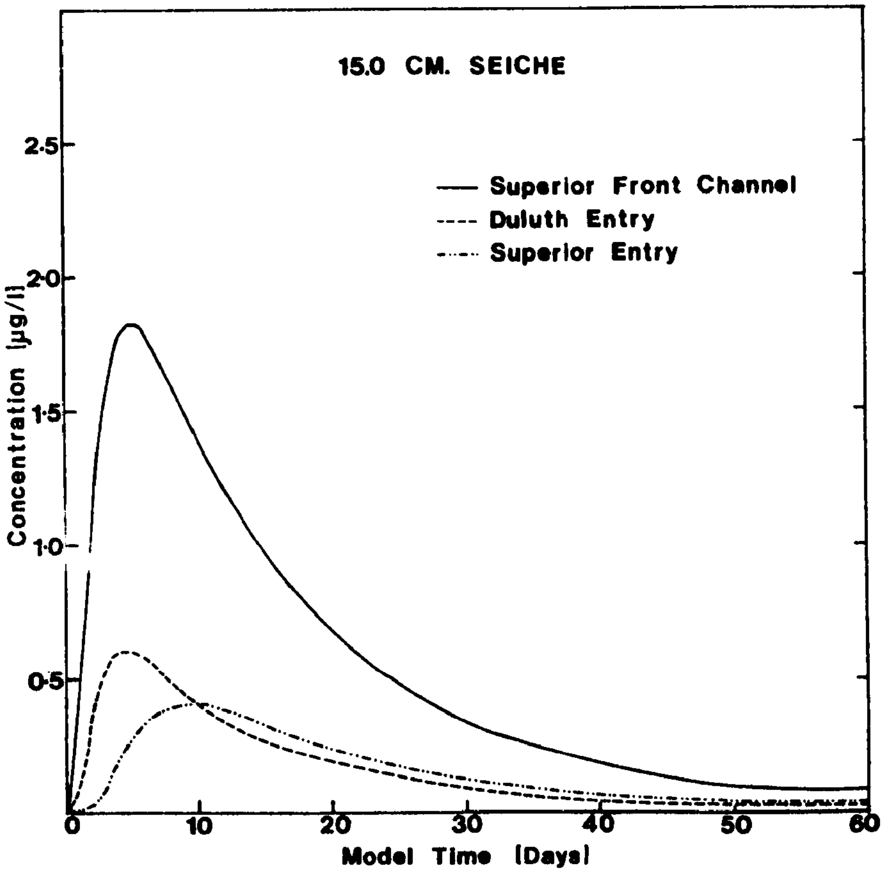


Figure 30. Contaminant concentration at lake entries for a 200 kg conservative input at coal dock (15 cm seiche conditions).

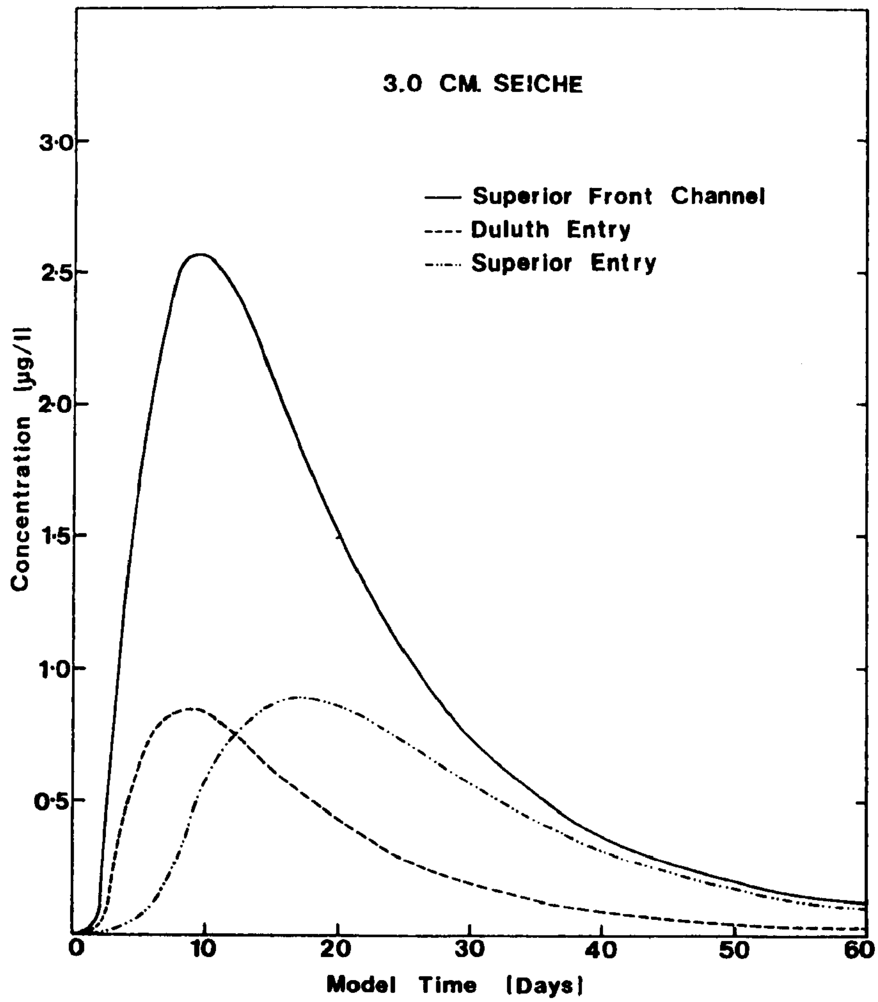


Figure 31. Contaminant concentration at lake entries for a 200 kg conservative input at coal dock (3 cm seiche conditions).

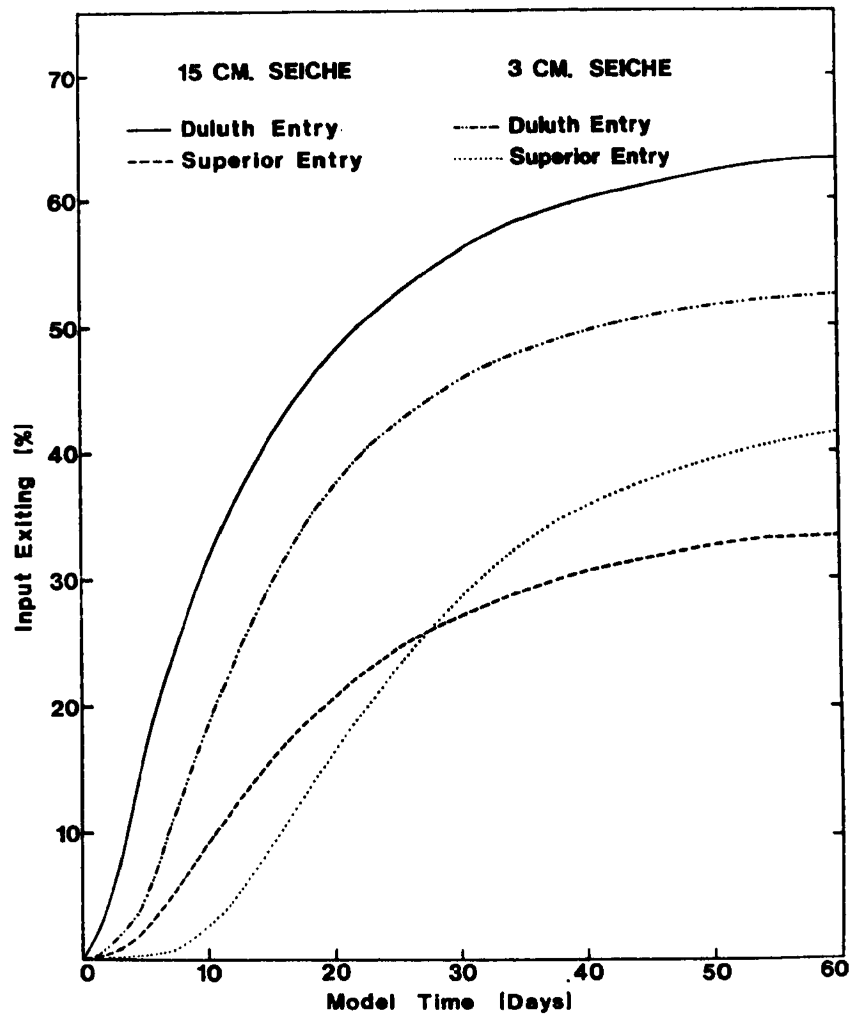


Figure 32. Accumulated output at lake entries of a conservative contaminant initially put in at the coal dock.

SECTION 12

SNOW ALBEDO

Dustfall quickly deteriorates the reflectivity of snow cover. One of the important consequences of the dispersal of coal dust is its effect on the energy budget for the environment. On a local scale the relationship between snow albedo and the heat balance in the Duluth-Superior harbor is discussed by Sydor (1978). In view of the pending world-wide conversion to coal as the major source of energy, change in albedo also has an implication on the heat balance on a global scale (Physics Today, News, October 1977). Thus the effects of coal dust on the environment has a long range environmental importance.

The relationship between snow reflectivity and dustfall was investigated here as a method for determining the distribution of dustfall as a function of winds. Albedo monitored through remote sensing also provided a much needed method for surveillance of fugitive dust sources since private property restrictions generally made location of sampling stations difficult. Measurements of dustfall distribution were especially needed for validation of dust dispersal models which were used in obtaining the estimates for the total magnitude of the dust sources.

In considering albedo as a measure of accumulated dustfall, it was necessary to perform detailed measurements regarding the effects on reflectivity due to temperature, insolation, and the snow aging produced by the global dust background. So far, only preliminary results are available here.

A series of measurements on snow reflectivity were made using Science Associates Model 615 solarimeters, one facing up and one down. The radiometers were calibrated against an Eppley 8-48 pyranometer. In determining the relationship between snow reflectivity and the particle deposition rates, knowledge of particle size distributions was also needed to determine the effective cross sectional area of the accumulated fallout. The total cross section was correlated directly with snow reflectivity. Measurements for particle sizes and deposition rates were performed at several stations along a southwesterly transect in an open field downwind from the coal pile. The relationship between the cross sectional area and mass deposition is shown in Figure 33. The relationship between the albedo and the cross sectional area is shown in Figure 34. If a constant particle deposition rate is assumed, the results in Figure 34 are comparable to those given by Dirmhirn (1975). Figure 34 can also be interpreted in terms of pigment scattering theory (Kortum 1969).

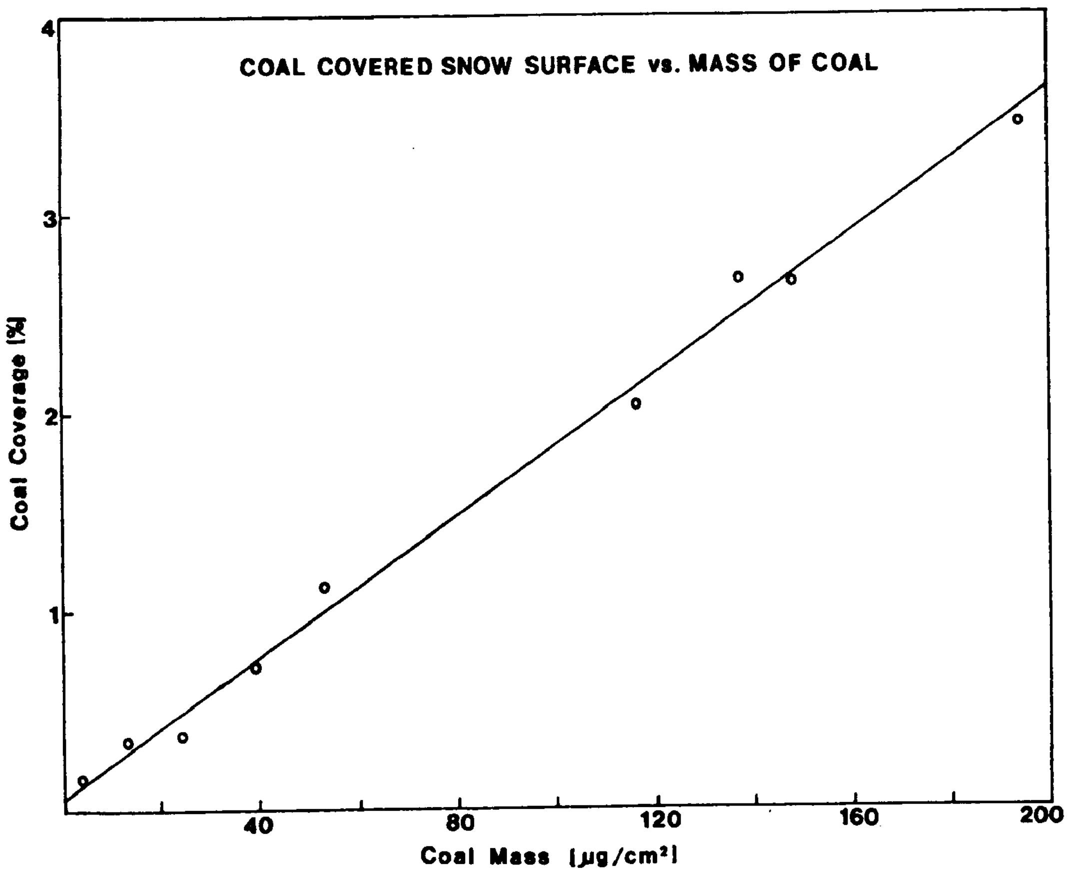


Figure 33. Relationship between fallout mass and cross-sectional area for coal particulates deposited over snow.

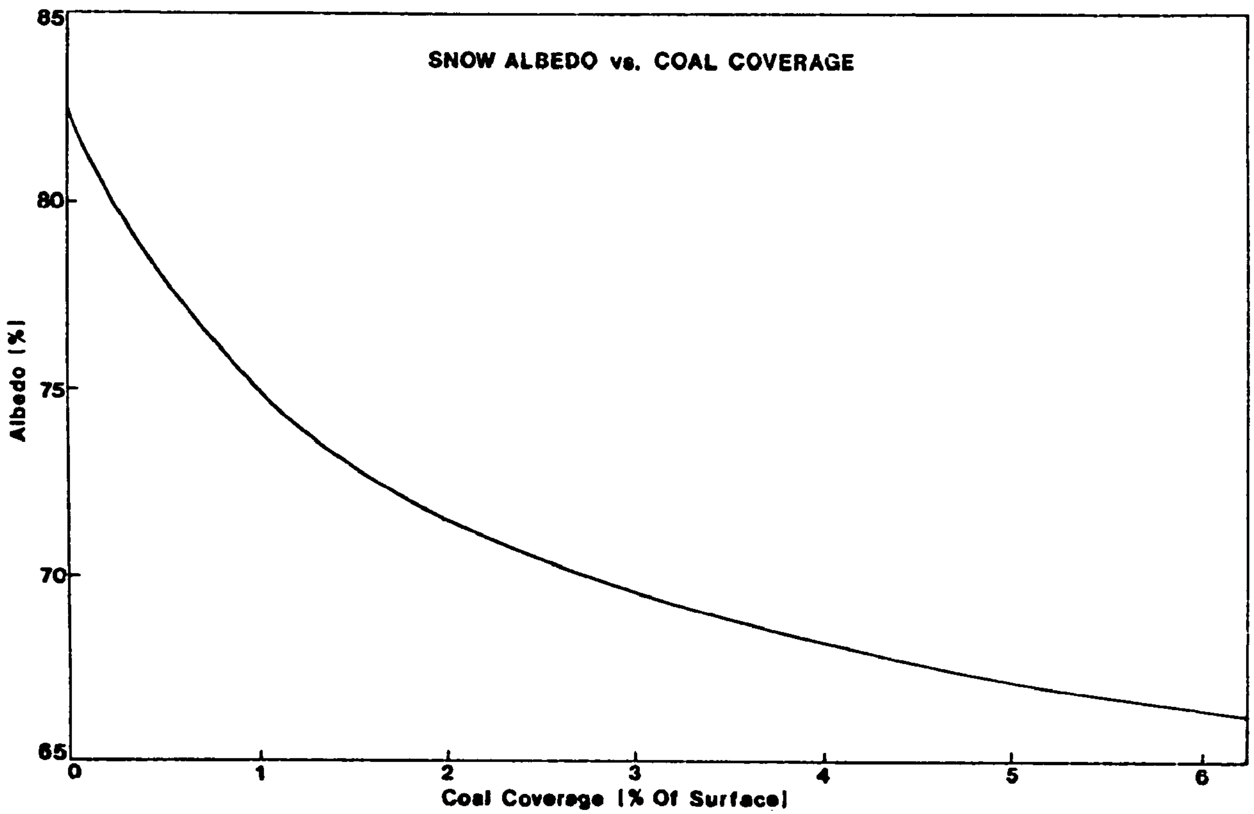


Figure 34. Relationship between snow albedo and percent of snow surface covered with coal.

Measurements of albedo were made at some of the stations used in dust plume modeling. Table 10 shows a reasonable comparison between measured coal

TABLE 10. COAL DUST·DEPOSITION ($\mu g/cm^2/day$)

Station	Slides		Albedo	
	Downwind	Background	Downwind	Background
1	8.0	3.6	8.1	4.2
2	10.0	3.7	8.6	4.5
3	24.0	3.1	19.0	4.8
4	116.0	8.1	54.0	7.4

deposition rates and the deposition rates calculated from the albedo measurements and the relationships in Figures 33 and 34.

To examine the application of albedo measurements for determination of dustfall distributions, Landsat satellite data was considered. The satellite readings were calibrated using Rice Lake as a reference target. The lake, located 20 km northwest of the contamination sources, provided an excellent calibration site because of the uniformity of its spatial and temporal distribution of albedo. It was found that there is a sharp natural decay of albedo immediately after snowfall. This is expected on the basis of pigment theory. There is also a dependence of albedo on temperatures (Dirmhirn 1975). However, for Duluth, temperatures are generally well below freezing. The seasonal dependence of the reflected signal at Nadir for the 81% snow reflectance at Rice Lake is shown in Figure 35. The maximum reflectance is obtained for clear viewing conditions and fresh snow (2 - 10 days old). Rice Lake data for clear days provides the reference reflectance for the near zero dust deposition rate above the global dust background. The data in Figure 35 is of preliminary nature because of the limited number of available overflights to date.

Landsat data for 1977 provide images clearly showing the location of major dust sources within the Duluth harbor. For example, the low albedo areas surrounding various coal storage and taconite storage facilities in the harbor can be seen in Figure 36, which shows albedo determined from Landsat

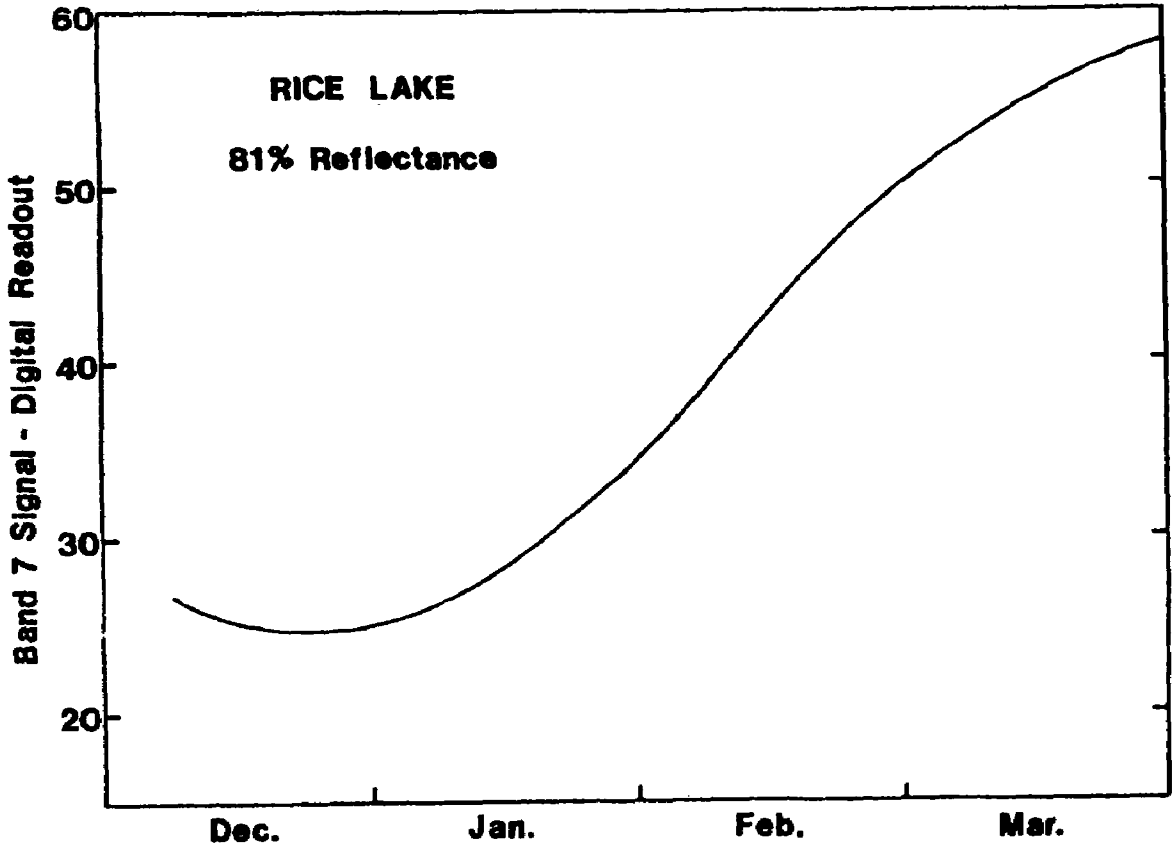


Figure 35. Seasonal variation in Landsat CCT maximum reflectance for Rice Lake.

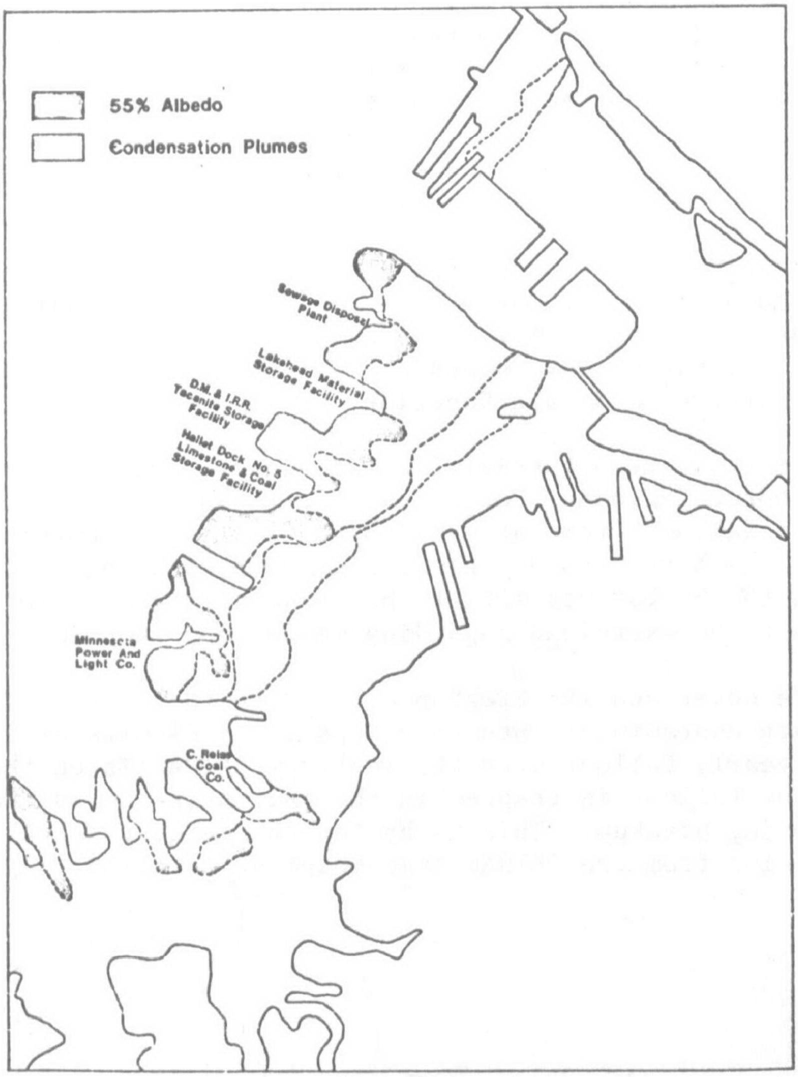


Figure 36. Snow albedo derived from the 09JAN77 Landsat scene. Low albedo areas show deposition of dust from various storage piles in Duluth harbor. Condensation plumes show up as high albedo.

data for 09JAN77. Notice in particular the Reiss Inland Coal Storage and Hallet Storage Facilities, where low albedo areas adjacent to the sources outline zones where particulate fallout is high enough to reduce the albedo to 55 percent. This corresponds to an accumulated deposition in excess of 200 $\mu g/cm^2$ of coal dust. The accumulation has occurred as a result of dust fallout from the piles during a week of moderate northwest winds. Notice also in Figure 36 distinct high albedo stripes. The stripes are vapor trails from major industrial plants. The air temperature at the time of the overflight on January 9 was -30^oC, and the winds were calm. Thus, condensation plumes remained dense and clearly visible in the Landsat data. The vapor plumes are not visible in Landsat data for January 10 when the temperature was only -20^o and winds increased to 7 m/sec.

A striking case of dust deposition over the harbor ice cover is seen in the 27JAN77 Landsat image, Figure 37. This deposition resulted from 10 - 15 m/sec northwest winds on 26JAN77. The image indicates that coal piles on the Duluth side of the harbor may indeed be the largest contributors of coal dust to the harbor waterway and Lake Superior.

The images show the potential for the use of remote sensing data in studies of airborne fallout. For instance, it can be seen from Landsat images that the fallout from taconite and coal piles in Duluth extends over the ice across the harbor to Superior, Wisconsin, showing that numerous sources within the harbor may affect the measurements at sampling stations. Thus, care had to be exercised regarding winds when sampling was performed.

Harbor ice cover and its breakup constitute the most important source of coal particulate contaminant into Lake Superior. Results of Section 7 indicate that yearly fallout over the ice from ORTRAN is on the order of 4 - 5 tons. The fallout is trapped in the ice cover and is transported to the lake at spring breakup. This is by far the largest input of coal dust into Lake Superior from the ORTRAN transshipment facility.

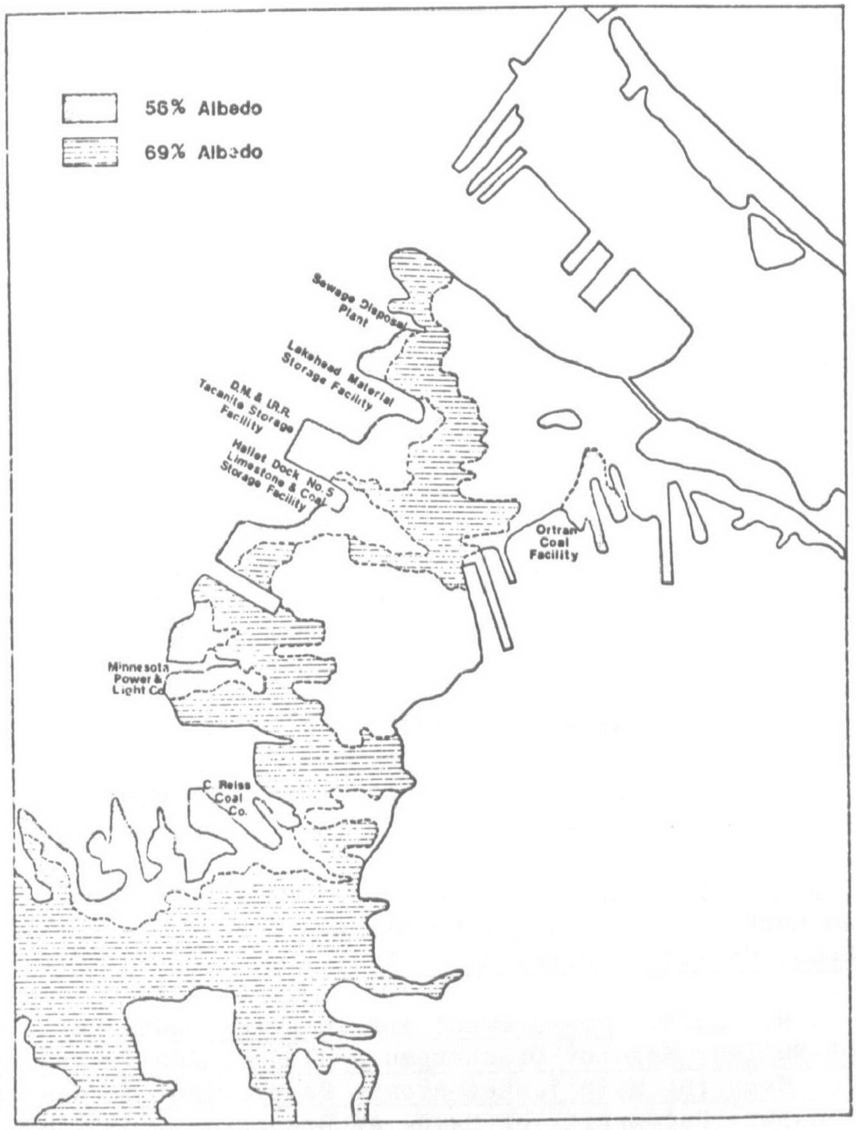


Figure 37. Snow albedo derived from the 27JAN77 Landsat scene showing dust deposition from Duluth storage piles under action of 10 - 15 m/s northwest winds on 26JAN77.

REFERENCES

Ariathurai, R., R. C. MacArthur, and R. B. Krone. 1977. Mathematical Model of Estuarial Sediment Transport. Technical Report D-7712. U.S.A.C.E., P.O. Box 631, Vicksburg, Mississippi 39100.

Bennett, J. P. 1974. "Concepts of Mathematical Modeling of Sediment Yield." Water Resources Research 10(3):485.

Bierman, Jr., V. J., and W. R. Swain. 1978. "DDT Loss Rates in Low Lipid Fishes in the Great Lakes." 21st Conference on Great Lakes Research, Windsor, Ontario.

Brun-Cottan, J. C. 1976. "Stokes Settling and Dissolution Rate Model for Marine Particles as a Function of Size Distribution." J. Geophys. Res. 81(9):1601.

Busse, A. D., and J. R. Zimmerman. 1973. User's Guide for the Climatological Dispersion Model. U.S. E.P.A. Publ. No. R4-73-024. Prepared for E.P.A., Research Triangle Park, N.C., December.

Callaway, R. J., and K. V. Byran, and G. R. Dittsworth. 1970. Mathematical Model of the Columbia River. NITS, U.S. Dept. of Commerce, PB202.

Carlson, R., and R. Caple. 1978. Final Report for Coal Leachate Studies. U.S. E.P.A. Grant R803952-03-3. University of Minnesota, Duluth.

Carrier, G. F., R. P. Shaw, and M. Miyata. 1971. "Response of Narrow-Mouthed Harbor in a Straight Coastline to Periodic Incident Wave." J. Eng. Mech. Division. Proc. A.S.C.E. EM6 p. 1703.

Churchill, J. H. 1976. Measurement and Computer Modeling of the Distribution of Nuclear Reactor Discharged Radionuclides in the Estuarine Sediment Near the Main Yankee Atomic Power Plant in Wiscasset, Maine. M.S. Thesis. University of Maine at Orono.

Csanady, G. T. 1973. Turbulent Diffusion in the Environment. D. Reidel: Boston.

Defant, A. 1961. Physical Oceanography. Pergamon Press:London.

Diehl, S. R., D. T. Smith, and M. Sydor. 1978. Optical Detection of Fiber Particles in Water. Final Report U.S. E.P.A. Grant R804361.

Dirmhirn, I., and F. D. Eaton. 1975. "Some Characteristics of the Albedo of Snow." J. Appl. Meteorol. 14:375-379.

Feigner, K. D., and H. S. Harris. 1970. Documentation Report - FWQA Dynamic Estuary Model. NTIS Publ. No. PB 197 103.

Freeman, N. G., P. F. Hamblin, and T. S. Murty. 1974. "Helmholtz Resonance in Harbours of the Great Lakes." Proc. 17th Conference on Great Lakes Research, p. 399-411.

Galloway, Jr., F. M., and S. J. Vakil. 1977. "Criteria for the Use of Vertical Averaging in Great Lakes Dispersion Models." J. Great Lakes Res. 3(1-2):20-28.

Hess, C. S. 1973. Study of Shoreline Erosion on the Western Arm of Lake Superior. A report to Reserve Mining Company, Silver Bay, Minnesota.

Hwang, Li-San, and E. O. Tuck. 1970. "On the Oscillations of Harbours of Arbitrary Shape." J. Fluid Mech. 42(3):447.

Ippen, A. T., and Y. Goday. 1963. Wave Induced Oscillations in Harbours. Hydrolab Massachusetts Institute of Technology.

Keillor, J. P. and R. A. Ragotzkie. 1976. An Assessment of the Environmental Effects of Dredged Material Disposal in Lake Superior, Vol. 1. Marine Studies Center, University of Wisconsin, Madison.

Kerker, M. 1969. The Scattering of Light. Academic Press.

Koch, R. C., and S. D. Thayer. 1971. Validation and Sensitivity Analysis of the Gaussian Plume Multiple - Source Urban Diffusion Model. Contract No. CPA 70-94. Prepared for E.P.A., Research Triangle Park, N.C. by GROMET, Inc., Gaithensburg, Maryland.

Koch, R. C., and G. E. Fisher. 1973. Evaluation of the Multiple-Source Gaussian Plume Diffusion Model, Phase I Report. Contract No. 68-02-0281. Prepared for E.P.A., Research Triangle Park, N.C., by GROMET, Inc., Gaithensburg, Maryland.

Koch, R. C., D. J. Pelton, and P. H. Hwang. 1976. Sampled Chronological Input Model (SCIM) Applied to Air Quality Planning in Two Large Metropolitan Areas. E.P.A. Publ. No. 600/9-76-016. Prepared for E.P.A., Research Triangle Park, N.C., by GROMET, Inc., Gaithensburg, Maryland.

Koh, R. C. Y., and Y. C. Chang. 1973. Mathematical Model for Barged Ocean Disposal of Wastes. E.P.A. 66012-73-029.

Kortum, G. 1969. Reflectance Spectroscopy. Springer-Verlag: New York.

McCave, I. N. 1975. "Vertical Flux of Particles in Ocean." Deep Sea Res. 22:491, Pergamon Press.

McElroy, J. L., and F. Pooler. 1968. St. Louis Dispersion Study, Vol. II - Analysis. AP-53, E.P.A., Research Triangle Park, N.C.

McElroy, A. D., and S. Y. Chiu. 1974. Water Quality Investigation:Duluth-Superior Harbor. E.P.A. Contract No. 68-01-1593. Midwest Research Institute, Kansas City, Missouri.

Miles, J. W. 1974. "Harbor Seiching." Annual Review of Fluid Mechanics 6:17.

Moore, D. J. 1975. "Application of CEGB Plume Rise and Dispersion Results to Prediction Models for Ground Level Concentrations." International Clean Air Conference, Rotorua, New Zealand.

Mortimer, C. H., and E. J. Fee. 1976. "Surface Oscillations and Tides of Lake Michigan and Superior." Phil. Trans. Roy. Soc. London 281:1-61.

Oman, G. J., and M. Sydor. 1978. "Use of Remote Sensing in Determination of Chemical Loading of Lake Superior Due to Spring Runoff." Canadian J. Spectroscopy 23(2):52.

Orlob, G. T. 1959. "Eddy Diffusion in Homogenous Turbulence." J. of Hydraulics Division of A.S.C.E., p. 1149.

Pasquill, F. 1962. Atmospheric Diffusion. D. Van Nostrand Co., Ltd. London.

Santer, G. D. 1976. A Generic Survey of Air Quality Simulation Models. University of California Lawrence Livermore Laboratory, E.R.D.A. Contract No. W-7405-Eng.-48.

Seeling, W. N., and R. M. Sorensen. 1977. Hydraulics of Great Lakes Inlets. Technical Paper No. 77-8, U.S. Army Corps of Engineers Coastal Engineering Research Center, Kingman Building, Fort Belvoir, Virginia 22060, July.

Shackman, T. A. 1978. Duluth Metropolitan Area Bulk Storage Facility Inventory and Fugitive Emission Summary. M.P.C.A. Report.

Smith, F. B. 1962. "The Problem of Deposition in Atmospheric Diffusion of Particulate Matter." J. Atmospheric Sciences 19:429-434.

Stortz, K. R., R. T. Clapper, and M. Sydor. 1976. "Turbidity Sources in Lake Superior." J. Great Lakes Res. 2:393.

Sundborg, A. 1956. "The River Klaralven: A Study of Fluvial Processes." Geografiska Annaler Vol. 38 A, Sweden.

Sydor, M. 1976. Red Clay Turbidity and Its Transport in Western Lake Superior. U.S. E.P.A. R-005175. Final Report.

Sydor, M. 1978. "Ice Growth in Duluth-Superior Harbor." J. Geophys. Res. 83(C8):4074.

Sydor, M. 1978. "Analysis of Suspended Solids in Lakes Using Landsat Data." Canadian J. Spectroscopy 23:91.

Turner, D. B. 1970. Workbook of Atmospheric Dispersion Estimates. Public Health Service Publ. No. 999-AP-26.

U.S. E.P.A. Report. 1976. Report on the Degree of Pollution of Bottom Sediments - Duluth-Superior Harbor - Sampled June 29-30, 1976. Region V, U.S. E.P.A.

Van Tassell, J., and J. R. Moore. 1976. An Assessment of the Environmental Effects of Dredged Material Disposal in Lake Superior. Vol. 2. Marine Studies Center Publication, University of Wisconsin, Madison.

Winslow, J. 1976. M.P.C.A. Propeller Wash Study Duluth-Superior Harbor. Minnesota Pollution Control Agency, St. Paul, Minnesota.

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/3-80-007	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE Sources and Transports of Coal in the Duluth-Superior Harbor		5. REPORT DATE January 1980 issuing date 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Michael Sydor and Kirby Stortz		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of Physics University of Minnesota--Duluth Duluth, Minnesota 55812		10. PROGRAM ELEMENT NO. 1NE625 11. CONTRACT/GRANT NO. Grant No. R-803952
12. SPONSORING AGENCY NAME AND ADDRESS Environmental Research Laboratory - Duluth, MN Office of Research and Development U.S. Environmental Protection Agency Duluth, Minnesota 55804		13. TYPE OF REPORT AND PERIOD COVERED 14. SPONSORING AGENCY CODE EPA/600/03

15. SUPPLEMENTARY NOTES

16. ABSTRACT

Dispersion of particulates from an ORTRAN coal transshipment facility was investigated to estimate the input of coal dust into the Duluth harbor and to determine the transport of coal particulates to Lake Superior. A numerical model was used to discuss dispersal of contaminants and determine the residence time of pollutants in the water way. The model was verified using measurements of water levels, currents and water quality parameters.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Particulate dispersion Coal dust tranport Coal handling	Coal Harbor Particulates	55/Ø 62/E 67/E 63/F 64/K 80/G

18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS *(This Report)* UNCLASSIFIED	21. NO. OF PAGES 94
	20. SECURITY CLASS *(This page)* UNCLASSIFIED	22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

U S GOVERNMENT PRINTING OFFICE 1980 -657-146/5545