IES Report 131

Diversion of Great Lakes Water
Part 2: Economic Impacts

Martin H. David, Stuart S. Rosenthal, Eric D. Loucks,
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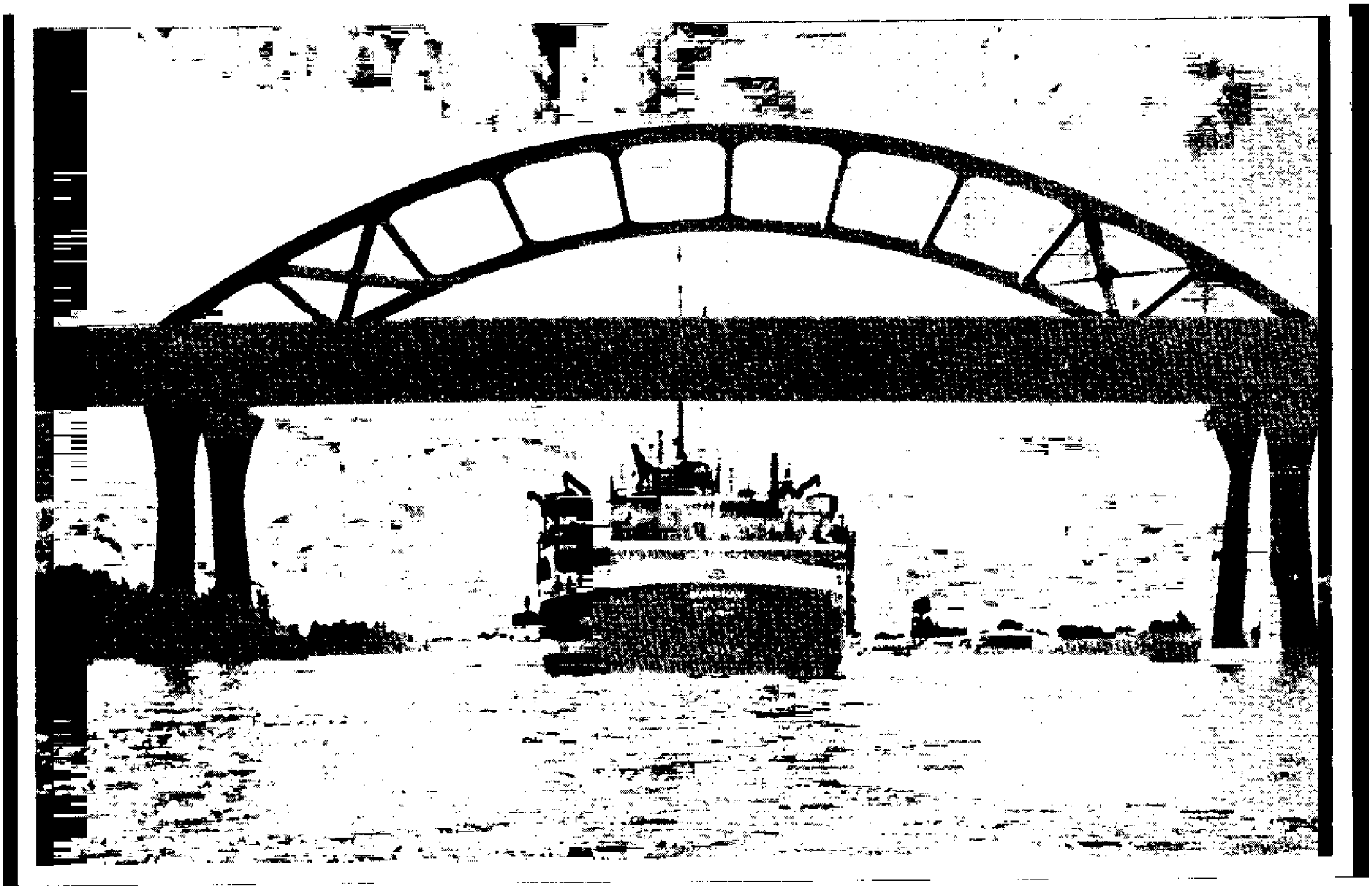

IES Institute for Environmental Studies ■ in cooperation with the University of Wisconsin Sea Grant Institute

University of Wisconsin–Madison

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PART 2: ECONOMIC IMPACTS

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ABSTRACT

A research team at the University of Wisconsin-Madison developed models to evaluate the hydrologic and economic impacts of potential large-scale Great Lakes water diversions. The team then applied the models to five hypothetical diversions ranging from five thousand cubic feet per second (tcfs) to 30 tcfs. The potential impacts of the diversions on lake levels and water flow, and the hydrologic model from which they were derived, are addressed in a companion report (IES Report 130/UW Sea Grant Technical Report WIS-SG-87-246).

This report develops an economic model to assess the monetary impacts of diversions on the shipping and hydropower industries in the Great Lakes region. The model indicates that a moderate-sized (10 tcfs) diversion would cost the industries $70 million to $90 million annually, depending on the lake used as the source. A large diversion (30 tcfs) would cost them $250 million annually. In each case, the added costs to the Great Lakes hydropower industry are roughly 10 times those to the shipping industry. Although the added costs would be significant to these industries, they probably would be minor to the regional economy as a whole. However, neither the water-transmission costs of diversions nor the economic effects on environmental attributes such as recreation, wetlands, and wildlife are considered.

THE AUTHORS

Martin H. David is a professor of economics and environmental studies.

Stuart S. Rosenthal earned a Ph.D. in economics in May 1986 and is an economist with the Federal Reserve Board in Washington, D.C.

Eric D. Loucks is a research assistant and Ph.D. candidate in the Department of Civil and Environmental Engineering.

Erhard F. Joeres is a professor of civil and environmental engineering and environmental studies, and chairman of the Water Resources Management Graduate Program in the Institute for Environmental Studies.

Kenneth W. Potter is a professor of civil and environmental engineering.

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Mr. Darrel Marchand, University of Windsor; Mr. Gregory Hedden (ret.) UW Sea Grant Institute; Ms. Pixie Newman, now at Ch2M-Hill, Milwaukee; Ms. Kim L.E. Hanson, Stanford University; and Dr. George Parsons, now at the University of Delaware.

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CHAPTER 1

AN ECONOMIC FRAMEWORK FOR ESTIMATING THE WELFARE EFFECTS ASSOCIATED WITH CHANGES IN GREAT LAKES WATER LEVELS

Potential diversions of water from the Great Lakes to arid regions in the West have become an increasingly controversial issue in the states and provinces bordering the Great Lakes. The predominant concern is that large diversions of water could significantly reduce the volume of water in the lakes, lowering lake levels and harming economic activities dependent on those lake levels. The major activities most likely to be affected are transportation services (shipping), electrical power generation (hydropower), shoreline property values, and various environmental attributes. In this chapter, we will develop an economic model which, in principle, is capable of analyzing the impact of different lake levels on these activities. In doing so, we will provide a theoretical foundation from which the impact of regulations designed to control lake levels can be reviewed. Later chapters will address the availability of data, which may restrict our ability to implement the model. The fifth chapter will present empirical estimates of the impact of diversions.

We should note that while this study was motivated by interest in diversions, the impact of consumptive use of water on the hydrology of the Great Lakes and the industries cited above is no different from that for diversions. The only salient difference between diversions and consumptive use for our purposes is the location at which water is removed. Otherwise, the economic effects reported in this study can best be thought of as the result of permanent withdrawals of water from the Great Lakes watershed. The withdrawals could come entirely from diversions or consumptive uses, or they could be a combination of both. Throughout the report, we use the word "diversions" to refer to withdrawals of water from the lakes that are not returned to the basin. However, the reader should keep in mind that this refers to consumptive uses as well.

Numerous issues could be considered in evaluating the economic impact of regulations that affect lake levels. For this chapter, regulation will be classified into two types: direct regulation of lake levels through the construction and operation of facilities designed specifically to control lake levels (such as the compensating works on the St. Marys River) and regulation of diversions (which imposes externalities on demanders of lake levels). In the economic model, lake levels are treated as a factor of production like any other factor because lake levels affect the cost of producing goods and services in the industries mentioned. The model must also account for the presence of four distinct lakes in the Great lakes system and, because all users of the lakes face the same lake levels, the relationship of lake levels to overall social welfare.

To address the issues cited above, the discussion is divided into five sections. The first section develops the basic model necessary to measure the social welfare associated with different lake levels. This model is discussed in a simplified setting, assuming no natural variation in lake levels and a single-lake system in order to concentrate on conceptual issues. The second section extends the model to a four-lake system appropriate for the Great Lakes. The third section extends further to account for natural variation in lake levels. The fourth section addresses how this natural variation leads to a distribution of impacts from diversions and how that distribution is accounted for in our empirical results. The final section will summarize any qualitative guidelines for regulation of lake levels implied by analysis of the economic model.

Measuring Social Welfare Associated with Different Lake Levels

This section develops the basic model for measuring the level of social welfare associated with a given lake level (LL). To concentrate on measurement issues, we assume a single lake system and ignore natural variation in LL. Initially, suppose that transportation is the only industry whose production costs are sensitive to LL, and assume that over the range of LL relevant for our planning horizon, increases in LL always decrease the cost of production for a given level of output. The least expensive way to produce a given level of output Q for a given technology, factor prices, and LL is described by a firm's cost function. The total cost of producing transportation services is:

$$TC = C(\underline{W}, LL, Q) \tag{1.1}$$

where $C(\cdot)$ is the cost function, $\underline{W}$ is an n by 1 vector of factor prices, and the other variables are defined as before.

To obtain the marginal cost curve for the firm, expression (1.1) is differentiated with respect to Q. Under a competitive allocation this gives the supply curve for the industry, which is drawn in figure 1. Note that marginal cost, and hence the supply curve, is sensitive to LL. Market equilibrium occurs where the supply curve intersects the market Marshallian demand curve. The equilibrium price and quantity when lake levels equal LL' are P' and Q', where P is the price for Q.

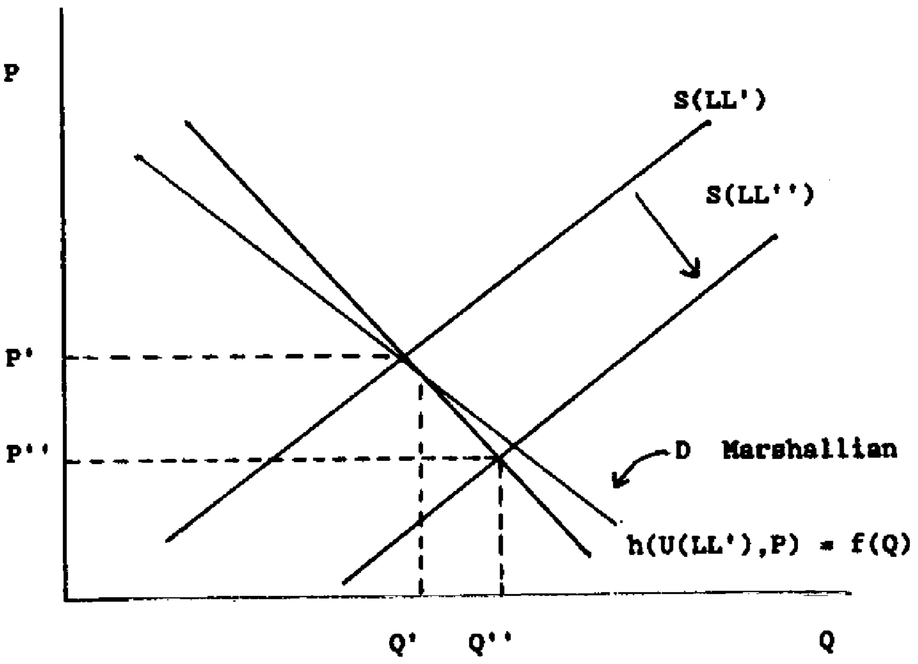

Figure 1. Product market equilibrium

To determine the level of social welfare associated with LL', recall that the compensated demand curve h(U, P), is the derivative of the consumer's expenditure function. The expenditure function describes the minimum expenditure necessary to achieve a specific level of utility for a given set of product prices. For Q = Q', the integral of the compensated demand curve up to Q' gives the total amount consumers would be willing to pay for Q'. (This equals the area under the compensated demand curve up to Q'.) Let e(U', P') be the expenditure function where U' is the level of utility associated with Q' and LL'. Then the total benefit to consumers from Q' is the area under the compensated demand curve, which equals:

$$TB = \int_0^{Q'} f(Q)dQ = e(U', f(0)) - e(U', f(Q')) \qquad (2.1)$$

where f(Q) = P.

The total cost to society in foregone resources in producing Q' is the area under the supply curve, which equals:

$$TC = \int_0^{Q'} \frac{\partial C(\underline{W}, LL', Q)}{\partial Q} dQ = C(\underline{W}, LL', Q'). \qquad (3.1)$$

The net benefit to society is the difference between TB and TC or:

$$NB(LL') = e(U', f(0)) - e(U', f(Q')) - C(\underline{W}, LL', Q'). \tag{4.1}$$

Now suppose a diversion into the lake increases LL from LL' to LL''. The supply curve shifts out to S(LL''), and the new equilibrium price and quantity are P'' and Q''. Consumer utility increases to U'' because Q is now less expensive. Using an equivalent variation measure, the welfare change associated with the change in LL from LL' to LL'' is:

$$\begin{aligned} \Delta NB(LL', LL'') &= NB(LL'') - NB(LL') \\ &= e(U', P') - e(U'', P') - C(W, LL'', Q'') \\ &+ C(W, LL', Q') \end{aligned} \tag{5.1}$$

where P' is the market price level associated with LL'.

Measuring Welfare When More than One Industry Depends on LL

The previous model can be expanded with little difficulty to include other industries that depend on LL. Because past studies have been concerned primarily with the impact of LL on transportation, power production, and shoreline property values, we will use these three industries as an example. Assume that over the range of LL relevant for our planning horizon an increase in LL always reduces production costs for power generation and transportation services. However, because of damages to property values caused by flooding during high LL years, the costs of maintaining property values are assumed to increase with increases in LL.

We can simplify our analysis considerably by assuming that consumer preferences are additively separable over the goods mentioned above. This implies that the compensated cross-price elasticities are equal to zero; a change in the price of electricity, for example, will have no effect on the compensated demand curve for shoreline property. Hence, as we integrate under the demand curve for electricity, changing its price, the total willingness to pay for a given amount of shoreline property is unaffected. This assumption seems reasonable in the context of this study because the effect on product prices from diversions is likely to be small. Under this assumption, the total benefit to consumers from a given level of output in each of the three industries is just the sum of the total benefits associated with each individual industry. The net benefit associated with a given lake level, LL', is obtained by summing the net benefits associated with the three industries. This gives:

$$NB_{Agg}(LL') = \sum_{j=1}^{3} NB_j(LL') \tag{6.1}$$

where $NB_j(LL')$ is defined in equation (4.1), and j refers to the industry type. Note that all industries face the same LL, but the cost functions, demand curves, and equilibrium price and output are unique to each industry. The change in aggregate net welfare for an increase in LL from LL' to LL'' is given by:

$$\Delta NB_{Agg}\ (LL', LL'') = \sum_{j=1}^{3} \Delta NB_j \tag{7.1}$$

where ΔNB is defined in equation (5.1).

It is important to note that we cannot determine on a qualitative basis whether ΔNB_{Agg} is positive or negative for a given change in LL. For an increase in LL, $\Delta NB_{shoreline}$ is negative, whereas ΔNB is positive for transportation and power generation. Whether the change in net benefits for shoreline property is greater or less than the sum of the changes in net benefits for transportation and power generation is an empirical question. Suppose that government adopted a policy of charging demanders of water the opportunity cost of the water. If the initial LL is high, government may actually want to pay consumers of water to divert water from the system. This is fairly intuitive because in high LL years diversions of water out of the system impose positive externalities by reducing the risk of severe flooding.

The Impact of LL on Multipurpose Industries

The size and sign of the change in welfare associated with a change in LL depend critically on the elasticity of the supply curve. Both transportation and power generation can be characterized as multiple-process industries in which only one process depends on LL. In the transportation industry, goods can be transported by boat, rail, or truck. Power, on the other hand, can be generated by hydropower, coal, oil, or nuclear plants. To explore the effect that multiple processes have on changes in welfare associated with changes in LL, consider a representative industry with two processes. The cost function has the form:

$$TC = \min[C_A(W, LL, Q_A) + C_B(W, Q_B)] \tag{8.1}$$

$$\text{s.t. } Q = Q_A + Q_B.$$

This industry can use either process A or B to produce Q. Process B does not depend on LL, whereas process A does. For simplicity, suppose that neither process has any fixed costs and let figure 2 describe the marginal costs of production for each process.

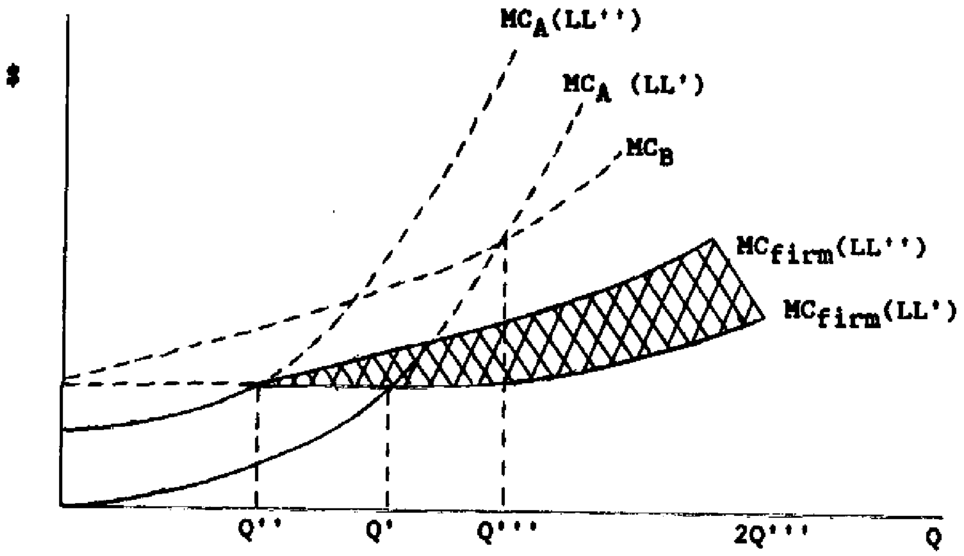

Figure 2. Production costs for multiprocess industries

If LL = LL' and Q is less than Q', the industry will use only process A with $Q_A = Q$. If Q is greater than Q' though, the industry will use both processes, and it will allocate production between them in a manner that ensures that their marginal costs of production are equal. This increases the elasticity of the firm's marginal cost (supply) curve compared to the marginal cost curve the firm would have if only one process were used. For an initial LL, LL', the firm's marginal cost curve is MC_{firm} (LL'). Suppose now an adverse change in LL from LL' to LL'' shifts MC_A in, raising production costs for all levels of Q. The industry's new marginal cost curve is MC(LL''). Note that the firm begins to use process B earlier at Q = Q'' instead of Q = Q'. This reduces the impact of the change in LL on the firm's production costs; however, for a given level of output the firm still finds it more expensive to produce under LL'' than under LL'. For instance, if Q = 2Q''', with LL = LL', each plant produces Q'''. When LL changes to LL'' costs increase by an amount equal to the hatched area between the firm's marginal cost curves.

Measuring the Welfare Effects from a Change in LL in a Four-Lake System

In the Great Lakes system there are actually four distinct lakes. The economic principles developed for measuring changes in welfare in a single-lake system hold equally well in a multiple-lake system. The principal difference is that the four-lake system requires a hydraulic model to explain how LL and outflow from one lake affect LL and outflow from the other three lakes. Let L_1, L_2, L_3, and L_4 stand for Lake Superior, Lake Michigan-Huron, Lake Erie, and Lake Ontario, respectively. Then the hydraulic model has the form:

$$LL_1 = f(\psi_1, D_1) \tag{9.1}$$

$$LL_2 = f[f(\psi_1, D_1), \psi_2, D_2] = g(LL_1, \psi_2, D_2) \tag{10.1}$$

$$LL_3 = f\ [f[f(\psi_1, D_1), \psi_2, D_2], \psi_3, D_3] = h(LL_1, LL_2, \psi_3, D_3) \tag{11.1}$$

$$LL_4 = i(LL_1, LL_2, LL_3, \psi_4, D_4) \tag{12.1}$$

where ψ_i is an m by 1 vector of physical factors affecting LL_i directly (like rainfall onto L_i, runoff into L_i, etc.), and D_i is an n by 1 vector of artificial diversions and consumptive uses from L_i. Note that the ψ_i and LL from the downstream lakes are dependent on the D_i from the upstream lakes. This occurs because withdrawals of water from the upper lakes affect the amount of water flowing into the lower lakes. In an unregulated system we could characterize the problem by noting that diversions from LL_1 affect LL_2, LL_3, and LL_4. Similarly, actions taken to regulate LL_2 impose externalities on demanders of LL_3 and LL_4, while actions taken to regulate LL_3 impose externalities on users of LL_4. However, with artificial control of LL, changes in downstream LL do affect upstream LL through operation of the compensating works on the St. Marys River.

This is particularly true for changes in Michigan-Huron lake levels as discussed in our hydrology report. (Changes in the gradient between lakes also have an effect but are second-order in nature.) To control for these externalities we must account for the impact of changes in upstream lake levels on the costs of production for industries located on the downstream lakes. To do this we specify cost functions for industries located on different lakes that account for the interactions among LL according to the hydraulic model. The cost functions become:

$$C_{j1} = C_{j1}(W, Q, \psi_1, LL_1, LL_2, LL_3, LL_4) \tag{13.1}$$

$$C_{j2} = C_{j2}(W, Q, \psi_2, LL_1, LL_2, LL_3, LL_4) \tag{14.1}$$

$$C_{j3} = C_{j3}(W,\ Q,\ \psi_3,\ LL_1,\ LL_2,\ LL_3,\ LL_4) \qquad (15.1)$$

$$C_{j4} = C_{j4}(W,\ Q,\ \psi_4,\ LL_1,\ LL_2,\ LL_3,\ LL_4) \qquad (16.1)$$

where $j = 1,2,3$, for shoreline values, transportation, and hydropower. Observe that the C_{ji} are dependent on diversions through LL_i as modeled by equations (9.1) to (12.1).

We should also note that the efficiency of a hydroelectric plant, and hence the cost of producing hydropower, depends on the water level at the plant and on the flow of water through the plant. The flows of water entering and leaving each lake are elements of the ψ_i vectors and therefore affect lake levels. However, shipping and shoreline property values are assumed to depend only on lake levels.

Suppose now a diversion on L_1 causes LL_1 to change from LL'_1 to LL''_1. From the hydraulic model this causes the other lake levels to change as well. Let $\underline{LL}$ be a 1 by 4 vector of LL on the four lakes. Then the diversion causes $\underline{LL}$ to change from $\underline{LL}'$ to $\underline{LL}''$. The change in net benefit for an arbitrary industry on L_i has the same form as the change in net benefit in a single lake system described in equation (5.1). The only difference is that the cost function will be more complex as shown in equations (13.1), (14.1), (15.1), and (16.1). The change in aggregate net benefits from the diversion on L_i is:

$$NB_{Agg}\ (\underline{LL}',\ \underline{LL}'') = \sum_{i=1}^{4}\ \sum_{j=1}^{3} NB_{ij}(\underline{LL}'_{ij},\ LL''_{ij}) \qquad (17.1)$$

where $i = 1,2,3,4$ for each of the lakes and $j = 1,2,3$ for each of the industries.

Although the multiple-lake system makes estimation of the welfare effects associated with changes in $\underline{LL}$ more complex, there seemingly is one important advantage for regulation. From the hydraulic model we see that in a single lake system, government has only one set of control variables to regulate LL, namely D. However, for a multiple-lake system our control options are increased. For instance, to regulate LL_2, D_2 or D_1 could be used. To regulate LL_3, D_3, D_2 or D_1 could be used; and to regulate LL_4, D_1, D_2, D_3, or D_4 could be used. In principle this greatly increases the potential for government to regulate lake levels in a desirable manner because it has many more control options than in a single-lake system. However, the International Great Lakes Diversions and Consumptive Uses Study Board (DCU) concluded that the response times of the system are too slow to use diversions as a control mechanism to select desired lake levels.

The Impact of Natural Variation in LL on Regulation

The previous sections have ignored natural variation in LL and instead assumed that desired levels of LL could be attained with certainty. To relax that assumption we can define a probability distribution function for $\underline{LL}$, $f(\underline{LL})$, which, in the absence of artificial regulation of $\underline{LL}$ will tell us the probability that the lakes will take on certain values in a given year. This creates uncertainty for producers because they do not know what value $\underline{LL}$ will take in a given year. The variability of $\underline{LL}$ creates two additional costs for producers that we will refer to as capacity costs and adjustment costs. Assume the firm uses both durable capital K_d and variable capital K_v. Durable capital is defined as capital that lasts for several periods, whereas variable capital is capital that can be adjusted quickly enough to respond to changes in LL in a cost-minimizing manner. When purchasing durable capital the firm tries to minimize the expected value of the present discounted costs of production over the lifetime of the capital where expectations are taken over LL. The solution to this problem yields K^*_d. In each period over the lifetime of K^*_d the firm's cost function becomes:

$$C(\underline{LL}) = C(\underline{W}_v, \underline{\psi}, K^*_d, \underline{LL}, Q). \tag{18.1}$$

Because the firm cannot adjust K^*_d once it has made its purchasing decision, in a given year K^*_d will generally not be the optimal level of durable capital for the $\underline{LL}$ that actually occurred. For instance, in the power industry excess capacity is built into the system to ensure that sufficient power generation will be available in low LL years when hydropower is less productive. However, in high LL years the excess capacity is underutilized and creates a loss for the firm. If funds were not tied up in the unused durable capital they could be invested in alternative activities to earn a higher return. But in general, the lower the variability of $\underline{LL}$ the less frequently the durable capital is underutilized and the higher its return. This implies that one guideline for operation of facilities designed to control $\underline{LL}$ is to reduce the variability of $\underline{LL}$ regardless of the mean $\underline{LL}$ desired.

The second way in which variation in $\underline{LL}$ increases production costs is through increased adjustment costs of variable capital. It is reasonable to assume that when firms adjust their variable capital in response to changes in $\underline{LL}$, for a given level of output Q_j they incur an adjustment cost that is a nonlinear function of the change in the $\underline{LL}$. If we let A_{jt} equal the adjustment costs in year t for industry j, then:

$$A_{jt} = A(\underline{LL}_{jt} - \underline{LL}_{j,t-1}, Q_j). \tag{19.1}$$

The cost function must therefore be modified to include A_{jt}. For a typical firm we get:

$$C_{jt}(\underline{LL}_{jt}, \underline{LL}_{j,t-1}) = C_{jt}(W_v, \underline{\psi}, \underline{LL}_{jt}, K^*_d, A_{jt}, Q). \tag{20.1}$$

As in the previous section, the change in aggregate net benefits is estimated for a given firm in the same way as originally described in equation (5.1). The only difference is that the cost function has been modified to the form shown in equation (20.1). We can update our formula for estimating the change in aggregate net benefits by substituting the cost function in (20.1) for each industry into the formula developed for aggregate net benefits in the previous section, equation (17.1). As with durable capital, it is clear that firms will generally benefit from a reduction in the variance of LL because it will reduce their adjustment costs.

Distribution of Economic Impacts from Diversions

An obvious implication of the preceding section is that we are unable to predict the exact level of future damages from a diversion even if all future economic data are known with certainty. This is because lake level variations are stochastic and follow a distribution as explained in our hydrology report. To address this problem, the distribution of damages from diversions corresponding to natural variations in lake levels was estimated. This was done by estimating the damages from diversions for each year of the 77-year historical series of lake levels while keeping economic conditions constant. This generated 77 different estimates of the yearly damages from diversions, each based on different lake levels but on the same economic conditions.

It is important to note that this approach uses the lake level series as a random sample of natural lake levels with the effect of the particular diversion factored in. In addition, the economic conditions used in this report were chosen to be representative of current "typical" conditions. The estimated distribution of damages, therefore, represents the range of impacts we might expect diversions to have on some year in the near future given "current" economic conditions and the distribution of possible lake levels.

The presentation of economic effects described above differs from the approach used by the International Lake Erie Regulation Study Board (ILER) and the International Great Lakes Levels Board (IGLLB). Their studies projected the damages from diversions for 1985, 2000, and 2035 based on forecasts for economic conditions over the period. Using the forecasted economic conditions in each of these three years, the mean level of damages in each year was calculated based on the historical sequence of LL. This generated three estimates of mean damages whose differences were due only to the difference in economic conditions used in each year. Values for mean damages in years between these points were interpolated and the discounted sum of mean costs over the 50-year study period (1985-2035) calculated using an assumed discount rate. The discounted sum of costs was the principal estimate reported by the earlier studies.

The full distribution of effects, including estimates of the variance around the damage forecasts, has not previously been reported. By focusing on the mean values, after amortization, information about the frequency distribution of economic effects is lost. Thus, while two diversion scenarios might both predict similar mean values for the damages, we are unable to assess whether differences exist in the variance of their damages. Results from our empirical section suggest that there are important differences in the variance and distribution of damages from different diversion scenarios with otherwise similar mean values. As indicated in the last section, it is believed there are positive gains from reducing the variance of lake levels to all users of lake levels in the Great Lakes system. The methodology of previous studies in this area, however, does not allow us to address this question.

Summary of Guidelines for Regulatory Policy Implied by the Economic Model

When developing regulatory policy for LL on the Great Lakes, it is useful to distinguish between demanders of LL versus demanders of water. The two groups conceptually are quite distinct, and the impact of regulations on each can be very different. Demanders of water impose externalities on demanders of LL through their diversions and consumptive uses of water. The interest in regulating diversions appears to arise out of a desire to protect demanders of LL from these externalities. Alternatively, regulation could take the form of direct control of LL through the locks on the St. Marys and Niagara Rivers. Regulation of this kind has little to do with demanders of water but is used to improve LL for demanders of LL. For both kinds of regulation the welfare level associated with a given LL and for changes in LL depends critically on both the sensitivity of production costs to changes in LL and on the elasticity of demand for the product being produced. If multiple processes exist in production, or if demand for the product is very elastic, changes in LL will not have significant effects on welfare. However, the fewer the substitutes for LL in the production process and the more inelastic the demand for the product, the more sensitive welfare will be to changes in LL.

We should also note that in the Great Lakes system where transportation, power, shoreline property values, and environmental attributes are the economic interests most sensitive to changes in LL, we cannot determine on a qualitative basis whether changes in LL will have positive or negative effects on aggregate welfare. This is because for a given regime of LL, diversions might have a positive effect on some interests and a negative effect on others. This has important implications for the regulation of diversions. Suppose government adopts a policy of charging water users the opportunity cost of the water (in terms of the impact of the diversion on users of LL). In high LL years diversions may reduce the impact of severe flooding damage, causing a positive externality for users of lake levels. In this case government may actually want to pay demanders of water to divert water from the system because the welfare of people around the Great Lakes would be improved by a reduction in flooding.

Finally, we should note that the principal impact of natural variability in LL is to create additional capacity and adjustment costs for firms. This implies that regardless of the mean lake level desired, society will in general always benefit from regulations that reduce the variance of LL. To evaluate the impact of diversion scenarios on the variance of lake levels, the hydrologic and economic results are presented in terms of the distribution of possible effects in a given year.

CHAPTER 2

THE SHIPPING MODEL AND DATA

Introduction

This chapter describes the actual model and data used to measure the impact of changes in lake levels on Great Lakes shipping. Empirical results are presented in chapter 5. In the following section the model is described, highlighting any simplifying assumptions used and their effect on the estimated change in welfare associated with a change in lake levels. Section three describes what types of cargo were considered in this report. The cargo types are the same as those studied by ILER. A section of the ILER report is included that explains why only certain cargo types were studied and others were not. Section four discusses the economic data used in this study and, where appropriate, compares our data to those used by ILER. Section five presents some brief conclusions concerning the overall accuracy of our estimates and the likely direction of any bias that may be present.

The Model

In principle, to estimate the welfare effects of diversions on activities sensitive to Great Lakes shipping, the procedure discussed in the previous chapter should be used. To review, the welfare loss from an adverse change in lake levels is the area ACDE in figure 3.

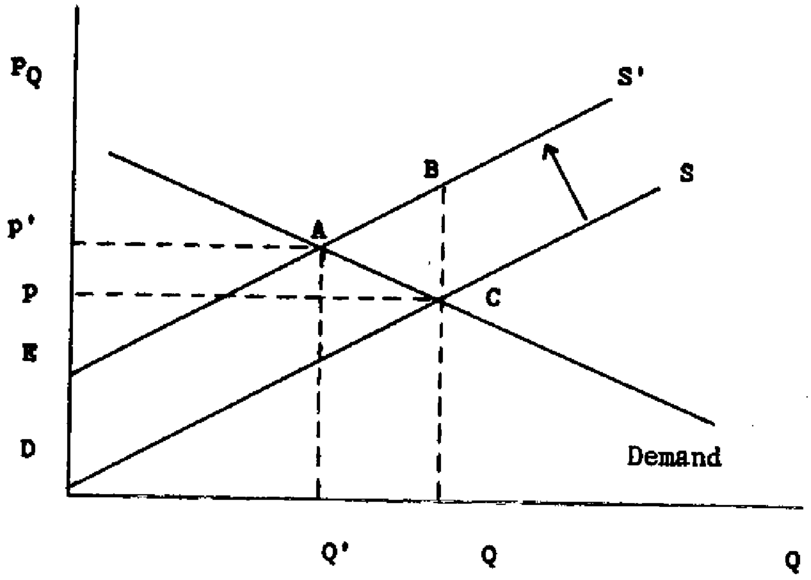

Figure 3. Transportation model 1

Recall that changes in consumer welfare associated with the shift in supply from S to S' because of a diversion should be measured by integrating under the Hicksian, not the Marshallian, demand curve. We can simplify the analysis and our data requirements greatly by assuming that the integral of the area under the Marshallian demand curve for a change in the supply curve is approximately equal to the integral under the Hicksian demand curve. Moreover, we assume that the Marshallian demand curve is perfectly inelastic. This simplifies the model to the representation shown in figure 4.

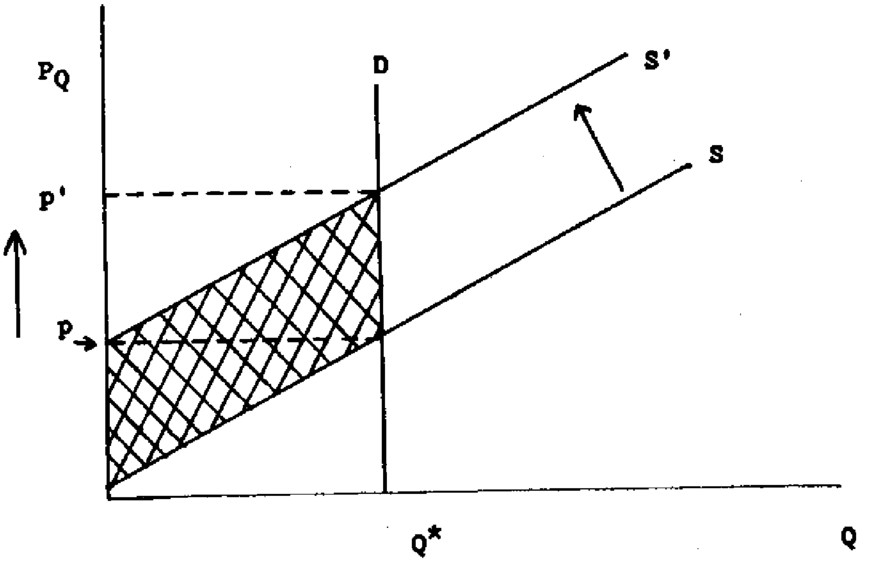

Figure 4. Transportation model 2

The welfare loss from the adverse change in lake levels is now just the shaded region between the two supply curves to the left of Q*. Theoretically this measure is not correct for reasons indicated in the previous chapter. However, for the range of diversions under consideration and the degree of accuracy required for our empirical work, the measure in figure 4 is believed to be sufficiently close to the true welfare change. By comparing the model in figure 4 to that in figure 3 we also see that the welfare change in figure 4 overestimates the welfare loss by not accounting for the reduction in the quantity demanded when the price for Q rises. This is represented by area ABC in figure 3. This change in quantity demanded occurs because consumers substitute alternative products for Q as P_Q rises, reducing their losses.

A second simplification implicitly assumed in model 2 is that firms have no cost-effective substitutes for Great Lakes shipping to switch to in the event of adverse lake conditions. Since some substitutes may exist, this results in further overestimates of the true cost of the diversion as also discussed in the preceding chapter. However, for most commodities with which we are concerned, shipping is significantly cheaper than the next best alternative (generally unit trains). For the magnitude of the diversions in question, therefore, this overestimate is likely to be small.

A third implicit assumption in model 2 is that the social costs of the diversion are equal to the firm's private costs. This implies, among other things, that the additional resources employed to transport goods after a diversion occurs are already employed in a productive activity. Hence, these extra resources are taken away from a productive enterprise, reducing output in some other activity. This imposes a real cost on society equal to the reduction in the total value of goods produced. If, instead, the extra resources are idle, as in a recession, society does not have to give up as much real output to allocate additional resources to transporting goods on the Great Lakes, and the social costs will be less than the firm's private costs. Particularly in periods of severe recession, the assumption that private and social costs are equal could significantly overstate the true social costs associated with a diversion.

As an example of the potential magnitude of this problem, the Lake Carriers Association (LCA) reported that in 1980 "nearly 40 percent of the [Great Lakes shipping] fleet was inactive during portions of 1980, though the trend by the end of the year was toward increased activity in 1981 (LCA 1981, p. 1)." We should emphasize that some social costs would occur even in times of the worst recession because scarce fuel supplies would be used to power the additional boat trips, preventing the fuel from being used in some future activity. However, to the extent that the additional labor and boats necessary to ship the required tonnage had been unemployed or underutilized, any extra wages or rental costs would not be counted as additional social costs. This point, combined with the previous assumptions, suggests that model 2 overestimates the welfare costs of a diversion. The overestimate is relatively small in times of low unemployment but could be quite large in periods of high unemployment.

Cargo Types Considered in this Report

The cargo types considered in this report are the same as those studied in the ILER report. For this reason, a section of the ILER report that describes what cargoes were studied, and why, is reprinted here:

> The methodology is based on the four principal dry bulk commodities in the system, namely iron ore, coal, limestone, and grain. These four commodities comprise about 85 percent of the system's commerce. Currently more than 200 million tons of cargo move in these trades annually in a complex network of domestic, export, and import trades. In addition to being the major portion of the system's traffic, the bulk trades are the most sensitive to changes in water level because the vessels employed in these trades generally grasp every opportunity to take full advantage of available water depths.
>
> The bulk commodities are shipped in specially developed lake vessels which are designed to operate efficiently in the Great Lakes system. There are two national fleets of lake vessels, one Canadian and one U.S., which transport all of the trades in these four commodities within and between the two countries.

The remaining 15 percent of Great Lakes traffic is composed of a number of cargoes including petroleum products, newsprint, rock salt, iron and steel products, cement, chemicals, and many other goods which either are carried by smaller, lesser draft vessels which generally do not take full advantage of available water depths, or are shipped in quantities too small to warrant separate analysis in this study. For example, petroleum products move in small tankers to a large number of receiving ports, with a tanker typically making many calls on each trip. The effect of low water levels is to cause the shippers to alter their sailing plans to call at deeper harbors first, then at shallower harbors when their load has been reduced. While this can cause some inconvenience, the effect on costs is not great and would be extremely difficult to calculate. For this reason, no detailed evaluation of this traffic was carried out. Newsprint is carried entirely in small ships which are rarely affected by water levels in the ports to which they trade. Commerce in rock salt on the Great Lakes has increased somewhat in recent years. However, it too is moved mainly in relatively small vessels which are not greatly affected by water level fluctuations, and therefore no detailed evaluation of this traffic has been made.

The 15 percent also includes overseas general cargo trades which employ specialized lake-ocean carriers. Although overseas cargo is of high value, traffic to and from the Great Lakes must transit the 27-foot St. Lawrence Seaway. Since the seaway restricts draft to 26 feet, this traffic cannot take advantage of water depths greater than about 27.5 feet in the harbors on the lakes (allowing 1.5 feet for underkeel clearance). Since lake levels are such that harbor depths are rarely below this depth, overseas, general cargo traffic would not be affected significantly by a small change in the levels regime. In addition, many of these vessels call at several ports and therefore often do not travel fully loaded. Thus they do not normally take full advantage of water depths available. For these reasons, overseas general cargo traffic was excluded from this analysis (ILER 1981, p. D-12).

Data Requirements

Using model 2, three sets of economic information are necessary to estimate the effects of a diversion on Great Lakes shipping in a given year. These are (1) the real operating costs of the vessels, (2) the base-year tonnage of shipments by commodity and trade route, and (3) the projected growth rates of shipments by commodities and trade routes over a 50-year period. Projected growth rates of shipments are necessary to estimate the expected cost of a diversion in some future year. Each of these will be considered in turn.

Vessel Operating Costs

The ILER study contains detailed data on the vessel operating costs for July 1979. For most of the vessels, updated data have been obtained for January 1983. However, since nominal operating costs should increase roughly according to the inflation rate and new information was not available for all vessel classes, the complete data set from 1979 was used for the modeling in our study.

The daily operating expenses by vessel type for July 1979 and January 1983 appear in the table.

TABLE 1. Daily operating expenses

Vessel Class	Daily Operating Expenses*	
	July 1979	January 1983
1	-	-
2	-	11,997
3	-	13,533
4	-	16,718
5	14,029	17,263
6	15,127	18,258
6w	18,500	-
7	15,657	18,668
7w	19,240	-
8	16,521	19,700
8a	18,173	-
8w	22,527	-
9	20,479	24,378
10	21,269	25,345
11	23,029	-

*Data are in nominal U.S. dollars for the years shown

The data in table 1 differ from data in the ILER study in four important ways. First, the ILER study included an additional amount (approximately 35 percent of the values shown) for the daily amortized construction cost of the vessel. This is a fixed cost insensitive to the number of trips made by the vessel and has been excluded from our data. The ILER study also included an additional 12% for overhead and 15% for the opportunity cost on the equity invested in the vessels (what it calls profit). These measures are also fixed costs and have been excluded from our data. Finally, the ILER report assumed a 5% real increase in fuel costs for each year in its 50-year study period.

Considering the historical change in real fuel prices, we believe a 5% real rate of cost increase seems too high. A more realistic estimate would be a zero real rate of increase in fuel prices.

The effect of the four changes identified above is to reduce the ILER real operating costs by 50 to 70 percent depending on the vessel type and the number of years in the future to which costs are projected. The percentage reductions because of these changes for selected vessel type and year are given in table 2.

TABLE 2. Percentage reduction in real daily operating costs relative to data used by the ILER study*

Vessel Type	1979	1985	2000	2035
5	48	52	64	68
7	50	54	66	70
9	52	56	68	72
10	55	59	73	79

*The larger the vessel (higher the vessel type) the greater the fuel consumption relative to other operating costs. This explains the difference in percentage reduction by vessel type and over time.

Base-Year Tonnage of Shipments

Tonnage shipped along the various Great Lakes trade routes varies from year to year largely because of fluctuations in the business cycle that affect demand for the commodities shipped. This is particularly true for iron ore, coal, and limestone; grain shipments are more sensitive to political and weather conditions. We wish to select an initial (base-year) set of "typical" economic conditions from which future shipping tonnages can be projected. The specific level of goods shipped in a given previous year may not be a very good guide for selecting the initial conditions. This is because variations in tonnage shipped are likely to be as large as, or even larger than, long-term changes in the average tonnage shipped. As a result, we would not want to use tonnage amounts shipped during a severe recession or during a boom year as a base from which to project future tonnage because this would be equivalent to projecting a series of recession-type or boom-type years.

We should also note that for a given set of trade routes and distributions of total tonnage across the three bulk commodities, the welfare costs from a diversion estimated by model 2 are approximately proportional to the total tonnage shipped. Hence, for a given change in lake levels, if the tonnage shipped in each of the commodities were doubled, the number of trips required to ship the cargo would double, and model 2 would predict that the welfare costs would also double. The proportional relationship between shipping costs and total tonnage will hold unless lake levels get so low that sufficient capacity does not exist to ship the required tonnage during the shipping season. In that case, either additional boats would have to be built, or more expensive substitutes, like unit trains, would have to be used to ship the necessary cargo. However, this scenario is unlikely because shipping firms must already build in excess capacity to insure against variations in the length of the shipping season. This point, combined with the presence of cyclical excess capacity, cited for 1980 previously in this chapter, suggests that additional capacity will not be necessary to compensate for diversions.

Because we seek a "typical" year on which to base our estimations, the ILER study base year is probably as good as any other we could develop. The ILER study describes its base year as follows:

> The "present" (1976) or base condition on a trade route was taken to be either the average of recent historical trade volumes (for the years 1973 through 1976), or if a trend was known to exist, the latest trade figure on that route (ILER 1981, p. D-13).

The ILER study reported base-year figures (what it calls present average) for all types of trade except U.S. domestic trade. These figures are presented in tables 3a, 3b, 3c, and 3d. Data for U.S. domestic present average values are listed separately in table 4 and had to be constructed from other information contained in the ILER report. The data were constructed using a three-step procedure. First, we chose what seemed to be "appropriate" base-year figures for the total trade volume by commodity type on the Great Lakes. The rationale for those choices is explained in appendix A. Because the present average values for all other trade types were reported by ILER, the total trade volume for non-U.S. domestic trades (present average figures) was subtracted from the total trade numbers to get the present average for total U.S. domestic trade. ILER reported 1985 projections of U.S. domestic trade by trade route and commodity. Finally, we used the 1985 distribution of tonnage shipped across trade routes for all commodity types to distribute total U.S. domestic present average tonnage across their respective trade routes.

TABLE 3a. Present average non-U.S. domestic shipments for iron ore (1000s of short tons)

Trade Type	Route From	Route To	Present Average
Canadian Domestic	S	S	1,200
		E	100
		O	1,700
	H	E	–
	EX	O	2,800
Total			5,800
U.S. Export-Canadian Import	S	S	900
		E	100
		O	1,700
	M	O	200
Total			2,900
Canadian Export-U.S. Import	S	M	1,900
		E	200
	H	H	700
		M	300
		E	500
	O	E	400
	EX	M	3,200
		E	10,100
Total			17,300

Source: ILER 1981

Note: The route designators used in these data tables are the first letters of the lakes or waterway names, for example, "S" for Superior, "SLS" for St. Lawrence Seaway, and so on. The category "EX" refers to all points below (downstream from) Montreal.

TABLE 3b. Present average non-U.S. domestic shipments for coal (1000s of short tons)

Trade Type	Route From	Route To	Present Average
Canadian Domestic	S	H	-
		E	100
		O	200
	EX	E	200
Total			500
U.S. Export-Canadian Import	E	S	2,500
		H	4,600
		E	3,800
		O	8,000
		SLS	200
Total			19,100
Canadian Export-U.S. Import	Nil		

Source: ILER 1981

TABLE 3c. Present average non-U.S. domestic shipments for grain (1000s of short tons)

	Route		Present
Trade Type	From	To	Average
Canadian Domestic	S	H	1,300
		E	400
		O	400
		SLS	3,000
		EX	6,500
	H	H	-
		E	-
		SLS	200
		EX	100
		EX	200
	E	H	-
		SLS	100
	SLS	SLS	-
		EX	100
Total			12,300
U.S. Export-Canadian Import	S	SLS	200
		EX	600
	H	SLS	100
		EX	100
	M	O	200
		SLS	100
		EX	800
	E	O	500
		SLS	200
		EX	1,500
Total			4,300
Canadian Export-U.S. Import	S	M	300
		E	-
Total			300

Source: ILER 1981

TABLE 3d. Present average non-U.S. domestic shipments for limestone (1000s of short tons)

Trade Type	Route		Present
	From	To	Average
Canadian Domestic	SLS	O	2,400
U.S. Export-Canadian Import	H	S	600
		H	600
		E	400
		SLS	100
	E	H	100
Total			1,900
Canadian Export-U.S. Import	E	E	1,200

Source: ILER 1981

TABLE 4. Present average U.S. domestic shipments by commodity type

Trade Type	Route		Total Annual Trade (1000s of Short Tons)			
	From	To	Iron Ore	Coal	Limestone	Grain
U.S. Domestic	S	S	--	250	--	--
		H	5,500	6,400	500	--
		M	16,700	1,200	750	100
		E	31,600	--	500	600
		O	--	--	--	1,300
		SLS	--	--	--	100
	M	S	--	420	--	--
		H	2,000	--	600	--
		M	4,400	3,600	2,600	--
		E	3,400	--	750	--
	H	S	--	--	500	--
		H	--	--	5,000	--
		M	--	--	6,400	--
		E	--	--	5,200	--
	E	S	--	2,000	--	--
		H	--	85	500	--
		M	--	3,600	--	--
		E	--	2,900	1,200	--
Total			63,600	20,455	25,000	2,100

Source: ILER 1981

Projected Growth Rates of Shipments

In this study our empirical work is based on economic values corresponding to a "typical" year near to the present. Growth rates for tonnage shipped are included so that readers may infer for themselves how our estimates may change for some future year. In general, growth of the iron ore and limestone shipments is assumed to be very closely correlated with growth in the U.S. steel industry along the Great Lakes. In his book, The U.S. Steel Industry in Recurrent Crisis, Robert Crandall analyzes the status of the industry in the world market. One of his conclusions is that it "will lose capacity gradually over the next decade [1980 to 1990] but this loss will be no more than 10% even without trade protection (Candall 1981, p. 153)." Crandall also concludes that "production of steel will continue to move towards the Great Lakes regardless of trade policy (p. 146)." This is because the Great Lakes steel mills are closer to the principal sources of iron ore and limestone, reducing transportation costs for the raw materials. Great Lakes steel mills are also farther from the major seaports, reducing competition from foreign steel imports. Hence, while the U.S. steel industry will likely decline somewhat, it will also become concentrated around the Great Lakes. Crandall does not specify a projected growth rate, but based on his conclusions it seems reasonable to assume the Great Lakes steel industry will hold its own in the future with a zero growth rate. From this we assume a zero growth rate for tonnage of iron ore and limestone.

The ILER report estimated coal traffic on the Great Lakes would increase at a rate of 1.89% per year from 1985 to 2035. The arguments included in the ILER report supporting this estimate are presented in appendix B. Given the reduced emphasis on nuclear power and oil-burning electrical plants and the abundance of coal in both the western and eastern United States, the ILER study's estimate seems reasonable. It seems especially plausible given that two-thirds of all coal produced in the mid-1970s was used in electric power generation, whereas only 15% was used in coking (see appendix B). This suggests that growth and changes in the composition of the electric power industry will have a significant effect on the growth of coal shipments in the future; changes in the steel industry will have less impact. For these reasons, this report will adopt the ILER estimate of a 1.89% growth rate for coal trade.

There appear to be no compelling reasons why domestic grain shipments on the Great Lakes would change much in the future. Unless there is a significant increase in population in the East, domestic demand for grain will probably continue to show a zero growth rate.

The growth rates for iron ore and limestone are the most defensible of these figures because of the close ties these commodities have to the steel industry. We should also note that of the four commodities, iron ore makes up the greatest fraction of the total tonnage shipped, followed by coal, limestone, and then grain. According to the Lake Carriers Association, in 1979 iron ore comprised 50% of the total tonnage shipped of the four commodities, followed by coal at 22%, limestone at 18%, and grain at 10%. Iron ore and limestone combined make up approximately 70% of the bulk tonnage shipped on the Great Lakes (LCA 1980). For this reason, if the growth rates for coal and grain shipments are in error because of oversimplification, the net effect on the final cost estimates from a diversion is likely to be small.

As an indication of the recent trend in the size of shipments by commodity type, we can consider the bulk tonnage shipped by commodity type from 1972 to 1980 (table 5). Note that it is difficult to see any clear trend in the overall rate of growth over the period for any of the commodities. Also, the large drop in iron ore, limestone, and coal shipments from 1979 to 1980 is due to the downturn in the steel and power industry at the onset of the 1980 recession.

Conclusions

The results of our use of model 2 in this chapter indicate that our method overestimates the social welfare loss from adverse lake conditions on shipping for a given set of lake conditions. This overestimate is relatively small in periods of low unemployment but could be large in periods of high unemployment. We should note, however, that this is the same method used in the ILER study. The differences in our results from those of previous work arise because our economic data significantly differ from the ILER data. The changes in the daily operating costs alone reduce the estimated welfare costs by about 50% in the base year. Because our growth rates for the real cost of fuel and for tonnage shipped are lower than ILER's, this difference will be even larger for years in the future.

TABLE 5. U.S. and Canadian bulk commerce on the Great Lakes 1972-1980

	1972	1973	1974	1975	1976	1977	1978	1979	1980
				(1,000s of short tons)					
Total All Commodities	190,832	208,590	195,363	186,395	191,515	170,781	199,602	208,229	176,903
Iron Ore Shipments									
Total	90,283	105,890	98,098	89,562	97,096	75,096	99,584	103,101	81,723
From U.S.-Canadian Great Lakes	78,052	90,534	84,473	76,194	77,050	53,686	86,012	88,197	N.A.
From Eastern Canada	12,231	15,356	13,615	13,368	19,962	21,410	13,572	14,904	N.A.
Coal Shipments									
Total	43,196	39,586	34,966	39,179	37,487	38,984	37,766	45,833	41,306
From Lake Erie Ports	38,001	34,101	29,801	33,175	31,736	32,032	31,628	37,044	N.A.
From Lake Michigan Ports	5,195	5,354	4,044	3,943	3,199	3,035	2,762	2,392	--
From Lake Superior Ports	--	131	1,121	2,061	2,552	3,917	3,376	6,397	--
Grain Shipments									
Total	20,007	20,226	19,213	19,973	18,812	19,481	22,498	22,319	25,863
To U.S. Ports	1,879	1,461	1,288	1,567	1,706	1,520	1,595	1,466	1,621
To Canadian Ports	18,128	18,765	17,925	18,406	17,106	17,961	20,903	20,853	24,242
Limestone Shipments									
Total	37,346	42,888	43,096	37,681	38,204	37,220	39,754	36,976	28,011
				INDEXES 1972 = 100					
TOTAL ALL COMMODITIES	100	109	102	98	100	89	105	109	93
Iron Ore	100	117	109	99	107	83	110	114	90
Coal	100	92	81	91	87	90	87	106	96
Grain	100	101	96	100	94	97	112	112	129
Limestone	100	115	115	101	102	100	106	99	75

Source: Lake Carriers Association annual reports

Note: Lake Carriers Association iron ore statistics in long tons were converted to short tons. Also, the grain statistics were converted from bushels to short tons. For statistical convenience the weight factors for wheat and soybeans were applied to the total. Slightly lower tonnage figures would have resulted if the lesser weight per bushel of corn and barley were averaged into the total.

CHAPTER 3

THE HYDROPOWER MODEL AND DATA

We present our empirical results in chapter 5 and restrict ourselves here to a discussion of the hydropower model and data. As before, we simplify the demand side for power generation by assuming that the Marshallian and Hicksian demand curves for electricity are identical and that the demand curve is vertical. This implies a demand curve of the type shown in figure 5.

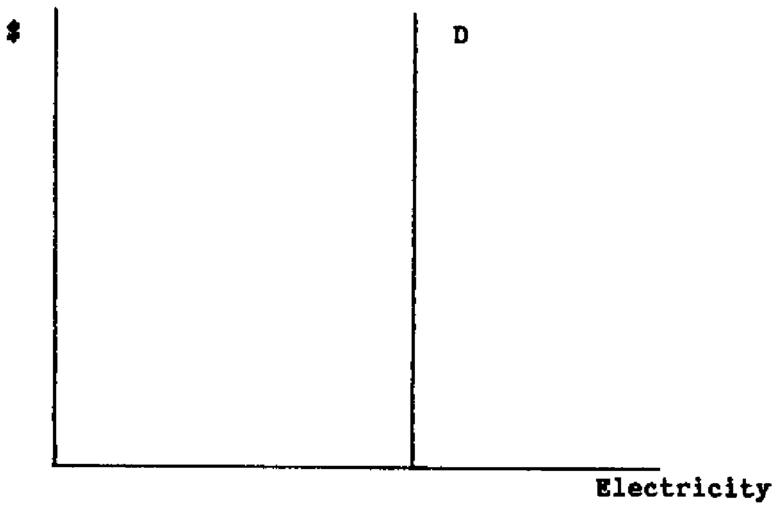

Figure 5. Assumed demand for electricity

The problems with imposing such restrictive (and unrealistic) assumptions on demand were discussed in the shipping section of chapter 2 and will not be repeated. However, as with shipping, it is felt that the likely drop in lake levels because of diversions and consumptive use is small enough that the errors in estimating damages from assuming a vertical demand curve are small. Moreover, as indicated earlier, the use of a vertical demand curve tends to overestimate damages to the power industry. To the extent that the estimated damages appear small (as our empirical results suggest), we need not be overly concerned with the measurement errors from the simplified model.

In contrast to shipping, there are numerous affordable substitutes to hydropower for power generation in the Great Lakes region. We say this for two reasons. First, for some regions the differential between marginal costs from Great Lakes hydropower and alternative energy sources is quite small. Second, hydropower on the Great Lakes has a limited capacity that is generally exceeded by the demand for power in the region. This forces power companies to develop and use additional, more expensive substitutes for hydropower to make up the difference. This contrasts with the transportation model, in which much of the Great Lakes shipping fleet is idle or underutilized at relatively frequent intervals.

If we assume marginal costs are constant within a given power plant, the cost structure for power generation in the Great Lakes region can be characterized by a step-wise marginal cost curve as shown in figure 6.

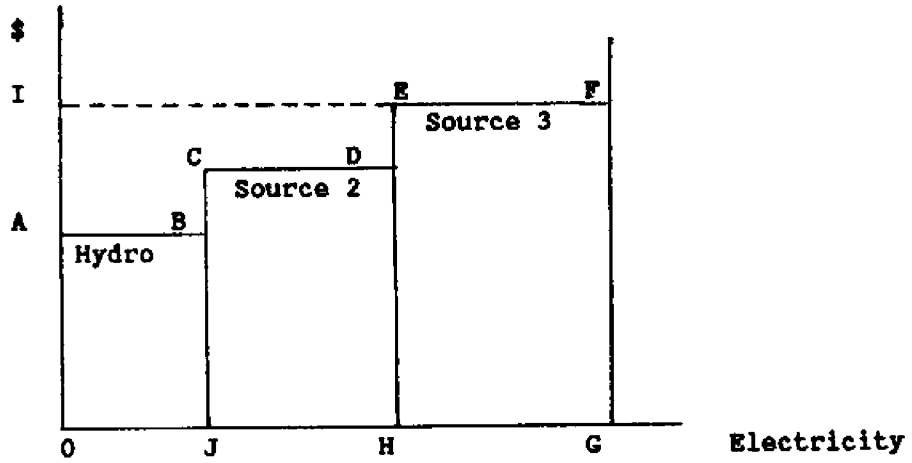

Figure 6. Marginal cost of producing electricity

Assuming firms minimize costs, they will operate plants in the order of their respective marginal costs, with the least expensive plants used first. Suppose, for instance, firms with the cost schedule in figure 6 produce G units of electricity. Total costs would be the region under the curve ABCDEF, whereas marginal costs would be at level I. A reduction in output from G to H would reduce production costs by EFGH and eliminate source 3 from production.

The model used to estimate impacts on power production from diversions is formed by combining figures 5 and 6 into the single graph shown in figure 7.

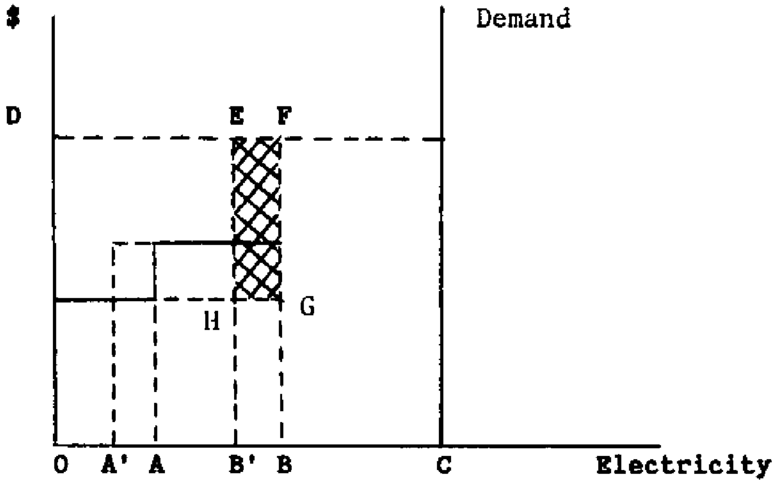

Figure 7. Hydropower model

Here we assume that hydropower and source 2 are both used to capacity. With demand at point C, a third, more expensive source must be used with marginal costs of D. We assume that the third source is not used to capacity, so small increases in demand will not affect the marginal costs of production.

Note that hydropower has a capacity of OA and source 2 has a capacity of AB. Now, suppose a diversion reduces the productivity of hydropower. The capacity of hydropower falls to OA'. However, the capacity of source 2 is unaffected and remains at its previous level. In order to meet demand at C, source 3 must take up the slack, expanding its output from BC to B'C. The marginal cost of production stays the same, but total costs increase by the shaded region FEGH. This area equals the difference in marginal costs between hydropower and source 3 times the reduction in output from the hydro plants.

The Data

To implement the model, we require information about the power sources used in each region and their marginal costs. The ILER study divided the Great Lakes region into four separate power grids: upper Michigan, Ontario, Quebec, and New York state. It simplifies the problem by implicitly assuming that no trading of power takes place among the four regions. Thus, even though excess low-cost hydropower is available from Quebec's northern plants, New York is assumed to use more expensive oil-fired plants as its marginal units rather than buy hydropower from Quebec. The effect of this approach is to overstate the damages from diversions because cost-savings options exist but are not utilized.

Previous studies have further simplified the problem by assuming that the cost of producing electricity is the same at all times of year as well as during both daytime and nighttime hours. In reality, there is considerable variation in the cost of producing electricity depending on the time of day and year. However, the gain in accuracy from accounting for this variation is sufficiently small to justify adopting the simpler "average" cost approach (used previously). To facilitate comparison of our results to those in the ILER study, we will use the ILER estimates for the marginal cost of electricity production for each of the regions in 1985. These are given in table 6.

TABLE 6. Marginal costs of power production by region

Upper Michigan	Ontario	Quebec	New York
3.36 mills	0.0 mills	0.0 mills	50.0 mills

Source: ILER 1985 forecast

The marginal plant for the New York grid was assumed to be an oil-fired plant near New York City. Quebec has excess hydropower at its northern plants. Ontario uses a mix of nuclear and hydro to back up its Great Lakes hydro plants, and upper Michigan has a contract with Consumer's Power Group from lower Michigan to supply backup power to the power grid served by the hydro plants on the St. Marys River.

Numerous phone calls to state energy offices and utilities failed to turn up any significant changes in the composition and cost structure of the power industry in these regions since the ILER report was completed. The one exception was New York, which reportedly has purchased hydropower from Quebec at approximately 30 mills/kwh at various times. In contrast, operation of the oil-fired plant near New York City costs up to 80 mills/kwh. The alternative source used varies depending on the time of year and economic conditions. The ILER Study Board presumably recognized this because it describes its 50 mills/kwh figure as a middle-range value for the marginal cost of power in New York. This is consistent with the 80 mills and 30 mills estimates we found for the potential range of marginal costs in New York.

Capacity Costs

The ILER study attempts to determine the impact of diversions on the number and types of future plants built. To the extent that diversions cause additional plants to be built, these added "capacity costs" are amortized and included as part of the yearly costs of power production resulting from diversions. Our work diverges sharply from the ILER study by including no capacity costs. We believe this is reasonable because future changes in capacity will be much more sensitive to changes in the level and pattern of demand than to impacts from diversions. This is true for two reasons. First, power industries have already built excess capacity to safeguard against natural variation in hydropower and variability in output from the many nuclear plants in the region. Second, reduced rates of increase in demand for electricity over the last few years have increased the amount of excess capacity in the industry, and this trend seems likely to continue. This suggests that in figure 7, the effects of diversions are small enough that the capacity of source 3 will not be exceeded. In that case, marginal costs remain constant, and no new fixed costs of constructing additional plants are incurred.

CHAPTER 4

THE IMPACT OF DIVERSIONS ON SHORELINE PROPERTY VALUES AND ENVIRONMENTAL AMENITIES

Shoreline Property Values

In contrast to previous studies, this report will not attempt to estimate the impact of diversions on shoreline property values. We believe the data necessary to estimate shoreline effects simply do not exist at this time. Collection of the data would be a monumental task beyond the scope of this project. To highlight some of the problems inherent in trying to estimate the impact of diversions on property values, we cite the conclusions from An Analysis of the International Great Lakes Levels Board Report on Regulation of Great Lakes Water Levels: Shoreline Property and Recreation, a report produced by the Institute for Environmental Studies at the University of Wisconsin-Madison in 1976.

> Conclusions
>
> Given the current state of knowledge about the prediction of lake levels and associated shore damages, the IGLLB method is careful and consistent. However, because information on shore damage is so scarce and general, the IGLLB estimates provide at best a very general indication of possible shore losses under various regulation plans and not an accurate, quantitative analysis. The following outline points out major problem areas in the IGLLB method.
>
> Ten simulated supply sequences in the main report (p. 136) indicate possible damages from SO-901 ranging between $100,000 and $2,300,000 on Lake Superior, while on Lake Michigan the same plan yields possible benefits ranging from $300,000 to $1,000,000. Four of the ten sequences indicate that shore benefits on Lakes Michigan and Huron do not exceed the losses on Lake Superior. The actual economic effect of SO-901 may be within these ranges depending upon the actual sequence of net basin supplies which occur. In order to adequately assess the possible effects of other regulation plans, these plans should also be evaluated under alternative simulated net basin supplies.
>
> All U.S. damages are based on a damage record of only one year (1951-1952) and on an assumed relationship between lake level and damage. The IGLLB provides inadequate evidence to confirm the curvilinear function used to define this relationship.

More recent economic projections of future property values in Wisconsin are 10 to 50% lower than the 1968 estimates used by the IGLLB. Although the net effect of these lower estimates will be discounted heavily, the benefits of regulation to Lake Michigan shorelands will be less than the IGLLB indicates.

The index of change in value of residential damages is a major determinant of damages, particularly in the urban reaches. Some questionable assumptions made by the IGLLB can affect this index.

-- The IGLLB assumes that land development patterns continue as they have in the past, although Wisconsin's Water Resources Act and the National Flood Insurance Program have already established more strict control on shore development. However, when assumptions on the effect of future land use controls are altered, the IGLLB method indicates only slight changes in projected damages.

-- A major questionable assumption is that protected shoreline will incur no further damage once a protective work is constructed.

The IGLLB assumption that ultimate water level reflects the storm intensity within a month is not adequately documented. The frequency of storm events within months over a number of years should be studied.

There are some biases in the IGLLB method which tend to overestimate the benefits of regulation.

-- The IGLLB assumes that all shore damages are caused by lake level effects and does not differentiate those erosive factors (e.g., surface runoff, groundwater seepage, raindrop impact, frost action) which will continue to occur in spite of regulation.

-- In calculating ultimate water level (damaging capacity), the IGLLB overestimates the benefits from reducing mean monthly levels and overestimates the damages from raising mean monthly levels.

-- Since the effect of regulation on most lakes is to reduce mean monthly levels, overall damages under regulation plans are probably underestimated. This bias results from use of an inadequate definition of breaking depth in the ultimate water level calculation (IES Working Paper 29, 1976, pp. 49-50).

Additional commentary on the methodologies and data used by IGLLB to estimate shoreline effects can be found in Shoreline Valuations in the IGLLB Study by George Parsons, a document written as part of this project (Parsons 1982).

Environmental Attributes

The IGLLB report estimates damages to certain environmental attributes such as swimming opportunities. An extensive body of literature has addressed the difficulties in, and possible solutions to, valuing nonmarketed environmental attributes such as swimming opportunities, marsh lands, and wildlife. Most of the techniques used to value nonmarketed goods tend to provide lower bounds on the total value of the "goods" provided. For instance, the IGLLB report estimates the value of swimming opportunities using travel costs and entrance fees as indicators of what consumers would be willing to pay for the opportunity to swim in the Great Lakes. Travel costs provide a lower bound on the amount consumers would be willing to pay because people might be willing to travel farther than they have to to swim in the Great Lakes. Entrance fees, on the other hand, are generally set by public authorities and do not reflect market clearing prices. Entrance fees may therefore overstate or understate the competitive market price consumers would be willing to pay to visit a public swimming area.

A further difficulty arises because a diversion would change the depth of swimming areas and amount of beachfront available. It is not at all clear what the benefit or loss from this change would be without valuing the new regime of swimming opportunities under the diversion. Because entry fees and travel costs do not fully represent the market price for swimming opportunities, this would be difficult to do; standard Hedonic techniques could not be used to find the marginal value of the individual attributes of swimming opportunities.

Even if we could somehow quantify the marginal impact of diversions on swimming opportunities, swimming opportunities are only one of a myriad important environmental amenities sensitive to lake levels. Other amenities include wilderness areas, wetlands, bird and aquatic life, and scenic landscapes. All would suffer impacts from change in the long-term positions of shoreline areas. For both theoretical and empirical reasons, an approximate, let alone accurate, measure of the dollar values associated with marginal changes in these attributes is difficult, if not impossible, to formulate. It is not even clear a priori whether marginal changes in lake levels have a positive or negative effect on the overall welfare derived from environmental attributes around the Great Lakes. For this reason, we make no attempt to quantify the impact of diversions on environmental attributes in this report.

CHAPTER 5

EMPIRICAL ESTIMATES OF THE ECONOMIC MODEL

Our goal in this chapter is to estimate the distribution of economic impacts from diversions that could occur in an arbitrary year characterized by a given set of economic conditions. The economic conditions we refer to are the tonnage shipped and cost of operating boats on the Great Lakes and the marginal cost of electricity in each of the four power regions bordering the Great Lakes system. The economic data used are described in the shipping and hydropower chapters. As indicated in those chapters, the data were selected to represent a "typical" year near to the present, accounting for the uncertainties of economic business cycles. As such, our results can be interpreted as representative of what one might expect in some year in the near future.

With economic conditions fixed, all variation in the effects of diversions arises from natural variation in lake levels. Different lake levels have nonlinear effects on the impact of diversions, generating a distribution of damages from diversions based on the distribution of lake levels. We will show that the impact of diversions in years when lake levels are already low are substantially greater than when water levels are high because of the nonlinear response of shipping and hydropower costs to decreasing lake levels.

A 77-year series of levels is used to simulate natural variation in lake levels. For the given sets of economic conditions and diversion scenarios, we then evaluate the impact of diversions in each year of the 77-year sequence. The distribution of these effects represents the potential effects of diversions in a given year. This distribution does not depend on any knowledge of prior lake levels. This simplifies the problem because with serial correlation of lake levels across time, knowledge of previous levels would generate a conditional distribution that differs from the one used in this study. To model the conditional distribution would require additional information on the structure of the serial correlation of lake levels.

As discussed in our hydrology report, five diversion scenarios were simulated. Diversions of 10 thousand and 30 thousand cubic feet per second (tcfs) from Lake Michigan-Huron were examined and are referred to as MH10 and MH30. The 30-tcfs diversion is thought to represent a "worst-case" scenario in which a large diversion out of the basin is accompanied by greatly increased consumptive use within the basin. Five- and 10-tcfs diversions from Lake Superior were also simulated and are referred to as SU5 and SU10. A fifth diversion examined the effect of reducing minimum flow requirements to the hydro plants on the St. Marys River. This was accomplished by simulating a 10-tcfs diversion from Lake Superior accompanied by a 10-tcfs reduction in the guaranteed minimum allocation to the St. Marys power plants. This scenario is referred to as SU10L.

Summary Statistics

Summary statistics of the total damages to shipping and hydropower from the different diversion scenarios are given in table 7. The values are in millions of 1979 dollars per year. These units were used in the previous water level studies and are used in this paper to facilitate comparison to those studies.

TABLE 7. Summary statistics on total damages to hydropower and shipping by diversion type (millions of dollars per year)

	SU5	SU10	SU10L	MH10	MH30
MEAN	38.13	80.0	78.74	76.35	237.3
MEDIAN	38.03	79.8	78.56	76.13	231.8
STDEV	6.77	13.8	4.64	4.75	19.8
MAX	57.39	126.1	89.60	86.00	295.3
MIN	17.01	36.2	68.79	67.02	203.5
Q3	42.17	85.2	81.81	80.12	250.3
Q1	34.70	74.6	75.50	72.42	223.2

N = 77

N = Numbers of observations on X_i, $i=1,\ldots,N$

STDEV = Standard deviation of X_i

Q_1 = 25th Percentile

Q_3 = 75th Percentile

It is immediately clear from table 7 that the overall impact of diversions on hydropower and shipping in the Great Lakes is very small by any normal standard of economic value in a regional economy. Even for MH30, the worst-case scenario, damages are only about $250 million per year, a very small sum relative to the total value of goods and services produced in the region. To further clarify the size of the damage estimates, consider the cost of moving the water out of the basin. In a study by Banks, the cost of moving 10 tcfs from the Great Lakes to the high plains farm region in mid-America was estimated to be about $10 billion in fixed costs followed by $10 million in operating costs per year (Banks 1982, p. 59). Even if there are large errors in the cost estimates, the opportunity cost of diverted water to industries on the Great Lakes is several orders of magnitude lower than the actual cost of moving the water.

A comparison of our results to those of previous studies further underscores this view because our total-cost estimates from similar diversions are even lower than those previously estimated. For instance, the DCU study estimates the impact of a 5.5-tcfs diversion from Lake Superior to be about $50 million per year, whereas we project a sum of about $40 million for a 5-tcfs diversion. These results suggest that rather than focusing on a review of whether diversions are "economical," it would be more useful to analyze the impact different types of diversions would have on Great Lakes industries. This will allow us to establish some guidelines about the manner in which different diversions would affect shipping and hydropower and which scenarios appear least harmful to the industries.

Using information in table 7, we first compute the elasticity of total damages with respect to the size of a diversion at the median. The result is presented in table 8.

TABLE 8. Damage elasticities by diversion type*

	Base to SU5	SU5 to SU10
Superior Diversions	1.00	1.06
	Base to MH10	MH10 to MH30
Michigan-Huron Diversions	1.00	1.01

$$*\text{Elasticity} = \frac{\%\text{ change in costs}}{\%\text{ change in diversion}} = \frac{(C_2-C_1)/(C_2+C_1)/2}{(D_2-D_1)/(D_2+D_1)/2}$$

Note that damages from diversions out of Lake Michigan-Huron increase in a near-linear fashion with the size of the diversion, whereas damages increase at a slightly nonlinear rate from diversions out of Lake Superior. Some explanation for this difference can be found by disaggregating total damages into impacts on shipping and hydropower. These results appear in tables 9 and 10.

TABLE 9. Summary statistics on damages to hydropower by diversion type (millions of dollars per year)

	SU5	SU10	SU10L	MH10	MH30
MEAN	34.27	71.5	71.75	71.36	217.1
MEDIAN	34.45	72.4	71.95	71.21	215.9
STDEV	6.62	13.2	4.00	3.65	12.0
MAX	48.14	108.0	84.53	83.74	253.7
MIN	10.90	18.7	63.09	63.43	191.8
Q3	37.96	76.3	73.85	73.14	223.6
Q1	31.47	67.5	69.72	68.65	208.7

N = 77

TABLE 10. Summary statistics on damages to shipping by diversion type (millions of dollars per year)

	SU5	SU10	SU10L	MH10	MH30
MEAN	3.86	8.57	6.99	4.98	20.25
MEDIAN	3.37	7.60	6.53	4.17	16.53
STDEV	1.67	3.33	1.63	2.20	9.38
MAX	10.25	24.44	12.51	11.95	45.95
MIN	1.64	4.23	4.15	2.09	8.29
Q3	4.33	9.59	7.93	5.54	26.16
Q1	2.84	6.54	5.91	3.58	12.61

N = 77

Tables 9 and 10 indicate that impacts on hydropower are roughly 10 times those on shipping in each of the scenarios. Total damages and elasticities are therefore much more sensitive to changes in the cost of producing electricity than to changes in shipping. The disaggregated elasticities of damages at the median for shipping and hydropower are given in table 11.

TABLE 11. Elasticities of damages for hydropower and shipping

Superior Diversions	Base to SU5	SU5 to SU10
Shipping	1.00	1.16
Hydro	1.00	1.07

Michigan-Huron Diversions	Base to MH10	MH10 to MH30
Shipping	1.00	1.19
Hydro	1.00	1.01

Note that the elasticities for shipping are far greater than for hydropower. This suggests that larger diversions have nonlinear impacts on harbor depths, which in turn have nonlinear impacts on the tonnage limits per boat, thus requiring ever-increasing numbers of boat trips to move the same amount of tonnage. In contrast, hydropower facilities are much more sensitive to flow than head (lake level at the dam), particularly the large dams in the St. Lawrence River. The flow-to-power relationship is essentially linear, which accounts for the near-linear relationship between diversions and power produced.

Diverting water out of Lake Superior instead of Lake Michigan-Huron has a slightly greater impact, as seen from SU10 and MH10 in table 7. Withdrawing water from Superior lowers channel depths in the St. Marys River. This affects a greater portion of the shipping routes than diversions from Michigan-Huron, increasing the required number of boat trips and damages to shipping. Results from table 10 support this view because median damages to shipping for SU10 are $7.6 million, whereas damages from MH10 are only $4.2 million.

There is much less difference between SU10 and MH10 in damages to hydropower. Median damages from table 9 for SU10 and MH10 are $72.4 and $71.2 million respectively, and the mean values are nearly identical. The effects on hydropower and shipping are different for two reasons. First, power production on the St. Marys River represents a small fraction of Great Lakes power production, whereas the majority of bulk tonnage shipped on the lakes (including all of the iron ore from western Lake Superior) must travel the St. Marys River. Shipping is therefore much more sensitive to changes affecting the depth and flow through the St. Marys. Second, the situation is compounded by stipulations in the regulation plan governing the operation of the St. Marys River Compensating Works. The plan guarantees a minimum flow of 65 tcfs to the St. Marys power plants except in times of low water, when the minimum is reduced to 55 tcfs. During periods of moderate low water, power production on the St. Marys is insulated from further low-water effects by the minimum flow requirements. To compensate for the minimum flow requirements, channel depths for shipping are lowered, forcing shipping to bear the brunt of low-water periods on the St. Marys. This situation is exacerbated by diversions from Lake Superior that increase the frequency of low-water periods on the St. Marys.

To examine the impact of reducing minimum flow requirements to 55 tcfs under "normal" conditions and 45 tcfs under extreme low-water conditions, consider the scenario SU10L. From tables 9 and 10 we see that under SU10L, hydropower damages increase relative to SU10 while shipping damages fall. Median total damages in table 7 are about $1.3 million less for SU10L than for SU10.

A better comparison of SU10 and SU10L is obtained by forming the measure

$$L^{*} = \underset{\text{shipping}}{(SU10 - SU10L)} - \underset{\text{hydropower}}{(SU10L - SU10)} \qquad (5.1)$$

where L* represents the gains to shipping minus the losses to hydropower from using SU10L instead of SU10. Summary statistics for L* appear in table 12.

TABLE 12. Summary statistics for L* (millions of dollars per year)

MEAN	1.3
MEDIAN	0.9
STDEV	12.5
MAX	40.0
MIN	-39.5
Q3	5.4
Q1	-1.9

N = 77

From table 12 we see that on average there is a net benefit to reducing minimum flow requirements to hydropower. However, many periods may still exist during which net benefits are negative. To address this issue and others we turn to a discussion of the distribution of damages.

The Distribution of Damages

As indicated earlier, a major difference between our work and previous studies is our emphasis on presenting the distribution of damages as well as mean effects. Consider total damages in table 7 once more. Observe that the standard deviations for SU10L and MH10 are nearly identical, and both are $2 million less than SU5, a diversion only half as large. By contrast, SU10 has a standard deviation three times that of SU10L and MH10 but just two-thirds that of MH30. Clearly, major differences in the variance of damages from different diversion scenarios exist. As with earlier discussions, it seems reasonable to assume that, all else being equal, lower-variance lake level regimes are preferred by most industries. This suggests that SU10L or MH10 would be the better choice for a 10-tcfs diversion than SU10.

To further explore this issue, a quick visual picture of the distributions across diversion scenarios is obtained by plotting the histograms of total damages for each scenario.

```
                                     SU5

Middle of Interval      Number of Observations

        15                     1          *
        20                     2          **
        25                     0
        30                     6          ******
        35                    27          ***************************
        40                    23          ***********************
        45                    11          ***********
        50                     6          ******
        55                     1          *
```

```
                                     SU10

Middle of Interval      Number of Observations

        40                     2          **
        50                     3          ***
        60                     1          *
        70                    15          ***************
        80                    37          *************************************
        90                    13          *************
       100                     4          ****
       110                     0
       120                     1          *
       130                     1          *
```

Figure 8. Histograms by diversion type

```
                                    SU10L

Middle of Interval       Number of Observations

        68                     1           *
        70                     3           ***
        72                     5           *****
        74                     6           ******
        76                    13           *************
        78                    12           ************
        80                    14           **************
        82                     8           ********
        84                     6           ******
        86                     8           ********
        88                     0
        90                     1           *


                                    MH10

Middle of Interval       Number of Observations

        68                     1           *
        70                    11           ***********
        72                    11           ***********
        74                    10           **********
        76                    14           **************
        78                     9           *********
        80                     5           *****
        82                     6           ******
        84                     7           *******
        86                     3           ***


                                    MH30

Middle of Interval       Number of Observations

       200                     1           *
       210                     6           ******
       220                    15           ***************
       230                    22           **********************
       240                    10           **********
       250                    10           **********
       260                     6           ******
       270                     1           *
       280                     3           ***
       290                     2           **
       300                     1           *
```

Figure 8 -- continued

The cell widths in each histogram are adjusted to help portray the shape of each individual distribution and are therefore not equal across scenarios. Note that for most cases the distribution is skewed to the right, suggesting a greater frequency of very "bad" years than of very "good" years. This is consistent with data (see table 7) that show the mean exceeding the median damage cost for each scenario.

It is particularly interesting to compare the distributions of MH10, SU10, and SU10L. Although the ranges for MH10 and SU10L are nearly identical, we see that the distribution for SU10L is nearly symmetric, whereas that of MH10 has more mass on the lower values. This accounts for why the median damages from MH10 are about $2 million less than those from SU10L. By contrast, the distribution for SU10 is much more spread out, with a range extending 30 points below and 40 points above that of either SU10L or MH10 (although closer inspection reveals that roughly 90% of the mass in the SU10 distribution is concentrated in a relatively narrow range between $70 million and $100 million per year). The tighter distribution of SU10L is therefore achieved by eliminating most of the outliers from both ends of the distribution in SU10.

To further examine this point we plot the histogram for L*, the difference between SU10 and SU10L for shipping and hydropower.

```
Middle of Interval      Number of Observations

      -40                  2        **
      -30                  1        *
      -20                  2        **
      -10                  7        *******
        0                 44        ******************************************
       10                 15        ***************
       20                  3        ***
       30                  1        *
       40                  2        **
```

Figure 9. Histogram for L*

The distribution of L* appears nearly symmetric, although from table 12 the median is $.4 million below the mean. Also evident is the large variance in effects with the range spanning $80 million. It is also clear from the near symmetry of the distribution that although the median value of L* is positive, there are many years when hydropower would incur additional costs from SU10L that exceed the benefits to shipping. This point would not be apparent if we focused only on the mean or median values for L*.

A final issue to be addressed is the persistence of adverse effects from diversions over time. An industry might be able to withstand one isolated bad year because of diversions but be seriously damaged by a succession of bad years. For the electric power industry this does not appear to be significant because persistent higher production costs from diversions could be passed on to consumers through rate increases. Shipping, however, is potentially more sensitive to a series of bad years; it is less able to pass on higher costs to its consumers because many of the products shipped are sold in highly competitive markets. We should note, however, that this argument runs contrary to the shipping model described in chapter 2, which assumes a perfectly inelastic demand curve. For the sake of realism we relax that assumption here to address the persistence issue.

In table 13 we describe potential clusters of "bad" years using the 77-year historical record. A bad year is defined as one in which the impact from a diversion exceeds the 75th percentile of impact for that scenario. Thus, all bad years are among the 25% worst estimated impacts over the 77-year historical record. In the table, starred years refer to good years (years with damages below the 75th percentile), and pluses indicate bad years. The diversion scenarios are defined as before, whereas the base case refers to the total cost of shipping the tonnage level used in the shipping model in the absence of diversions.

Two points are immediately clear from table 13. First, in general, diversions make bad years worse for shipping. This is clear from the close correlation between bad years in the base-case and diversion scenarios. This should come as no surprise; with water levels already low, the marginal impact of diversions on harbors and channel depths will be greater because of the nonlinear relationship between shallow water depths and the quantity of water in the system.

The second point from table 13 is that there appear to be roughly three periods over the 77-year record when diversions generate more than four bad years in succession. This would correspond to three or four episodes of persistent bad years per hundred years because of diversions. It is difficult to say whether this level of persistence is strong enough to harm the shipping industry more than is estimated by the basic shipping model in chapter 2. However, awareness of the potential for persistent bad years seems important given the importance of Great Lakes shipping.

TABLE 13. Clusters of years with values greater than the 75th percentile: base case and diversions, shipping only

Year	Base	SU10L	SU5	SU10	MH10	MH30
1	*	*	*	*	*	*
2	*	*	*	*	*	*
3	*	*	*	*	*	*
4	*	*	*	*	*	*
5	*	*	*	*	*	*
6	*	*	*	*	*	*
7	*	*	*	*	*	*
8	*	*	*	*	*	*
9	*	*	*	*	*	*
10	*	*	*	*	*	*
11	*	++	*	*	*	*
12	*	++	++	++	*	*
13	*	*	*	*	*	*
14	*	*	*	*	*	*
15	*	*	*	*	*	*
16	*	*	*	*	*	*
17	*	*	*	*	*	*
18	*	*	*	*	*	*
19	*	*	*	*	*	*
20	*	*	*	*	*	*
21	*	*	*	*	*	*
22	*	*	*	*	*	*
23	*	*	*	*	*	*
24	++	*	++	++	*	*
25	++	*	++	++	*	*
26	++	++	++	++	++	++
27	++	++	++	++	++	++
28	*	*	++	++	*	*
29	*	*	*	++	*	*
30	*	*	*	*	*	*
31	*	*	*	*	*	*
32	++	*	*	++	++	*
33	++	++	++	++	++	++
34	++	++	++	++	++	++
35	++	++	++	++	++	++
36	++	++	++	++	++	++
37	++	++	++	++	++	++
38	++	++	++	++	++	++
39	*	*	*	*	*	*
40	*	*	*	*	*	*

TABLE 13 -- continued

Year	Base	SU10L	SU5	SU10	MH10	MH30
41	++	*	*	*	++	++
42	++	++	++	*	++	++
43	*	*	*	*	*	*
44	*	*	*	*	*	*
45	*	*	*	*	*	*
46	*	*	*	*	*	*
47	*	*	*	*	*	*
48	*	*	*	*	*	*
49	*	*	*	*	*	*
50	*	+	*	*	++	++
51	*	*	*	*	*	*
52	*	*	*	*	*	*
53	*	*	*	*	*	*
54	*	*	*	*	*	*
55	*	*	*	*	*	*
56	*	*	*	*	*	*
57	*	*	*	*	*	*
58	*	*	*	*	*	*
59	++	++	++	++	++	++
60	++	++	++	*	++	++
61	*	*	*	*	*	*
62	*	*	*	*	*	*
63	*	++	*	*	++	++
64	++	++	++	++	++	++
65	++	++	++	++	++	++
66	++	++	++	++	++	++
67	++	++	++	++	++	++
68	*	*	*	*	*	++
69	*	*	*	*	*	*
70	*	*	*	*	*	*
71	*	*	*	*	*	*
72	*	*	*	*	*	*
73	*	*	*	*	*	*
74	*	*	*	*	*	*
75	*	*	*	*	*	*
76	*	*	*	*	*	*
77	*	*	*	*	*	*

	Base	SU10L	SU5	SU10	MH10	MH30
75th Percentile	268.36	7.93	4.33	9.59	5.54	26.16

* = values below the 75th percentile

+ = values above the 75th percentile

CHAPTER 6

CONCLUSION

Diverting large amounts of water from the Great Lakes to dry regions of the country would impose significant costs on two industries -- shipping and hydroelectric power production -- in the Great Lakes Basin. It would also undoubtedly affect shoreline property values and a variety of environmental attributes of the region, though to what extent and with what overall economic effect we are unable to say.

Our analysis indicates that a moderate-sized diversion of 10,000 cubic feet of water per second could cost the shipping and electric power industries between $70 million and $90 million a year depending on the lake used as the primary source of water. A larger diversion of 30,000 cubic feet per second, coupled with a major increase in consumptive use of water within the basin, could cost these industries almost $250 million a year.

Although these added costs would be significant to the industries involved, it is important to point out that they would be minor in the context of the overall regional economy.

Our estimates are derived from the application of a hydrologic model developed in a companion report, <u>Diversion of Great Lakes Water Part 1: Hydrologic Impacts</u>, to the economic model developed in this report. The model indicates that the economic impact of diversions on hydropower is roughly 10 times that on shipping. In other words, the electric power industry is much more sensitive than the shipping industry to changes in the water-level regime of the lakes. On the other hand, there are many affordable alternatives to hydropower for generating electricity in the Great Lakes region, whereas shipping has fewer substitutes.

Our empirical results indicated great variability in economic effects among different diversion scenarios, even for diversions with similar average impacts. Further analysis revealed that the shipping industry would be likely to experience two to three episodes, each about five years long, of persistently high diversion-induced costs every one hundred years. Although this study did not model any additional costs associated with such episodes, the potential risk to the industry of a string of years of low lake levels and high diversion costs must be recognized.

We made a variety of assumptions to simplify the task of applying the economic model. These assumptions may have caused our empirical estimates to overstate the potential effect of diversions on the shipping and power industries, so the actual costs to these industries might be somewhat less than projected. Shipping may decline as the structure of American industry changes, and hydropower may be available from Canada to replace that produced on the Great Lakes. In either case, the costs of diversions from lakes would be smaller.

On the other hand, our analysis did not consider a number of likely additional costs of large water diversions from the Great Lakes. It did not, for example, attempt to quantify the economic impact of diversions on environmental attributes (such as recreation, wetlands, wildlife, and scenery) that would be affected by changes in lake levels resulting from diversions. Even an approximate measure of the dollar values associated with these attributes would be difficult, if not impossible, to develop. We also did not consider the cost of physically moving large amounts of water from the Great Lakes, which we believe would far exceed the previously mentioned diversion costs to the shipping and hydropower industries. For these reasons, we believe our findings significantly understate the total potential costs of diverting water from the lakes.

It is not clear a priori whether diversions would have a negative or positive overall effect on the aggregate economic welfare of the Great Lakes region. Although a drop in lake levels would have a negative effect on such activities as shipping and power production, it would have a positive effect in other areas, such as shoreline flooding. Diversions presumably would reduce flooding and help raise the value of shoreline property during periods of high water. We did not, however, attempt to estimate the economic impact of diversions on shoreline property values because we believe any valid attempt would require far more data than are currently available, and it was beyond the scope of this project to collect the necessary additional data.

Many gaps and problems remain in the complex task of estimating the economic impacts of Great Lakes water diversions and recommending what might be done about them, but we offer the following thoughts to those who would try.

First, several qualitative rules of thumb may be used to evaluate the potential effects of diversions on industries. Changes in the economic welfare of the region associated with different diversion scenarios (and corresponding shifts in the regime of lake levels) depend critically on (1) the sensitivity of production costs to changes in lake levels and (2) the sensitivity of demand to price changes among products whose production costs depend on lake levels. If a number of substitute production processes exist, or if demand for a product is very sensitive to price changes, fluctuations in lake levels will have less effect on the economic welfare of the region. However, the fewer the substitutes for lake levels in production and the more rigid the demand for the product, the more the economic welfare of the region will be affected by diversions and changes in lake levels.

Second, any analysis of the effect of diverting water out of the Great Lakes Basin must recognize the weather-driven natural variation of lake levels in the system because diversion effects are sensitive to the range of levels of the lakes. Previous studies tended to ignore this fact and focused only on the average effect of diversions. Our study estimated the entire distribution of diversion effects where the variance of effects depends on the natural variation in lake levels over time. This is important because the results from the economic model indicate that, on a qualitative basis, reducing the variability of diversion effects has cost advantages regardless of the average effect of the scenario in question.

Finally, it should be noted that previous studies indicated lake levels are slow to respond to changes in diversions. For this reason, we believe a short-term policy of varying the sizes of diversions to offset lake levels (diverting more water when levels are high and less when they are low) would be ineffective, and a long-term policy would be impossible to develop.

APPENDIX A

Selection of Base-Year Tonnage Values

The present average (or base-year) values for tonnage shipped by commodity type were selected after reviewing the data in table 5 on bulk commerce from 1972 to 1980 and any additional material presented in the "Data Requirements" section of chapter 2. The values initially chosen (in 1000s of short tons) were 90,000 for iron ore, 40,000 for coal, 30,000 for limestone, and 19,000 for grain. These numbers were not selected on the basis of any rigorous methodology but, as indicated, were chosen based on casual observation of the information presented in table 5 and the "Data Requirements" section. This approach is defensible on the grounds that our goal is to develop data for a "typical" base year, not data for any one year in particular. The numbers cited here seem to satisfy this criterion.

APPENDIX B

Growth Rates for Coal Shipments

Because our growth rate for coal shipments is based on the ILER study projection, the arguments ILER used to support a projected growth rate for coal shipments equal to 1.89% are reprinted here. The reader will note that we have revised the ILER study's approach somewhat by assuming an equal growth rate for all coal trade routes on the Great Lakes. This is done to simplify the analysis and is not considered to have a significant effect on the estimated welfare effects from diversions.

> Coal: Coal reserves in the United States are vast. During the forecast period under consideration in this study, there will not be any shortages of coal due to reserve depletion on either a national or regional basis. Spot shortages may occur in the short run due to limited production capacity.
>
> Approximately 25 million tons, or 60 percent of total movements in the 1970s, were domestic movements of coal, generally of thermal quality, moving annually to electric utilities in the U.S. The remaining 18 million tons were exported from Lake Erie ports to Canadian users. Approximately half of this exported coal is of thermal quality moving to Ontario Hydro electric generating plants located along the lake. The other half of this exported coal is of metallurgical grade moving to Canada's "Big Three" steelmakers for coking purposes.
>
> The traditional pattern of coal movements has been out of Lake Erie ports to Canadian and western U.S. lake destinations. Nearly 85 percent of all Great Lakes movements of coal have traditionally moved out of the Lake Erie ports of Ashtabula, Conneaut, Lorain, Sandusky, Toledo, and others. For movements to Lake Superior ports, a return haul of iron ore makes this route profitable to the ship owner. Movements to Canada (principally Lake Ontario) are relatively short-haul and can almost be considered a "shuttle" service. Coal also moves through Chicago to other Lake Michigan and Lake Superior ports to satisfy utility demands.
>
> These patterns of coal movement on the lakes have developed due to the location of utilities and steel plants on the lakes. Many of these facilities do not have rail handling terminals capable of the volume that is moved by water and therefore are restricted in large part to water receipt of coal unless major rail investments are made.

However, future growth of coal movements on the Great Lakes will come from movements of western coal to utilities located on Lake Huron and Lake Erie. These coal movements will be in addition to eastern coal movements.

In 1974, it was estimated that 45 percent of the total power generated by electric utilities was generated by coal. This fact is mirrored by the fact that about two-thirds of all coal production was used by electric utilities. Fifteen percent was used for coking, 8 percent for export, and the remainder for other industrial and retail users (primarily cement plants and paper mills).

On the Great Lakes, these markets are represented by the electric generating stations of Detroit Edison, Consumers Power, Wisconsin Electric, and the Upper Peninsula Generating Company, by the coking facilities of the Canadian steelmakers STELCO, DOFASCO, and Algoma Steel, and by the paper mill of Fort Howard Paper near Green Bay, Wisconsin.

The supply of coal traditionally moving on the Great Lakes comes from Kentucky, West Virginia, southern Ohio, western Pennsylvania and to some extent from southern Illinois. These coal sources typically have higher sulfur content but also have a high BTU content. This BTU/sulfur relationship is the single most important factor that will affect coal movements on the Great Lakes.

In this study, coal projections were based on assumptions which relied upon current conditions and plans. Western coal movements were not included in the forecast base unless some reasonable assurance could be made as to its ultimate usage. Specifically, it was assumed that:

1. Few, if any, existing facilities would be converted to western coal due to high conversion costs;

2. Only new facilities that have announced plans for use of western coal would be included in the forecast;

3. Stack gas scrubbers would be economically efficient and available by 1990;

4. Current emission standards will remain unchanged throughout the forecast period;

5. Variances to burn high-sulfur coal will be extended until stack gas scrubbing technology becomes available;

6. Canada will adopt emission standards that will not preclude usage of U.S. eastern coals; and,

7. Continued delays will retard the development of nuclear power generation facilities.

Projections were then made by contacting the individual utilities moving the coal or planning the move. This approach was taken since these movement volumes will show large jumps as new facilities come on stream. Timing, therefore, is of greatest importance in the forecast of western coal movements. This approach was feasible since relatively few users represent the majority of coal demanded in the Great Lakes.

Traditional movements of eastern coal to lakeside utilities (particularly on the southern shores of Lake Superior and on Lake Michigan) are projected to continue with moderate growth. Individual growth rates are based on the growth rates of utilities earnings in the destination region developed by the Bureau of Economic Analysis in its OBERS (Office of Business Economics - Economic Research Service) projections.

Projections of coal movements to Canada were taken directly from company contacts with Ontario Hydro, DOFASCO, STELCO, and Algoma Steel.

Where possible, all projections were checked relative to published forecasts and consistency was attained.

Actual coal traffic on the Great Lakes is expected to increase from 25 million tons in 1985 to 81 million tons in 2035 for an average annual rate of change of 1.89 percent. In particular, traffic with a Lake Superior origin is expected to show dramatic growth. Traffic levels do not increase after the year 2000 because of lock capacity constraints at Sault Ste. Marie. Overall, U.S. coal exports to Canada are expected to increase from 19 million tons to 35 million tons for an average annual rate of increase of 1.0 percent. Exports using the Welland Canal to get to Lake Ontario have no increase in traffic levels after the year 1990 because of capacity conditions. The Erie to Superior traffic is unconstrained because of utilization of ships that can fit through the smaller uncongested locks at Sault Ste. Marie (ILER 1981, p. D-21).

APPENDIX C

Description of Computer Models Used to Estimate Losses to Great Lakes Hydropower and Navigation

Navigation Model

Function

The Great Lakes navigation cost model estimates the average annual cost incurred by either the U.S. or Canadian commercial shipping fleets. The computer model computes costs for transporting given quantities of four commodities over a fixed set of routes that represent actual cargo movements on the Great Lakes for some specific year. The four commodities are iron ore, coal, grain, and quarry limestone. The model treats each year of water level data as if it were a possible realization of water levels during the year under investigation. Monthly shipping cost is computed based on a given set of commodity shipments and available shipping fleet, both of which remain fixed throughout the simulation. Annual cost is obtained for each calendar year, and the resulting annual average cost estimate is based on the analysis of all available years of water level data.

The model requires three groups of input data: the monthly water levels of the Great Lakes, descriptive data for the vessels comprising either the United States or Canadian fleets, and data giving the tonnages and routes over which commodity cargoes are to be moved. Water level data are required for Lake Superior, Lake Michigan-Huron, Lake Erie, and Lake Ontario. The input data series consist of monthly mean water surface elevations based on the 1955 Great Lakes data.

The vessel data are used to identify the composition and utilization patterns of ships in the Great Lakes commercial fleets. Each fleet consists of up to 11 vessel classes. The vessel classes are distinguished by overall length of vessel with a few exceptions where vessels of similar length have different capacities. The data set describes the fleet in terms of vessel operating characteristics and load-handling capabilities on a class-by-class basis. This is supplemented by information on how much each class is used. A list of the vessel operating characteristics included in the data set is provided in table 14.

The commodity data set gives the routes over which the cargoes are to be transported and the tonnage to be carried annually on each route. In addition, the commodity data are divided into three shipment types, either domestic, import, or export, and the percentages of shipments to shallow (substandard) harbors are given. It should be noted that the entire data set describing fleet usage changes from commodity to commodity.

TABLE 14. Navigation model input parameters (based on 11 vessel classes)

Parameter Name		Number of Values	Description and Units of Values
Capacity		11	Design cargo capacity (tons)
Draft		11	Draft at maximum capacity (feet)
Immersion		11	Net capacity per foot of draft at vessel drafts exceeding 18 feet (tons/ft.)
Speed		11	Vessel travel speed (miles per hour)
Cost		11	Vessel operating cost (dollars/hour)
Class	(U.S. runs) (CDN runs)	22 33	Distribution of cargo among the vessel classes and shipment types (percentage of total tons)
Months	(U.S. runs) (CDN runs)	24 12	Distribution of annual tonnages among the months of the year (percentage of total)
Round		11	Round-trip factor for class
Unload		11	Loading-unloading time (hours)
Loadline		44	Four sets of seasonal load-line limits, one for each quarter of the year (feet)
Percentage		2	Percentage of total imports and exports carried in U.S. ships
Deep		1	Design depth of standard harbors (feet)
Shallow		1	Average depth of shallow harbors (feet)

Methodology

The objective of the model is to compute the operating cost incurred by the shipping industry each month. Because it is impossible to know precisely when particular shipments will be transported or which vessel will be used, the model employs a priori distributions of commodity movements among vessel classes and among the months of the year. During each simulation month some small percentage of the annual traffic over each shipping route is charged to each vessel class. The cost of moving this cargo is computed based on marginal operating costs. Finally, these costs are summed over all vessel classes and shipment types to obtain the monthly and annual cost estimates.

The model calculations are described in detail in the next few pages. The calculation scheme has three basic parts: route and tonnage input data and computations, the vessel capacity determination, and the cost computations.

Routes and Tonnage

A database of actual commodity movements for one year is represented by a fixed set of 75 distinct commodity routes. A shipping "route" is defined by the following: (1) shipment type (domestic, import, or export), (2) lake of origin, (3) lake of destination, and (4) length in miles.

The model allows for one route of each shipment type over each possible path. The paths may begin or end in any of the five Great Lakes. Thus, there are 25 possible paths times three shipment types, or a total of 75 routes. The origin and destination lakes of all permitted routes are predetermined, but the route lengths are not. The route lengths may be adjusted in situations where cargoes of the same type travel between the same lakes but between different ports. In reality, not all of the defined routes are used; shipments typically occur on perhaps as many as 30 of the available routes.

The commodity input to the model consists of gross annual tonnages of a single commodity to be shipped along each route as previously defined. In reality, the shipments may be moving between several different pairs of harbors. For example, a grain shipment from Calumet, Illinois, to Toledo might be combined with one from from Milwaukee to Erie, Pennsylvania. For each route, the user may specify an optional percentage of shipments between shallow harbors.

The annual tonnages must be distributed among the available vessel classes in the shipping fleet and among the months of the year. The following multipliers, which are part of the input data, are used:

VPC = Percentage moved by vessel class
MPC = Percentage moved in month by all classes
PI,PX = Percentage of all imports and exports moved under the registry of the fleet being analyzed.

Let TOT equal any one of the gross annual tonnages given in the input data, then during the current month the tonnage assigned to the vessel class associated with this value of VPC is:

$$TONS = VPC * MPC * TOT * (PI \text{ or } PX \text{ or } 1.0).$$

Use PI for imports, PX for exports, and 1.0 for domestic shipments.

Capacity Determination

Two factors affect the usable capacity of a given vessel: (1) the maximum draft for safe operation and (2) the draft that permits the unobstructed passage through the Great Lakes connecting channel as well as into and out of the harbors at ports of call. Of these, the former takes precedence. A maximum permissible draft, called the load-line limit, is assigned to each vessel class. The load-line limit changes seasonally; it is lower in spring and winter when violent storms are more likely. Such storms not only cause marine accidents but also can cause sudden changes in harbor water levels.

When the program reads the water level data, it substracts the low-water datum (LWD) of the particular lake from the water level read as input. What remains is the excess (or deficit) depth above or below LWD. Because all harbor designs are based on the LWD, the harbor design depth may be added to the computed excess to obtain the available draft for shipping. A 1.5-foot safety clearance is subtracted; what remains is known as the available water. If the available water exceeds the current seasonal load-line limit, then the available water is reset to equal this load-line limit.

Each vessel class has a physical capacity stated in tons and a corresponding "at capacity" draft. These values change for different commodities. If the available water is less than the "at capacity" draft, the actual vessel capacity must be reduced so that the vessel will displace less water. The reduction of capacity is determined using an immersion factor defined for each vessel class. The immersion factor expresses the number of tons of cargo per foot of draft. These immersion factors assume that the draft is at least 18 feet. The capacity determination is made using the following expression:

$$CAP = PC - (DC - WATER) * IMM$$

where:

CAP = the actual load capacity (tons)
PC = the physical vessel capacity (tons)
DC = the draft at physical capacity (feet)
WATER = the available water (feet)
IMM = the immersion factor (tons/foot).

A capacity calculation must be made for each route and vessel class combination.

Cost Calculation

The computed cost is based on the operating time necessary to ship the specified cargo tonnages to their destinations. The vessel capacities determined above, along with the tonnages assigned to each vessel class, provide the means for calculating the number of trips required:

$$TRIPS = TONS/CAP.$$

From the number of trips, the operating time in hours may be computed from the average operating speed. The operating time is subject to two adjustments. First, a fixed number of hours for each class is added to account for loading and unloading time. Second, a round-trip factor is employed to express the amount of operating time that can be saved through back-hauling another commodity. Normally, the round-trip factor is equal to 2.0 because a vessel usually returns to its port of origin empty. However, if a vessel class is able to carry cargo on the return trip, say, 30 percent of the time, then the round-trip factor (RTF) is only 1.7. Thus, the final expression for operating time is:

$$HRS = RTF * (TRIPS * VSP) + UNL$$

where:

HRS = total operating time (hours)
VSP = vessel cruising speed (miles per hour)
UNL = combined loading and unloading time (hours).

The monthly cost assigned for the particular vessel class and shipping route is the hours of operation multiplied by the vehicle operating cost given in the input data:

$$MC = HC * HRS$$

where:

C = monthly cost
HC = vehicle operating cost for labor and fuel (dollars/hour).

Average Monthly Cost

The three steps already described produce the operating cost incurred by vessels of one size class transporting shipments along one of the defined routes during the current month. The calculations are repeated for each of the 11 vessel classes and for whatever subset of the 75 possible commodity routes for which tonnages are given. The sum of the cost computed in each loop is the estimated monthly cost incurred by the industry. It is not the actual cost that the industry would incur under the particular water level conditions because the actual vessel used to make a given shipment cannot be predicted. For this reason the model uses the average mix of vessels used to move the commodity in question; a different mix of vessels would result in a different cost. In the model, a piece of each shipment is assigned to each vessel class according to the likelihood of its use. In reality, ships representing one or two classes might actually be used, but this would change from month to month and year to year. The shipping industry usually does not make drastic changes in vessel assignments in response to water levels because the operating cost of each vessel is not affected, only the capacity. Thus, the computed cost is an average monthly cost in the sense that it is based on the average behavior of the commercial shipping industry.

Hydropower Production Models

Function

Hydroelectric power production on connecting channels of the Great Lakes system is estimated using three computer simulation models. A separate model is used for each regional electric power grid to which the hydropower facilities are linked. Twelve individual facilities utilize Great Lakes connecting channel flows to produce electric power. However, they can be grouped according to their locations and the power grids to which they are connected, reducing the number of separate simulation models to three.

Hydropower facilities are located on three rivers that are Great Lakes connecting channels. Flow through the St. Marys River is divided among two U.S. facilities and one Canadian facility. As is the practice throughout the system, available flow is divided equally between power interests representing the two countries. The flow of the Niagara River that remains for power generation, after an allocation to preserve the aesthetic value of Niagara Falls, is shared by five generating facilities. A single hydropower dam spans the St. Lawrence River a short distance downstream of Lake Ontario. Because the power produced here is split by the same two utilities that operate the Niagara River facilities, the production of this plant is included in the Niagara River model. Finally, there are two plants in the Montreal area whose hydropower production is sensitive to Great Lakes water level regulation policies. The three computer models will be referred to as the St. Marys, Niagara, and Quebec hydropower models. Table 15 provides a list of the facilities addressed by these models and a summary of the general operating characteristics of the power plants.

Methodology

The objective of these simulation models is to estimate monthly energy production at each plant in the system. The energy produced is the power output multiplied by the time over which it is produced. Therefore, it is necessary to compute average hourly power output for a typical day during each month and then to multiply this average by the number of hours in the month. The basic time unit of one month is chosen to correspond to the intervals of available water level and flow records that are to be used as input data.

The computational procedure used to estimate overall energy production is generally the same for all the Great Lakes facilities. There are profound differences, however, in the methods used to calculate certain energy production parameters. Also, circumstances such as ponding and low-flow restrictions are present at some facilities.

TABLE 15. General operating characteristics of Great Lakes hydroelectric power facilities

Facility	National Affiliation	Head[1] (ft.)	Flow[2] (cfs)	Output[3] (MW)
<u>St. Marys River</u>				
Great Lakes Power	Canada	16-22	27.4-39.6	32-62
Edison-Sault	United States	16-18.5	27.4-30.5	27.6-41.3
U.S. Government	United States	16-22	12.7	14-18.7
<u>Niagara River</u>				
DeCew Falls[4]	Canada	266-283	0-6.8	147
Robert Moses	United States	300	<30-102	1950
Sir Adam Beck	Canada	291-301	30-62.5	1638
Canadian Niagara	Canada	126	0-9.9	95
Toronto Power/ Ontario Hydro[5]	Canada	75/205	0-8.3	101
<u>Upper St. Lawrence River</u>	(Niagara model)			
Moses-Saunders[6]	U.S.-Canada	81	210-320	1824
<u>Lower St. Lawrence River</u>	(Quebec model)			
Beauharnois	Canada	79-87	160-288	1574
Les Cedres	Canada	39-46	10-60	162

[1] Operating range unless fixed
[2] Permissible range of flows except U.S. Government, which is fixed
[3] Range or maximum possible
[4] DeCew Falls is located on the Welland Canal
[5] Two plants in series
[6] Moses-Saunders is an international facility

In theory, the power output from a water turbine is a function of the flow through the turbine multiplied by the elevation drop across the turbine. The engineering term for the elevation change is head (from headwater). It is significant because it measures the pressure drop of the water flow as it passes through the turbine. The power is given by the formula:

$$P = wQHe \qquad (C.1)$$

where Q and H are the flow and head, w is the specific weight of water, and e is the overall efficiency of the turbine-generator system. When flow is given in m^3/s (cubic meters per second), head in meters, and w is 9,806 N/m^3 (newtons per cubic meter), the equation yields power in Nm/s or watts. When flow is in cfs (cubic feet per second), the head is in feet, and w is set to 62.4 lb/ft^3, then the resulting power would be in ft-lb./s (foot-pounds per second). There are 550 ft-lb./s in one horsepower, and one watt is equivalent to 0.722 ft-lbs.

The efficiency is assumed to be the product of the efficiencies of several processes. Among these are the conversion of water power to shaft power and the conversion of shaft power to electric power. The former changes significantly when the flow and head deviate from their design values. To improve plant efficiency, virtually all hydropower facilities have several turbines that may be brought in and out of service quickly as flow and head conditions warrant. This becomes a way to control the water level immediately upstream of the facility. This capability is important to plant operation.

The basic expression employed in the models to compute power is simply:

$$P = RQH \qquad (C.2)$$

where R is called the energy rate factor. It is assumed to be a known function of flow and head.

Each facility is allocated a portion of the available flow in the connecting channel under consideration according to procedures defined in various treaties or as ordered by the International Joint Commission. The effective plant head is calculated from the total elevation difference between the lakes upstream and downstream of the facility. As illustrated in figures 10 and 11, as many as four head losses might need to be computed to arrive at the desired plant head. First, there is head loss in the connecting channel between the upstream lake and the point where water is diverted from the river channel into a canal or tunnel. Another computation is made for losses in the conveyance structure that terminates the plant forebay. The channel into which the turbines empty is known as the tailrace; its most upstream elevation is called the tailwater. Additional head losses occur downstream of the plant in both the tailrace and in the main channel once the tailrace rejoins it. The effective head for the plant used in equation (C.2) is simply the difference between the forebay and tailwater elevations.

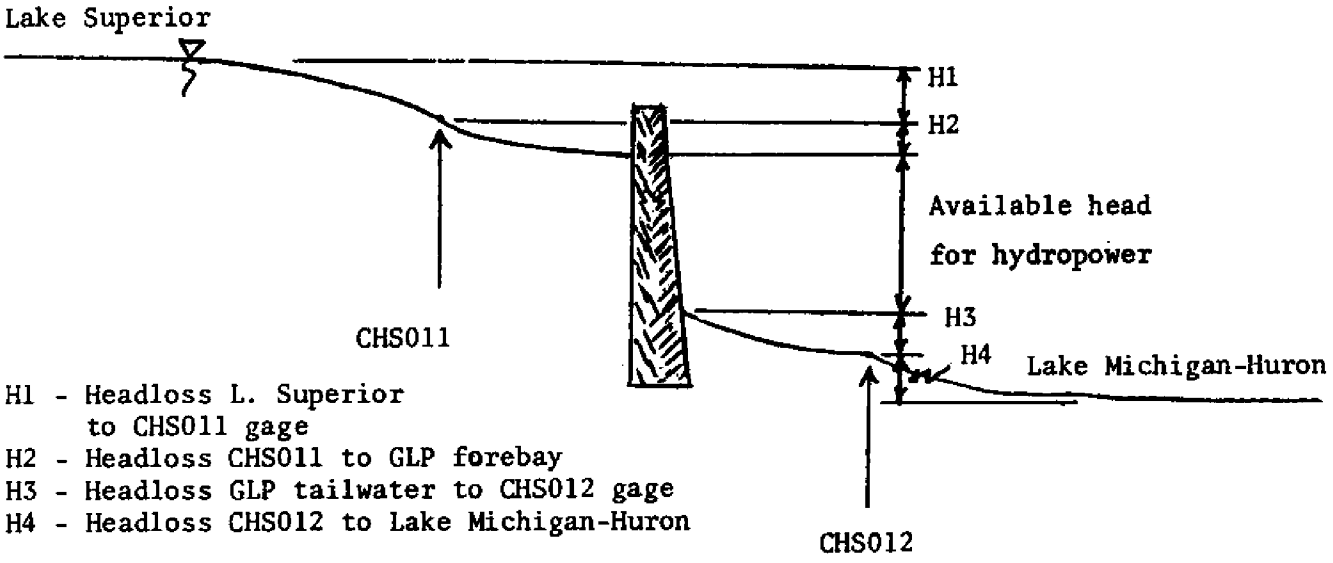

Figure 10. **Profile of the St. Marys River showing water level gage locations for power diversions to the Great Lakes Power facility**

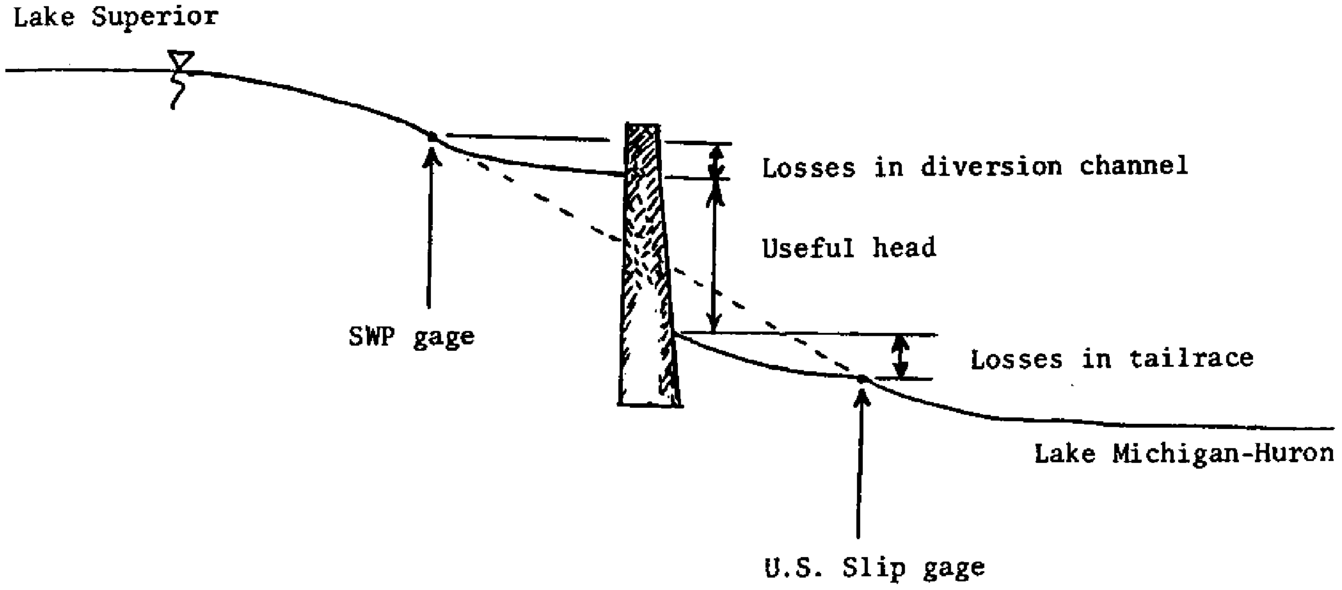

Figure 11. **Water level gage locations for diversions to the Edison-Sault power facility**

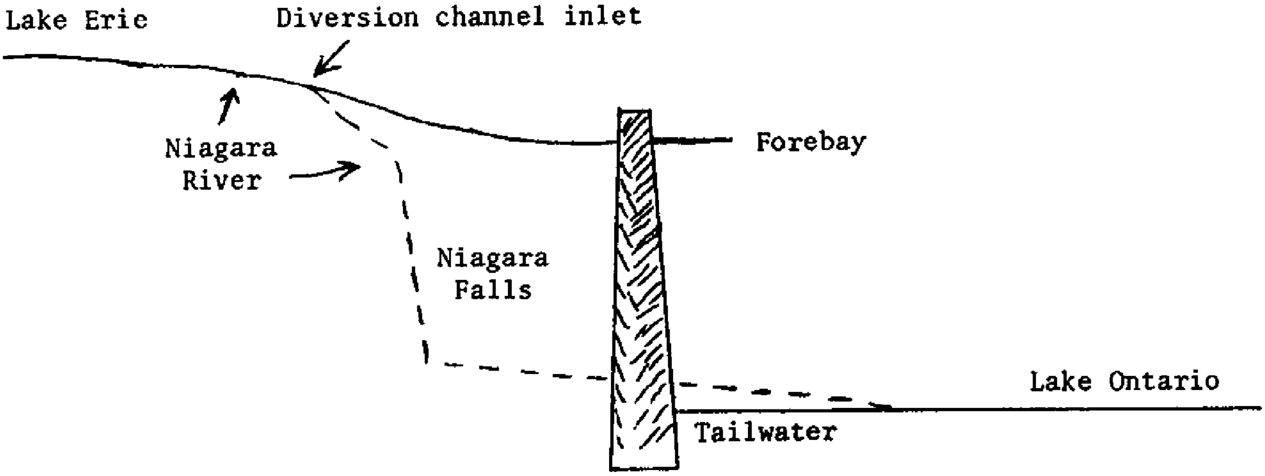

Figure 12. Niagara River profile

In summary, there are three steps to computing the average power output of a generating facility: (1) determine the facility's flow allocation, Q; (2) compute the effective head, H; and (3) compute the energy rate factor, R. The steps are always performed in this order because headloss is a function of flowrate and the energy factor is a function of head and flow. The actual procedures and formulas used to compute power output are summarized in the succeeding pages of this appendix.

Descriptions of the Individual Hydropower Models

St. Marys River

Flow allocation. A small nonpower diversion is subtracted from the total St. Marys River flow. An additional 2,000 cfs is subtracted because this amount is the minimum flow through the compensating works. The remainder is divided equally between the U.S. and Canada. The Canadian share is allocated entirely to the Great Lakes Power facility. On the U.S. side, 12,700 cfs is the allocation to the U.S. Government plant, and the remainder of the U.S. allotment is used by the Edison-Sault facility. Flows exceeding the upper bounds of 39,600 cfs and 43,000 cfs for Canada and the United States, respectively, are discarded (spilled) through the compensating works.

Effective head. For the Great Lakes Power facility, water elevations at gages CHS011 and CHS012 (fig. 10) must be determined. They are, respectively, functions of the Lake Superior and Lake Michigan-Huron water levels. Both gage heights depend on the full St. Marys River discharge. The head losses in the power diversion channels are a function of the diversion flow. The losses in the upstream channel are deducted from the CHS011 elevation to arrive at the Great Lakes Power forebay elevation. The tailwater elevation is similarly based on tailrace losses and CHS012. The plant head is the difference between the forebay and tailwater elevations.

For the Edison-Sault and U.S. Government facilities, calculations are similar to those for the Great Lakes Power facility except that the intermediate elevations used are for the southwest pier (SWP) and U.S. Slip gages indicated in figure 11. The tailrace losses at Edison-Sault are assumed to be constant relative to the U.S. Slip gage.

Energy computation. The output of the St. Marys River facility is obtained not by computing an energy rate factor but directly from formulas that yield power in megawatts (MW) for given values of flow and effective head.

Niagara River

Flow allocation. Two modes of operation govern allocation of Lake Erie outflow to hydropower facilities in the Niagara River. These are known as daytime and nighttime operations, although their purpose is to differentiate between the peak and off-peak tourist hours. For example, during the winter period (November 15 to April 15), nighttime operations are in force around the clock. At other times of year, eight to 16 hours per day are under daytime rules. During daytime hours, the minimum permitted flow over Niagara Falls is 100,600 cfs; the minimum nighttime flow is 50,600 cfs. In almost all circumstances, the remaining Lake Erie outflow is used to generate electric power. This flow is divided equally between the United States and Canada except for an equity adjustment in which the Canadian entitlement is increased by 2,500 cfs and the U.S. entitlement is reduced by the same amount. The 5,000-cfs advantage for Canada compensates for the Long Lake-Ogoki diversion in Lake Superior from Ontario's Albany River watershed.

On the U.S. side, only one power facilty uses the flow of the Niagara River. It is the Robert Moses plant operated by the Power Authority of the State of New York (PASNY). The entire U.S. entitlement is diverted to Robert Moses, which has a seldom-reached capacity of 102,500 cfs.

Niagara River water contributes to five Canadian facilities. Flow is allocated to these plants in a specific order. The DeCew Falls plant is located on the Welland Canal and uses the diversion flow to generate power up to a maximum of 6,800 cfs. The largest Canadian plant, Sir Adam Beck, usually takes all that remains in the Canadian entitlement. The actual flow diverted to this plant is based on a complex head calculation intended to prevent excessive head losses in Sir Adam Beck's two diversion canals. If any entitlement remains, it is diverted to the Canadian Niagara plant up to its capacity and then to the Toronto Power/Ontario Hydro plants. In rare instances when these five facilities do not use the entire Canadian entitlement, PASNY is free to divert the excess to the Robert Moses plant.

Because of restrictions governing Niagara Falls, the generating facilities often have more flow available than can be usefully exploited during the night and less during the day when the minimum flow over the falls must be met. The facilities compensate for this through ponding and pumped storage.

In pumped storage, a plant uses energy produced at night to pump water from its own tailrace into a higher-elevation storage reservoir near the plant. The stored water is then used to generate electricity during peak demand hours the next day. This process results in a net loss of gross energy production but is still economically efficient because energy produced during the day is far more valuable than the nighttime energy used to do the pumping. Since the production is independent of water levels, no pumped storage calculations are performed in the models described here.

The models do, on the other hand, account for ponding, a process in which water is stored at night for use the following day. In this case, some water allotted to Canadian plants is stored in a semiartificial pool in the upper reaches of the Niagara River. This allows power facilities to have greater diversion flows during daytime without affecting the flow over the falls.

Head. The effective heads at most Niagara River power plants do not vary appreciably. Computations are performed only for the Sir Adam Beck facility because the diversion flow depends on the forebay elevation. The others are assumed to take the values given in table 15.

Energy. The energy computations for all Niagara River plants follow the rate factor methodology described previously.

Upper St. Lawrence River

Flow Allocation. The Moses-Saunders power facility consists of two identical plants located near Cornwall. Except for a nonpower diversion of 2,800 cfs or less, the entire flow of the St. Lawrence River is used to generate electricity here. Flow ponding is also employed, but it is not economical if the resulting flow exceeds 280,000 cfs.

Head. For a given flowrate and Lake Ontario surface elevation, a formula is available for computing the forebay elevation. There is a near-linear relationship between plant throughflow and tailwater elevation. Thus, gross head can be computed. Two forms of each equation describe average conditions with, and free of, ice cover.

Energy. When the flowrate is less than 280,000 cfs, the energy factor is a linear function of gross head. At higher flows, a family of curves is available to compute the total plant output as a function of flow and head.

Quebec

The Quebec hydropower model computes energy production at two large St. Lawrence River plants near Montreal: the Beauharnois and Les Cedres facilities.

Flow allocation. Nonpower flow diversions range from 750 to 3,275 cfs. Once this is deducted, flow is diverted to the Beauharnois plant up to the maximum permitted rate, which varies monthly. Remaining flow is diverted to the Les Cedres plant, provided at least 10,000 cfs are available. The maximum permitted flow is 60,000 cfs in winter except during January, when the maximum is just 30,000 cfs.

Head. The Beauharnois plant head is determined from elevation-outflow relationshops derived for Lakes St. Francis and St. Louis, the pools upstream and downstream of the plant. Lake St. Louis outflow is the sum of Lake Ontario outflow and local inflows including the Ottawa River discharge. The local inflow is either read in from an independent database or estimated by the Quebec hydro computer model. For example, the IGLLB study estimated that Lake St. Francis outflow is, on average, 2.3% greater than the Lake Ontario outflow. A second linear relationship has been derived relating the Beauharnois headwater and the St. Francis outflow. Given the Lake St. Louis outflow, its elevation may also be determined. This elevation is assumed to be the Beauharnois tailwater elevation. The head at Les Cedres is fixed at 39 feet during summer months (April through November), whereas during winter, when ice presumably is present, a linear function of the Les Cedres diversion is used.

Energy. The gross power output at Beauharnois is only slightly sensitive to changes in head, thus the computation is largely a function of flow. The rate factor 5.7 KW/cfs gives a very good approximation. The model adjusts this figure (downward) slightly when the plant head is less than 82 feet. The Les Cedres plant has a known output factor at each discrete head value between 39 and 46 feet. The model interpolates between the appropriate values to arrive at the rate factor used.

REFERENCES

Banks, H. 1982. Future Water Demands in the United States. Proceedings, The Interbasin Transfer of Water . . . the Great Lakes Connections, Milwaukee, Wisc., May 1982, pp. 49-64.

Crandall, R.W. 1981. The U.S. Steel Industry in Recurrent Crisis: Policy Options in a Competitive World. Washington, D.C.: Brookings Institution.

Institute for Environmental Studies (IES), Water Resources Management Workshop. 1976. An Analysis of the International Great Lakes Levels Board Report on Regulation of Great Lakes Water Levels. IES Working Papers 28-32. University of Wisconsin-Madison.

International Great Lakes Diversions and Consumptive Uses Study Board (DCU). Great Lakes Diversions and Consumptive Uses, September 1981. Report includes eight annexes in three volumes, plus three appendices in three volumes.

International Great Lakes Levels Board (IGLLB). 1973. Regulation of Great Lakes Water Levels. Summary report plus seven appendices in nine volumes.

International Lake Erie Regulation Study Board (ILER). 1981. Lake Erie Water Level Study. July. Report plus eight appendices in 10 volumes.

Lake Carriers Association. 1980. 1979 Annual Report.

________. 1981. 1980 Annual Report.

Loucks, E.D., E.F. Joeres, K.W. Potter, M.H. David, and S.S. Rosenthal. 1987. Diversion of Great Lakes Water Part 1: Hydrologic Impacts. Institute for Environmental Studies Report 130. University of Wisconsin-Madison.

Parsons, G. 1982. Shoreline Valuations in the IGLLB Study. Unpublished report written as part of Great Lakes water management study. University of Wisconsin-Madison.