IC bureau of mines information circular 8461

TRANSPORTATION OF IRON ORE, LIMESTONE, AND BITUMINOUS COAL ON THE GREAT LAKES WATERWAY SYSTEM

With Projections to 1995

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

1970

TRANSPORTATION OF IRON ORE, LIMESTONE, AND BITUMINOUS COAL ON THE GREAT LAKES WATERWAY SYSTEM

With Projections to 1995

By James H. Aase

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This publication has been cataloged as follows:

Aase, James H

Transportation of iron ore, limestone, and bituminous coal on the Great Lakes waterway system: with projections to 1995. [Washington] U.S. Dept. of the Interior, Bureau of Mines [1970]

61 p. illus., tables. (U.S. Bureau of Mines. Information circular 8461)

Includes bibliography.

1. Mineral industries—U.S.—Transportation. I. Title. (Series)

TN23.U71 no. 8461 622.06173

U.S. Dept. of the Int. Library

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price $1

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TRANSPORTATION OF IRON ORE, LIMESTONE, AND BITUMINOUS COAL ON THE GREAT LAKES WATERWAY SYSTEM

With Projections to 1995

by

James H. Aase[1]

ABSTRACT

This study provides data on the physical and hydrological makeup of the Great Lakes waterway system and forecasts quantities, traffic patterns, and shipping cost of prospective bulk mineral commerce projected to be transported upon it. Factors affecting the shipping cost of iron ore, bituminous coal, and limestone were quantified and integrated into a computer program that can be used to estimate costs under varying sets of conditions. Combined shipments of iron ore, bituminous coal, and limestone in 1995 were estimated at 276.5 million tons. The cost of operating the U.S. vessel fleet for transporting an indicated 80 percent of this traffic tonnage was projected to be $163.5 million.

INTRODUCTION

An important part of our national transportation network is the Great Lakes. This waterway system provides access to a region notable for the magnitude of its mineral resources. In point of volume and importance of traffic, this group of lakes has no equal as an inland route for waterborne commerce of bulk mineral commodities. In 1966, approximately 179 million net tons of the total 222 million net tons of commerce handled at U.S. Great Lakes ports consisted of iron ore, bituminous coal, and limestone (7).[2]

Great Lakes vessel operators have always taken advantage of any increased water depths that become available for increasing cargo loadings. However, it often happens that vessels in the fleet are forced to load at reduced draft when water levels fall below the high stage. Any reduction in the cargo-carrying capacity of a vessel results in more trips to carry the same quantity of cargo between two points and thus increases the cost of transporting a given quantity of a commodity.

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[1] Physical scientist, Twin Cities Office of Mineral Resources, Bureau of Mines, Minneapolis, Minn.

[2] Underlined numbers in parentheses refer to items in the list of references preceding the appendixes.

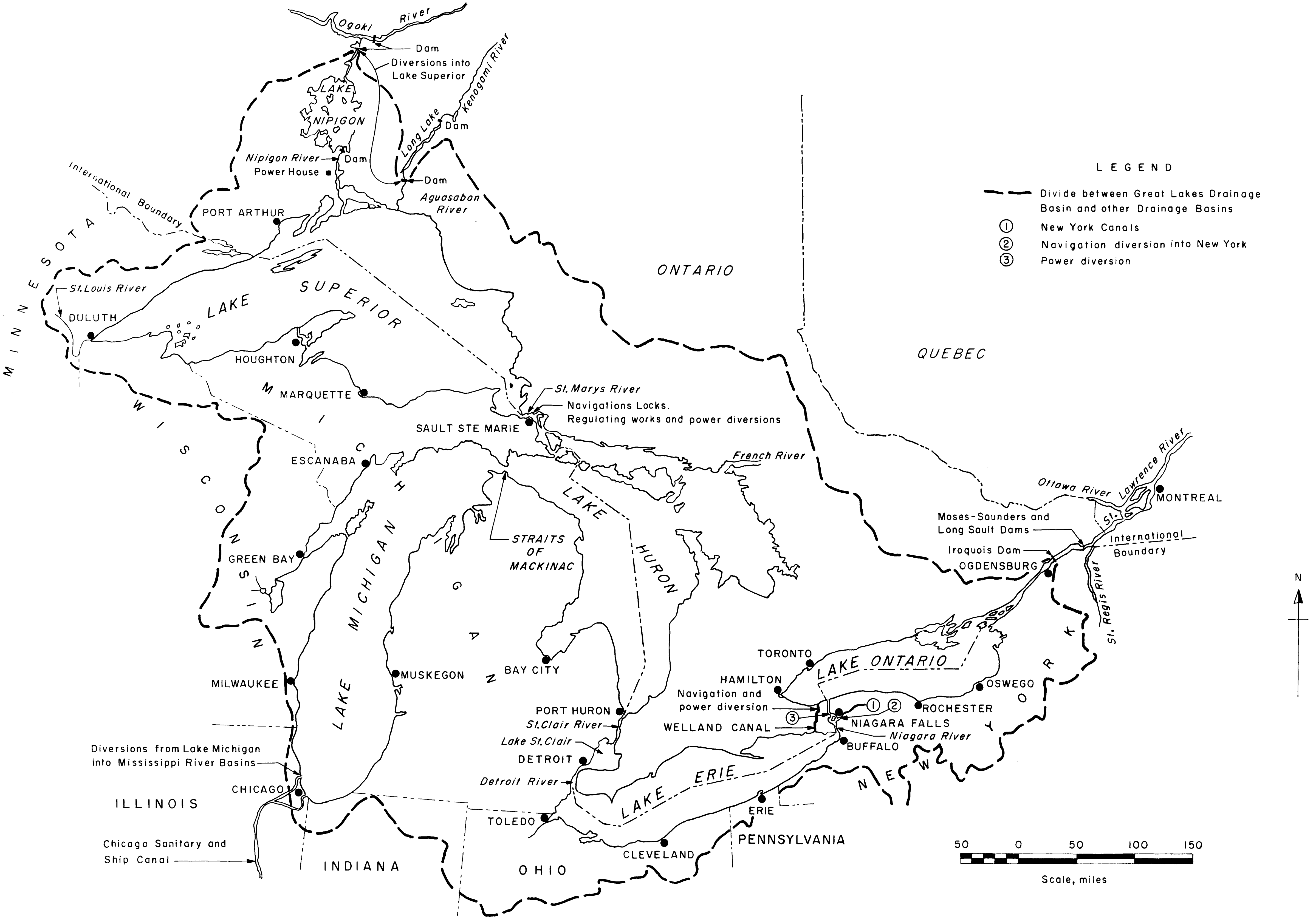

FIGURE 1. - Map of Great Lakes-St. Lawrence River Drainage Basin. Based on plate 1 (8).

The purpose of this Bureau of Mines study is to provide basic information to Government, industry, and the public on mineral commodity movements that play an important role in maintaining essential supplies of mineral materials. The report presents data on the physical and hydrological makeup of the Great Lakes waterway system; quantity estimates of prospective Great Lakes bulk mineral commodity commerce; and projected composition, characteristics, and operating costs of the U.S. vessel fleet required to handle this commerce. Included in the report is an identification, evaluation, and quantification of natural and manmade factors influencing transportation costs and a technique that could be used to determine the effect of various water levels on the transportation cost of the forecast bulk mineral commodity shipments over the Great Lakes waterway system.

ACKNOWLEDGMENTS

The author gratefully acknowledges the cooperation and assistance received from the U.S. Army Corps of Engineers, North Central Division; the U.S. Department of Commerce, Maritime Administration, Division of Operations, Office of Ship Operations; the Canadian Department of Transport, Transportation Policy and Research Branch, Marine Economic Section; and from staff members of the Twin Cities Office of Mineral Resources and the Systems Analysis Group of the Twin Cities Mining Research Center, Bureau of Mines.

GREAT LAKES SYSTEM

The Great Lakes and their tributary land areas (fig. 1) form a major part of the drainage basin of the St. Lawrence River. The water from the drainage basin, in large part the drainage from the lakes, flows to the Atlantic Ocean. The five Great Lakes--Superior, Michigan, Huron, Erie, and Ontario--their connecting rivers, and Lake St. Clair have a water surface area of about 95,000 square miles. The total land and water area of the Great Lakes Basin is approximately 295,000 square miles. Of this area, about 59 percent is in the United States and 41 percent is in Canada.

Figure 1 locates the limits of the land areas draining into the lakes, the lakes themselves, and the outlet river of each lake that links it to the lake next downstream in the system. Figure 1 also indicates the location of the locks of Sault Ste. Marie, which allow navigation to bypass the rapids of the St. Marys River, and the Welland Canal, which allows navigation to bypass Niagara Falls; the points where water is diverted into Lake Superior from the Albany River Basin and from Lake Michigan into the Mississippi River Basin; the points where the lake outflows are utilized for power generation; and the locations of works in the St. Marys and St. Lawrence Rivers for regulating Lakes Superior and Ontario, respectively. Table 1 lists the general dimensions of the Great Lakes-St. Lawrence River drainage system, including lengths of coastlines, water surface areas, total drainage basin areas, and depths. Appendix C contains a detailed description of physical and hydrological features of the Great Lakes system.

U.S. commerce on the Great Lakes system during the 10-year period 1957-66 constituted about 17 percent of the total waterborne commerce in the United States (7). During this period, the annual commerce on the Great Lakes, including imports and exports, ranged from about 158 million net tons in 1958 to 222.5 million net tons in 1966 and averaged approximately 191 million net tons. Shipments of iron ore, bituminous coal, and limestone accounted for about 80 percent of the total Great Lakes waterborne commerce tonnages handled from 1957 to 1966. Table 2 summarizes the iron ore, bituminous coal, and limestone commerce at U.S. harbors on the Great Lakes for the period 1956-66.

TABLE 1. - Dimensions of Great Lakes-St. Lawrence River drainage system

	Lake Superior	Lake Michigan	Lake Huron	Lake St. Clair	Lake Erie	Lake Ontario
Length....miles..	350	307	206	26	241	193
Breadth....do...	160	[1] 118	[2] 183	24	57	53
Length of coastline, including islands....do...	2,976	1,661	[3] 3,185	169	856	726
Water surface area....square miles..	[4] 31,820	22,400	[5] 23,010	[6] 490	9,930	[7] 7,520
Drainage basin....do...	80,000	67,860	72,620	7,430	32,490	34,800
Maximum recorded depth....feet..	1,333	923	750	[8] 21	210	802
Average depth....do...	487	276	195	10	58	283

[1] Measured at wide point through Green Bay.
[2] Measured at wide point through Georgian Bay.
[3] Includes Georgian Bay and North Channel.
[4] Includes St. Marys River above St. Marys Falls.
[5] Includes St. Marys River below St. Marys Falls, North Channel, and Georgian Bay.
[6] Includes St. Clair River and Detroit River.
[7] Includes Niagara River and St. Lawrence River to Iroquois Dam.
[8] Natural maximum depth. Dredged navigation channel has 25-foot depth.

TABLE 2. - Iron ore, bituminous coal, and limestone commerce at U.S. Great Lakes harbors, 1956-66, thousand net tons

Commodity and type of traffic	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966
Iron ore:											
Lakewise[1]........	76,449	85,945	52,754	45,859	68,465	55,145	54,704	56,474	63,552	64,357	70,279
Export..........	5,063	4,494	3,353	2,741	4,949	4,459	5,166	5,638	5,425	4,983	4,382
Import..........	6,989	6,141	4,189	9,620	8,133	7,356	10,193	12,332	17,586	16,302	17,227
Total........	88,501	96,581	60,296	58,221	81,548	66,962	70,064	74,446	86,563	85,642	91,888
Bituminous coal:											
Lakewise[1]........	41,512	41,336	34,711	35,777	36,099	33,947	35,830	38,547	38,518	39,846	40,677
Export..........	16,003	15,745	10,563	11,070	10,738	10,312	10,659	13,148	13,148	14,871	14,912
Import..........	0	0	0	0	0	0	0	0	0	0	0
Total........	57,516	57,082	45,274	46,847	46,837	44,259	46,489	51,695	52,080	54,717	55,589
Limestone:											
Lakewise[1]........	28,534	28,455	21,327	23,972	25,633	23,590	23,064	24,761	27,882	26,789	30,012
Export..........	1,033	1,010	684	946	832	660	586	241	916	1,107	1,059
Import..........	61	102	82	85	25	0	34	0	0	0	0
Total........	29,630	29,568	22,094	25,009	26,490	24,250	23,685	25,002	28,798	27,896	31,070
Grand total...	175,647	183,231	127,664	130,077	154,875	135,471	140,238	151,143	167,441	168,255	178,547

[1] Applies to traffic between U.S. ports on the Great Lakes.

PROJECTED PRODUCTION AND COMMERCE

The estimates of potential Great Lakes traffic in iron ore, bituminous coal, and limestone were made for the 50-year period 1970-2020. Year 1995, the midyear, was assumed to represent an average annual commerce flow for the period, and shipment quantities were estimated for that year. In developing the shipment estimates for each of the three mineral commodities, consideration was given to the past and anticipated demand requirements of the consuming industries in geographic areas favorably located to use Great Lakes transportation, to the present and future production capability of suppliers, and to resource availability in the Great Lakes region.

The projected traffic distribution patterns for shipment of bituminous coal, iron ore, and limestone were developed from waterborne commerce data obtained through the U.S. Army Corps of Engineers. Tonnages for each type of U.S. Great Lakes traffic (lakewise, export, and import), by commodity, over each of the 25 different origin and destination combinations of water routes, were recorded by years for the period 1956-64. A computer program was written to process the data. The computer program calculated by commodity the yearly percentages of traffic carried over each route according to traffic type.

The proportions for the base years 1956-64 were projected to year 1995 by regression analysis. The proportions projected for 1995 over each of the traffic routes were normalized to 100 percent for each category (lakewise, export, and import).

The distances each commodity will be transported over the projected traffic routes were calculated from origin and destination data obtained on each shipment of these commodities over the same routes during the 4-year period 1961-64. These mileages represent average lake-to-lake distances.

Round-trip times were determined for the various size vessels engaged in the different commodity trades. The U.S. Army Corps of Engineers have investigated the amounts and types of cargo handled on the return trips for the various vessel classes, in conjunction with its Great Lakes harbor studies. From these findings, the ratio of round-trip time to loaded-trip time for the vessel classes in a specific commodity trade was estimated for 1995. If, for example, part of the fleet is committed to the iron ore trade and returns empty after each shipment, the factor would be 200 percent plus loading and unloading time; if, however, it carries limestone or some other commodity on the return trip for part or all of the way, the factor would then be between 100 to 200 percent plus loading and unloading time.

Iron Ore

The Bureau of Mines and the University of Minnesota studies on future U.S. iron ore demand indicate an expected annual growth rate of approximately 2 percent based on iron units (4). The Bureau of Mines estimates the average grade of iron ore for blast furnace feed will increase from 57 percent in iron content in 1967 to 60 percent in 1970, 70 percent in 1985, and 80 percent in the year 2000. This increase in grade is expected to result from gradual conversion to prereduced agglomerates and pellets for producing pig iron. Because less ore will be required as grade increases, transportation costs will be less and consequently the productivity of the furnaces will increase. When the projected iron-unit requirements are adjusted to reflect the expected increase in iron content, the ore tonnage requirements indicate an average annual growth rate of 1.5 percent for the projection period.

Iron ore production from States bordering the Great Lakes will increase at approximately the same rate as the expected demand. Table 3 shows the base used for projecting ore production from these States and represents the modified arithmetic average of total annual production for the 11-year period 1955-65. A regression analysis of the Minnesota production data, representing the largest percentage of the total production, indicated the computed value for the base year (1960) was 3 percent less than the arithmetic average; hence the arithmetic average was reduced slightly. Because of the much smaller difference for the other States, no adjustment of their production figures was required. The production projections developed are presented in table 4.

TABLE 3. - Iron ore production at base year (1960) in States bordering the Great Lakes, million short tons

Production source	Production
Michigan	12.5
Minnesota	57.1
New York	2.8
Pennsylvania	1.5
Wisconsin	1.2
Total	75.1

TABLE 4. - Projected Great Lakes area iron ore production and Great Lakes shipments, million net tons

	Base year, 1960	1970	1975	1980	1985	1990	1995
Production	75.1	87.2	93.9	101.2	109.0	117.4	126.5
Shipments:							
Lakewise	-	76.6	82.1	88.4	95.3	102.7	110.7
Export	-	5.2	5.1	5.0	4.9	4.8	4.8
Import	-	21.5	24.0	25.3	26.9	28.4	30.1

Iron ore shipments by all modes of transportation from these States were analyzed to determine what percentage of the total annual production was carried on the Great Lakes waterway system. During the 9-year period studied (1956-64), the percentage of lake shipments to total production ranged from 87 to 93 percent. The arithmetic average was 91 percent. A regression analysis showed also that 91 percent of production was shipped on the lakes in the base year (1960). It is not expected that patterns and methods of lake shipment from U.S. origins will change enough by 1995 to cause any long-term change in the percentage of lake shipments to total production.

Imports of iron ore handled over the Great Lakes waterway have in recent years accounted for approximately 20 percent of the total Great Lakes iron ore commerce. Principally from Canadian sources, these imports are expected to remain at this same percentage level throughout the projection period. Estimates made by Canadian authorities also agree with this percentage. Table 4 shows the projected iron ore shipments. The projected traffic distribution pattern for 1995 iron ore shipments on the lakes is shown in table 5. Tables 6 and 7 show respectively the projected average distances of the traffic routes and the round-trip time factor for the vessels projected to handle the movements.

TABLE 5. - Projected iron ore traffic distribution pattern, 1995

Route		Type of traffic		
From	To	U.S. lakewise, percent	U.S. export,[1] percent	U.S. import,[2] percent
Superior	Michigan	33.15	0	10.60
	Erie	57.37	0	5.70
	Ontario or St. Lawrence	0	100.00	0
Michigan	Michigan	4.78	0	0
	Erie	4.69	0	0
Huron	Michigan	0	0	1.70
	Erie	0	0	6.60
Ontario or St. Lawrence	Michigan	0	0	17.60
	Erie	0	0	57.80
Total		100.00	100.00	100.00

[1]To Canada.
[2]From Canada.

TABLE 6. - Projected average distances of traffic routes for iron ore shipments, 1995

Route		Type of traffic		
From	To	Lakewise, miles	U.S. export, miles	U.S. import, miles
Superior	Michigan	797	-	699
	Erie	792	-	703
	Ontario or St. Lawrence	-	971	-
Michigan	Michigan	276	-	-
	Erie	507	-	-
Huron	Michigan	-	-	474
	Erie	-	-	304
Ontario or St. Lawrence	Michigan	-	-	1,172
	Erie	-	-	416

TABLE 7. - Round-trip time factor of loaded-trip time for iron ore shipments by vessel class, 1995

Vessel class	Overall length, feet	Round-trip time factor
5	600-649	180 pct + 16 hr
6	650-699	200 pct + 16 hr
7	700-730	200 pct + 16 hr
8	731-849	200 pct + 10 hr
9	850-949	200 pct + 12 hr
10	950-1,000	200 pct + 14 hr

Figure 2 represents the traffic flow of iron based on the foregoing projected shipment quantities and traffic distribution pattern for 1995. Because the present sources and markets for iron ore are not expected to change radically, the 1995 general traffic pattern follows closely that of today.

Indicated iron ore reserves are apparently adequate to meet the projected demands for at least 100 years. Iron ore resources in the United States have been estimated at approximately 111 billion tons. Ninety percent of these resources are located in the Lake Superior region and are principally in the form of taconite, which requires beneficiation to make them acceptable for blast furnace use.

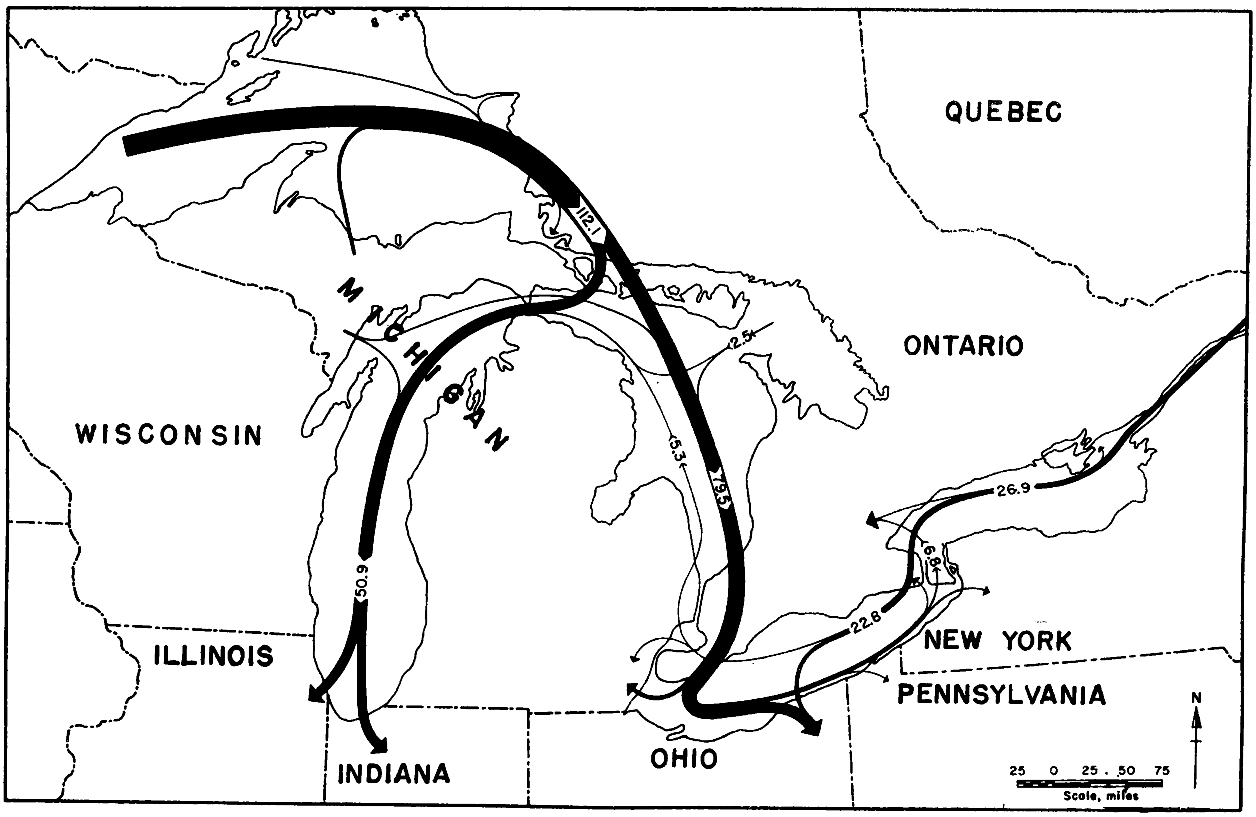

FIGURE 2. - Projected Iron Ore Traffic Flow, 1995. Million net tons.

The minable iron ore reserves, estimated by the Bureau of Mines at varying price levels, are shown in table 8. The figures, based on 1966 costs and technology, indicate the amount of usable iron ore that may be produced at the indicated price levels. The apparent average mine price is $12 per long ton, and the lowest price limit at which most domestic mines could operate without subsidy is estimated at $9 per long ton. Under today's conditions about 10 billion long tons of domestic ore is considered economically minable. Nine billion long tons of this ore is in the Lake Superior region adjacent to the Great Lakes waterway.

TABLE 8. - U.S. reserves of iron ore minable at various prices per long ton

Region	Amount, million long tons		
	At $12	At $14	At $16
Northeastern	150	200	300
Southeastern	250	550	7,000
Lake Superior	9,000	11,000	>100,000
Central and Gulf	150	650	700
Western	450	1,000	3,000
Total	10,000	13,500	>111,000

Limestone

The future demand for limestone from sources tributary to the Great Lakes will depend on economic factors that will similarly affect much of our future national economy. Limestone demands are tied in part to the rate of steel output and are subject to changing technology in the composition of blast furnace feed. In 1955, 0.389 net ton of limestone and dolomite was used to produce 1 net ton of pig iron. This amount had been reduced to 0.279 net ton by 1965 (2). Present technology indicates that these requirements will be further reduced to about 0.270 net ton per ton of pig iron produced. Limestone requirements for construction material will depend on population growth, the growth of the gross material product, road building, and residential, commercial, and industrial construction. Other factors such as the demand for lime and industrial chemicals will have a direct bearing on future limestone requirements from Great Lakes sources.

The State of Michigan has historically been and is forecast to be the principal source of limestone entering commerce on the Great Lakes. The limestone industry in Michigan is concentrated in a few large companies, which operate not only quarries, but mills, processing plants, ports, and fleets of ships. Historically, from 33 to 40 percent of the waterborne limestone shipments have gone to steel mills for use as a fluxing agent. Another 40 percent goes to the construction industry for use in manufacturing cement and for aggregate in road building and building construction. About 20 percent is sold to manufacturers of lime and other chemicals and for a variety of miscellaneous uses (various types of filler, poultry grit, etc.). About 2 percent of the crushed stone is used as fertilizer.

The State of Michigan was selected as the source area for projecting future limestone production. Projected limestone production was based in part on the linear trend of Michigan limestone production for the period 1924-64. An annual growth rate, modified to reflect changing blast furnace technology, of about 2.8 percent was indicated by this trend. This growth trend was applied to the base year 1960 at a calculated production level of 31.6 million tons, the arithmetic average of production for 1955 through 1965. A regression analysis was also made of Michigan's production for this same 11-year period, and little difference was noted between the computed 1960 base year figure and the arithmetic average. The projected production figures for Michigan are presented in table 9.

TABLE 9. - Projected Michigan limestone production and Great Lakes shipments, million net tons

	Base year, 1960	1970	1975	1980	1985	1990	1995
Production (Michigan)..	31.6	42	48	55	63	72	83
Shipments:							
Lakewise.............	25.63	31.4	34.7	38.3	42.3	46.7	51.6
Exports..............	.84	1.7	2.2	2.8	3.4	3.9	4.4
Imports..............	.12	.5	.8	1.1	1.4	1.7	2.0

Great Lakes shipments from Michigan averaged approximately 84 percent of the State's limestone production during the 10-year period 1955-65. A regression analysis of the relationship between the annual percentage of shipments and production for this period indicates a downward trend at an average annual rate of approximately 0.5 percent. When applied to the 84-percent shipment-to-production rate calculated for base year 1960, this trend indicates that by 1995 lake shipments from Michigan will approximate 70 percent of the State limestone production. Table 9 presents the projected Great Lakes limestone shipments based on the assumption that the State of Michigan will be the principal production source. Lakewise and export quantities have been projected from 26.5 million net tons (6) in 1960 to 56 million net tons by 1995, an annual growth rate of about 2.1 percent. The import shipments of limestone to U.S. Great Lakes ports are expected to come solely from Canada. It is expected that they will increase from approximately 0.5 million net tons in 1970 to 2.0 million net tons by 1995.

The projected traffic distribution pattern for 1995 limestone shipments on the lakes is shown in table 10. The projected average distances of the traffic routes, and the round-trip time factor of loaded-trip time for vessels projected to handle this commerce are shown in tables 11 and 12, respectively. Figure 3 represents the traffic flow of limestone based on the projected shipment quantities and traffic distribution pattern for 1995.

Limestone reserves near the shores of the Great Lakes are expected to continue as the principal source of supply for stone commerce on the Great Lakes. The high-bulk, low-unit value of limestone influences the economic utility of a deposit, which must compete with other sources on a delivered-cost basis. The availability and cost of transportation usually determine whether a particular deposit is a commercially desirable reserve. Limestone reserves in the Great Lakes area occur near the western end of Lake Erie in Ohio and Michigan, around the northern end of the lower peninsula of Michigan, and along the south shore of the upper peninsula of Michigan. Although the reserves of limestone in these areas have not been quantitatively estimated, they appear to be extremely large and able to support the present and projected production and shipping requirements for at least 50 years.

TABLE 10. - Projected limestone traffic distribution pattern, 1995

Route		Type of traffic		
From	To	U.S. lakewise, percent	U.S. export,[1] percent	U.S. import,[2] percent
Superior.......	Huron..........	0.34	0	0
	Erie...........	6.99	0	0
Michigan.......	Michigan.......	14.48	0	0
	Huron..........	6.44	0	0
	Erie...........	8.11	0	0
Huron..........	Superior.......	4.47	30.70	0
	Michigan.......	20.46	0	0
	Huron..........	8.90	19.30	0
	Erie...........	17.88	8.00	0
Erie...........	Superior.......	0	3.40	0
	Huron..........	.03	19.30	0
	Erie...........	11.85	19.30	100.00
	Ontario........	.05	0	0
Total.....................		100.00	100.00	100.00

[1]To Canada.
[2]From Canada.

TABLE 11. - Projected average distances of traffic routes for limestone shipments, 1995

Route		Type of traffic		
From	To	Lakewise, miles	U.S. export, miles	U.S. import, miles
Superior.......	Huron..........	158	-	-
	Erie...........	452	-	-
Michigan.......	Michigan.......	268	-	-
	Huron..........	279	-	-
	Erie...........	462	-	-
Huron..........	Superior.......	-	104	-
	Michigan.......	364	-	-
	Huron..........	132	238	-
	Erie...........	354	333	-
Erie...........	Superior.......	-	481	-
	Huron..........	129	97	-
	Erie...........	53	62	36
	Ontario........	160	-	-

TABLE 12. - Round-trip time factor of loaded-trip time for limestone shipments by vessel class, 1995

Vessel class	Overall length, feet	Round-trip time factor
4	500-599	125 pct 10 hr
5	600-649	180 pct 16 hr
6	650-699	200 pct 16 hr
7	700-730	200 pct 16 hr
8	731-849	200 pct 10 hr
9	850-949	200 pct 12 hr

Bituminous Coal

Districts that contribute to coal commerce on the Great Lakes include Indiana, Illinois, Kentucky, Ohio, Pennsylvania, Tennessee, Virginia, and West Virginia. These States historically have provided about 90 percent of total U.S. coal production. Coal production from these States is expected to follow closely the growth in national energy consumption. Bureau of Mines forecasts estimate an energy consumption growth rate of 3.2 percent annually for period 1966-80. Consumption estimates of bituminous coal have been forecast for this period at an average annual growth rate of 3.0 percent.

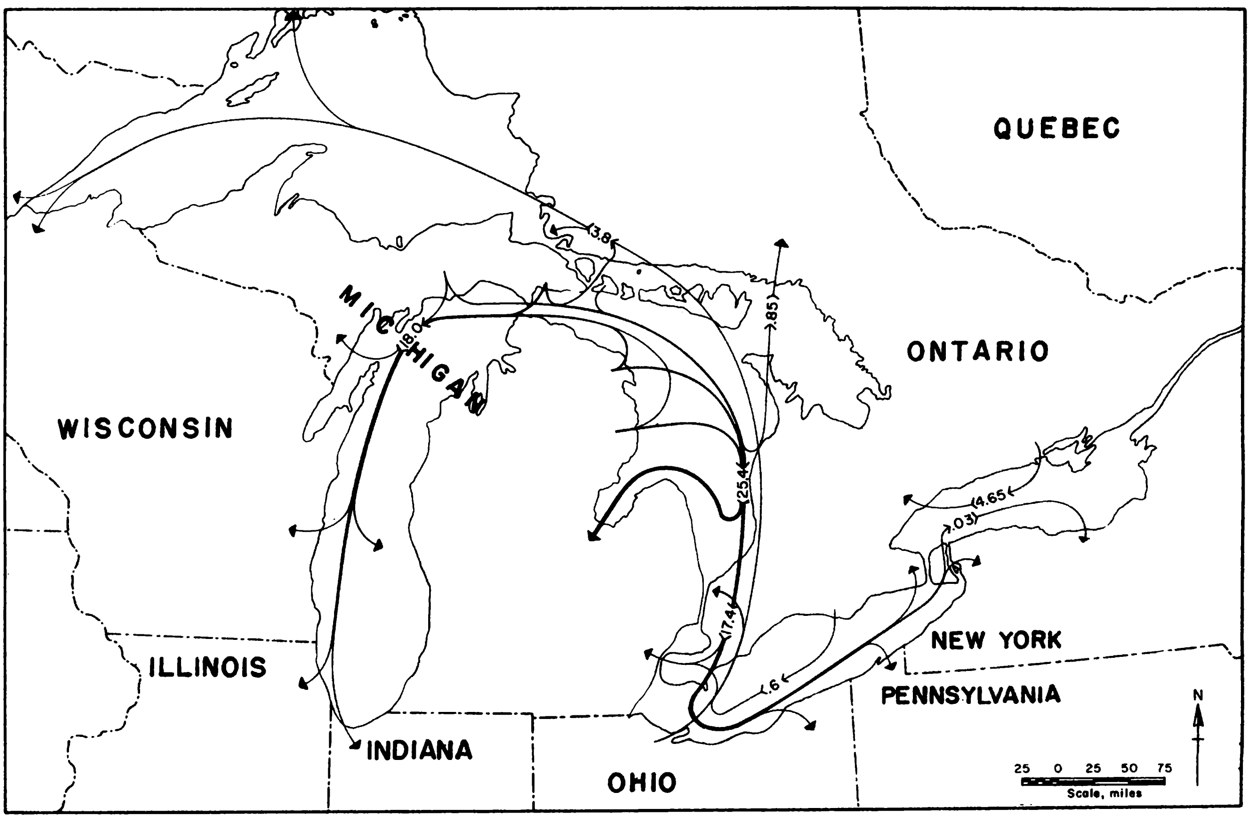

FIGURE 3. - Projected Limestone Traffic Flow, 1995. Million net tons.

In this study, a modification of these two nationwide growth rates was used in projecting bituminous coal production for those areas contributing to bituminous coal commerce on the Great Lakes. An annual growth rate of 3.1 percent was set for bituminous coal production up to year 1980. For the period beyond 1980, the annual growth rate was reduced to 2.5 percent. This reduction compensates for the loss of some coal output to nuclear energy, but still provides for some new requirements for coal as technology for coal liquefaction and gasification is perfected and utilized. It should be pointed out that any large increase in nuclear energy for electric power generation will depend on the successful development of an efficient breeder reactor.

Projected coal output is not expected to increase at a uniform rate throughout all States contributing to Great Lakes commerce for a variety of reasons. In Illinois, where a high nuclear energy growth rate is projected by the Federal Power Commission, the growth rate of coal production has been estimated to be less than that for other areas of the Great Lakes region. In Pennsylvania, data developed for the Susquehanna River Basin Mineral Economic Survey in 1964 by the Bureau of Mines indicate a negative growth rate for anthracitic coal and a relatively slow growth rate for output of bituminous coal in the eastern part of the State. Data from the Projective Economic Study of the Ohio River Basin, prepared in 1964 by Arthur D. Little, Inc., for the Corps of Engineers, indicate a higher growth rate for bituminous coal up to the year 2000 in western Pennsylvania, as well as in Ohio and Indiana. All of these factors were considered in estimating future coal production from areas contributing to commerce on the Great Lakes for base year 1960 as presented in table 13.

TABLE 13. - Projected bituminous coal production and Great Lakes shipments, million net tons

	Base year, 1960	1970	1975	1980	1985	1990	1995
Production[1]............	380	516	600	700	792	896	1,014
Shipments:							
Lakewise.............	36	42	45	47	49	50	52
Export..............	9	11	13	15	17	19	21
Import..............	0	0	0	0	0	0	0

[1] Indiana, Illinois, Kentucky, Ohio, Pennsylvania, Tennessee, Virginia, and West Virginia.

Bituminous coal shipments from districts contributing to coal commerce on the Great Lakes were analyzed to determine what percentage of the total annual production from each district was being transported on the Great Lakes. In 1960, the base year used for projecting future shipments, Bureau of Mines data indicated that 11.91 percent of the total production from the districts listed in table 14 was shipped on the Great Lakes. A time trend analysis, using the percentage of lake shipments to total production for selected years from 1957 to 1966, indicated an average annual decline of approximately 1.4 percent. This trend was applied to the 11.91 percent established for the base year 1960 and was used as the basis for projecting the shipments given in table 13.

TABLE 14. - Bituminous coal production and Great Lakes shipments, 1960

District	States included in districts	Production, thousand net tons	Great Lakes shipments, thousand net tons	Percentage production shipped on Great Lakes
1	Eastern Pennsylvania, Maryland, West Virginia..................	29,553	1,386	4.69
2	Western Pennsylvania............	37,027	2,958	7.99
3, 6	West Virginia..................	40,544	3,707	9.14
4	Ohio...........................	33,957	6,643	19.56
7	West Virginia, Virginia.........	33,661	4,763	14.15
8	West Virginia, Tennessee, Virginia, Kentucky, North Carolina......................	112,666	19,709	17.49
9	Western Kentucky................	30,587	2,726	8.91
10	Illinois.......................	45,977	2,887	6.28
11	Indiana........................	15,538	407	2.62
	Total......................	379,510	45,186	11.91

The projected traffic distribution pattern for 1995 bituminous coal shipments on the lakes is shown in table 15. Table 16 shows the projected average distance of traffic routes for the bituminous coal shipments. Round-trip time factors of loaded-trip times for vessels projected to handle this commerce are shown in table 17. Figure 4 represents the traffic flow of bituminous coal based on the projected shipment quantities and traffic distribution pattern for 1995.

TABLE 15. - Projected bituminous coal traffic distribution pattern, 1995

Route		Type of traffic[1]	
From	To	U.S. lakewise, percent	U.S. export,[2] percent
Michigan.............	Michigan..............	17.82	0
	Huron.................	1.16	0
Erie.................	Superior..............	8.98	14.00
	Michigan..............	5.66	0
	Huron.................	31.67	15.40
	Erie..................	34.71	19.50
	Ontario or St. Lawrence	0	49.80
Ontario..............	.........do..........	0	1.30
Total..................................		100.00	100.00

[1]No U.S. imports are projected.
[2]To Canada.

TABLE 16. - Projected average distances of traffic routes for bituminous coal shipments, 1995

Route		Type of traffic[1]	
From	To	Lakewise, miles	U.S. export, miles
Michigan.............	Michigan..............	126	-
	Huron.................	533	-
Erie.................	Superior..............	717	396
	Michigan..............	628	-
	Huron.................	184	239
	Erie..................	74	94
	Ontario or St. Lawrence	-	237
Ontario..............	..........do...........	-	117

[1]No U.S. imports are projected.

TABLE 17. - Round-trip time factor of loaded-trip time for bituminous coal shipments by vessel class, 1995

Vessel class	Overall length, feet	Round-trip time factor
4	500-599	125 pct + 10 hr
5	600-649	180 pct + 16 hr
6	650-699	200 pct + 16 hr
7	700-730	200 pct + 16 hr

Coal-bearing rocks underlie about 14 percent of the continental United States. Coal reserves have been identified in 34 States. The bituminous coal resources contributing to the coal commerce of the Great Lakes are in the nearby States bordering on Lakes Ontario, Erie, and Michigan (table 18). These States are close enough to the lakes to hold transportation costs to the lake harbors at a reasonable figure. Approximately 90 percent of the total U.S. bituminous coal production has come from these States in recent years (1957-66). During this period, approximately 10 percent of the total tonnage produced from these States was involved in commerce on the Great Lakes. The recoverable bituminous coal reserves from these States are apparently adequate to meet the Nation's projected requirements for at least the next 100 years.

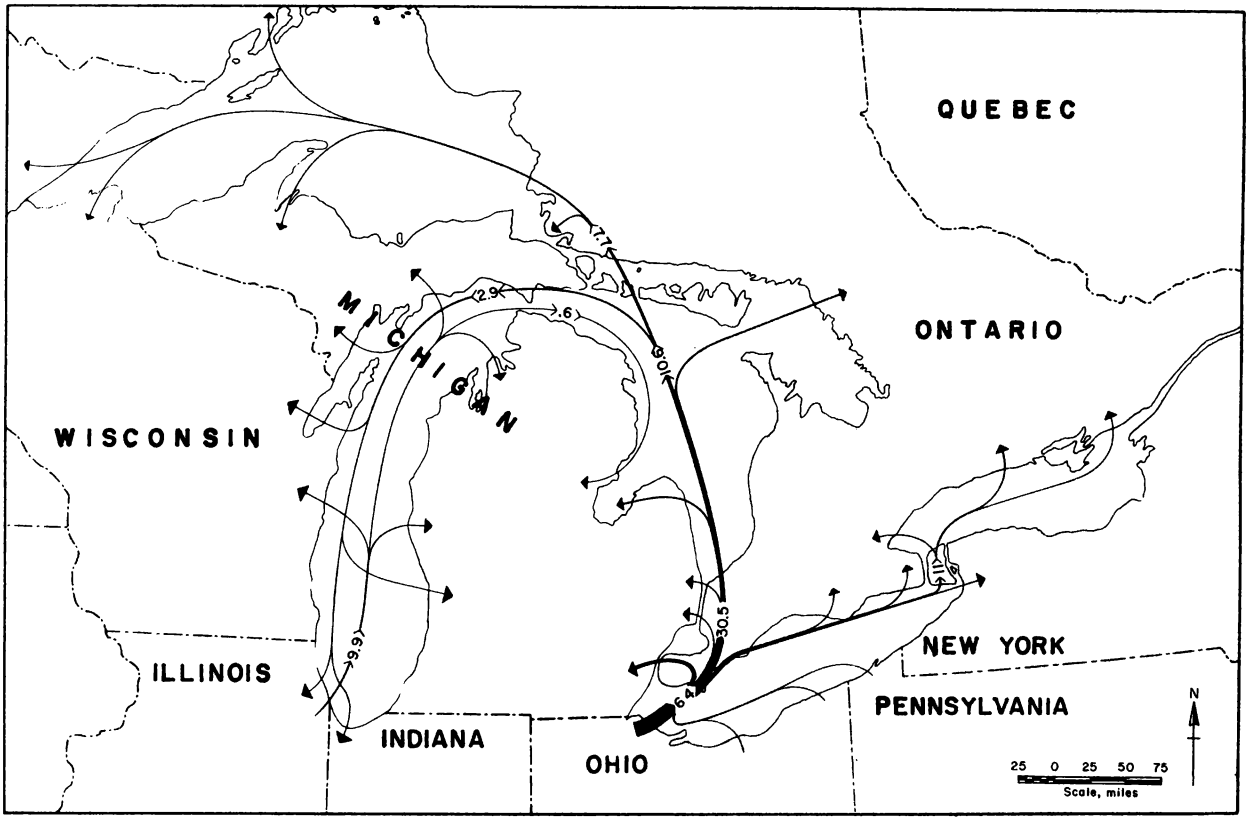

FIGURE 4. - Projected Bituminous Coal Traffic Flow, 1995. Million net tons.

TABLE 18. - Estimated bituminous coal reserves in principal States contributing to coal commerce on the Great Lakes, million net tons[1]

State	Estimated original reserves	Reserves depleted to Jan. 1, 1960	Remaining reserves Jan. 1, 1960	Recoverable reserves Jan. 1, 1960, assuming 50-percent recovery
Illinois............	137,329	948	136,381	68,190
Indiana.............	37,293	2,296	34,997	17,499
Kentucky............	72,318	5,292	67,026	33,513
Ohio................	46,488	4,104	42,384	21,192
Pennsylvania........	75,093	16,566	58,527	29,263
Tennessee...........	1,912	12	1,900	950
Virginia............	11,696	1,544	10,152	5,076
West Virginia.......	116,618	12,738	103,880	51,940
Total..........	498,747	43,500	455,247	227,623

[1] Averitt (3)

COMPOSITION AND CHARACTERISTICS OF PROJECTED U.S. GREAT LAKES BULK CARGO FLEET

The various reports prepared by the U.S. Army Corps of Engineers, in connection with its "Water Levels on the Great Lakes" study (11) and "Great Lakes Harbors Study" (12), present data and estimates on the anticipated composition and characteristics of the U.S. bulk cargo fleet in 1985. The data presented in these reports, together with information currently being developed for the International Joint Commission's study of water level on the Great Lakes in which the Bureau of Mines is cooperating, formed the basis for predicting the makeup of the 1995 fleet that will handle the bulk commerce of the mineral commodities under study in this report.

In determining the makeup of the fleet required to handle the anticipated traffic, consideration was given to the proportion of the shipping season used up in idle time, ballast trips, loading and unloading, and average loaded-trip time on each traffic route. The following factors were also considered:

1. The number of vessels of each class of the present fleet which will survive to 1995 or later, assuming a 50-year life.

2. Immediate past trends in the composition of the fleet and in replacing older vessels with larger, more efficient vessels.

3. The probable future trends in shipbuilding, taking into account the needs and competitive situation of particular trades and the economics, in ton-per-mile cost, of operating the largest feasible vessel.

Table 19 illustrates the trend over recent years of replacing smaller, older vessels with larger and more efficient vessels. The bulk cargo fleets listed in the table are those carrying iron ore, coal, limestone, and grain.

A recent innovation in shipbuilding is expected to enhance bulk-material handling, especially in the iron ore trade. In its Hewitt-Robins and Marine Consultants & Designers Division, Litton Industries has designed and placed under construction a bulk carrier, 1,000 feet long with a 105-foot beam, that is expected to appear in Great Lakes trade in early 1970. This vessel is being built to the maximum size that will pass through the recently completed new lock at Sault Ste. Marie, Mich. It is expected that vessels of this size will replace older and smaller vessels.

In predicting the makeup of the Great Lakes fleet, it was assumed that by 1995 only vessels less than 50 years old would still be in the fleet. The age and number of ships in each vessel class of the entire U.S. Great Lakes bulk cargo fleet as of 1965 are listed in table 20. Approximately 82 percent of the vessels were engaged in the iron ore, bituminous coal, and limestone trades.

TABLE 19. - Composition of U.S. Great Lakes bulk cargo fleet in 1953, 1957, 1964, and 1965

Vessel class	Overall length, feet	Number of ships by year			
		1953	1957	1964	1965
BULK CARRIERS					
1	Under 400	18	1	0	0
2	400-499	69	35	14	4
3	500-549	77	53	28	16
4	550-599	74	45	23	15
5	600-649	29	107	101	96
6	650-699	2	3	8	8
7	700-730	2	4	12	12
Total......................		271	248	186	151
SELF-UNLOADERS					
1	Under 400	3	6	0	0
2	400-499	6	10	4	3
3	500-549	16	10	9	9
4	550-599	4	13	13	13
5	600-649	2	8	11	11
6	650-699	1	1	2	4
7	700-730	0	0	0	0
Total......................		32	48	39	40

TABLE 20. - Age and number of vessels in U.S. Great Lakes bulk carrier fleet as of 1965[1]

Period built	Average age at 1968	Number of ships by vessel class								Total ships, all classes
		1	2	3	4	5	6	7	Other	
1891-95	75	1	0	0	0	0	0	0	0	1
1896-1900	70	0	1	0	0	0	0	0	1	2
1901-05	65	5	3	7	3	0	0	0	0	18
1906-10	60	4	7	23	19	23	0	0	0	76
1911-15	55	0	1	3	3	6	0	0	0	13
Subtotal.........		10	12	33	25	29	0	0	1	110
1916-20	50	0	1	0	3	13	0	0	1	18
1921-25	45	2	0	0	4	13	2	0	1	22
1926-30	40	2	1	0	0	13	0	0	0	16
1931-35	35	0	0	0	0	0	0	0	0	0
1936-40	30	0	0	0	0	4	0	0	0	4
Subtotal.........		4	2	0	7	43	2	0	2	60
1941-45	25	4	1	0	0	21	0	0	0	26
1946-50	20	0	0	0	0	0	1	0	0	1
1951-55	15	0	0	0	0	15	5	4	0	24
1956-60	10	0	0	0	1	0	2	5	0	8
1961-65	5	0	0	0	0	0	0	4	0	4
Subtotal.........		4	1	0	1	36	8	13	0	63
Grand total......		18	15	33	33	108	10	13	3	233

[1]U.S. Army Corps of Engineers (13).

The projected composition and characteristics of the U.S. Great Lakes bulk dry cargo fleet, as developed in this study for year 1995, are given in table 21. Based on the current trends in shipbuilding of Great Lakes vessels and other assumptions previously cited, it is anticipated that vessels engaging in the iron ore, bituminous coal, and limestone trades by year 1995 will be of the class 4 through class 10 types. Vessels in classes 4 through 7 are expected to consist of both self-unloaders and bulk carriers; those in the classes 8 through 10 are likely to be exclusively self-unloaders.

TABLE 21. - Vessel characteristics of projected U.S. Great Lakes bulk dry cargo fleet, 1995

Class	Overall length, feet	Cargo capacity, net tons			Draft at maximum cargo-carrying capacity, feet	Average speed, statute miles/hr	Net capacity/foot of immersion in excess of 18 feet of draft, tons	Estimated operating cost/hr
		Iron ore	Bituminous coal	Limestone				
4	500-599	-	13,300	16,100	22.5	14	920	$165
5	600-649	22,800	18,400	22,800	25.6	14	1,170	215
6	650-699	24,000	19,500	24,000	26.3	14	1,230	230
7	700-730	28,900	21,900	28,900	27.2	14	1,390	260
8	731-849	45,000	-	45,000	29.5	17	2,150	340
9	850-949	51,000	-	51,000	31.0	17	2,300	370
10	950-1,000	62,000	-	-	32.0	17	2,650	440

The operating costs per hour shown in table 21 are those calculated for an 8-month navigation season. Class 4 through class 7 operating costs represent those estimated for bulk carriers; the estimates for classes 8 through 10 are for self-unloaders. Estimates of vessel operating costs (table 22) were developed from a wide variety of data supplied in part by the U.S. Army Corps of Engineers, U.S. Maritime Administration, Canadian Department of Transport, and others. The various costing items used in table 22 are as follows:

Budget cost. Contract price, an allowance for changes, owners' engineering, and inspection.

Fixed charges. The daily costs are for a 365-day year.

Interest. Average interest of 5 percent on loan. Down payment of 12.5 percent assumed.

Amortization. 87.5 percent of the budget cost amortized over a 50-year period.

Overhead. 12 percent of vessel operating expenses.

Vessel expenses. The daily costs are for a 240-day operating year, with the exception of insurance, which is based on a 365-day year.

Wages. Base pay, overtime, and other expenses such as taxes, contributions to vacation, and welfare plans.

Subsistence. Cost of all edibles, including sales taxes and delivery charges.

Stores, supplies, and equipment. Cost of all consumable stores and supplies and expendable equipment, other than edibles, fuel, and water.

Insurance (annual). 1.5 percent of the cost of the vessel.

Maintenance and repair. All repair work not recoverable from insurance, including a reserve for special surveys, drydocking, inspection, and layup.

TABLE 22. - Operating costs[1] of projected U.S. bulk dry cargo fleet, 1995

Costs[2]	Class 4 nonautomated bulk carrier		Class 5 nonautomated bulk carrier		Class 6 nonautomated bulk carrier		Class 7 nonautomated bulk carrier	
Budget cost	$8,000,000		$9,500,000		$11,600,000		$13,700,000	
	Yearly	Daily	Yearly	Daily	Yearly	Daily	Yearly	Daily
Fixed charges:[3]								
Interest (5 percent)	$175,000	$479	$207,812	$569	$253,750	$695	$299,688	$821
Amortization	140,000	384	166,250	455	203,000	556	239,750	657
Overhead	73,969	203	97,981	268	99,603	273	108,928	298
Total fixed charges	388,969	1,066	472,043	1,292	556,353	1,524	648,366	1,776
Vessel expenses (daily):								
Wages (crew of 32)	$1,306		$1,322		$1,322		$1,322	
Subsistence	70		70		70		70	
Stores, supplies, and equipment	77		94		105		116	
Insurance	329		390		477		563	
Maintenance and repair	241		294		327		361	
Fuel	194		829		709		857	
Tug charges	80		100		100		100	
Layup	100		100		100		100	
Total daily vessel expenses	2,397		3,199		3,210		3,489	

Costs[2]	Class 8 nonautomated self-unloader		Class 9 nonautomated self-unloader		Class 10 nonautomated self-unloader	
Budget cost	$17,300,000		$18,700,000		$22,600,000	
	Yearly	Daily	Yearly	Daily	Yearly	Daily
Fixed charges:[3]						
Interest (5 percent)	$378,437	$1,037	$409,062	$1,121	$494,375	$1,354
Amortization	302,750	829	327,250	897	395,500	1,084
Overhead	146,601	402	162,749	446	192,236	527
Total fixed charges	827,788	2,268	899,061	2,464	1,082,111	2,965
Vessel expenses (daily):						
Wages (crew of 32)	$1,322		$1,322		$1,322	
Subsistence	70		70		70	
Stores, supplies, and equipment	143		180		212	
Insurance	711		768		929	
Maintenance and repair	448		562		663	
Fuel	1,826		2,149		2,795	
Tug charges	100		100		100	
Layup	100		100		100	
Total daily vessel expenses	4,720		5,251		6,191	

[1] 1967 dollars.
[2] See explanation of entries in text.
[3] Daily fixed charges rounded to nearest dollar.

Vessels operating in the present U.S. Great Lakes fleet cannot always carry capacity loads because of limitations imposed by the Coast Guard load-line regulations governing maximum draft for various periods of the navigation season. The load-line limits, or draft, of the anticipated vessel in the 1995 fleet are listed in table 23. These were based upon anticipated vessel construction, including reconstruction of existing vessels.

TABLE 23. - Seasonal load-line limits for vessels of projected 1995 Great Lakes bulk dry cargo fleet, feet

Vessel class	Shipping seasons			
	Winter (November through March)	Intermediate (April and October)	Summer (May and September)	Midsummer (June through August)
4	20.1	21.1	21.9	22.5
5	22.9	24.1	25.0	25.6
6	23.6	24.7	25.7	26.3
7	24.3	25.5	26.5	27.2
8	26.6	27.8	28.8	29.5
9	27.9	29.2	30.3	31.0
10	28.8	30.1	31.2	32.0

Past and future trends in fleet composition established in this study for the various dry bulk mineral commodity trades suggest that by 1995 the smaller vessels (class 4) will be restricted to the coal and limestone trades. The intermediate size vessels (classes 5 through 7) will handle all three bulk mineral commodities, and the larger vessels (classes 8 through 10) will be used mainly in the iron ore and limestone trades.

The distribution of projected shipments of iron ore, bituminous coal, and limestone by the various vessel classes in the projected 1995 fleet is shown in table 24. Figure 5 shows the actual combined tonnages of iron ore, bituminous coal, and limestone handled in each vessel class of the fleet during 1964 and compares these with the same combined tonnages forecast for year 1995.

TABLE 24. - Distribution of projected shipments by vessel class and commodity trade, 1995

Vessel class	Percentage of annual shipment tonnage		
	Iron ore	Bituminous coal	Limestone
4	0	25	20
5	20	25	20
6	10	25	10
7	10	25	10
8	20	0	20
9	20	0	20
10	20	0	0
Total...	100	100	100

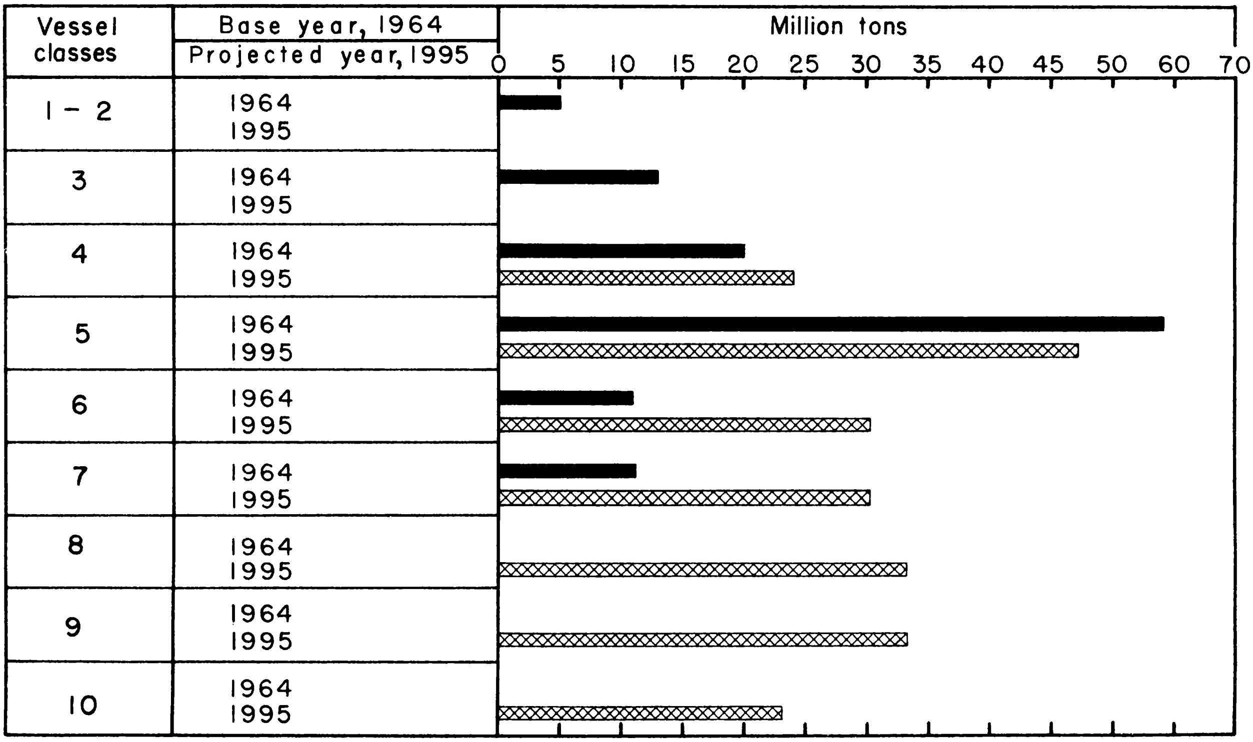

FIGURE 5. - Combined Tonnages of Iron Ore, Bituminous Coal, and Limestone Shipped by Various Class Vessels in 1964 and Projected Tonnages for 1995.

HISTORIC AND PROJECTED GREAT LAKES WATER LEVELS

The water levels of each of the Great Lakes have been recorded monthly since 1860 by the U.S. Army Corps of Engineers. The water levels are an important factor affecting the cost of transportation. In this study, the transportation costs estimated for 1995 were based on a range of lake levels simulated to represent proportionally the conditions that occurred during the period of record (1900-1967). The simulated ranges of water levels were developed by integrating the 68 elevations recorded from 1900 to 1968 for each lake and month into a time period representing a month and having a corresponding range of levels. Appendix A lists the observed level of each lake at the beginning of the month after adjustment to reflect the effects of manmade changes in supplies to and outflows from the lake over different periods of time since 1860.

The significant changes are these:

1. Long Lake and Ogoki diversion into Lake Superior in Canada.

2. Regulatory works in the St. Marys River.

3. Diversion out of the Lake Michigan Basin at Chicago.

4. Channel changes in the St. Clair-Detroit River system.

5. Diversion via the Welland Canal bypassing the Niagara River.

6. The Gut Dam and channel changes in the St. Lawrence River.

7. Regulatory works in the St. Lawrence River.

METHOD OF DETERMINING TRANSPORTATION COSTS

Methodology

The methodology used in estimating future transportation costs took into account three general conditions:

First, any increase or decrease in lake levels resulting from natural or manmade causes will change the cargo-carrying capacity of the fleet to some degree. For purposes of calculating the extent and effect of these changes, the projected vessel fleet was categorized into the various classes (sizes) of ships. These classes included prospective vessels.

Second, to the extent that the cargo-carrying capacity of the prospective fleet is increased by regulatory measures or natural causes, the volume of the commodities available for shipment can be carried in fewer trips; and conversely, to the extent that the fleet capacity is decreased, more trips will be required.

Third, the number of trips required, multiplied by the average length of trip (in hours) over the various routes, multiplied by total vessel cost per hour (calculated separately for each size of vessel) was taken as the measure of cost for transporting the selected mineral commodities.

In addition, four assumptions were made:

First, improvements to channels, locks, and harbors will be made if and when these are required to accommodate the future projected traffic, but such improvements will not include any increase in the present controlling 27-foot depths of the St. Lawrence Seaway and Welland Canal.

Second, the sources and markets of the principal mineral commodities moving on the Great Lakes will not be radically changed, and therefore the present general pattern of traffic will not change except to reflect the differential growth rates in particular segments of the traffic.

Third, any changes to the present regulatory water level controls for Lake Ontario and Lake Superior will not reduce the present controlling depths in the locks and channels of the Great Lakes system, including the St. Lawrence Seaway.

Fourth, all harbors with significant volume of traffic in the future will be deepened to 27 feet.

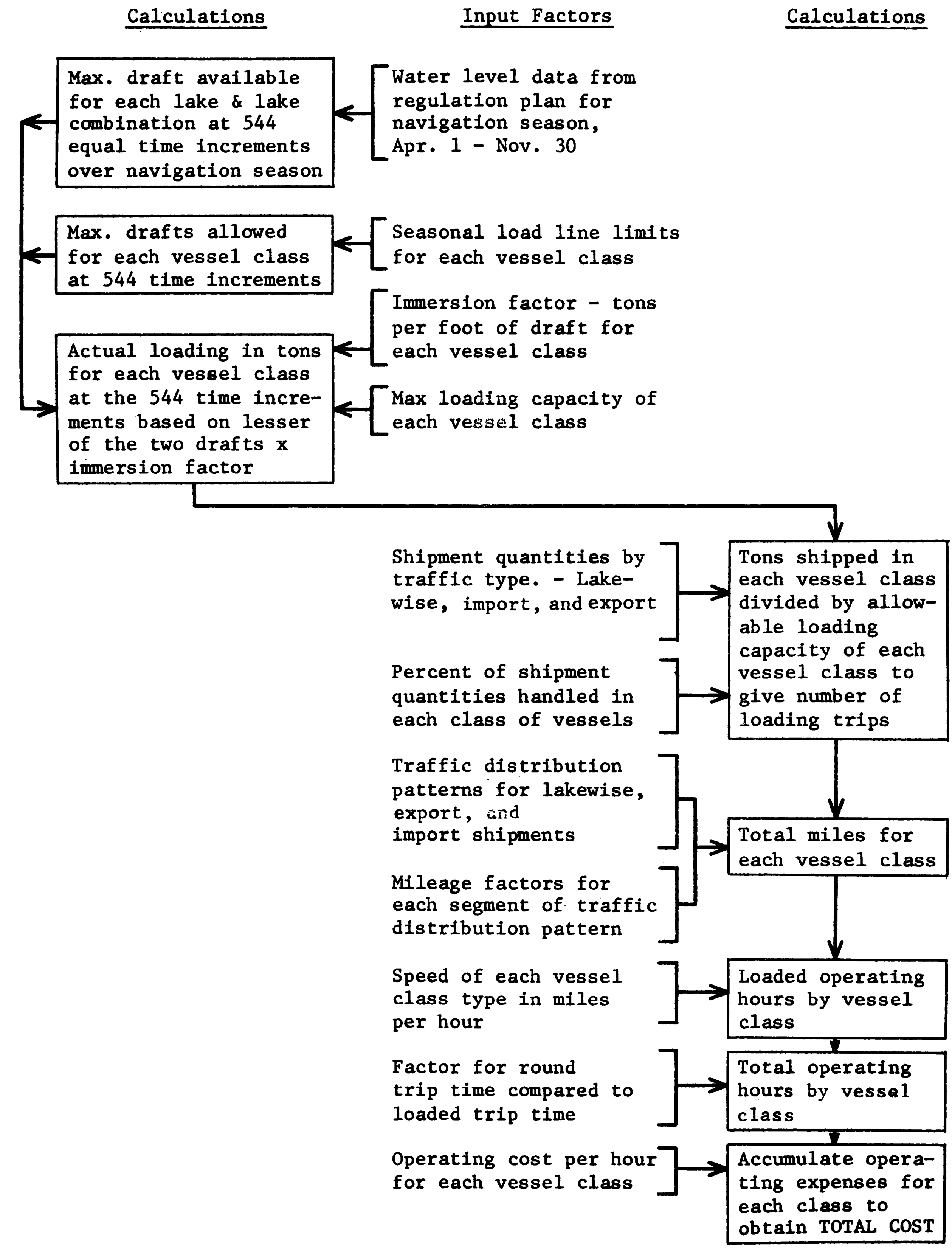

FIGURE 6. - Flow Diagram of Input Factors Used To Project Transportation Costs.

Data Input and Transportation Cost Model

Estimating the future transportation costs for Great Lakes shipments of the bulk mineral commodities considered in this study required the input and analysis of data as shown in figure 6. A computerized model was developed to integrate all the data. The computer program used for making the analysis is presented in appendix B, together with a flowsheet identifying and explaining all input and output variables used.

PROJECTED TRANSPORTATION COSTS

The analysis made to determine the Great Lakes waterborne transportation cost of prospective commerce in 1995, using the methodology and input data previously cited, indicates an annual cost of $163.5 million for the combined iron ore, bituminous coal, and limestone trades. The breakdowns of shipping costs for each commodity by types of traffic and routes involved appear in tables 25-27. The costs were estimated on the assumption that the U.S. bulk carrier fleet will handle all the lakewise shipments and 15 percent of the U.S. export and import shipments.

TABLE 25. - Projected transportation costs of iron ore shipments in 1995, million dollars

Route		Type of traffic			
From	To	Lakewise	Export	Import	Total
Superior............	Michigan............	38.99	0	0.45	39.44
	Erie................	67.10	0	.24	67.34
	Ontario.............	0	.91	0	.91
Michigan............	Michigan............	2.28	0	0	2.28
	Erie................	3.59	0	0	3.59
Huron...............	Michigan............	0	0	.05	.05
	Erie................	0	0	.13	.13
Ontario.............	Michigan............	0	0	1.19	1.19
	Erie................	0	0	1.61	1.61
Total...............................		111.96	.91	3.67	116.54

TABLE 26. - Projected transportation costs of bituminous coal shipments in 1995, million dollars

Route		Type of traffic[1]		
From	To	Lakewise	Export	Total
Michigan..............	Michigan................	3.34	0	3.34
	Huron...................	.58	0	.58
Erie..................	Superior................	5.81	.35	6.16
	Michigan................	3.27	0	3.27
	Huron...................	7.37	.27	7.64
	Erie....................	5.11	.20	5.31
Ontario...............	Ontario.................	0	.01	.01
Total....................................		25.48	.83	26.31

[1] No imports projected.

TABLE 27. - Projected transportation costs of limestone shipments in 1995, million dollars

Route		Type of traffic			
From	To	Lakewise	Export	Import	Total
Superior.............	Huron................	0.04	0	0	0.04
	Erie.................	1.93	0	0	1.93
Michigan.............	Michigan.............	2.59	0	0	2.59
	Huron................	1.18	0	0	1.18
	Erie.................	2.20	0	0	2.20
Huron................	Superior.............	1.17	.04	0	1.21
	Michigan.............	4.60	0	0	4.60
	Huron................	1.01	.04	0	1.05
	Erie.................	3.94	.02	0	3.96
Erie.................	Superior.............	0	.01	0	.01
	Huron................	0	.02	0	.02
	Erie.................	.90	.01	.04	.95
Total................................		19.56	.14	.04	19.74

SHIPPING COST AS A FUNCTION OF WATER LEVELS

The effect of various Great Lakes water level elevations on transportation costs for projected commerce is graphically analyzed in figures 7-15. The curves shown represent a monthly cost of transportation at various increments of water levels on each traffic route. The water level increments indicated, in feet above or below the low water datum plane, are taken to be the least depth that would be available in any one group of lakes making up the traffic route considered.

In all traffic routes, except those requiring passage through the Welland Canal between Lakes Erie and Ontario, a reduction in transportation cost is indicated with increases in water levels throughout a full range of stages between -2.0 to +4.0 feet of the low water datum plane.

Traffic routes involving the Welland Canal are limited to a controlling water depth of 27 feet by canal design. Therefore, any increased water depths available on Lakes Erie and Ontario that exceed 27 feet (controlling depth below the low water datum plane) cannot be taken advantage of in reducing transportation costs for these traffic routes.

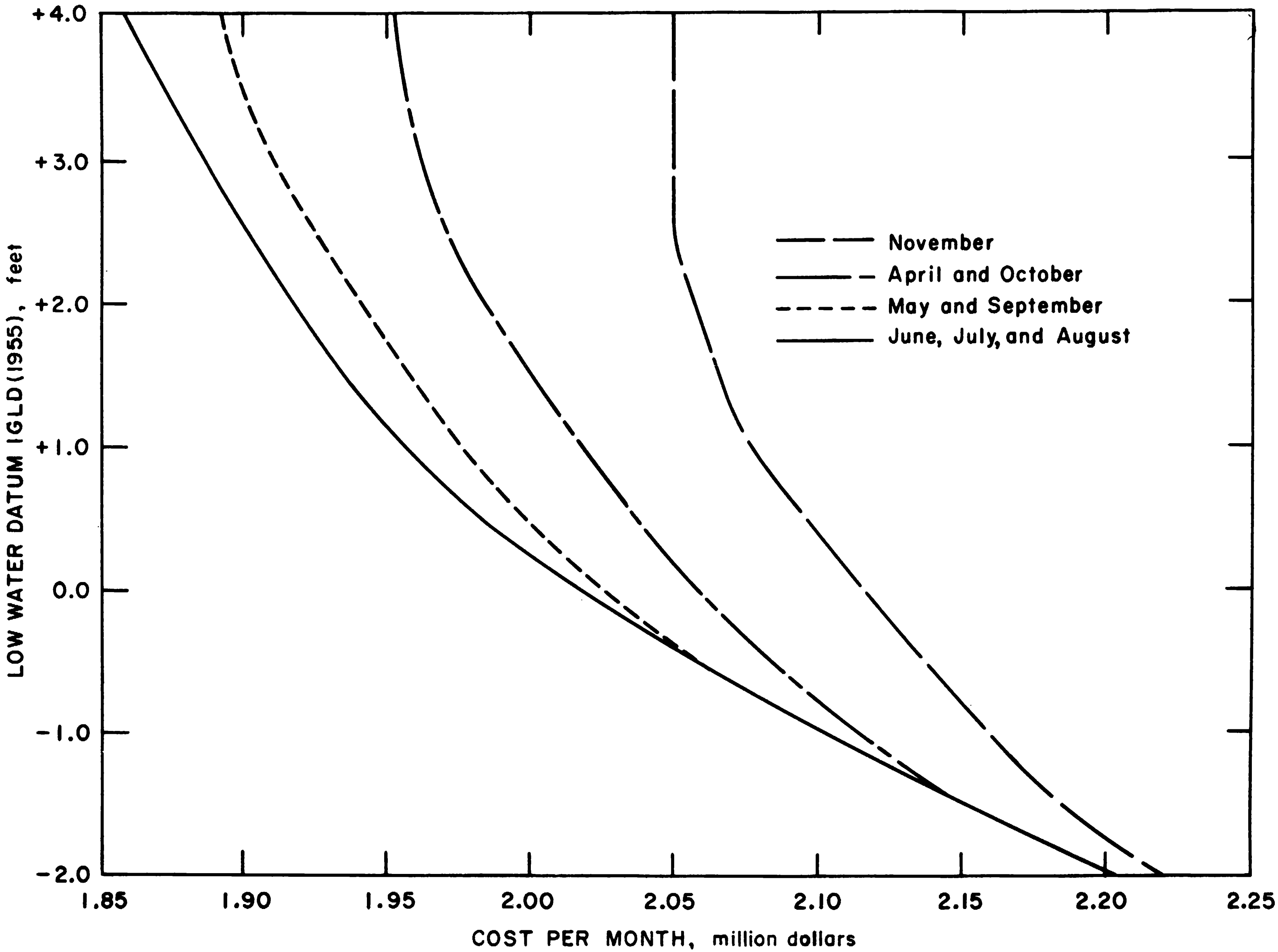

FIGURE 7.-Shipping Cost as a Function of Water Levels: Lakes Michigan-Huron Traffic. Costs related to year 1995 for combined shipments of iron ore, bituminous coal, and limestone during 8-month shipping season, April through November.

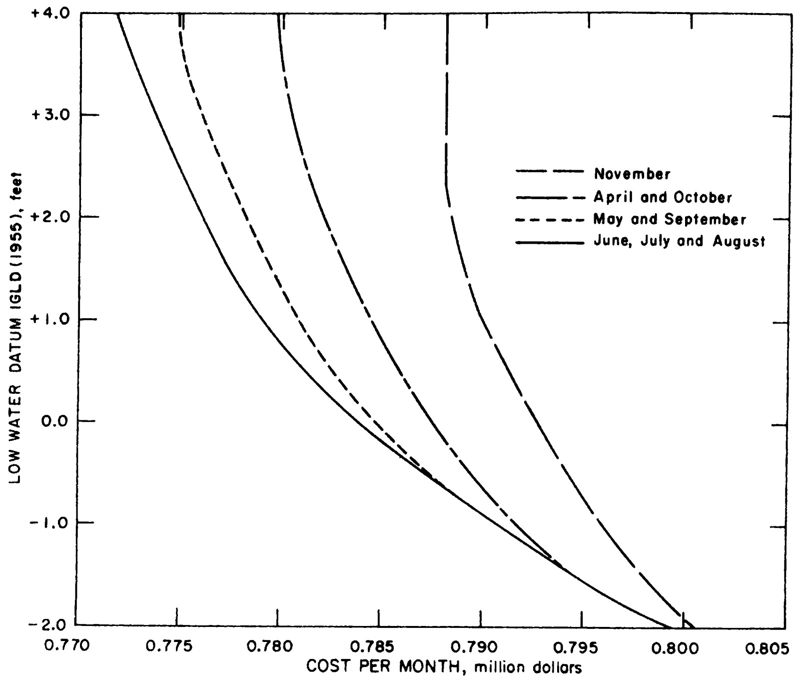

FIGURE 8. - Shipping Cost as a Function of Water Levels: Lake Erie Traffic. Costs related to year 1995 for projected combined shipments of iron ore, bituminous coal, and limestone during 8-month shipping season (April through November).

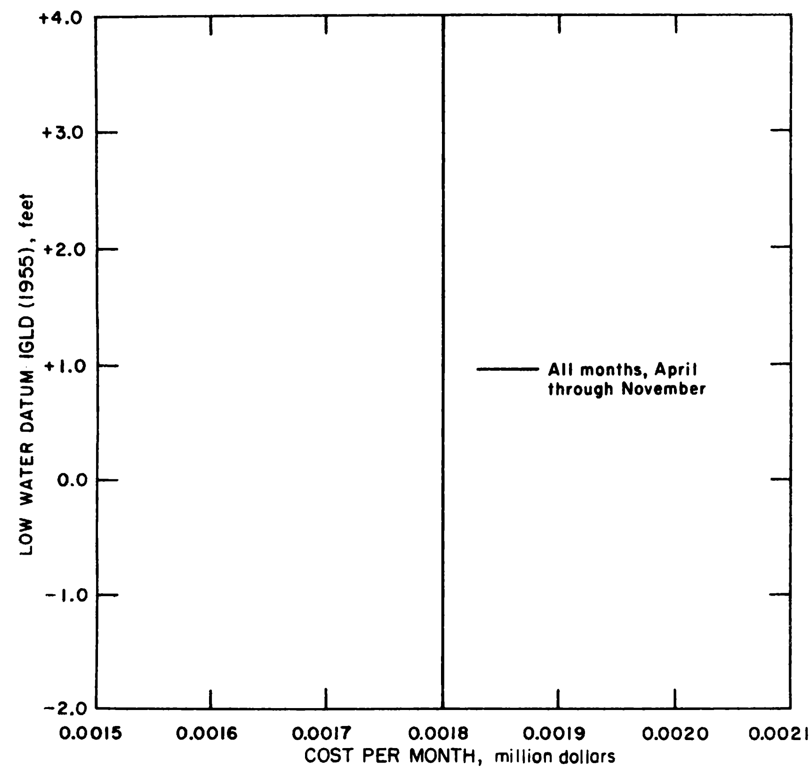

FIGURE 9. - Shipping Cost as a Function of Water Levels: Lake Ontario Traffic. Costs related to year 1995 for projected combined shipments of iron ore, bituminous coal, and limestone during 8-month shipping season, April through November.

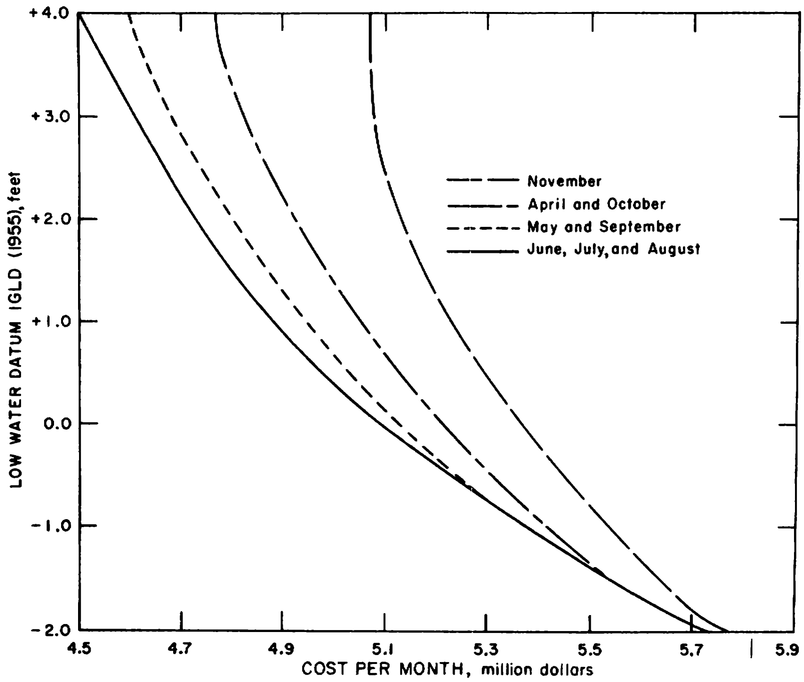

FIGURE 10. - Shipping Cost as a Function of Water Levels: Lakes Superior, Michigan-Huron Traffic. Costs related to year 1995 for projected combined shipments of iron ore, bituminous coal, and limestone during 8-month shipping season, April through November.

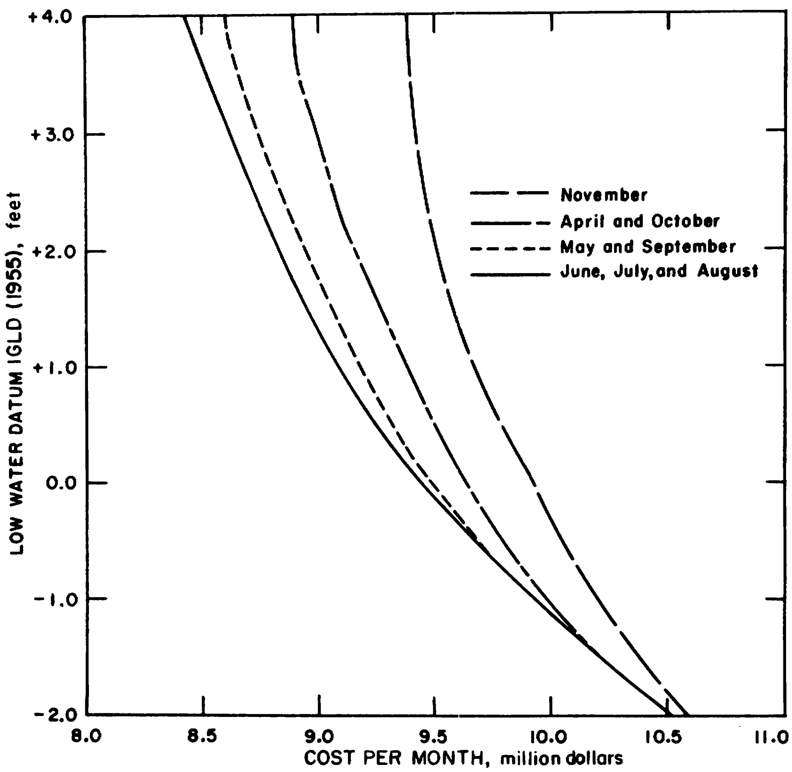

FIGURE 11. - Shipping Cost as a Function of Water Levels: Lakes Superior, Michigan-Huron, Erie Traffic. Costs related to year 1995 for projected combined shipments of iron ore, bituminous coal, and limestone during 8-month shipping season, April through November.

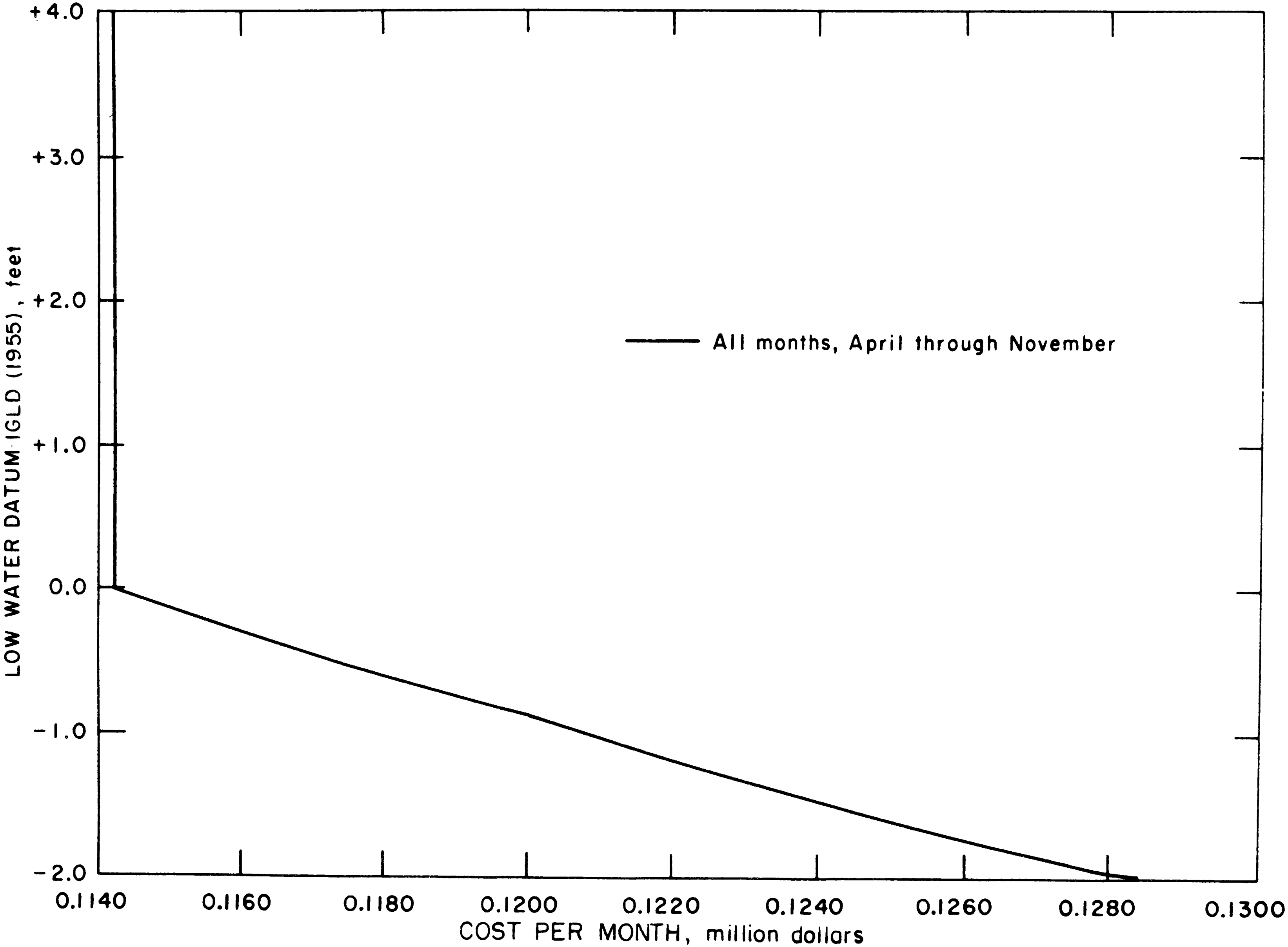

FIGURE 12. - Shipping Cost as a Function of Water Levels: Lakes Superior, Michigan-Huron, Erie, Ontario Traffic. Costs related to year 1995 for projected combined shipments of iron ore, bituminous coal, and limestone during 8-month shipping season, April through November.

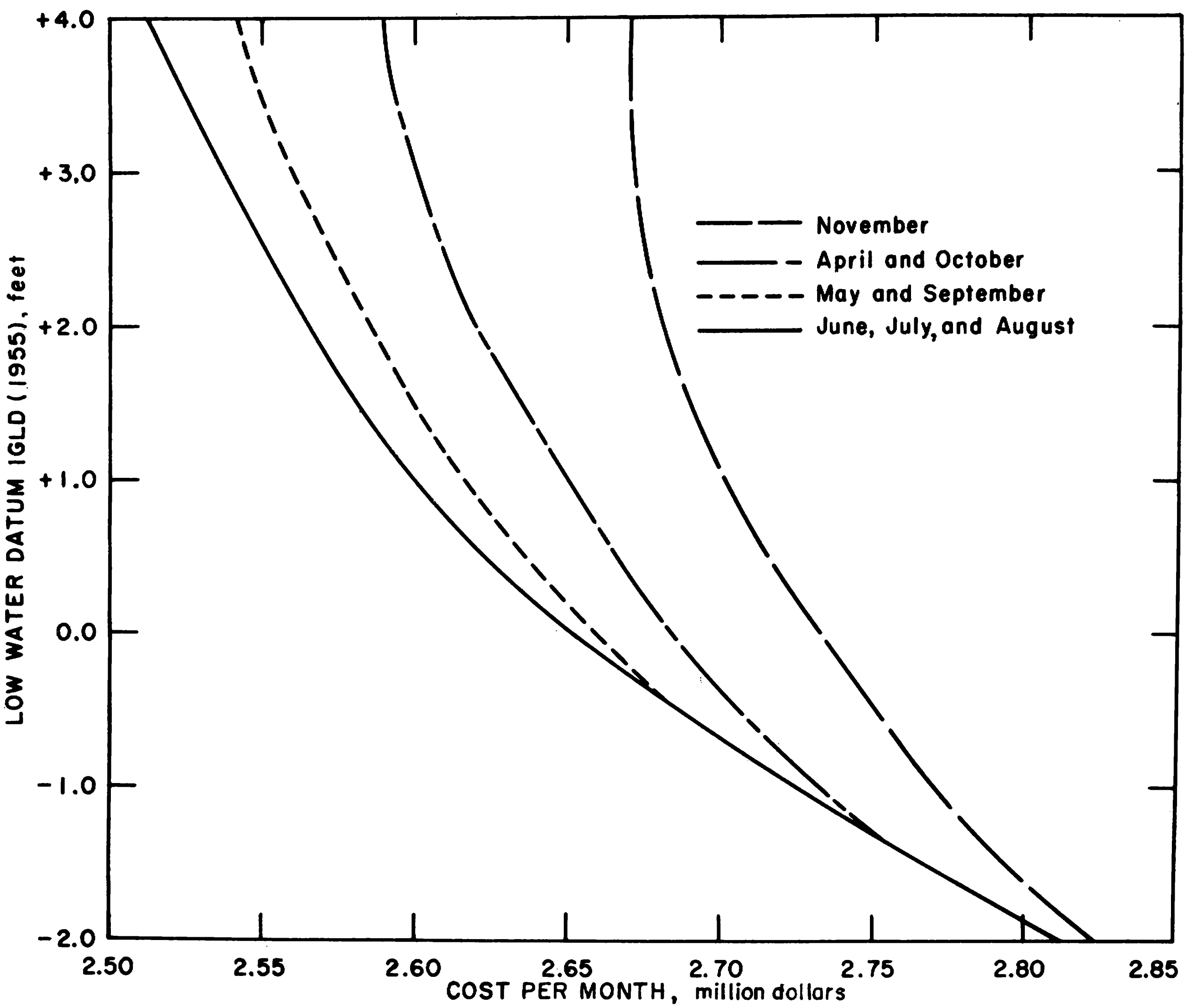

FIGURE 13. - Shipping Cost as a Function of Water Levels: Lakes Michigan-Huron, Erie Traffic. Costs related to year 1995 for projected combined shipments of iron ore, bituminous coal, and limestone during 8-month shipping season, April through November.

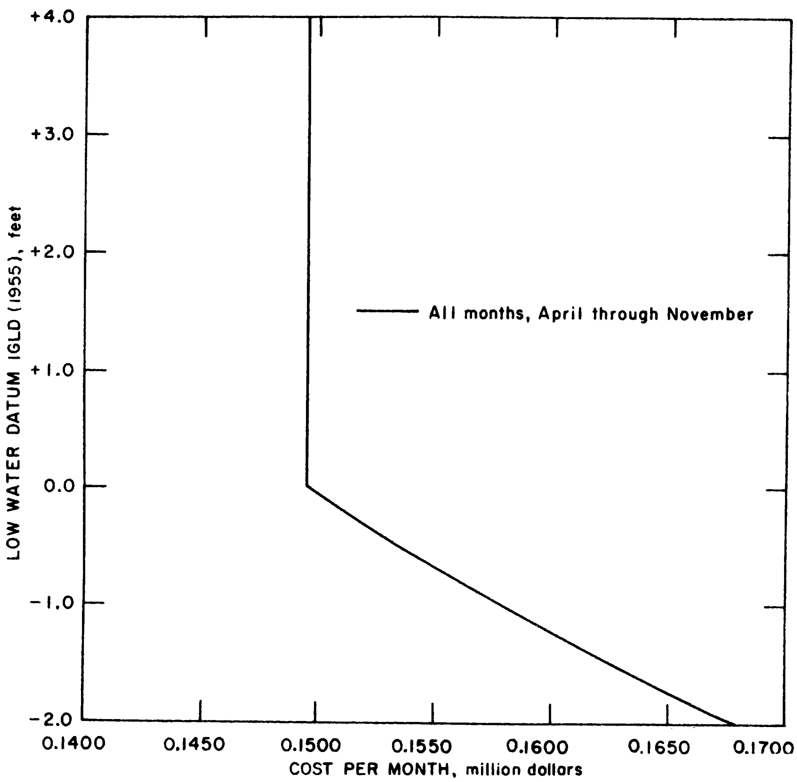

FIGURE 14. - Shipping Cost as a Function of Water Levels: Lakes Michigan-Huron, Erie, Ontario Traffic. Costs related to year 1995 for projected combined shipments of iron ore, bituminous coal, and limestone during 8-month shipping season, April through November.

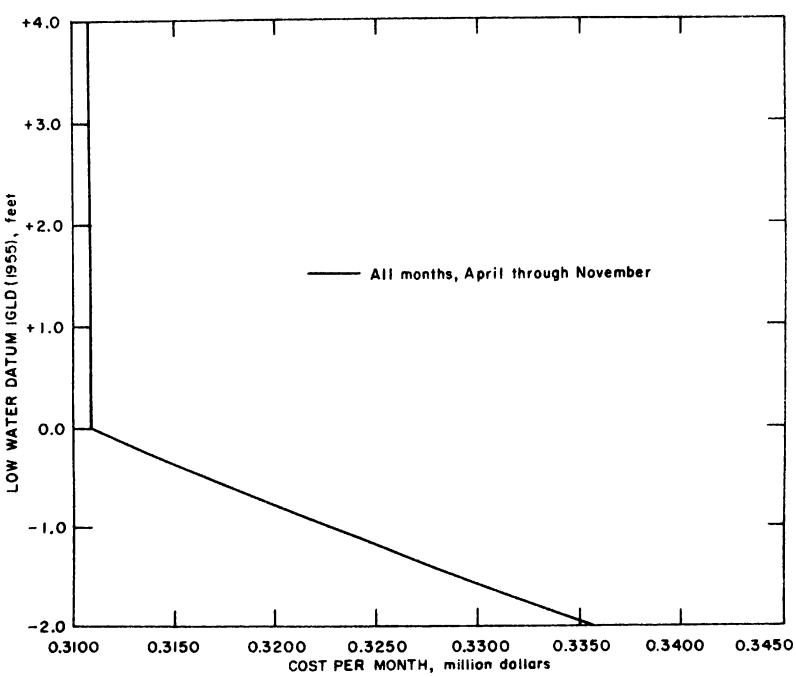

FIGURE 15. - Shipping Cost as a Function of Water Levels: Lakes Erie-Ontario Traffic. Costs related to year 1995 for projected combined shipments of iron ore, bituminous coal, and limestone during 8-month shipping season, April through November.

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12. _____. Great Lakes Harbors Study. November 1966, p. 27.

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APPENDIX A.--GREAT LAKES WATER LEVEL ELEVATIONS

TABLE A-1. - Adjusted beginning of month water level elevations on Lake Superior, 1900-1967[1]

Year	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.
1900	600.85	600.99	601.04	600.95	601.22	601.54	601.97	601.85
1901	600.44	600.57	600.63	600.93	601.16	601.09	600.81	600.85
1902	599.70	599.87	600.18	600.53	600.67	600.71	600.75	600.73
1903	599.85	600.07	600.73	600.76	600.96	600.99	601.07	600.95
1904	599.79	599.79	600.33	600.59	600.65	600.91	601.08	601.19
1905	600.06	600.17	600.53	600.85	601.02	601.13	601.25	601.00
1906	599.92	600.19	600.46	600.84	600.85	600.86	600.84	600.72
1907	600.04	600.00	600.52	600.81	600.90	601.20	601.33	601.06
1908	599.61	599.74	600.43	600.83	600.98	600.89	600.79	600.56
1909	599.53	599.65	600.21	600.29	600.74	600.83	600.81	600.69
1910	599.86	600.02	600.15	600.21	600.30	600.45	600.40	600.24
1911	599.16	599.20	599.70	600.06	600.52	600.75	600.85	600.69
1912	599.77	600.14	600.42	600.68	600.75	600.96	600.89	600.82
1913	599.79	600.03	600.44	600.60	600.92	601.01	601.13	601.02
1914	599.82	600.10	600.46	600.65	600.80	600.88	600.89	600.67
1915	599.47	599.67	599.97	600.52	600.73	600.76	601.09	601.13
1916	600.41	601.00	601.47	601.77	601.77	601.73	601.82	601.63
1917	600.51	600.50	600.66	600.88	600.89	601.00	600.93	600.74
1918	599.55	599.70	600.19	600.52	600.67	600.79	600.72	600.83
1919	600.00	600.25	600.44	600.52	600.56	600.50	600.52	600.34
1920	600.09	600.30	600.51	600.83	600.96	600.92	600.64	600.60
1921	599.56	600.00	600.33	600.38	600.54	600.56	600.51	600.29
1922	599.16	599.52	599.92	600.17	600.39	600.43	600.37	600.14
1923	599.08	599.23	599.39	599.54	599.76	599.82	599.83	599.81
1924	598.77	599.00	599.07	599.19	599.39	599.67	599.74	599.67
1925	598.64	598.82	598.99	599.26	599.43	599.47	599.55	599.30
1926	598.36	598.37	598.64	598.99	599.34	599.51	599.83	599.88
1927	599.77	600.09	600.70	600.95	601.17	601.01	600.90	600.80
1928	599.97	600.27	600.62	601.01	601.18	601.31	601.39	601.49
1929	600.52	600.66	600.72	600.74	600.90	600.76	600.80	600.71
1930	599.67	599.76	600.12	600.58	600.83	600.72	600.69	600.55
1931	599.30	599.39	599.64	599.88	600.07	600.01	600.12	600.17
1932	599.55	599.70	600.14	600.25	600.60	600.80	600.54	600.37
1933	599.53	599.83	600.38	600.54	600.66	600.61	600.68	600.62
1934	599.84	599.99	600.40	600.57	600.70	600.70	601.01	600.94
1935	600.30	600.55	600.69	600.95	601.15	601.03	600.83	600.85
1936	600.13	600.30	600.89	600.96	600.79	600.83	600.72	600.49
1937	599.79	600.17	600.63	600.64	600.90	601.01	600.85	600.76
1938	600.03	600.57	600.87	601.20	601.17	601.18	601.04	600.83
1939	600.18	600.40	600.89	601.29	601.35	601.37	601.17	600.85
1940	599.46	599.56	600.16	600.63	600.79	600.70	600.58	600.39
1941	599.39	599.94	600.22	600.51	600.63	600.71	601.11	601.20
1942	600.11	600.31	600.75	600.76	600.84	600.91	600.85	600.87
1943	600.02	600.18	600.73	601.35	601.36	601.35	601.09	600.83
1944	599.48	599.67	600.24	600.83	601.16	601.25	601.21	600.79
1945	600.22	600.56	600.68	600.75	600.82	600.94	600.92	600.69
1946	600.12	600.22	600.36	600.61	600.71	600.69	600.83	600.89
1947	599.72	600.10	600.55	601.19	601.12	601.10	600.98	600.76
1948	599.54	600.19	600.27	600.35	600.47	600.67	600.51	600.27
1949	599.59	599.75	600.14	600.51	600.85	600.80	600.66	600.71
1950	599.87	600.12	600.97	601.36	601.58	601.60	601.48	601.41
1951	600.70	601.18	601.43	601.67	601.68	601.79	601.87	601.76
1952	600.69	601.04	601.03	601.30	601.66	601.67	601.39	600.80
1953	599.90	600.18	600.70	601.14	601.28	601.33	601.07	600.71
1954	599.73	600.21	600.81	601.14	601.07	600.88	600.79	600.61
1955	599.62	600.03	600.26	600.37	600.55	600.70	600.61	600.62
1956	599.54	599.69	600.16	600.37	600.69	600.74	600.66	600.48
1957	599.62	599.98	600.17	600.50	600.65	600.62	600.61	600.37
1958	599.54	599.66	599.77	600.08	600.38	600.52	600.63	600.50
1959	599.61	599.75	600.32	600.54	600.62	601.03	601.20	601.09
1960	599.74	600.23	600.82	600.93	600.94	600.90	600.75	600.56
1961	599.77	599.94	600.25	600.38	600.46	600.40	600.50	600.49
1962	599.62	599.71	600.20	600.33	600.42	600.59	600.65	600.42
1963	599.62	599.89	600.09	600.52	600.57	600.64	600.59	600.42
1964	599.42	599.87	600.50	600.83	600.84	600.99	601.07	600.87
1965	599.96	600.20	600.73	600.87	600.90	600.99	601.13	601.03
1966	600.46	600.64	600.89	600.90	600.90	601.04	600.76	600.76
1967	600.04	600.55	600.59	600.86	600.88	600.94	600.66	600.67

[1]Elevations are in feet above sea level, IGLD (1955).

TABLE A-2. - Adjusted beginning of month water level elevations on Lakes Michigan-Huron, 1900-1967[1]

Year	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.
1900	578.14	578.44	578.64	578.79	579.17	579.29	579.26	579.23
1901	578.96	579.32	579.57	579.70	579.92	579.86	579.50	579.32
1902	578.67	578.84	579.09	579.36	579.65	579.38	579.19	578.82
1903	578.86	579.06	579.31	579.40	579.50	579.48	579.55	579.32
1904	579.17	579.61	580.07	580.21	580.19	580.05	579.88	579.68
1905	579.20	579.32	579.75	580.07	580.21	580.15	579.96	579.64
1906	579.51	579.75	579.93	580.09	580.05	579.80	579.59	579.34
1907	579.30	579.48	579.75	579.94	578.00	579.87	579.77	579.50
1908	579.31	579.65	580.15	580.23	580.37	580.01	579.67	579.25
1909	578.48	579.01	579.44	579.57	579.52	579.32	579.07	578.57
1910	578.51	578.89	579.02	579.05	578.90	578.77	578.61	578.38
1911	577.73	578.02	578.37	578.48	578.32	578.15	578.06	577.98
1912	577.87	578.26	579.02	579.14	579.23	579.31	579.31	579.14
1913	579.09	579.65	580.02	580.09	580.09	579.92	579.63	579.46
1914	579.01	579.18	579.40	579.67	570.67	579.51	579.29	579.01
1915	578.32	578.37	578.50	578.65	578.69	578.64	578.67	578.29
1916	578.46	579.09	579.65	580.12	580.17	579.92	579.75	579.64
1917	579.42	579.80	580.07	580.65	580.90	580.70	580.43	580.09
1918	580.14	580.40	580.82	580.75	580.69	580.46	580.09	579.90
1919	579.73	580.09	580.46	580.40	580.32	580.00	579.73	579.57
1920	579.34	579.70	579.75	579.96	580.00	579.90	579.77	579.46
1921	579.05	579.55	579.57	579.57	579.39	579.23	579.05	578.73
1922	578.57	579.23	579.48	579.63	579.75	579.46	579.23	578.75
1923	578.01	578.39	578.73	578.88	578.82	578.65	578.54	578.26
1924	577.73	577.98	578.32	578.48	578.56	578.68	578.44	578.00
1925	577.31	577.37	577.26	577.43	577.43	577.14	576.89	576.59
1926	576.30	576.69	576.98	577.31	577.34	577.30	577.23	577.12
1927	577.38	577.62	578.07	578.25	578.40	578.15	578.11	577.92
1928	578.02	578.62	578.93	579.25	579.46	579.54	579.45	579.65
1929	579.98	580.69	581.29	581.50	581.48	581.25	580.86	580.52
1930	579.98	580.11	580.30	580.46	580.45	580.09	579.67	579.23
1931	578.20	578.20	578.32	578.37	578.21	577.84	577.92	577.59
1932	577.40	577.55	577.80	577.79	577.76	577.61	577.26	577.09
1933	576.67	577.21	577.73	577.84	577.76	577.42	577.15	576.88
1934	576.50	576.88	576.96	577.09	576.98	576.70	576.78	576.48
1935	576.79	576.95	577.07	577.44	577.52	577.40	577.26	576.96
1936	577.00	577.21	577.56	577.61	577.54	577.48	577.45	577.26
1937	576.76	577.23	577.48	577.65	577.65	577.57	577.39	577.18
1938	577.71	578.02	578.34	578.63	578.70	578.70	578.59	578.25
1939	577.89	578.27	578.56	578.93	578.92	578.94	578.70	578.40
1940	577.46	577.59	577.96	578.23	578.25	578.26	578.14	577.81
1941	577.48	577.84	577.93	577.94	577.87	577.59	577.62	577.77
1942	578.14	578.36	578.81	579.09	579.11	578.84	578.71	578.54
1943	578.73	579.06	579.57	580.15	580.32	580.29	580.00	579.73
1944	579.13	579.21	579.39	579.62	579.55	579.34	579.32	579.00
1945	578.51	578.75	579.20	579.64	579.70	579.52	579.45	579.25
1946	579.32	579.34	579.54	579.70	579.54	579.23	578.95	578.62
1947	577.96	578.68	579.25	579.59	579.73	579.65	579.54	579.34
1948	578.75	579.09	579.30	579.37	579.29	578.98	578.52	577.98
1949	577.67	577.92	578.00	578.25	578.25	577.90	577.57	577.26
1950	577.27	577.80	578.02	578.34	578.54	578.51	578.42	578.23
1951	578.46	579.25	579.50	579.71	580.00	580.01	579.86	579.98
1952	580.12	580.65	580.87	581.05	581.30	581.26	580.90	580.26
1953	579.93	580.18	580.38	580.63	580.64	580.56	580.18	579.88
1954	579.09	579.55	579.75	580.17	580.20	580.06	579.96	580.21
1955	579.48	579.84	579.93	579.92	579.73	579.38	578.84	578.68
1956	578.07	578.38	578.79	578.89	578.96	578.98	578.61	578.29
1957	577.51	577.80	578.09	578.34	578.48	578.21	578.00	577.76
1958	577.43	577.55	577.44	577.50	577.52	577.34	577.18	576.87
1959	576.48	577.09	577.40	577.42	577.40	577.51	577.38	577.39
1960	577.55	578.21	579.00	579.34	579.56	579.54	579.30	578.90
1961	578.19	578.42	578.48	578.65	578.65	578.51	578.52	578.31
1962	577.96	578.21	578.43	578.46	578.32	578.19	577.90	577.62
1963	576.88	577.09	577.34	577.34	577.36	577.25	577.02	576.74
1964	575.81	576.11	576.34	576.38	576.48	576.39	576.30	575.99
1965	575.99	576.57	576.94	577.02	577.04	577.06	577.30	577.23
1966	577.63	577.86	578.01	578.15	578.09	577.95	577.59	577.27
1967	577.59	578.30	578.48	578.96	578.92	578.79	578.54	578.40

[1]Elevations are in feet above sea level, IGLD (1955).

TABLE A-3. - Adjusted beginning of month water level elevations on Lake Erie, 1900-1967[1]

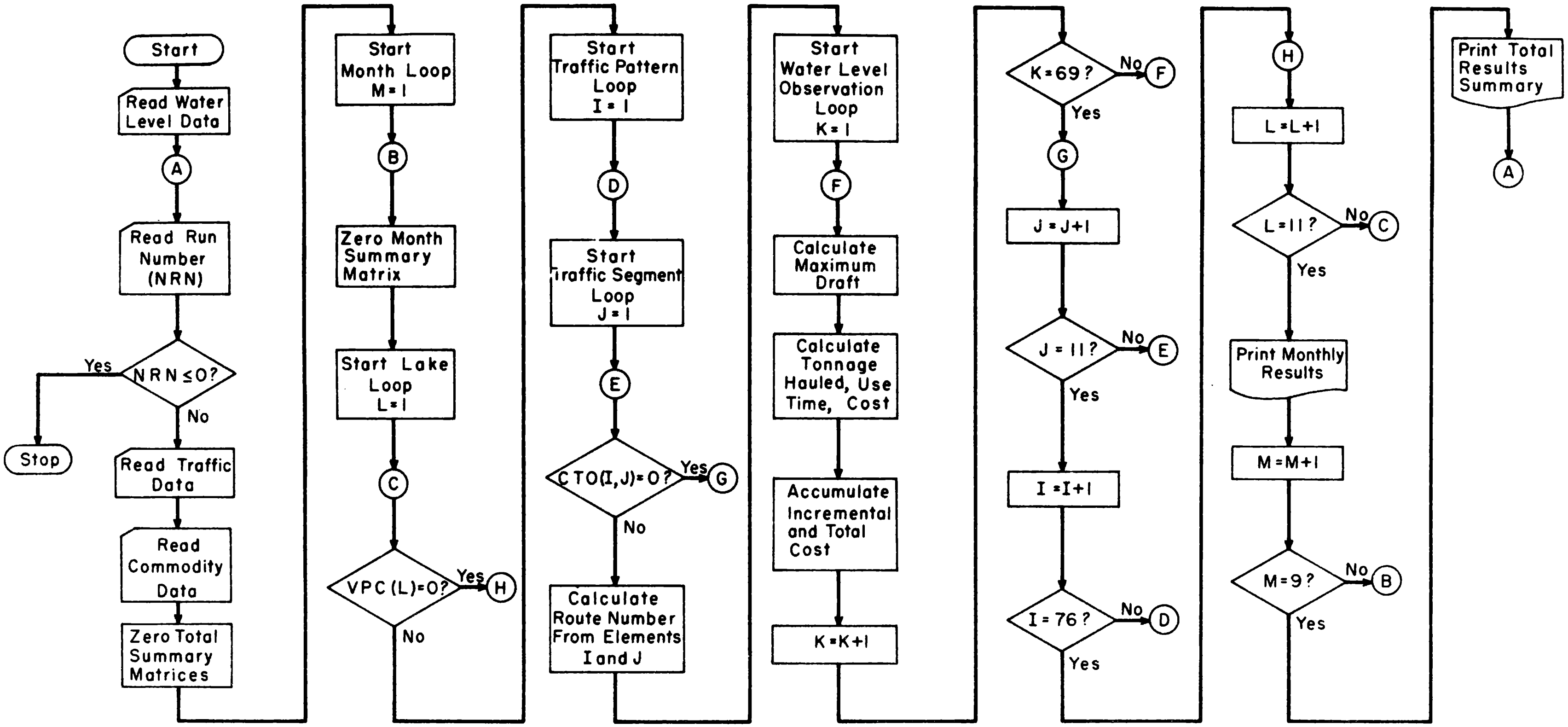
Year	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.
1900	570.11	570.51	570.73	570.76	570.75	570.71	570.38	570.16
1901	569.93	569.92	570.22	570.54	570.62	570.59	570.32	570.07
1902	570.13	570.48	570.81	571.19	571.78	571.28	571.28	570.94
1903	571.28	571.85	571.69	571.69	571.64	571.46	571.07	570.71
1904	571.47	572.05	572.25	572.15	572.05	571.75	571.44	571.04
1905	570.41	570.95	571.45	571.82	571.76	571.54	571.32	570.85
1906	570.78	571.18	571.26	571.46	571.46	571.36	571.07	571.00
1907	571.39	571.44	571.72	571.94	571.86	571.45	571.40	571.25
1908	571.76	572.01	572.32	572.11	571.96	571.65	571.22	570.84
1909	570.56	571.07	571.76	571.88	571.59	571.26	570.75	570.28
1910	570.50	571.04	571.24	571.11	571.05	570.80	570.51	570.32
1911	569.82	570.36	570.41	570.43	570.16	570.09	570.06	569.89
1912	570.38	571.13	571.30	571.29	571.20	571.19	571.06	570.87
1913	572.46	572.82	572.63	572.38	572.14	571.68	571.25	570.90
1914	570.74	571.28	571.90	571.71	571.54	571.35	571.10	570.65
1915	570.17	570.24	570.51	570.61	570.87	570.96	570.92	570.47
1916	571.03	571.49	571.96	572.18	571.94	571.44	571.04	570.71
1917	571.00	571.66	572.16	572.62	572.72	572.32	571.98	571.92
1918	571.23	570.79	571.28	571.42	571.47	571.35	571.20	571.14
1919	571.74	572.09	572.67	572.45	572.12	571.84	571.45	571.31
1920	570.13	571.07	571.25	571.48	571.51	571.38	571.05	570.82
1921	571.30	571.92	571.84	571.73	571.40	571.09	570.74	570.51
1922	570.66	571.40	571.65	571.57	571.44	571.15	570.89	570.40
1923	570.10	570.44	570.86	570.84	570.71	570.29	570.26	569.81
1924	570.18	570.69	570.92	571.24	571.04	570.64	570.50	570.12
1925	570.01	570.07	569.89	569.89	569.80	569.63	569.57	569.18
1926	568.74	569.57	569.55	569.74	569.70	569.71	570.18	570.14
1927	570.11	570.29	570.71	570.70	570.74	570.32	570.06	569.78
1928	570.25	570.59	570.69	571.26	571.32	571.06	570.63	570.54
1929	571.81	572.86	573.07	572.93	572.82	572.35	572.03	571.75
1930	572.60	572.74	572.47	572.42	572.07	571.68	571.31	570.92
1931	569.81	570.23	570.39	570.50	570.44	570.12	569.93	569.64
1932	570.34	570.51	570.87	570.68	570.53	570.22	569.73	569.45
1933	570.00	570.42	570.79	570.56	570.26	569.89	569.57	569.16
1934	568.46	569.07	569.14	569.21	569.03	568.86	568.86	568.38
1935	568.75	568.92	569.31	569.45	569.51	569.31	568.99	568.85
1936	569.12	569.50	569.56	569.54	569.36	569.40	569.30	569.12
1937	569.84	570.82	570.78	571.22	571.06	570.74	570.03	569.68
1938	570.32	570.64	570.76	570.81	570.82	570.55	570.34	569.97
1939	570.10	570.81	570.75	570.86	570.81	570.50	570.16	569.91
1940	569.40	570.26	570.60	570.82	570.68	570.59	570.30	569.98
1941	569.64	569.93	570.05	570.12	570.04	569.74	569.32	569.22
1942	569.95	570.54	570.92	571.00	571.07	570.81	570.53	570.40
1943	570.89	571.38	572.43	572.45	572.48	572.04	571.62	571.32
1944	570.65	571.59	571.86	571.85	571.42	571.12	570.96	570.50
1945	570.96	571.30	571.82	572.16	571.99	571.51	571.63	571.51
1946	571.10	571.04	571.43	571.89	571.64	571.12	570.76	570.55
1947	570.35	571.57	572.18	572.45	572.16	572.00	571.42	571.22
1948	571.51	571.84	572.14	572.12	571.76	571.40	570.85	570.46
1949	570.92	571.01	571.05	570.95	570.72	570.29	569.92	569.62
1950	571.26	571.74	571.49	571.32	571.18	570.86	570.57	570.43
1951	571.71	572.07	572.14	572.11	571.86	571.49	571.11	570.92
1952	572.67	572.97	573.01	572.76	572.44	572.26	571.91	571.22
1953	571.94	572.07	572.43	572.35	572.13	571.86	571.36	570.95
1954	571.44	572.22	571.98	571.88	571.63	571.42	571.14	571.69
1955	572.34	572.60	572.34	572.06	571.79	571.51	571.04	570.85
1956	570.56	571.15	571.90	571.80	571.64	571.62	571.03	570.65
1957	570.31	571.22	571.29	571.41	571.35	570.86	570.56	570.16
1958	569.76	569.99	570.01	570.23	570.35	570.16	569.97	569.53
1959	570.04	570.54	570.72	570.48	570.22	570.03	569.59	569.54
1960	570.31	570.87	571.18	571.46	571.31	571.15	570.73	570.21
1961	570.50	571.53	571.46	571.41	571.30	571.06	570.62	570.07
1962	570.11	570.26	570.26	570.35	570.15	569.97	569.69	569.42
1963	569.57	569.92	569.90	569.76	569.60	569.36	568.99	568.68
1964	569.13	569.71	569.63	569.51	569.29	569.18	568.73	568.31
1965	569.14	569.57	569.66	569.57	569.39	569.23	569.11	568.93
1966	569.84	570.22	570.32	570.42	570.26	570.14	569.68	569.57
1967	570.39	570.80	571.01	571.09	570.96	570.66	570.37	570.26

[1] Elevations are in feet above sea level, IGLD (1955).

TABLE A-4. - Adjusted beginning of month water level elevations on Lake Ontario, 1900-1967[1]

Year	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.
1900	244.61	245.53	245.53	245.82	246.00	245.87	245.26	244.62
1901	244.35	245.60	245.53	245.66	245.33	245.05	244.55	243.89
1902	244.72	244.94	245.20	245.78	246.33	245.76	244.87	244.16
1903	245.06	245.62	245.32	245.50	245.62	245.22	244.48	244.06
1904	244.74	245.82	246.25	246.37	246.16	245.53	244.71	244.14
1905	243.62	244.62	245.30	245.84	245.82	245.47	244.57	244.07
1906	243.97	244.48	244.83	245.42	245.51	244.96	244.34	244.24
1907	244.49	244.73	245.19	245.49	245.56	245.12	244.66	244.21
1908	245.14	245.62	246.26	246.18	245.82	245.01	244.28	243.76
1909	243.84	245.00	245.87	245.68	245.53	245.00	244.31	243.69
1910	244.30	244.89	245.39	245.45	245.36	245.11	244.58	244.01
1911	243.76	244.72	245.32	245.72	245.59	245.26	244.99	244.72
1912	244.39	245.78	246.48	246.51	245.96	245.33	244.91	244.36
1913	245.49	246.07	246.21	246.01	245.55	245.12	244.45	244.00
1914	244.09	245.08	245.49	245.48	245.20	245.01	244.51	243.92
1915	243.92	244.26	244.71	244.92	245.03	245.41	244.87	244.22
1916	244.18	245.31	245.97	246.64	246.03	245.03	244.23	243.71
1917	244.48	245.33	245.42	246.03	246.20	245.45	244.68	244.43
1918	244.62	244.94	244.94	245.12	245.10	244.76	244.53	244.33
1919	244.34	245.06	246.16	246.06	245.60	244.93	244.28	243.87
1920	243.94	244.55	245.01	245.37	245.84	245.51	244.89	244.37
1921	244.73	245.03	245.26	245.26	245.11	244.66	244.23	243.91
1922	244.26	245.48	245.55	245.85	245.57	244.93	244.33	243.72
1923	243.69	244.64	245.46	246.00	245.72	245.41	244.97	244.55
1924	244.30	245.10	245.82	245.78	245.62	245.14	244.72	244.00
1925	244.16	244.37	244.55	244.61	244.51	244.09	243.95	243.61
1926	243.08	244.45	244.97	245.22	245.05	245.01	245.01	244.70
1927	244.37	244.31	244.87	245.24	245.51	245.10	244.62	244.22
1928	245.21	245.67	245.66	245.95	245.95	245.55	244.64	244.24
1929	245.05	246.21	246.86	246.69	246.43	245.59	244.84	244.28
1930	245.97	246.17	246.26	246.18	245.75	245.01	244.36	243.62
1931	243.53	244.23	245.06	245.30	245.31	244.87	244.56	244.14
1932	244.87	245.60	245.73	245.67	245.76	245.57	244.97	244.62
1933	244.75	245.92	246.26	246.28	246.03	245.73	245.18	244.51
1934	243.60	244.49	244.68	244.89	244.66	244.09	244.07	243.45
1935	242.53	242.79	243.30	243.82	243.92	243.49	243.11	242.71
1936	242.73	243.91	244.28	244.26	243.97	243.58	243.31	243.06
1937	243.62	244.66	245.35	245.74	245.48	245.10	244.37	244.12
1938	244.64	244.99	245.10	245.25	245.37	245.23	245.09	244.28
1939	244.24	245.30	245.39	245.41	245.39	245.28	244.80	244.37
1940	243.03	244.80	245.73	245.84	245.68	244.94	244.57	243.95
1941	243.96	244.78	245.07	245.14	245.16	244.74	244.36	244.09
1942	244.61	245.21	245.67	245.62	245.64	245.16	244.71	244.22
1943	244.93	245.39	246.81	246.92	246.50	245.83	244.91	244.42
1944	243.86	244.83	245.44	245.78	245.48	244.83	244.35	243.72
1945	244.92	245.44	246.12	246.18	245.89	245.11	244.84	244.68
1946	244.60	244.30	244.71	245.12	245.07	244.73	244.53	244.11
1947	244.24	245.42	246.23	246.97	246.91	246.10	245.06	244.21
1948	244.74	245.30	245.70	245.62	245.33	244.81	244.11	243.67
1949	244.46	244.89	244.97	245.10	245.01	244.53	244.20	243.80
1950	244.95	245.82	245.69	245.64	245.46	245.14	244.44	244.10
1951	243.39	246.49	246.41	246.12	245.86	245.14	244.49	243.92
1952	245.69	246.45	246.76	246.47	245.92	245.26	244.68	243.86
1953	244.83	245.01	245.80	245.68	245.42	244.95	244.39	243.76
1954	244.81	245.78	245.97	245.85	245.26	244.87	244.49	244.42
1955	245.46	246.12	245.95	245.60	245.22	244.93	244.25	244.53
1956	243.83	244.95	245.75	245.56	245.20	244.94	244.34	243.75
1957	244.07	244.69	245.33	245.87	245.78	245.03	244.53	243.87
1958	244.20	245.11	245.57	245.82	245.76	245.49	245.37	244.75
1959	244.71	245.78	245.89	245.62	245.43	245.03	244.43	244.14
1960	244.61	246.00	246.43	246.26	245.64	245.06	244.34	243.86
1961	243.44	244.69	245.35	245.62	245.35	244.84	244.21	243.61
1962	243.37	244.47	245.01	245.09	244.92	244.75	244.34	244.06
1963	243.21	244.31	245.03	245.03	244.85	244.62	244.00	243.46
1964	242.53	243.41	243.99	244.12	243.98	243.73	243.06	242.44
1965	241.18	242.04	242.50	242.71	242.59	242.42	242.17	241.91
1966	243.19	243.59	244.08	244.35	244.11	243.87	243.46	243.03
1967	243.84	244.62	245.26	245.69	245.69	245.25	244.83	244.58

[1]Elevations are in feet above sea level, IGLD (1955).



KEY

WATER LEVEL DATA PARAMETERS
- ITJ - Alpha numeric title
- DEE - Controlling lake elevation

TRAFFIC DATA PARAMETERS
- ITI, MON, NCA, NCB } Alpha numeric column and heading titles
- VLA, VLB, VLC } Vessel loading characteristic
- VSC Speed of vessel by vessel class
- VCH Operating cost per hour by vessel class
- VCP Vessel capacity by vessel class
- VPC Percentage of commodity hauled in vessel class
- RTF Round-trip time factor
- TLU Loading and unloading time

COMMODITY DATA PARAMETERS
- CTO Tonnage of commodity
- ATL Average trip length
- SLR Seasonal loading restrictions

FIGURE B-1. - Flowsheet of Cost Analysis Program.

```
      PROGRAM GRTLAKES
C
C     THIS PROGRAM IS A COMPUTERIZED MODEL TO ANALYZE THE EFFECTS OF
C     WATER LEVEL REGULATION ON THE COSTS OF TRANSPORTING SELECTED
C     COMMODITIES ON THE GREAT LAKES
C
      DIMENSION VSC(10),VCH(10),VPC(10),RTF(10),TLU(10)
      DIMENSION EXP(10,8),SHP(10,8),REM(10,8),SME(10,8)
      DIMENSION ACC(17,5),ACM(17,5),CTO(22,5),ATL(22,5)
      DIMENSION TMP(10)
      COMMON NRN,NPG,III,JJJ,KKK,LLL,MMM,NNN,DPT
      COMMON MON(2,9),ITI(20),ITJ(10),SLR(10,8)
      COMMON NCA(2,5),NCB(2,5),DEE(8,68,10)
      COMMON VLA(10),VLB(10),VLC(10),VCP(10)
      INTEGER 0
C
C     READ WATER LEVEL DATA
C
      READ 1000,ITJ
      DO 100 I=1,8
      DO 100 J=1,68
      READ 1010,TMP
      DO 100 K=1,10
  100 DEE(I,J,K)=TMP(K)+25.5
      READ 1020,MON
      READ 1030,NCA
      READ 1040,NCB
  110 NPG=0
      READ 1050,NRN
      IF (NRN)290,290,120
  120 READ 1060,ITI
      READ 1070,VLA
      READ 1080,VLB
      READ 1090,VLC
      READ 1100,VSC
      READ 1110,VCH
      READ 1120,VCP
      READ 1130,VPC
      READ 1140,RTF
      READ 1150,TLU
      DO 130 I=1,22
  130 READ 1160, (CTO(I,J),J=1,5)
      DO 140 I=1,22
  140 READ 1170, (ATL(I,J),J=1,5)
      DO 150 I=1,8
  150 READ 1180, (SLR(J,I),J=1,10)
C
C     INITIALIZE PRINTOUT ACCUMULATORS
C
      DO 160 J=1,5
      DO 160 I=1,17
  160 ACC(I,J)=0.0
      DO 170 J=1,8
      DO 170 I=1,10
      EXP(I,J)=0.0
      SHP(I,J)=0.0
```

```
      REM(I,J)=0.0
  170 SME(I,J)=0.0
C
C     LOOP FOR EACH MONTH
C
      DO 280 N=1,8
      CALL HED
      DO 180 J=1,5
      DO 180 I=1,17
  180 ACM(I,J)=0.0
C
C     LOOP FOR EACH OBSERVATION
C
      DO 270 M=1,68
      DO 270 L=1,10
      IF (VPC(L)) 270,270,190
  190 CON=VPC(L)/VCP(L)*1.8382352
      DO 260 I=6,22
      K=1-5
      DO 260 J=1,5
      IF (CTO(I,J)) 260,260,200
  200 III=I
      JJJ=J
      LLL=L
      MMM=M
      NNN=N
      CALL DEP
      O=MMM
      TRI=CTO(I,J)*CON
      TMI=TRI*ATL(I,J)
      HRS=TMI/VSC(L)
      HRS=HRS*RTF(L)+TRI*TLU(L)*0.001
      COM=VCH(L)*HRS
      CALL TNS(TON)
      COA=COM*VCP(L)/TON
      ACM(K,J)=ACM(K,J)+COA
      ACC(K,J)=ACC(K,J)+COA
      SME(O,N)=SME(O,N)+COA
      IF(K-6) 210,210,220
  210 EXP(O,N)=EXP(O,N)+COA
      GO TO 260
  220 IF(K-11) 230,230,240
  230 SHP(O,N)=SHP(O,N)+COA
      GO TO 260
  240 IF(K-16) 250,250,260
  250 REM(O,N)=REM(O,N)+COA
  260 CONTINUE
  270 CONTINUE
      CALL PTA(ACM,NNN)
  280 CONTINUE
      CALL HED
      CALL PTA(ACC,9)
      CALL HED
      PRINT 2000
```

```
      CALL SPT(SHP)
      CALL HED
      PRINT 2010
      CALL SPT(EXP)
      CALL HED
      PRINT 2020
      CALL SPT(REM)
      CALL HED
      PRINT 2030
      CALL SPT(SME)
      GO TO 110
  290 PRINT 2040
C
C     FORMAT STATEMENTS
C
 1000 FORMAT (10A6)
 1010 FORMAT (30X, 10F5.2)
 1020 FORMAT (18A2)
 1030 FORMAT (10A6)
 1040 FORMAT (10A6)
 1050 FORMAT (15)
 1060 FORMAT (20A2)
 1070 FORMAT (10F5.0)
 1080 FORMAT (10F5.0)
 1090 FORMAT (10F6.1)
 1100 FORMAT (10F5.0)
 1110 FORMAT (10F5.0)
 1120 FORMAT (10F5.0)
 1130 FORMAT (10F4.4)
 1140 FORMAT (10F3.2)
 1150 FORMAT (10F2.0)
 1160 FORMAT (5F10.6)
 1170 FORMAT (5F10.6)
 1180 FORMAT (10F5.1)
 2000 FORMAT (//,5X,27HCOST OF LAKEWISE SHIPMENTS, //)
 2010 FORMAT (//,5X,27HCOST OF EXPORT SHIPMENTS, //)
 2020 FORMAT (//,5X,27HCOST OF IMPORT SHIPMENTS, //)
 2030 FORMAT (//,5X,27HCOST OF TOTAL SHIPMENTS, //)
 2040 FORMAT (1H1)
      END
```

```
      SUBROUTINE DEP
C
C     THIS SUBPROGRAM COMPUTES MAXIMUM DRAFT ALLOWED FOR EACH
C     OBSERVATION UNDER EXISTING LOAD LIMIT RESTRICTIONS
C
      COMMON NRN,NPG,III,JJJ,KKK,LLL,MMM,NNN,DPT
      COMMON MON(2,9),ITI(20),ITJ(10),SLR(10,8)
      COMMON NCA(2,5),NCB(2,5),DEE(8,68,10)
      COMMON VLA(10),VLB(10),VLC(10),VCP(10)
      L=LLL
      M=MMM
      N=NNN
      IF (III-5)190,190,100
  100 IF (III-10)110,110,120
  110 III=III-5
      GO TO 190
  120 IF(III-11)130,130,140
  130 III=JJJ
      GO TO 190
  140 IF(III-16)150,150,160
  150 III=III-11
      GO TO 190
  160 IF(III-21)170,170,180
  170 III=III-16
      GO TO 190
  180 III=JJJ
  190 If(III-2)210,210,200
  200 III=III-1
  210 If(JJJ-2)230,230,220
  220 JJJ=JJJ-1
  230 IF(III-JJJ)250,240,260
  240 K=III
      DPT=DEE(N,M,K)
      MMM=III
      GO TO 300
  250 LMN=III
      GO TO 270
  260 LMN=JJJ
  270 KKK=IABS(III-JJJ)
      KKK=KKK+LMN
      MMM=2*LMN+KKK+1
      IF (LMN-3)290,280,290
  280 MMM=10
  290 K=MMM
      DPT=DEE(N,M,K)
  300 DPI=SLR(L,N)
      IF (MMM-4)340,330,310
  310 IF(MMM-7)340,330,320
  320 IF(MMM-8)340,340,330
  330 DPI=25.5
  340 IF(DPT-DPI)360,360,350
  350 DPT=DPI
  360 RETURN
      END
```

```
      SUBROUTINE TNS(TON)
C
C     THIS SUBPROGRAM COMPUTES THE TONS THAT A VESSEL CAN CARRY AS A
C     FUNCTION OF THE VESSEL LOADING CHARACTERISTICS AND THE AVAILABLE
C     DEPTH
C
      COMMON NRN,NPG,III,JJJ,KKK,LLL,MMM,NNN,DPT
      COMMON MON(2,9),ITI(20),ITJ(10),SLR(10,8)
      COMMON NCA(2,5),NCB(2,5),DEE(8,68,10)
      COMMON VLA(10),VLB(10),VLC(10),VCP(10)
      L=LL
      IF (DPT-VLC(L))100,100,110
  100 TON=VLA(L)+(DPT-18.)*VLB(L)
      GO TO 120
  110 TON=VCP(L)
  120 RETURN
      END
```

```
      SUBROUTINE HED
C
C     THIS SUBPROGRAM IS A HEADING PRINTOUT ROUTINE
C
      COMMON NRN,NPG,III,JJJ,KKK,LLL,MMM,NNN,DPT
      COMMON MON(2,9),ITI(20),ITJ(10),SLR(10,8)
      COMMON NCA(2,5),NCB(2,5),DEE(8,68,10)
      COMMON VLA(10),VLB(10),VLC(10),VCP(10)
      NPG=NPG+1
      PRINT 1000,NRN,NPG,ITI
      PRINT 1010,ITJ
      RETURN
 1000 FORMAT (47H1WATER LEVELS OF THE GREAT LAKES--INTERNATIONAL,
     / 31H JOINT COMMISSION SPECIAL STUDY, 22X, 5H RUN , I5,/,
     / 34H EFFECT OF LAKE LEVEL REGULATION--,
     / 29HBY SUBCOMMITTEE ON NAVIGATION, 37X, 5HPAGE , I5, //,
     / 10X, 50HCOST ANALYSIS OF TRANSPORTATION ON THE GREAT LAKES, /,
     / 10X, 20A2)
 1010 FORMAT (10A6, //)
      END
```

```
      SUBROUTINE PTA(AAA,NEW)
C
C     THIS SUBPROGRAM IS A PRINTOUT ROUTINE FOR UNITED STATES TRAFFIC
C
      COMMON NRN,NPG,III,JJJ,KKK,LLL,MMM,NNN,DPT
      COMMON MON(2,9),ITI(20),ITJ(10),SLR(10,8)
      COMMON NCA(2,5),NCB(2,5),DEE(8,68,10)
      COMMON VLA(10),VLB(10),VLC(10),VCP(10)
      DIMENSION AAA(17,5)
      N=NEW
      PRINT 1000,NCA
      DO 100 J=1,5
  100 PRINT 1010, (MON(I,N),I=1,2),(NCA(I,J),I=1,2),
     /            (AAA(I,J),I=7,11)
      PRINT 1020,NCB
      DO 100 J=1,5
  110 PRINT 1010, (MON(I,N),I=1,2),(NCA(I,J),I-1,2),
     /            (AAA(J,I),I=1,5)
      PRINT 1030,NCA
      DO 120 J=1,5
  120 PRINT 1010, (MON(I,N),I=1,2),(NCB(I,J),I=1,2),
     /            (AAA(I,J),I=12,16)
      RETURN
 1000 FORMAT(//,3X,19HLAKEWISE SHIPMENTS,28X,11HDESTINATION,/,
     /20X,5(2X,2A6),/,2X,2HMO,7X,6HORIGIN,/)
 1010 FORMAT (1X,2A2,3X,2A6,3X,F10.6,4(4X,F10.6))
 1020 FORMAT (//,3X,19HEXPORTS SHIPMENTS,28X,11HDESTINATION,/,
     /20X,5(2X,2A6),/,2X,2HMO,7X,6HORIGIN,/)
 1030 FORMAT (//,3X,19HIMPORT RECEIPTS,28X,11HDESTINATION,/,
     /20X,5(2X,2A6),/,2X,2HMO,7X,6HORIGIN,/)
      END
```

```
      SUBROUTINE  SPT(VAR)
C
C     THIS SUBPROGRAM IS A SUMMARY PRINTOUT ROUTINE
C
      COMMON NRN,NPG,III,JJJ,KKK,LLL,MMM,NNN,DPT
      COMMON MIN(2,9),ITI(20),ITJ(10),SLR(10,8)
      COMMON NCA(2,5),NCB(2,5),DEE(8,68,10)
      COMMON VLA(10),VLB(10),VLC(10),VCP(10)
      DIMENSION VAR(10,8)
      PRINT 1000
      DO 100 J=1,8
  100 PRINT 1010,(MON(I,J),I=1,2),(VAR(I,J),I=1,10)
      PRINT 1020
      TOT=0.0
      DO 120 J=1,8
      SUM=0.0
      DO 110 I=1,10
  110 SUM=SUM+VAR(I,J)
      TOT=TOT+SUM
      PRINT 1030, (MON(K,J),K=1,2),SUM
  120 CONTINUE
      PRINT 1040,TOT
      RETURN
 1000 FORMAT(//,11X,1HS,9X,2HMH,10X,1HE,10X,1HO,8X,4HS-MH,6
     /X, 6HS-MH-E,4X,8HS-MH-E-O,5X,4HMH-E,6X,6HMH-E-O,8X,3HE-O,
     / /)
 1010 FORMAT (/,1X,2A2,2X,F9.6,9(2X,F9.6))
 1020 FORMAT (///,15H MONTHLY TOTALS,//)
 1030 FORMAT (1X,2A2,5X,F10.6)
 1040 FORMAT (//,14H SYSTEM TOTAL=, F10.6, 16H MILLION DOLLARS)
      END
```

APPENDIX C.--PHYSICAL AND HYDROLOGICAL DESCRIPTION OF THE GREAT LAKES SYSTEM

Geology and History

The five Great Lakes, their outlets, and the approximate lake levels as they are today date back less than 5,000 years. As the continental ice sheet slowly melted and receded northward, vast amounts of entrained debris were released and irregular deposits of overburden were laid down. One important aspect in developing the topography and overburden conditions of the area bordering the present shores was the temporary formation of large glacial lakes. During the final northward recession of the ice front, there was ponding of the melt waters between the ice and the exposed glacial deposits. This resulted in a gradually enlarging body of lake waters many feet above present lake levels, with overflow outlets across present watershed divides. As the ice border receded and new, lower outlets were uncovered, the pattern and level of the lakes were repeatedly changed.

The effect of these glacial lakes on present shores is illustrated by such features as the perched, wave-cut cliffs of Mackinac Island, the lake-deposited clay flats of Chicago and Toledo, the variable, stratified sands and silts constituting or overlaying bluffs along the Ohio shore of Lake Erie, and the sand tracts of the dune areas. Following retreat of the ice mass, there was differential movement of the earth's crust in the region, as evidenced by the now tilted positions of shore features.

The process of stream and shore erosion, while continuous, has probably made only relatively slight changes in the topography since the recession of the ice sheet. Except where bedrock is exposed, glacial overburden comprising the shores of the Great Lakes is still vulnerable to the full activity of shore erosion. Inundation of the low-lying areas also occurred at all levels of the glacial lakes and continues at the present time depending upon the relation between the lake stage, storm activity over the lake surface, and elevation of the low-lying areas.

Geography

The Great Lakes Basin is situated in the interior of the North American Continent between the latitudes of approximately 40°30' and 50°30' N and between the longitudes of approximately 74°30' and 93°10' W. From the northern limit of the basin north of Lake Nipigon in the Canadian Province of Ontario to the southern limit in the State of Ohio, the difference in latitude is some 690 miles. From the eastern limit in the State of New York to the western limit in the State of Minnesota, the difference in longitude is some 860 miles. The extreme western limit of the basin is nearly halfway across the continent from the Atlantic Ocean.

Lake Superior, the largest of the Great Lakes, has a surface elevation above sea level of 600.0 feet, IGLD.[1] It occupies a relatively smooth northeast-southwest trending basin in its western half, where depths in excess of 600 feet are fairly common, and a strongly ridged portion in its eastern third, where depths over the ridges are commonly in excess of 500 feet and depths in the hollows are commonly from 800 to over 1,000 feet. The outlet of this lake is the St. Marys River.

Lake Michigan's surface elevation is 576.8 feet above sea level (IGLD). The lake occupies a relatively smooth basin in its southernmost third, where it is 564 feet deep; a large midlake area of relatively shallow water, between Milwaukee, Wis., and Muskegan, Mich., with depths less than 300 feet; and a main northern basin containing the greatest depths of the lake.

Lake Huron has a surface elevation of 576.8 feet above sea level (IGLD). The lake is separated from Georgian Bay and the North Channel, to the northeast and north, by a nearly continuous barrier composed of Saugeen Peninsula, Manitoulin Island, and several other islands. A submerged but prominent ridge in the lake is roughly concentric with the Saugeen Peninsula, Manitoulin Island Ridge, and extends across the lake from Alpena, Mich., to Kinkardine, Ontario. The lake is deepest in the main basin northeast of this ridge. Lakes Michigan and Huron are connected by the Straits of Mackinac, and their outlets are the St. Clair River through Lake St. Clair and the Detroit River to Lake Erie.

Lake Erie contains about one-thirtieth the volume of Lake Superior, and it is the only one of the Great Lakes whose bottom does not extend below sea level. The surface elevation of the lake is 568.6 feet (IGLD). The Niagara River is the outlet of this relatively shallow lake.

Lake Ontario is 242.8 feet above sea level (IGLD). The lake is the smallest of the Great Lakes and occupies a relatively smooth asymmetrical trough with the axis of its deepest portion lying south of the midline. The natural outlet of this lake, as well as that of the entire Great Lakes system, is the St. Lawrence River.

In the United States, the Great Lakes Basin includes all of the State of Michigan and parts of the States of Minnesota, Wisconsin, Illinois, Indiana, Ohio, Pennsylvania, and New York. The Canadian portion of the basin is entirely within the Province of Ontario.

In large part, the Great Lakes watershed falls into two broad categories: the physiographic province called the Laurentian Uplands, which comprises areas north and west of Lake Superior and north of Lake Huron, and the province called the Central Plains of North America, which comprises much of the remainder of the watershed.

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[1] IGLD (1955 International Great Lakes Datum) is the low water datum plane of reference on each lake to which Federal navigation depths are referred. Elevations are in feet above mean water level as established at Father's Point, Quebec, a point on the St. Lawrence River near the river's transition to the Gulf of St. Lawrence.

The land areas tributary to the Great Lakes consist essentially of peripheral bands around the lakeshores, which vary in width back from the lakes from less than 10 miles to about 100 miles. The stream system collecting the land drainage and discharging it into the lakes consists of many perennial and some intermittent streams, a large number of which drain only small areas. The larger tributaries to the Great Lakes, the State or Province in which each is located, and the size of their individual drainage areas are listed in table C-1.

TABLE C-1. - Principal tributaries to the Great Lakes

Lake	Tributary river	Location of river	Drainage area, square miles
Superior.........	Nipigon..........	Ontario.................	9,900
	Kamistikwia......	...do...................	3,600
Michigan.........	Fox..............	Wisconsin...............	6,300
	Grand............	Michigan................	5,800
Huron............	Saginaw..........	...do...................	6,100
	French...........	Ontario.................	5,600
Erie.............	Maumee...........	Ohio, Indiana, Michigan,	6,700
	Grand............	Ontario.................	2,400
Ontario..........	Oswego...........	New York................	5,200
	Trent............	Ontario.................	4,900

Climate

Although the Great Lakes Basin is entirely within the temperate zone, its latitudinal extent accounts for an appreciable range in climate over the basin. The annual average air temperature at Duluth, in the northern half of the basin, is 38° F; that at Cleveland, near the basin's southern limit and some 370 miles south from the latitude of Duluth is 49° F. The lakes have a moderating influence on air temperatures over the lakes themselves and over land areas contiguous to the lakes; generally they cool the air in the summer and warm it in the winter.

The average precipitation on the Great Lakes Basin is about 31 inches per year. In general, the annual precipitation in the northwestern portion of the basin is less than the basin average; in the southeastern portion it is greater than the average. Over the Lake Superior area the annual average is about 29 inches; over the Lakes Erie and Ontario area, it is about 34 inches. The northern areas of the basin usually have a snow cover that remains throughout the winter, whereas the snow cover over much of the southern and intermediate areas generally is intermittent. Records indicate that the annual precipitation over the basin for an individual year may be as much as 20 percent more or less than the long-term average amount and that there may be several years of above-normal or below-normal precipitation. In general, the prevailing wind over the Great Lakes area is westerly.

Average Lake Levels and Outflows

Figure C-1 indicates the long-term average levels of the lakes and the slopes along their connecting channels. The uppermost lake in the chain, Lake Superior, discharges at its eastern end through the St. Marys River into Lake Huron. The fall in the St. Marys River from the Lake Superior level to Lake Huron is about 22 feet, most of which occurs in the mile-long St. Marys Falls at Sault Ste. Marie. The Straits of Mackinac provide a broad and deep connection between Lake Michigan and Lake Huron, through which there is an average water flow of 48,000 cubic feet per second (cfs). The slope between the lakes is imperceptible, and the two lakes stand at virtually the same level. Hydrologically they are treated as though they were a single lake, with the St. Clair River its natural outlet. The St. Clair River extends from the southern end of Lake Huron to Lake St. Clair, the outlet of which is the Detroit River discharging into Lake Erie. From the Lake Huron level to Lake St. Clair, the fall is about 5 feet; from the Lake St. Clair level to Lake Erie, it is about 3 feet. The slopes of the St. Clair and Detroit Rivers are fairly uniform with no rapids or falls. Lake Erie discharges at its eastern end through the Niagara River into Lake Ontario. The fall from the Lake Erie level to Lake Ontario is about 326 feet, approximately one-half of which is at Niagara Falls. The cascades immediately above the falls and the rapids downstream from the falls account for nearly 150 feet of the total. Lake Ontario discharges at its eastern end through the St. Lawrence River, the natural outlet for excess waters from all of the Great Lakes. The fall from the Lake Ontario level to the Atlantic Ocean is about 244 feet with about 224 feet of the total occurring between the lake and Montreal. Table C-2 shows outflows for each of the Great Lakes through its natural outlet channel for the period of record (1860-1964), and the largest and smallest monthly average for the same period.

TABLE C-2. - Outflows of the Great Lakes, 1860-1964, cfs

Lake and natural outlet	Average for period 1860-1964	Maximum monthly	Minimum monthly
Superior through St. Marys River........	74,000	127,000	41,000
Michigan through Strait of Mackinac.....	48,000	([1])	([1])
Michigan-Huron through St. Clair River..	187,000	242,000	99,000
Erie through Niagara River..............	202,000	254,000	117,000
Ontario through St. Lawrence River......	239,000	314,000	154,000

[1] Unknown.

Supplies to System

The natural supplies of water to the Great Lakes consist principally of precipitation that falls on the lake surfaces and runoff from the land areas of the basin. Undetermined amounts of water, considered relatively small, also reach the lakes from ground water storage of the land areas around the lakes. For each of the lakes, except Lake Superior, the supply from the individual lake basin is augmented by inflow of excess water from the lake above. The total supply reaching any one of the lakes is reduced by surface evaporation. The items mentioned represent the supply factors. The total supply less the evaporation losses is the net total supply.

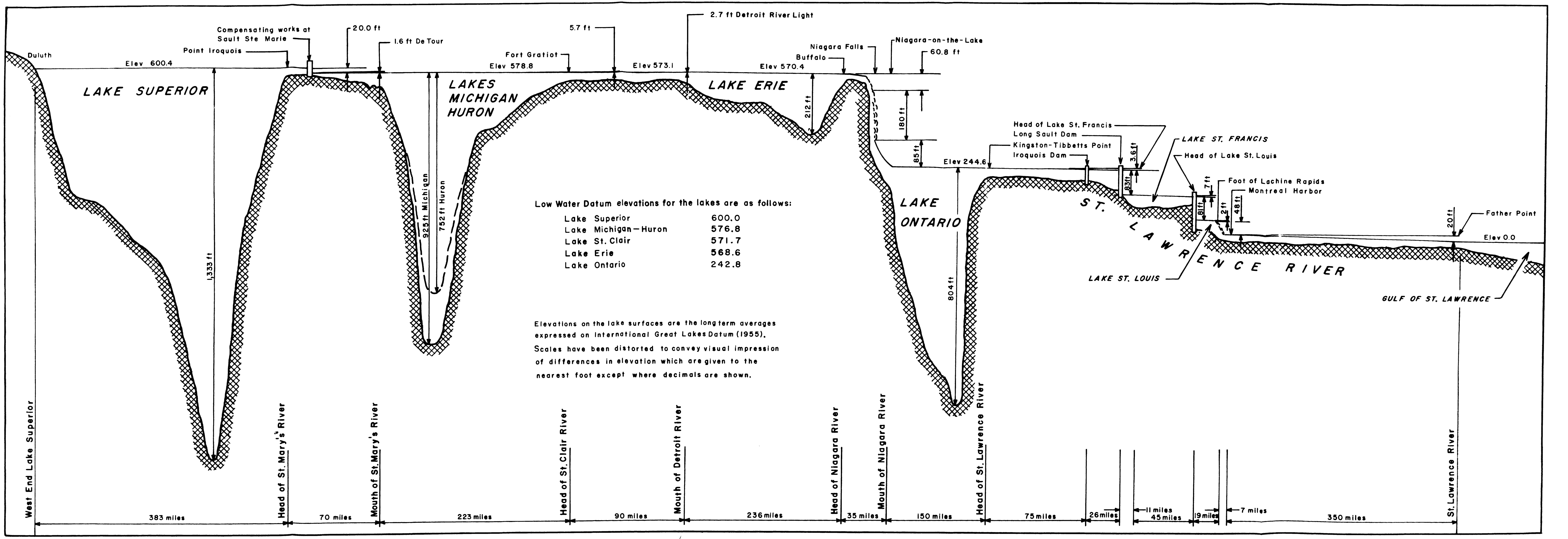

FIGURE C-1. - Great Lakes-St. Lawrence River Profile. Datum IGLD (1955). Based on plate 2 (8).

The natural supplies to the lakes have been increased by the diversion of water into Lake Superior from the Albany River watershed in Canada. They have been decreased by the diversion of water from the Lake Michigan Basin at Chicago into the Mississippi River Basin. In addition, a diversion within the Great Lakes Basin, from Lake Erie via the Welland Canal and into Lake Ontario, completely bypasses the Niagara River.

Figure C-2 illustrates the approximate relative proportions of the supply factors on the basis of average values for a representative 10-year period from October 1950 through September 1960. Also illustrated in figure C-2 are the average amounts of water supplied to each of the lakes through the several supply factors and the average disposition of water removed from the lakes. For example, the illustration shows that about 30 percent of the total supply to Lakes Michigan and Huron is inflow from Lake Superior, while about 80 percent of the total supply to Lake Ontario is from the upper lakes. It also shows that the amounts of water evaporated from the lake surfaces are significant portions of the total amounts removed from the lakes. Because figure C-2 is based on an average value, it does not indicate the variations that occur in the supply factors or variations in the net total supplies to the lakes. Variations in the net total supplies are correlated with the variations of the lake levels and variations of the lake outflows through the outlet rivers.

Net total supplies to the Great Lakes depend on the season. Normally, high supplies occur in the fall and winter months. The seasonal variations are superimposed on longer trends in the supplies that, from time to time, may persist at abnormally high or low rates for periods of 3 or more years.

Table C-3 shows the range of monthly net supply volumes expressed as average flow rates in cubic feet per second. The net supplies are the actual supplies adjusted to the conditions that would have occurred had the present diversions of 5,000 cfs into Lake Superior and 3,100 cfs out of Lake Michigan been in effect throughout the period of record.

TABLE C-3. - Monthly water supply volumes

Lake	Flow rate, cfs			
	Average	Maximum	Minimum[1]	Range
Superior	78,000	332,000	-102,000	434,000
Michigan-Huron	189,000	538,000	-111,000	649,000
Erie	208,000	367,000	104,000	263,000
Ontario	243,000	416,000	145,000	271,000

[1] Negative values indicate that evaporation from the lake surface is greater than the amount of water supplied to the lake.

Lake Storage

The vast storage areas of the Great Lakes are unique. Although relatively small changes in the levels of the lakes amount to enormous quantities of water, large variations in supplies to the lakes do not significantly alter the remarkably steady outflows. For example, a large monthly net supply of water to Lakes Michigan and Huron may be more than twice the monthly discharge

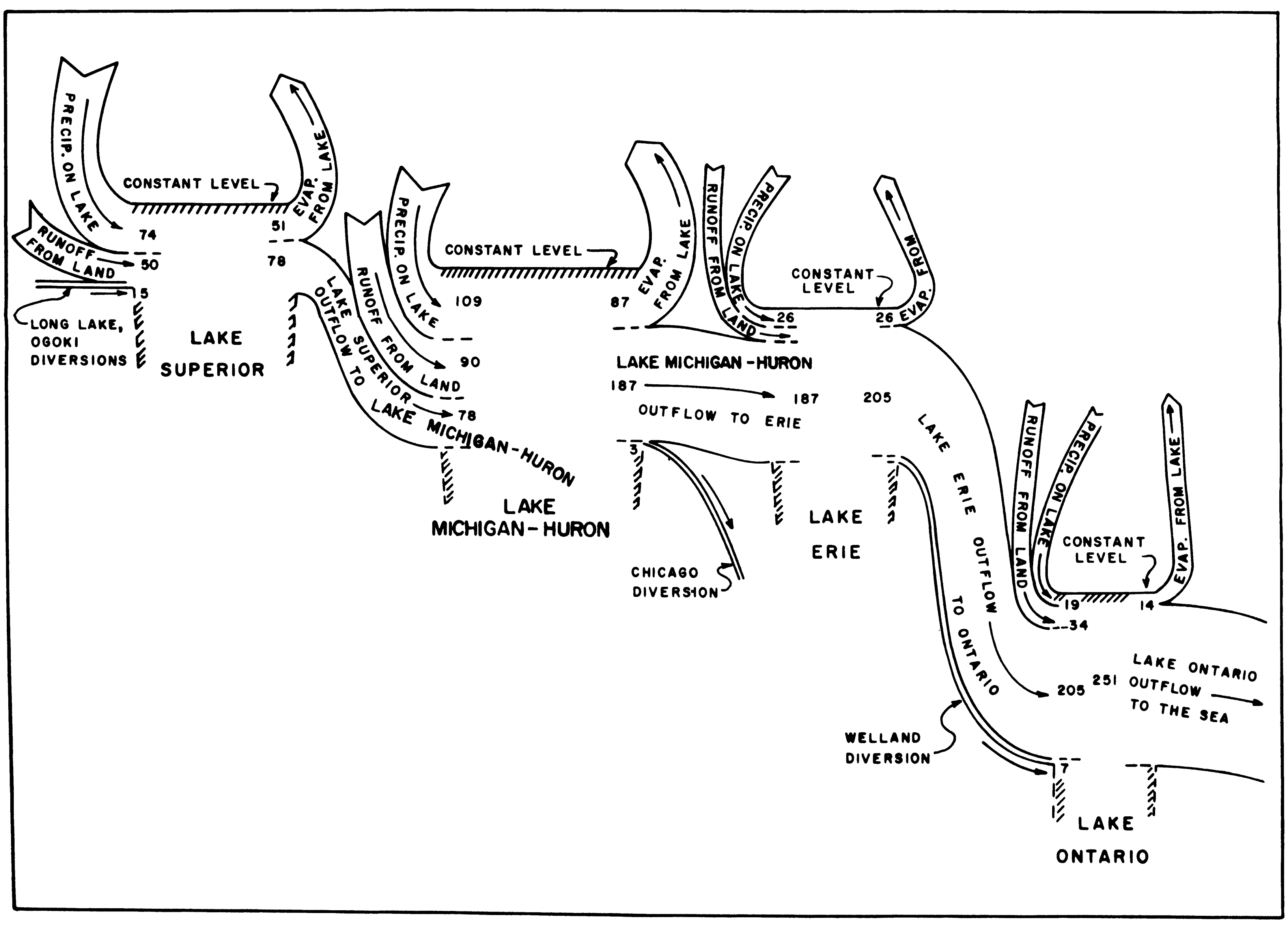

FIGURE C-2. - Factors of Water Supply to the Great Lakes. Figures are thousand cubic feet per second. Outflows adjusted to equal supplies; thus no change in lake storage is shown. Based on plate 3 (8).

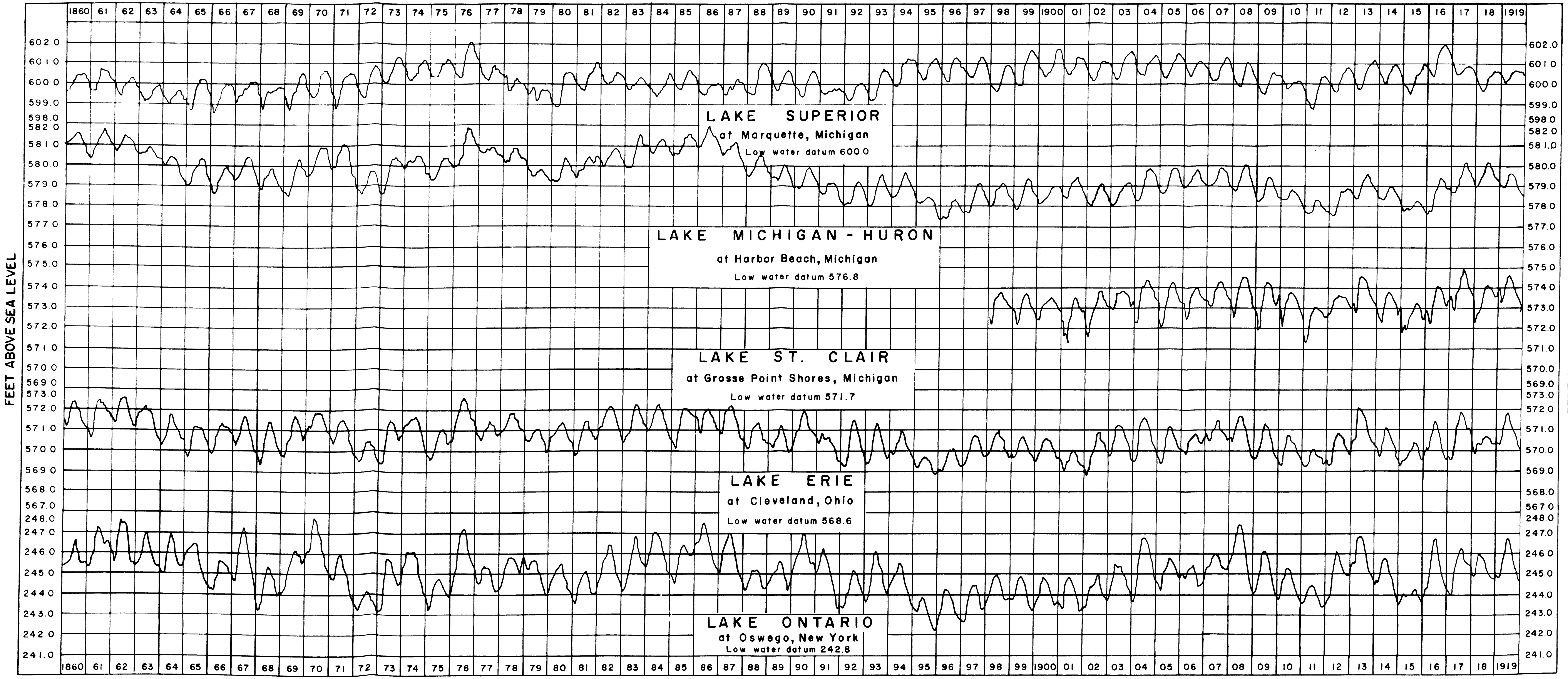

FIGURE C-3. - Hydrograph of Lake Levels. Datum IGLD (1955). Based on plate 4 (8).

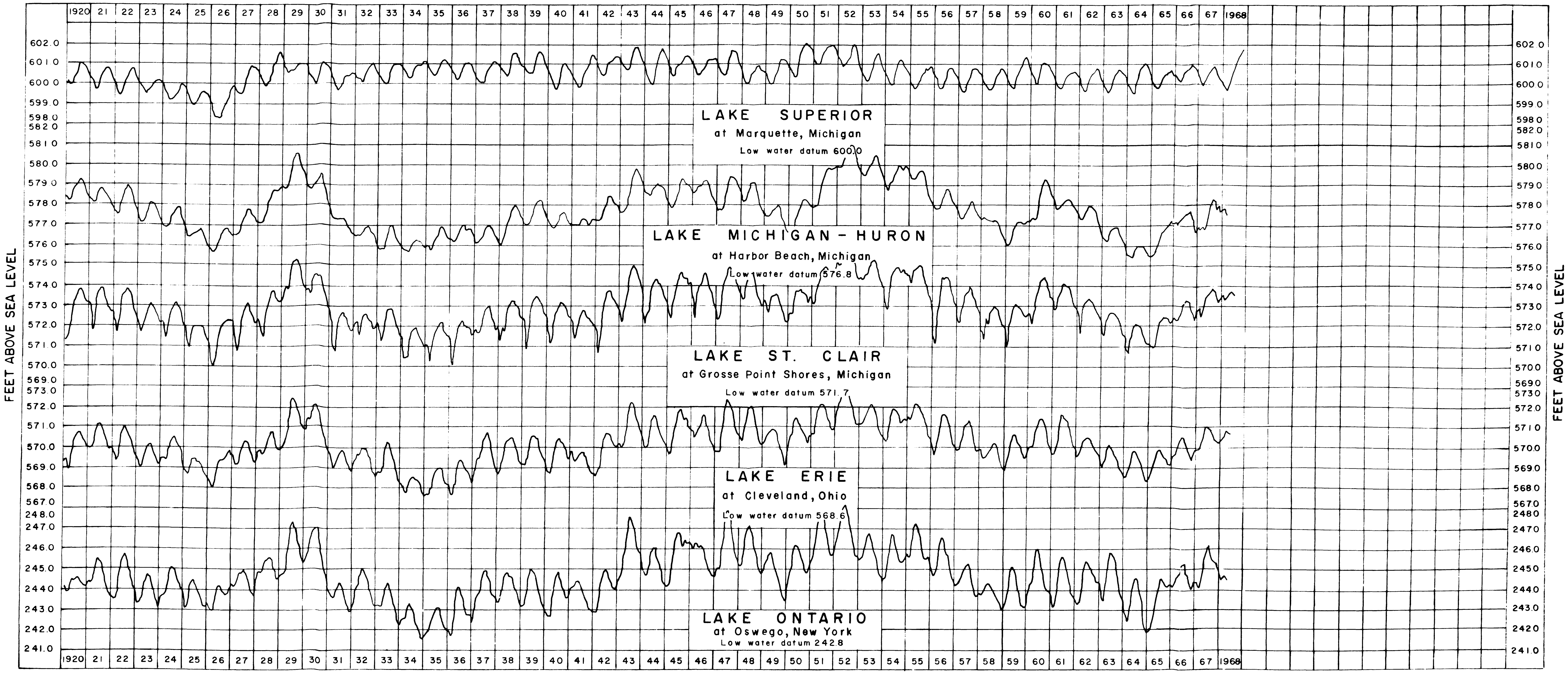

FIGURE C-3. - Hydrograph of Lake Levels. Datum IGLD (1955). Based on plate 4 (8).–Continued capacity of the St. Clair River. During such a month, at least one-half of the net supply will be added to the amount of water stored in this lake. The resulting rise in the water surface of the lakes during that month will be about 0.3 foot with the corresponding increase in the discharge rate through the St. Clair River of about 3 percent.

The level of each of the Great Lakes depends upon the balance between the quantities of water received by the lake and the quantities of water removed from the lake. Except where regulatory works have been provided in a lake outlet, the level of the lake and the outflow rise and fall together at a definite rate. Where the outflows are artificially controlled by regulatory works, the releases of water are made in accordance with a plan for the regulation of the lake levels and outflows.

In general, because the winter outflows are retarded by ice formed in the outlet channels, the winter outflow rates are less than outflows during open-water seasons. The minimum monthly outflows given for Lakes Michigan, Huron, and Erie (table C-2) occurred under severe ice conditions in the St. Clair and Niagara Rivers.

Lake Level Variations

Variations of the Great Lakes levels may be classified as long-period variations (those with general trends upward or downward, extending over several years); seasonal variations, representing an annually recurring cycle; and short-period variations lasting from several minutes to a day or two. The long-period and seasonal variations relate to the level of a lake as a whole, and such variations correspond to changes in the volume of water in the lake. The short-period variations consist of fluctuations that may occur at any lake stage involving temporary and frequently rapid changes in level in any one area of the lake. Figure C-3 is a hydrograph of monthly average levels recorded on each of the Great Lakes since 1860 and on Lake St. Clair since 1898. Long-period variations of the lake levels result principally from variations of the precipitation falling on the lake basins.

Figure C-3 shows that a high level in the summer and a low level in the winter occur on each of the Great Lakes almost every year. The amount of variation between highs and lows, however, as well as the months in which the highs and lows occur, may differ considerably from year to year. Such fluctuations are caused by seasonal patterns in the natural hydrologic factors.

Because of the reservoir effect of the lakes, there is a time lag between the seasonal peaks of water supply reaching the lakes and the lake level. The rate of rise in the level is most rapid when the rate of supply is greatest but, after the supply rate has passed its peak, the level continues to rise until the supply rate drops and the outflow rate increases to a point where the two rates are equal. For Lake Superior the peak lake level normally lags behind the peak supply rate about 3 months; for Lakes Michigan and Huron the lag is about 2 months; and for Lakes Erie and Ontario it is about 1½ months.

At any point on the lakes there are daily and hourly level fluctuations which vary from a few inches to several feet. They are caused by winds blowing over the lake surface or by differences in the atmospheric pressure on different areas of the lake surface. During such short-period disturbances, the level of one area of the lake rises while the level of another area falls. For example, the effect of wind in causing such a disturbance may be to drive the surface water forward in greater volume than it is carried by the lower return currents; thus the water level rises at the shore toward which the wind is blowing and falls at the opposite shore. Such effects are more pronounced in bays and at the extremities of the lakes, where the impelled water is concentrated in a restricted space by the converging shores, especially if a gradually sloping inshore bottom reduces the depth and checks the reverse flow.

Harbors

There are 64 Federal deep-draft commercial harbors (17 feet or over in depth) on the U.S. shores of the Great Lakes used by lake and ocean vessels. In addition to the Federal deep-draft harbors, 12 private U.S. harbors serve deep-draft navigation. The navigation system on the Great Lakes now has 17 Federal harbors and four private harbors that are 27 feet deep or over at low water datum. Table C-4 shows depths of U.S. commercial deep-draft harbors and selected channels on the Great Lakes.

Connecting Channels and Canals

Since 1962, a depth of 27 feet at low water datum has been provided in both downbound and upbound channels between the Great Lakes and through the St. Lawrence River. The channels are designed to provide a safe draft of 25.5 feet for Great Lakes freighters when the water level is at low water datum. To provide this safe draft, depths vary from 27 to 30 feet to provide allowances for squat of vessels when underway, for exposure to wave action, and for an additional foot of clearance between safe draft and channel depth over areas of hard or rock bottom.

In the St. Lawrence River from Lake Ontario to Montreal, Quebec, there are seven locks. The five in Canada are operated by the St. Lawrence Seaway Authority of Canada, and the two in the United States are operated by the St. Lawrence Seaway Development Corporation. All locks are 766 feet in length (from breast wall to gate fender), 80 feet in width, and have a water depth over the sills of 30 feet.[2]

Between Lake Ontario and Lake Erie, the Government of Canada has constructed the Welland Canal with a controlling depth of 27 feet. The seven lift locks and one guard lock of the Welland Canal have the same controlling dimensions as the St. Lawrence River locks. The canal is 27 miles long, and the difference in water level between the two lakes is 326 feet.

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[2]Depths over the sills are the controlling depths at low water datum.

TABLE C-4. - U.S. commercial deep-draft harbors and channels on the Great Lakes

Lake	Depth of harbors or channels in feet below low water data, January 1968					
	17 and less	18-19	20-21	22-24	25-26	27 and over
Superior	Ontonagon, Mich.	Grand Marais, Mich. Grand Marais, Minn.	-	-	Keweenaw Waterway, Mich.	Ashland, Wis. Duluth-Superior, Minn. and Wis. Marquette, Mich. Presque Isle, Mich. Two Harbors, Minn. Taconite, Minn. Silver Bay, Minn. St. Marys River, Mich.
Michigan	Algoma, Wis. White Lake, Mich.	Charlevoix, Mich. Frankfort, Mich. Ludington, Mich. Manistique, Mich. Michigan City Harbor, Ind. Portage Lake, Mich. South Haven, Mich. Two Rivers, Wis. Waukegan, Ill.	Chicago Harbor, Ill. Grand Haven, Mich. Holland, Mich. Kewaunee, Wis. Port Washington, Wis. Racine, Wis. Sheboygan, Wis. St. Joseph, Mich.	Gladstone-Kipling, Mich. Green Bay, Wis. Manistee, Mich. Manitowoc, Wis. Menominee, Mich. Sturgeon Bay and Lake Michigan Ship Canal, Wis.	Kenosha, Wis. Buffington, Ind. Port Inland, Mich. Oak Creek, Wis.	Burns Waterway, Ind. Calumet Harbor and River, Ill. Indiana Harbor, Ind. Milwaukee, Wis. Muskegon, Mich. Escanaba, Mich. Gary, Ind. Straits of Mackinac, Mich.
Huron...	Mackinac Island		Alpena, Mich. Black River, Mich. Cheboygan, Mich. Harbor Beach, Mich.	Saginaw River, Mich.	Detroit-Rouge River, Mich. Stoneport, Mich. Port Dolomite, Mich. Calcite, Mich. Alabaster, Mich. Port Gypsum, Mich.	Detroit-Trenton Channel, Mich. Detroit River, Mich. Lake St. Clair, Mich. St. Clair River, Mich.
Erie....	Dunkirk, N.Y.		Black Rock Channel and Tonawanda Harbor, N.Y. Monroe, Mich.		Fairport, Ohio Huron, Ohio Sandusky, Ohio	Ashtabula, Ohio Buffalo, N.Y. Cleveland, Ohio Conneaut, Ohio Erie, Pa. Lorain Harbor, Ohio Toledo Harbor, Ohio
Ontario.	Cape Vincent, N.Y. Niagara River, N.Y.	Ogdensburg, N.Y.	Rochester, N.Y.	Great Sodus, N.Y.	Oswego, N.Y.	

The connecting channel between Lake Erie and Lake Huron--the Detroit River, Lake St. Clair, and St. Clair River--has been deepened to provide a controlling project depth of 27 feet. Between Lakes Huron and Michigan, shoals in the vicinity of the Straits of Mackinac have been dredged to provide a depth of 30 feet at low water datum.

Between Lake Huron and Lake Superior the connecting channel is the St. Marys River, which has been deepened to provide a depth of 27 feet. There are four locks on the U.S. side and one on the Canadian side of the St. Marys River at Sault Ste. Marie. One U.S. lock is 870 feet long and 80 feet wide and has a depth of 31 feet over the sills. Two locks are 1,350 feet long and 80 feet wide and have depths of 23.1 feet over the sills. The fourth and newest lock is 1,200 feet long and 110 feet wide, with depth of 32 feet over the sills. The principal features of the four U.S. locks in operation in the St. Marys River at Sault Ste. Marie, Mich., are shown in table C-5. There is one lock at Sault Ste. Marie, Ontario, which is 59 feet wide and 900 feet long, with a depth of 16.8 feet over the sill. Vessels longer than 730 feet and wider than 75 feet cannot pass through the MacArthur Lock at St. Marys Falls Canal, the Welland Canal, and St. Lawrence River locks.

TABLE C-5. - Principal features of U.S. locks, St. Marys Falls Canal, feet

Principal features	Locks			
	MacArthur	Sabin	Davis	Poe
Width	80	80	80	110
Length between miter sills	800	1,350	1,350	1,200
Depth on upper miter sill	31	24.3	24.3	32
Depth on lower miter sill	31	23.1	23.1	32
Lift	21.7	21.7	21.7	21.7

St. Lawrence River and Seaway

The St. Lawrence River has its head at the eastern end of Lake Ontario. The river thus connects the Great Lakes Basin and the Atlantic Ocean. It has a number of major tributaries--the Ottawa, St. Maurice, Saguenay, and Richelieu (draining Lake Champlain).

On many official maps and the U.S. Navy Sailing Directions for the Gulf and River St. Lawrence, the locality taken as the river's mouth is extended as far seaward as the eastern part of the Gaspé Peninsula, where the west end of Anticosti Island serves as the transition point between the river and the Gulf of St. Lawrence. The distance from northern to southern shore at this point is about 70 miles and the distance to Lake Ontario at Kingston, Ontario, is 725 statute miles. A more restrictive definition places the mouth between Pointe-des-Monts and Cap-Chat on the northern and southern shores, respectively. At this point, about 595 miles downstream from Lake Ontario, the river is 25 miles wide; seaward from this point the width increases rapidly as the left shore turns abruptly northward.

From the Strait of Belle Isle, at the mouth of the Gulf of St. Lawrence, the sailing distance to Duluth, Minn., at the head or western end of Lake Superior is about 2,340 miles; to Chicago, at the head or southern end of Lake Michigan, it is about 2,250 miles. Approximately 1,000 miles of each distance is below Montreal, which is at the head of deep-draft ocean navigation on the St. Lawrence River.

The St. Lawrence Seaway, a major improvement of the St. Lawrence waterway, made an interior section of North America accessible for the first time to deep-draft, oceangoing vessels and also permitted the large Great Lakes freighters to extend their range of operations to the ports on the lower St. Lawrence. The waterway was completed for the opening of the navigation season on the St. Lawrence River and Great Lakes in April 1959.

This development was a joint undertaking of the Governments of the United States and Canada to provide 27-foot navigation channels between Montreal and Lake Erie. A related U.S. project provided for widening and deepening the connecting channels of the Great Lakes (the Detroit, St. Clair, and St. Marys Rivers) to make them commensurate in depth with those of the seaway.

Strictly speaking, the seaway is the St. Lawrence River portion of the waterway, but the Welland Canal was officially incorporated into the project through legislation, and improvements were made in it as a part of the total seaway undertaking. The seaway project consisted of constructing seven locks, dredging long sections of channel, constructing protective dikes, digging canals, and raising and building bridges.

Limitations on the size of ships operating through the seaway are imposed by channel depth, lock dimensions, and overhead clearances. The 27-foot depth restricts vessel drafts to 25½ feet for safe clearance. All locks are 800 feet long and 80 feet wide and have a 30-foot depth over the sills. Although these dimensions limit normal traffic to ships not more than 715 feet in length with a beam no wider than 72 feet, ships having a length up to 730 feet and a beam up to 75 feet can be accommodated. The seaway dimensions permit oceangoing vessels with cargo capacities up to 8,000 to 9,000 tons to enter the Great Lakes and allow the transit of bulk-cargo "lakers" with capacities up to about 25,000 tons.

The seaway route from Montreal to the head of Lake St. Francis is wholly in Canada. A canal about 16 miles long leads from Montreal Harbor to Lake St. Louis, and two locks, St. Lambert and Cote Ste. Catherine, provide the lift of about 45 feet, the difference in water levels between these two points. At the head of Lake St. Louis, the seaway bypasses the Beauharnois Power Dam to enter a 16-mile power canal. Two locks--the Upper and Lower Beauharnois--each have a lift of approximately 41 feet. The power canal, which extends to Lake St. Francis, was completed in 1932 with a navigable depth of 27 feet in anticipation of the seaway.

The international boundary extends along the St. Lawrence River from the head of Lake St. Francis to Lake Ontario. At the lower end of this section, the seaway route is constructed through U.S. territory in order to bypass the

Barnhart Power Dam, a structure divided evenly by the international boundary. The U.S. navigation works consist of the 10-mile, Wiley-Dondero ship channel and two locks--Bertrand H. Snell (lower, 45-foot lift) and Dwight D. Eisenhower (upper, 42-foot lift). These facilities were opened July 4, 1958. The upper end of the ship channel terminates in Lake St. Lawrence, a head pond created by flooding about 38,000 acres of land above the power dam.

The major structure in the power project is a dam. In addition to the power structure, it was necessary to build two control dams--Long Sault and Iroquois--to maintain the level of the head pond at an operating level of about 242 feet above sea level. The drop to the level below the dam is nearly 90 feet.

At the head of Lake St. Lawrence, about 25 miles above the power dam, are the Iroquois Dam and the Iroquois Canal and lock. The latter is the fifth Canadian lock on the St. Lawrence and has a lift of 2 to 6 feet to the level of the Thousand Islands section of the river. It was the first seaway lock opened to commercial traffic, having been placed in service in May 1958. Iroquois Dam controls and regulates the outflow from Lake Ontario.

From the Iroquois facilities to Lake Ontario, about 77 miles, is the Thousand Islands section of the seaway. The improvements required were channel enlargement and dredging of scattered rock shoals. The Welland Canal entrance on Lake Ontario is 157 miles west of the head of the St. Lawrence River. The eight locks--three are double for upbound and downbound traffic--required no alteration to serve deep-draft vessels.

Tolls for use of the seaway are used to liquidate the cost of the project within the 50-year period as required by legislation. Ice conditions limit the navigation season on the seaway to about 230 to 240 days from mid-April to early December.

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