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HYDROLOGIC-ECONOMIC FEASIBILITY STUDY ON PRECIPITATION AUGMENTATION OVER THE GREAT LAKES

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FINAL REPORT

to

NATIONAL OCEANOGRAPHIC ATMOSPHERIC ADMINISTRATION
Boulder, Colorado

on

Grant N22-207-72G

March 1974

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ABSTRACT

Thirty-two million people live within the Great Lakes Region and depend heavily upon this resource for transportation, power production, water supply, and recreation. The lake levels fluctuate on a long term as well as on an annual basis, depending upon the precipitation and the evaporation. During the past 113 years, the lowest lake levels occurred in 1963-64 and all time high water levels were measured in 1973. The large differences in lake levels create many social and economic problems.

Every increase of one inch in water level permits an additional 110 tons of cargo on the freighters now in use and 225 tons on the larger vessels now under construction. A change in water level of one inch in Lake Michigan is equivalent to one-third of the diversion of water that is used for domestic and waste water dilution for the city of Chicago. However, the greatest benefit of the higher water levels is the energy producing capacity of the power industries.

It has been proposed by Dr. H. Weickmann that through cloud seeding one could recycle, the evaporative water which occurs when polar and arctic air masses cross the open water surface directly into the lake. The benefits would be greatest during the period of low lake levels. For example, when the lake level is low, and one assumes a 10 percent increase in the Fall and early Winter snowfall over Lake Michigan (about one inch of melted precipitation), the net benefits exceed $2 million.

HYDROLOGIC - ECONOMIC FEASIBILITY STUDY ON PRECIPITATION AUGMENTATION OVER THE GREAT LAKES

Introduction

Although the Great Lakes appear to contain an adequate water supply for the people of the region, projection of future demands for good quality water suggest that problems will be developing especially in critical areas around large metropolitan areas. Furthermore, water uses for commercial navigation on the lakes, for once through cooling for power generation, and for shoreline recreation activities require a stable water level. Good management of this resource is most important to many of the U.S. and Canadian interests in this region. The hydroelectric power industry can use every available drop of water in its production of low cost electrical energy until its capacity is reached. Therefore, since little is known about the total management of the water resources of the Great Lakes and the great importance to utilize this resource to its optimum, research on the hydrologic-economic feasibility of precipitation augmentation was undertaken to determine its role in the future management of the Great Lakes.

The levels of the lakes vary considerably from one season to another and from year to year. Lake Michigan varies approximately 5 feet from low water to high water periods. This difference greatly affects the navigation to and from Chicago as well as the recreational endeavors along the shores. The difference in lake level depends primarily upon the precipitation over the lakes and its drainage area.

Studies by Jones and Merdith (1972) indicate that the calculated annual evaporation from the Lake Michigan surface exceed the precipitation over the lake. Monthly evaporation is greatest during the fall, winter, and spring months. Would it be feasible to recycle some of this moisture to the lake before it reaches the land mass?

This investigation was initiated as a follow-up to some of Dr. H. Weickmann's (1972) interest in the reduction of heavy lee shore snow storms in the Buffalo area. Several years ago seeding experiments were carried out over Lake Erie and the results suggests that one could enhance the snowfall over the lake surface.

At the time this study was initiated under Grant N22-207-72G from National Oceanic and Atmospheric Administration plans were being made to conduct a number of allied studies by other Universities in the Great Lakes area to develop the physical and climatological aspects of the seeding program, the legal situation, etc. Due to a shift in national priorities within NOAA, the weather modification program was not funded.

Objective of Study

Due to the fluctuating water levels in the Great Lakes and the many disbenefits from an uncontrolled system, the present day management of the lake levels is a major problem. This study was made to determine the economic benefits from a precipitation augmentation program over the Lake Michigan surface itself. Sixteen years of hydrologic data were used and it was modified to allow from an assumed increase in precipitation of 10, 20, or 30 percent.

Acknowledgments

The excellent support of Dr. Prank Quinn and Malcolm Todd of the NOAA Lake Survey Center in Detroit in performing the calculation of the hydrologic response is greatly appreciated. Similar support of Ben DeCooke and Ron Wilshaw of the Detroit District of the Corps of Engineers in the computation of benefits is likewise greatly appreciated. The Corps employed the economic model which was developed by that District for the International Joint Commission's Great Lakes Water Level Study.

Credit is due to Professor Rolf Deininger of the University of Michigan for his direction of the economic study which was performed under a subcontract by his students, Lawrence W. Farris and Roger L. Tobin. Their work is described in the Appendix.

Background

The Great Lakes are a source of water for recreation, aesthetic enjoyment, industrial development, power generation, transportation, urbanization, and public water supply. In order

to meet the demands of the 17.3 million water users in the Basin, municipal water supplies withdrew an estimated 3.4 billion gallons of water per day from the five Lakes in 1970.

The basin of the Great Lakes system encompasses 175,000 square miles of the United States and 120,000 square miles of Canada. This includes parts of seven states of the United States, all of Michigan, and one-third of the area of the Canadian province of Ontario. Situated at the center of the basin is the world's largest single supply of fresh water, the Great Lakes.

Compared with other lake systems, the Great Lakes' drainage area is unique in several respects. First the lakes occupy nearly a third of their entire drainage area — 95,000 of the total 295,000 square miles. Also the lakes and their basin divide are never more than 125 miles apart and at one point the divide lies within just 2 miles. Pew large rivers flow into the Great Lakes. The largest tributary, the Nipigon River, only contributes an annual average flow of less than 13,000 cubic feet per second. The flow at each lake outlet is almost uniform throughout the year owing to the enormous storage capacity of the lakes. The lowest recorded flow in the St. Lawrence is about one-half the maximum, in contrast the Columbia River's lowest flow is one-fortieth of its maximum.

The Great Lakes region is well endowed with natural resources. Iron ore and limestone near or on the shorelines of the upper lakes, and high-grade bituminous coal within 100 miles of Lake Erie ports, constitute an important resource combination. Lumbering and fishing industries have a long history in the basin although their economic value is less today. Forty percent of the basin's land area is used for agricultural production. A diversity of crops are grown, including corn, tobacco, and grapes. The basin has ample land for urban expansion in all directions and in the heart of the area lies its greatest natural resource, 5,500 cubic miles of water, available for recreation, transportation, power generation, and domestic purposes and to assist in the industrial development of its hinterland.

Within this resource-rich area is one of the largest and most rapidly growing industrial and urban complexes in the world. It has been estimated that the Great Lakes megalopolis has a potential for growth beyond all other large urban clusters in North America (Doxiadis, 1967).

It is difficult to measure the effect that weather has played in the development of this basin. Certainly the impact of climate on agriculture, forestry, and hydrology is realized but its effect on socio-economic development is less direct. Indeed Doxiadis (1967) claims that only with respect to climate may the Great Lakes region be considered at a disadvantage compared to the urban concentrations of California.

The unique features of the climate of the Great Lakes basin are: four distinct seasons; a variety of precipitation types and sources, but with almost no month to month variation in precipitation amount; marked temperature contrasts over 600 miles from north to south; and the influence of the Great Lakes in modifying continental air. (Phillips and McCullough, 1972)

Temperatures decrease from south to north with this latitudinal contrast in winter exceeding that of summer by 20-25 degrees. The basin has warm summers with frequent uncomfortable periods of hot, humid, tropical air from the Gulf of Mexico. In winter arctic air dominates the region with mean daily temperatures below freezing for 3 to 6 months. During spring and autumn, the passage of storms through the basin causes considerable change. Warm, sunny days and crisp, cool nights make the autumn season popular. However, from June through October hurricane remnants can pass close to the basin, producing heavy rain and strong wind.

Annual precipitation averages between 26 and 52 inches with a slight summer maximum. About 20 to 30 percent of the annual total occurs as snowfall with large regional differences depending on the proximity of open lakes.

An important characteristic of the climate of the Great Lakes basin is the variety of weather events from one location to another, and from one year to another. For example, there has been: a

winter season with only 25 inches of snow in the extreme north of the basin; another winter season with 125 inches of snow in the southern; a record daily maximum temperature at a northern station of 108°F; a record February minimum in the extreme south of -35°F; Octobers with almost no rainfall; and one October day during which over 7 inches of rain fell at one location.

Seasonal differences in the weather experienced by the basin from year to year depend upon the intensity and frequency of passing synoptic scale storm systems. During any season important local differences in weather can occur due to the effects of topography, proximity of large water bodies, and changes in land use such as urban expansion. To appreciate these differences, it is necessary to understand the physical controls influencing the climate of this region.

Natural Factors. Due to their immense storage capacity, the Great Lakes provide one of the best naturally regulated water systems.

Monthly levels of Lakes Superior, Michigan, and Huron normally vary only about 1 foot from the low in the winter to the high in the summer; those of Lake Erie vary about 1.25 feet; and those of Lake Ontario 1.5 feet. Over the period of record 1860 to date, the range of Lake Superior, from extreme low to extreme high (on a monthly mean level basis), has been about 4 feet; on Lakes Michigan, Huron, and Ontario, about 6.5 feet; and on Lake Erie, a little over 5 feet.

A drop of 1 foot in the water level of Lake Michigan-Huron reduces the outflow through the St. Clair-Detroit Rivers by only about 7 percent; however, the amount of storage represented by this 1 foot drop would itself sustain an average St. Clair-Detroit Rivers outflow for 2-1/2 months.

In comparison a drop of 1 foot in the water surface of Lake Erie would sustain its average outflow for 15 days. It takes 3-1/2 years for only 60 percent of the full effect of a

supply change to Lake Michigan-Huron to be realized in the outflows from Lake Ontario.

Economic Factors. The waters of the Great Lakes are used for power generation and cooling, shipping, recreation, and water supply. Power is produced by both Canada and the United States, however, the principle power industry is the New York Power Authority with a total production of over 8 million kilowatts. Use of the water for cooling for large nuclear power generation stations is increasing rapidly.

Shipping between lake ports and to and from international ports is increasing, the navigation season is being extended to 12 months instead of the usual 8-9 months, larger ships are being built, and the channel and port facilities are being improved. Every increase of one inch in water level permits an extra 110 tons of cargo on the typical freighters and 225 tons on the new 1000-foot freighters. The tonage through the St. Lawrence system has increased over 75 percent in the past decade, as shown in Figure 1, and now amounts of 53 million tons. In 1972, 6,000 transits occurred in the Great Lakes. Thirty-four percent of the traffic occurred between Canadian ports, 22 percent from Canada to the United States; eight percent from the United States to Canada; thirty percent to and from United States ports to overseas ports; and the remaining six percent occurred as minor trade movements (1972).

Water is diverted from Lake Michigan for domestic water and waste water dilutions at a rate of 3200 cfs. The revenue generated by the City Water Department of Chicago amounts to over $91 million per year. Lake Michigan water is used by other large cities, such as Milwaukee, Cleveland, etc. Economic gain for recreation such as boating, fishing, etc., is hard to determine, but it is a relatively small item. Losses to property are high when the lake levels approach their maximum levels.

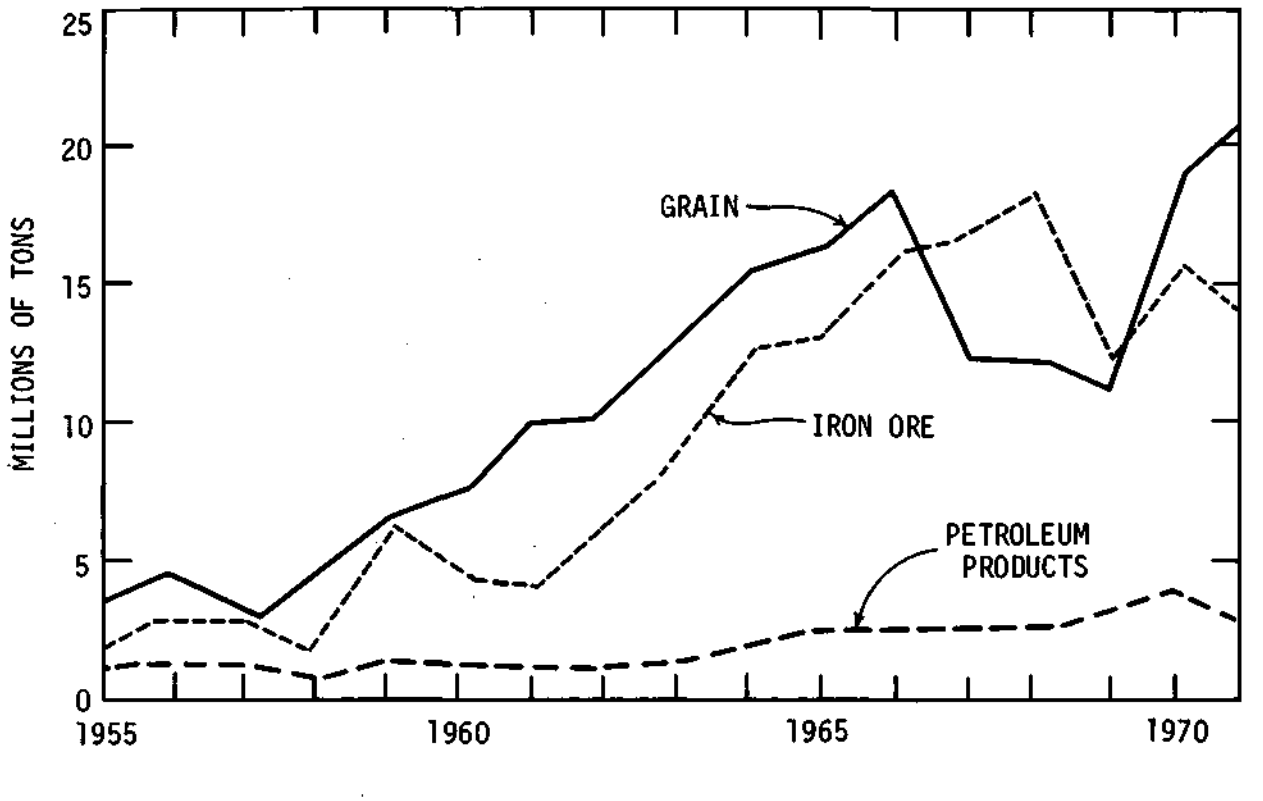

Figure 1. Trends tn tonnage of bulk cargo on the Great Lakes

Earlier studies, as reported by Judge Maris (1966) in his report on the diversion for Illinois in the early sixties, showed that any increase in the diversion from Lake Michigan would be detrimental to the power and navigation industries. For example, a flow of 1000 cfs at the Niagara plant is equivalent to a revenue gain of about $940,000 per year. Likewise, at that time the Corps of Engineers estimated that an increase of 1000 cfs would provide an annual benefit of $363,000 for navigation which was based upon the average annual carrying capacity of the Great Lakes cargo fleet over the next 50 years.

Data

Data on the monthly lake water levels and discharges from the lake were employed for the period of 1950 through 1966. These were obtained from the NOAA Lake Survey Center, having been calculated by Quinn (1971) in his model development. Computations Of changes in water level and discharge for assumed increases in precipitation over Lake Michigan were performed by the Lake Survey Center.

Economic data were developed by the subcontractor, Professor Rolf A. Deininger of the University of Michigan, through correspondence and from the literature. This data base is discussed in detail in the appendix. Changes in lake levels from the assumed increased precipitation from the Lake Survey were provided to the subcontractor. These data were used to develop the economic benefits and disbenefits.

A second economic study was accomplished through special arrangements with the Corps of Engineers. Economic data, developed by the Detroit District Office of the Corps for the International Joint Commission Great Lakes Water Level Study, were used by the Corps to determine benefits independent of the subcontractor's data bank.

Hydrologic Response Model

The hydrologic response model developed for the Great Lakes system by Quinn (1971) is a mathematical model designed to resemble

the water level and flow responses of the system. The model inputs were over-water precipitation, runoff from the drainage basins, diversions out of the system, evaporation losses, ice retardation in the connecting channels, and discharge equation parameters for the connecting channels. The modeled portion of the system consists of Lakes Michigan, Huron, St. Clair, and Erie, along with their connecting channels, the St. Clair, Detroit, and Niagara Rivers. Lakes Superior and Ontario were not modeled because of their complete regulation. However, the impact of Lake Superior was included by considering its outflow through the St. Marys River into Lake Huron. The system is subdivided into the Lake Michigan-Huron, Lake St. Clair, and Lake Erie subsystems for computational purposes. These subsystems will be denoted by the subscript j which will take the values of 1, 2, and 3 for the Michigan-Huron, St. Clair and Erie subsystems, respectively.

The model is derived by applying the continuity equation to each of the three subsystems in the form

$$I_j = O_j + \frac{dS_j}{dt} \quad \text{for } j = 1, 2, 3$$

where: I = the rate of inflow into the system,

O = the rate of outflow from the system,

$\frac{dS}{dt}$ = the rate of change of storage in the system.

The inflow into the individual subsystems consists of the over-lake precipitation, the tributary streamflow, the connecting channel inflows, and the net influx of groundwater. The outflows are comprised of the diversions, the connecting channel outflows, and the evaporation losses. The rate of change of storage is given by the equation

$$\frac{dS_j}{dt} = A_j \frac{dWS_j}{dt}$$

where WS is the water surface elevation in feet above the IGLD (1955) datum. The water surface area A is assumed to be constant for each lake.

The assumption is made that the net influx of groundwater is very small when compared with the other parameters and it is neglected in the computations. The connecting channel inflows and outflows, with the exception of the St. Mary's River, are computed by Quinn's discharge equation. The flow of the St. Mary's River is treated as a tributary inflow.

In developing the model three mathematical procedures were tested. All three solutions were found to converge upon the same end of the month levels, thus giving the same degree of accuracy. The versions differed in the programming effort required and in the amount of computer time required per model run. The explicit solution utilizing the Runge-Kutta algorithm was found to be the simplest to program, but this was insignificant when the model was to be used on a recurring basis. The most important consideration was the amount of computer time required for each model run. In this respect both the explicit solution and the 'hydrologic solution' required approximately 40 percent more running time than the implicit solution. In experimental exercises the implicit version with the Newton-Raphson algorithm with projected approximations was used.

Model Calibration and Sensitivity Analyses. The response model was calibrated by parameter optimization so that its responses best duplicated those which occurred in the natural system. This calibration was necessary to compensate for errors which occurred in the model connecting channel flows. These errors were primarily a result of errors in the discharge equations and differences between the mean lake levels and those in the vicinity of the connecting channels.

The two parameters in the model which lend themselves to this optimization are the constants and mean bottom elevations used in the discharge equation. Both parameters have the same effect of increasing or decreasing the flow, therefore it is necessary to optimize only one. The mean bottom elevations were selected because of the following advantages. The first is that

this allows both Niagara River equations to be optimized separately giving more accurate calibration. The second is that a change in bottom elevations causes a variable change in flow depending upon the lake elevation.

The accuracy of the model was then measured by comparing the magnitude of the deviations of the model water surface elevations and flows with the corresponding prototype data. The frequency and magnitude of the water surface elevation deviations show that, with the exception of Lake St. Clair, considerably greater accuracy is obtained from the end of the month elevations than from the monthly mean elevations. This difference in accuracy results from the model assumption that the rates of the system water quantity parameters are constant over a monthly time increment whereas the prototype rates vary considerably over this period. These differences in the time distribution of the water quantity parameters between the prototype and model result in the lower accuracy of the monthly mean elevations. For this reason the end-of-month water surface elevations were used as the basis of comparison for studies using the hydrologic model.

The accuracy of the monthly simulated flows in the connecting channels was shown in terms of the absolute deviations by the frequency curves. Approximately 95 percent of the time the errors in the monthly flows were less than 4 percent.

A sensitivity analysis of the system parameters was made to determine the sensitivity of each lake in the system to its input parameters. The sensitivity levels used in the analysis are 0.01 foot and 0.02 foot changes in the water levels for each lake. These particular values were used because they represent the precision of the model and the probable accuracy of the water level gages used in measuring the water levels respectively.

The parameters were divided into classifications of water quantity and discharge equation parameters. The former includes the parameters of precipitation, runoff, evaporation, diversion, and rates of change of storage. The sensitivity of the system

to changes in the ice retardation was developed. The sensitivity of each lake to the water quantity parameters was defined as the percentage change in each parameter required to raise or lower the water surface of the lake by 0.01 and 0.02 foot. The variation of the water surface with respect to the discharge equation parameters was determined by differentiating the discharge equations. The sensitivity functions were linear because of the assumption that the lake area was constant and did not vary with small changes in the water surface elevations.

Economic Models

Two models to develop the economic aspects were employed during the study. Literature on the subject was quite limited, but it was known that the International Joint Commission for the Great Lakes was developing a comprehensive model. First attempts to utilize their model were unsuccessful since their study was in progress. The model development and the data bank were part of a cooperative program with the Canadians, and premature release of the information would not have been feasible. Our literature search showed that Rolf A. Deininger had been working on economic aspects of water levels in the Great Lakes consequently, he was engaged to perform an economic study to demonstrate the benefit from a program of increased lake levels from a cloud seeding program. His model and the associated computer program is presented in the Appendix.

Later, use of the Corps of Engineer model to determine the benefits for various lake levels became a reality. The details of the model are not known, but through the cooperation of the Corps of Engineers, benefits from changing lake levels from cloud seeding were computed. These results were then compared with Deininger's values.

Results

Hydrologic Response. If one assumes that he can increase precipitation over a large body, such as one of the Great Lakes, the first question to ask is "What is the hydrologic response?"

Quinn's model was used to ascertain the influence of additional water to the system for a period of record between 1950-66. The top curve of Figure 2 shows the variations in mean lake level for Lake Michigan-Huron during the period of study. Note how the lake rises to about 581 feet in 1952 and drops to about 576 in 1959. It rises and then falls to its lowest value on record in 1964. Between 1966 and 1973, the lake levels continued to rise, except for the seasonal changes, and reached new all time high levels in 1973. The bottom three curves show the changes in lake levels based upon the 10, 20, and 30 percent increase in precipitation during October, November, and December. Cloud seeding produces an immediate response to the lake level. If the Fall season was wet, the response as shown here is large since the reported rainfall was used in this exercise. It is evident that after about five years of seeding, the lake levels reach an equilibrium condition. However, one wet year such as 1959 produced an abnormal increase and it took about five years for the lake to return to a normal or stabilized condition. Due to the large volume of water involved, lake levels require time to reach a stable status. Future calculations for the 30 percent increase in precipitation were not performed since other preliminary studies indicated that such an increase is highly improbable.

As one looks at the change of water level from 1950-66, it soon becomes apparent that one would not want to seed the clouds during the periods of high water. It is generally known that anytime the lake level exceeds the average lake level, the overall benefits from extra water would be negligible. Figure 3 shows what might happen to the lake level if one could add 20 percent precipitation during October-December in which the lake level was much below normal. For example, in 1958, one would have to add water because of the lake level approaching a very low condition, likewise again between 1962 through 1964. Note that the lake level would only rise about l/10th of a foot. This does not appear to be significant, but it is when one considers the total volume of water and the overall economic benefits.

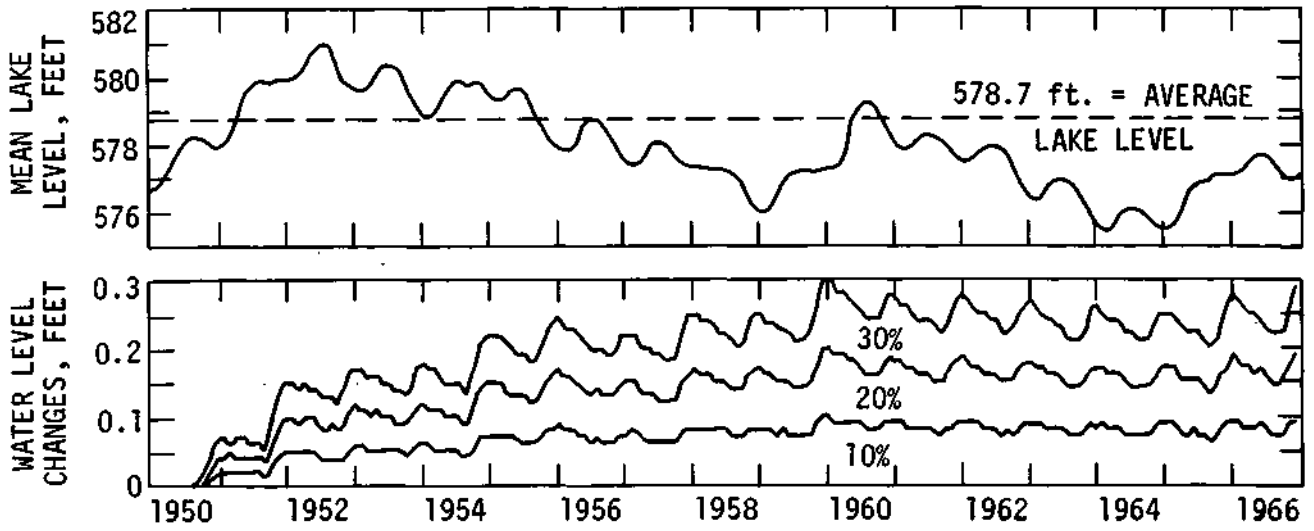

Figure 2. Hydrograph of Lakes Michigan - Huron and incremental water-level changes for 1950-66

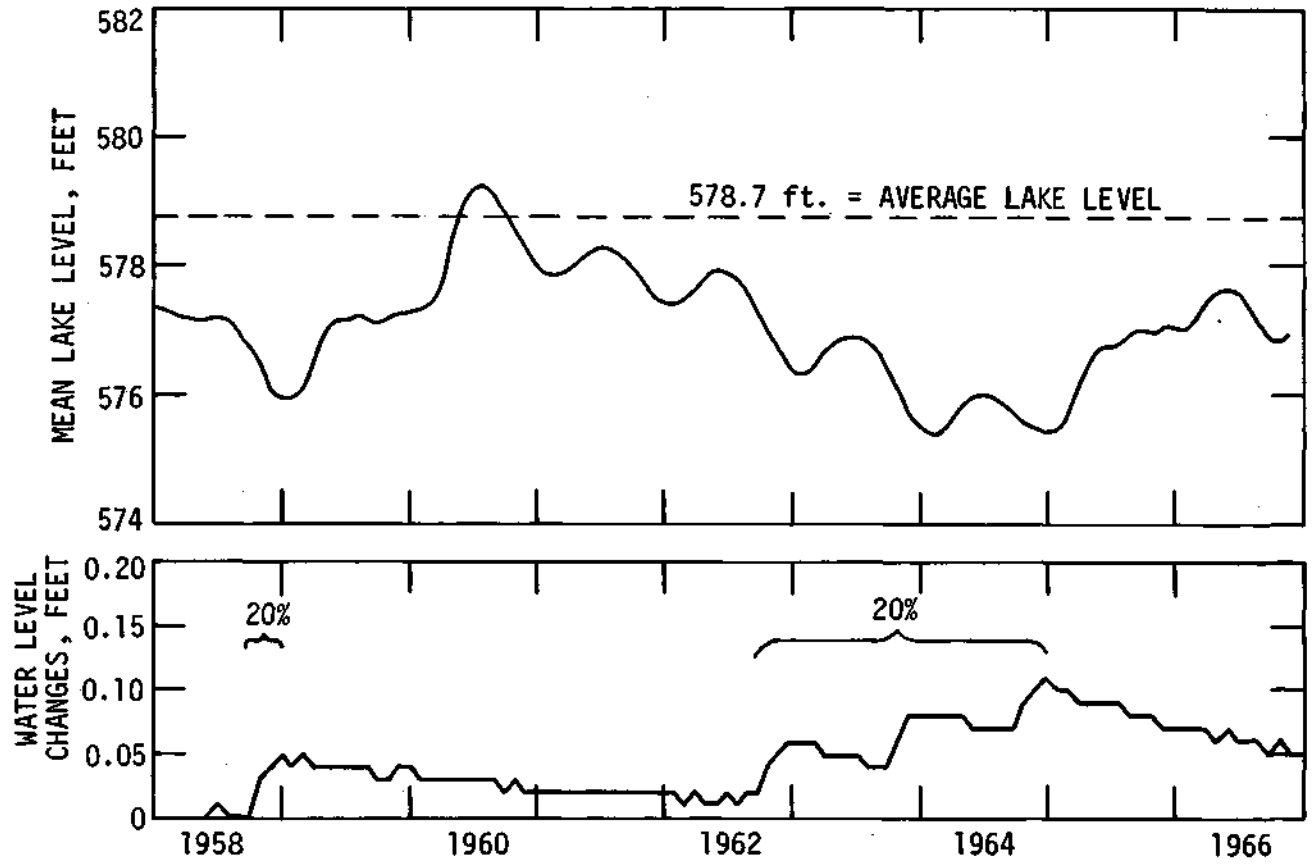

Figure 3. Changes in Lakes Michigan - Huron lake level from a *20%* increase in fall precititation for 1958 and 62-64

The next question in this feasibility study was concerned with the benefits downstream from Lake Michigan-Huron. Figure 4 shows that water added to Michigan-Huron would also be beneficial at times in the two downstream lakes. In this particular case, we assumed a 20 percent increase precipitation, starting in 1955, when the lake level dropped below the average level and we assumed that we would be permitted to add water each Fall season for an indefinite period of time or until the level approached its long-term average level. Again, the change in lake level from the augmented water reaches an equilibrium status after five years.

Calculations on the changes in discharges from the augmented water as well as the natural variability in the discharge is shown in Figure 5. Seasonal variation due to large evaporational losses in water and reduced runoff are evident in the Fall season. Likewise, rising lake levels in Spring from the melting of the snow and small evaporation shows increased discharge. The sharp decline in discharge in winter is due to freezing of the water and blockage of the flow. Seasonal variations of over 20 percent are readily evident. A 20 percent increase in Fall precipitation at the bottom of the figure shows that the change in discharge is only a few thousand cubic feet per second which is much less than the 40,000 cfs seasonal variation. Consequently, augmented water from cloud seeding would have a small effect on the discharge from Michigan-Huron.

Economic Aspects. Based upon Deininger's study, Figure 6 shows the benefits and disbenefits to power, navigation, and shore property if one were to increase the precipitation by 10 percent between 1950-66. The details of this model development and the results are shown in the Appendix by Farris, Tobin and Deininger (1973). These benefits are restricted to Lakes Michigan-Huron, St. Clair, and Erie. The figure shows the year by year

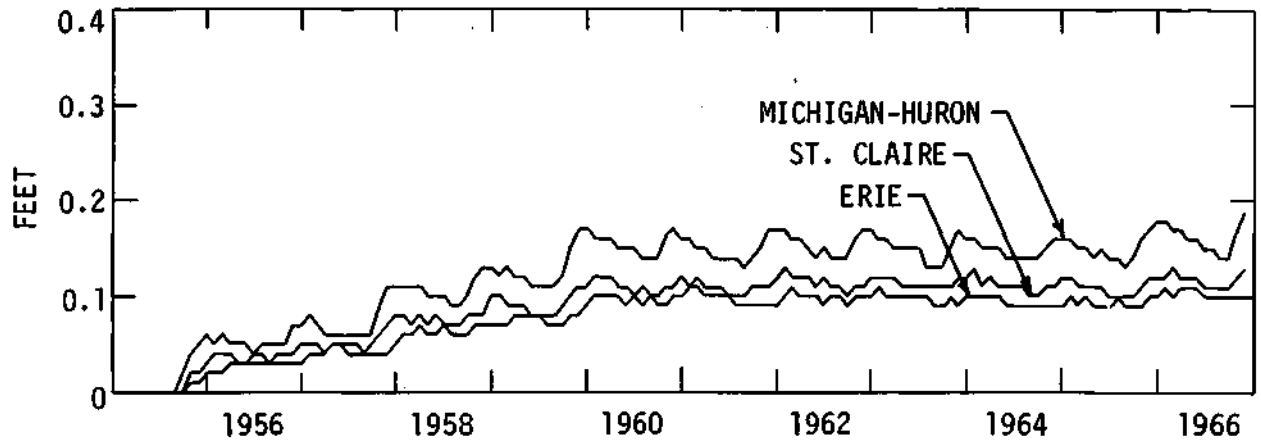

Figure 4. Hydrologic response to a 20% increase in precipitation each fall for 1955-66

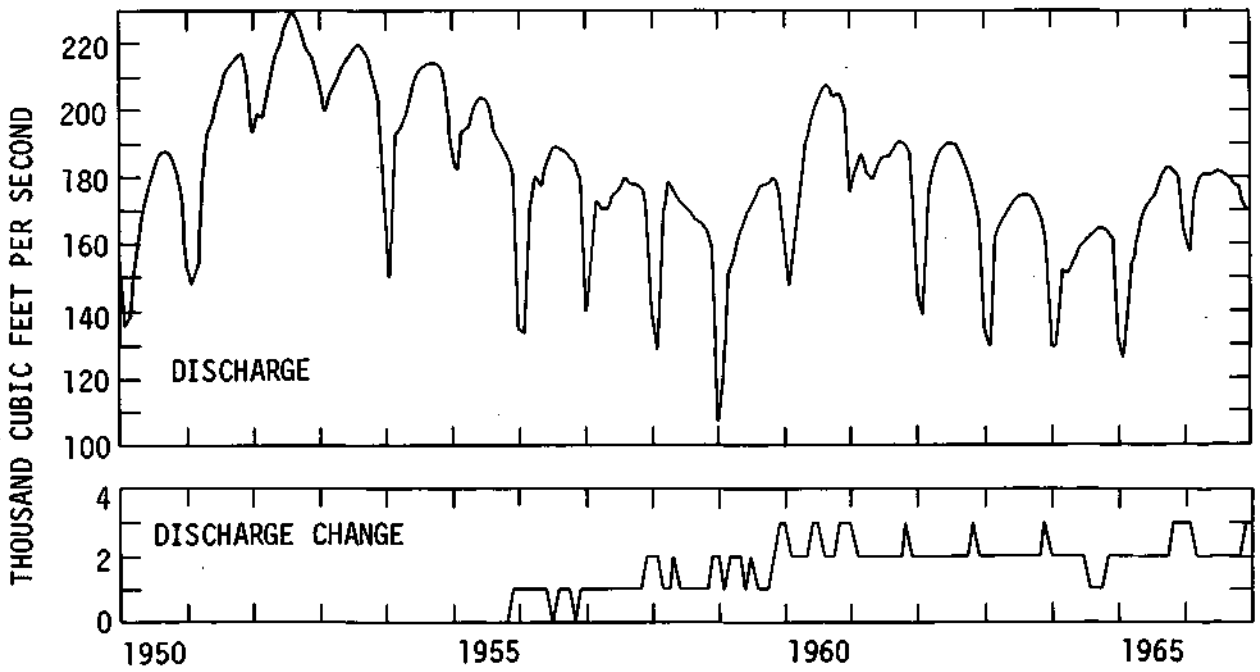

Figure 5. Monthly discharge from Lakes Michigan - Huron for 1950-66 and changes in discharge from a 20% increase in fall precipitation for 1955-66

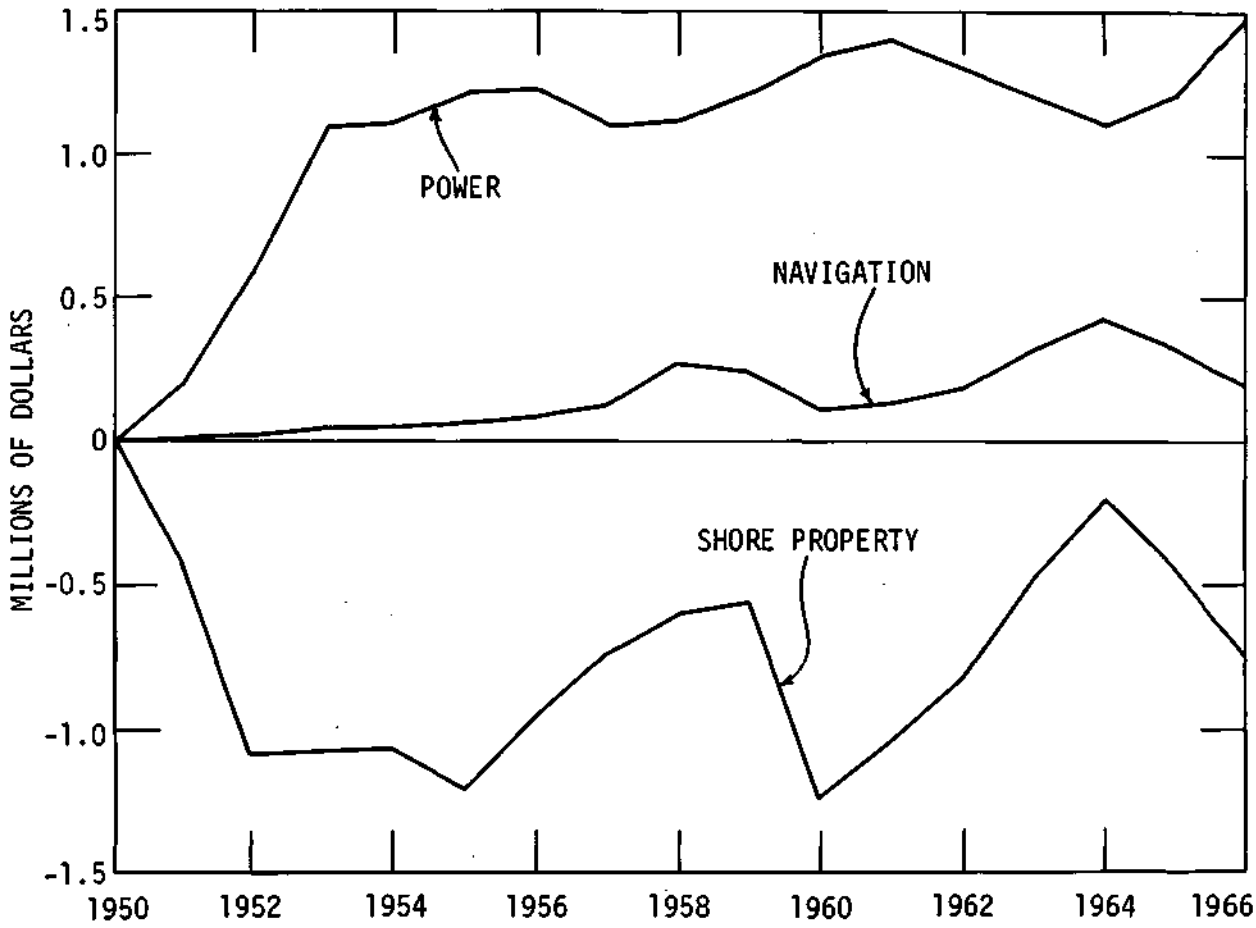

Figure 6. Annual benefits for power and navigation and disbenefits to shore property from a 10% increase in fall precipitation (Based upon Deininger)

variations in the benefits or disbenefits. Benefits from the higher water level are quite evident for the power generation and shipping. Added water during periods of high level would be very detrimental to property. Losses to shore property in periods of low water are due to inconveniences and losses from normal use of docking facilities, to wildlife for lack of water along the shore, etc.

The overall benefit for the entire period and for various seeding periods for either 10 or 20 percent are shown in Table 1. If one compares the 20 percent cases for either the continuous seeding program or for selective years, the total benefits do not change much. Large shore property losses are offset by increased benefits to power, etc. Prom these cases, the continous seeding program for 1955-1966 produced greater overall benefits than just seeding during periods of low water level years. During this period there was only one year that the lake level exceeded the average lake level of 578.7 feet. The benefits for a 10 percent increase would be about one half of the 20 percent.

In another analysis, we later arranged with the Corps of Engineers to determine a benefit evaluation by assuming the same change in lake levels due to the theoretical water augmentation program. The parameters and features of this model have not been published. However, much more data based upon recent evaluations from current users of the Great Lakes water were employed. They used the projected fleet in 1995, benefits to Lake Superior, etc. in their study for the International Joint Commission's Great Lakes Water Level Study. Table 2 indicates that according to the Corps model that the overall benefits may be three times larger than that developed by Deininger. An explanation for this difference has not been fully developed during the course of this study.

TABLE I

ANNUAL DOLLAR BENEFITS FROM WATER AUGMENTATION
BASED ON DEININGER'S MODEL
(millions of dollars)

	Power	Navigation	Shore Property	Total
10% in 1950-66	1.1	0.2	-0.7	0.6
20% in 1950-66	2.2	0.3	-1.5	1.0
20% in 1955-66	1.9	0.3	-1.0	1.2
20% in 1955-58, 1960-66	1.5	0.3	-0.9	0.9

TABLE II

ANNUAL DOLLAR BENEFITS FROM WATER AUGMENTATION
BASED ON CORPS OF ENGINEERS' STUDY
(millions of dollars)

	Power	Navigation	Shore Property	Total
10% in 1950-66	1.5	0.6	-0.6	1.5
20% in 1950-66	3.1	1.0	-1.4	2.7
20% in 1955-66	2.1	0.9	-0.3	2.7
20% in 1955-58, 1960-66	2.4	1.2	-0.3	3.3

In order to compare the two models Figure 7 shows three sets of curves to illustrate the benefits to navigation, power, and the disbenefits from shore property damages from a 10 percent increase in precipitation. Both models seem to ascertain the general trends with time quite well until 1963. For the shore property plots, damages were more severe during years of high water for the Corps model than for the University of Michigan (Deininger). Power benefits remain about the same through the fifties and then, the Corps model in the sixties shows increasing benefits from the extra water, which became twice as large in 1966. Navigation benefits remain nearly the same until 1963 when quite large benefits develop for the 10 percent increase in water. The lake levels were quite low in 1964, but rose in 1966 to be about the same as 1963. One would expect the benefits on the curve for the Corps to be similar for the two years, instead of the large departure. The University of Michigan curve appears to be more like what one would expect.

There is another important benefit from the Great Lakes waters which was not covered by the two economic models. Water is used for domestic and industrial water supply for cities like Chicago, Milwaukee, Cleveland, etc. Since no one is charged for use of the water that is withdrawn, the benefit is difficult to ascertain except to say that the entire economy depends upon the resource.

At the present time, the city of Chicago has an adequate water supply from the lake, but as the demands increase and the population grows in the suburbs, the city may eventually need to withdraw more water for domestic use. The second possible use for additional water would be as an alternative to tertiary treatment of the sewage effluent. The high per capita cost for tertiary treatment and the regular treatment operation to remove phosphate, etc., may be so prohibitive that the city may be forced to use water for dilution. This, of course, is contrary to the U. S. policy at this time.

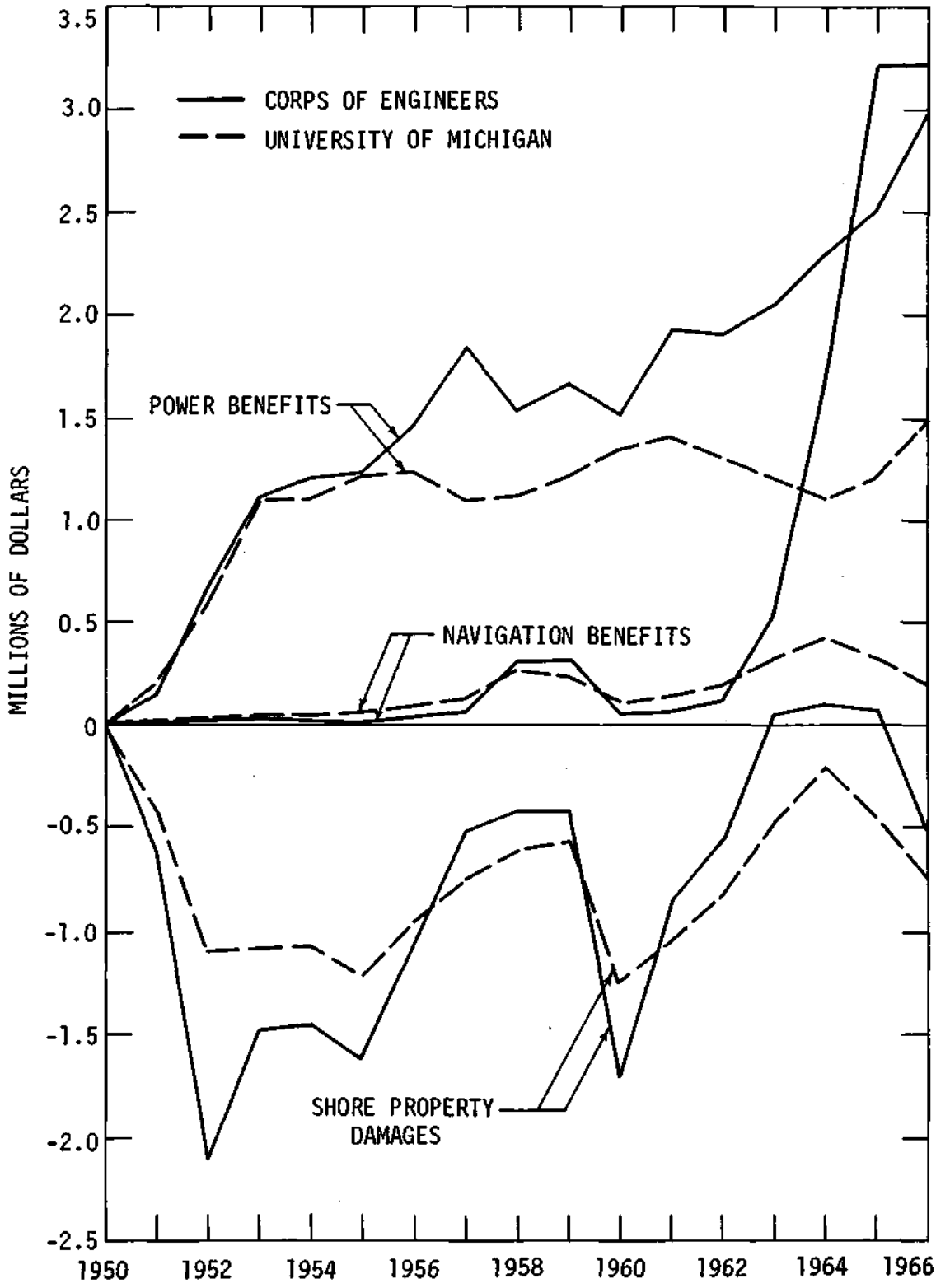

Figure 7. Comparfson of benefits and disbenefits for both models from a 10% increase in fall precipitation

The city of Chicago now withdraws about 2 billion gallons per day. If the water department had to pay a fee, such as only l/2¢/l,000 gallons, which is very low, then the cost of the water would be about $1.8 m/yr. Adding the value to the benefits to navigation, power, and shore property from a 10 percent increase from cloud seeding during the critical years, the gross dollar benefit would exceed $2.5 million. In this particular situation, one might assume that if the State of Illinois could add water to the lake that they would also be granted the right to remove the same amount of water for their own utilization.

Seeding Costs

In order to know the true value of such a program, one needs to determine the costs. The costs depend upon a number of factors which were to be determined as a part of a larger co-operative effort. Unfortunately, the other phases of the multiple university program were never funded. Information as to whether ground base or aircraft seeding or a combination of two, the number and duration of seedable cases, the efficiency of the seeding agent and many other factors should be determined.

Correspondence with a commercial cloud seeder, Mr. Thomas J. Henderson, President of Atmospherics Inc., Fresno, California, suggested that based upon a number of assumptions which would involve an aircraft seeding program, annual costs would approach $500,000. Discussion with NOAA personnel and review of cloud seeding reports elsewhere confirms the above costs. Since the annual net benefits would exceed $2 million, this would suggest a conservative benefit-cost ratio of 4:1.

Summary and Conclusions

A feasibility study to determine some of the hydrologic and economic aspects from a cloud seeding effort to augment the precipitation over Lake Michigan has been undertaken. Increases of 10 and 20 percent in the Pall precipitation were assumed to be feasible. Seeding was performed over Lake Michigan and the

augmented water was found to increase the water levels in the downstream lakes and the discharge from these lakes. The amount is not large in comparison to the total volume of water, but the extra water would play an important economic role.

The benefit-cost ratio appears to be in the order of 4 to 1. Benefits to power generator and navigation are significant until the lake level reaches a level where the system can no longer benefit from the added water. There are limiting factors such as the capacity of the power generators or the draft of the ship exceeds the depth of the channel for movement between ports. On the opposite side, damage to shore property increases as the lake level rises. According to the models there is always a dis-benefit to shore property, but it is less when water is added during periods of low levels.

Two different economic models were utilized in the study. In general the results compare favorably except during periods of extremely low lake levels. The overall order of magnitude of the results are in general agreement and provides a base for further study.

Ideally, the optimum height of the lake level should be near its long term average level. Investigations on the manage-ment of the Great Lakes endorse the need to reduce the great fluctuation in lake levels. Increasing lake levels from cloud seeding efforts during periods of low water would be one approach. The overall economic aspects readily support such a program.

There are numerous questions concerning the proper mechanism for increasing the snowfall, the technique or techniques to use, the frequency and duration of likely seeding periods, etc. are a few of the questions. Considerable more research on the climatological, cloud physics aspects and developing the technology for overwater seeding in winter needs to be performed.

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