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Nir Becker and K. William Easter

Department of Agricultural and Applied Economics

University of Minnesota
Institute of Agriculture, Forestry and Home Economics
St. Paul, Minnesota 55108

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DYNAMIC SUPPLY FROM A COMMON PROPERTY RESOURCE:
WATER DIVERSIONS FROM THE GREAT LAKES.

Nir Becker[1] and K. William Easter[2]

ABSTRACT: The five Great Lakes can be classified as a common property or open access resource. This is a consequence of the lack of a well-defined system of property rights governing water use in the lakes. Decisions by interested parties are interconnected, since withdrawing water from one point may affect water levels in the entire system. This, in turn, can adversely affect hydropower production and commercial navigation. Contributing to the complexity of the problem are the eight U.S. states, two Canadian provinces and the two federal governments. Game theory is implemented to describe this situation. Several games are constructed to describe different market structures. Of particular interest is the number of players that participate in the game, as well as the expectations which they hold. Open-loop (where players commit themselves to future actions) and closed-loop (where players do not commit themselves to future actions) are compared for the ten players game (eight states and two provinces), two players game (U.S. versus Canada) and one player game (a social planner's solution). It is shown that trying to solve an open-loop game ignores part of the externalities involved, and thus can underestimate the social loss involved in these lakes.

KEY TERMS: Common property resources, game theory, water diversions, Great Lakes

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[1]Ph.D. Candidate, Department of Agricultural and Applied Economics, University of Minnesota, St. Paul, MN 55108.

[2]Professor, Department of Agricultural and Applied Economics, University of Minnesota, St. Paul, MN 55108.

INTRODUCTION

The five Great Lakes, located between the U.S. and Canada, are tied together by one common outlet to the ocean. When combined, they are the largest fresh surface water body in the world (20% of the world's fresh water stock, and 95% of the American continent's). Lake Superior is considered the largest lake in the world, and Lakes Michigan and Huron are the fifth and sixth largest, respectively (Task Force, 1985). This enormous body of water, combined with an increasing demand for water, gives rise to proposals for transferring the water for use outside the lakes and basin.

Water from the lakes has both stock and flow uses. While the flow uses accrue only to the parties that withdraw water from the lakes, that is not necessarily true with respect to the use of water as a stock, which is spread over the whole system. This situation can be represented as a game, since the outcome of this situation to each and every player depends not only on his or her actions, but on other players actions (Becker and Easter, 1989). Since decisions and the benefits and costs to each player extend over time, the game is a dynamic one. The external effects on each player come indirectly through the lake level, which influences their uses.

This study concentrates on the two industries that will be the major losers when lake levels are reduced: commercial navigation and hydropower production. Damages to lakeshore properties are not included because water diversions decrease lake levels, while damages to shore property tend to occur during high lake levels. Other uses of water, i.e., fishing, recreation and wildlife, were found to be less sensitive, and will only change the results marginally (IJC, 1981).

It is important to understand why game theory should be applied to the Great Lakes management questions. One approach would be to perform several benefit-cost analyses, for several diversion proposals (David et al., 1988, IJC, 1981). However, the core issue is that, as long as there are a finite number of parties involved in lake management, a change in lake levels can and probably will bring about changes in their decisions with respect to how much water to take out of the lake. Performing a discrete benefit-cost analysis is not the "end of the game," but only one possible outcome. Thus, the results from benefit-cost analysis could be misleading.

The dynamic game theory makes a distinction between an open-loop and a closed-loop equilibria (Clemhout and Wan, 1979). The difference between those two equilibria is not only in the value of the variables, but in the environment that they try to describe. The open-loop equilibrium ignores part of the externalities involved in withdrawing water from the Great Lakes. The result of these two equilibria will be compared in this paper to determine the importance of this external cost.

THE GREAT LAKES SYSTEM

The Great Lakes system consists of a series of five major lakes which are connected by four channels. Flows out of lakes Superior and Ontario are regulated, while they are not in lakes Michigan-Huron and Erie. The system has a surface water area of 5,475 square miles. Lake Superior is the furthest to the west while Ontario is the farthest east. The direction of the flow is from Lake Superior through St. Mary's River into Lake Huron. Because of the wide connecting channel between Lake Huron and Lake Michigan, water can flow between these two lakes in both directions. This flow tends to equalize the lake levels, thus, they are usually considered as one lake. Lake Huron outflow runs through the St. Clair River and Lake St. Clair, and the Detroit River to Lake Erie, which drains through the Niagara River to Lake

Ontario. Lake Ontario outflows pass through the St. Lawrence River to the Atlantic Ocean.

Currently, there are five major diversions. Two diversions (Long Lake and Ogoki) divert water into Lake Superior from Ontario, Canada. Another takes water out of Lake Michigan, through the Chicago diversion, to the Mississippi River. The Welland Canal connects Lake Erie to Lake Ontario and it bypasses Niagara Falls. Finally, the New York State Barge Canal takes water from the Niagara River into Lake Ontario. Besides diversions to and from the lakes, there is also a consumptive use component which, in contrast to the diversions, is not well documented (Frerich and Easter, 1988).

While on the average water in equals water out, in reality these components are not fixed, and thus lake levels change from month to month. The seasonality of the hydrologic characteristics is reflected in higher lake levels in the spring and early summer, and a gradual drop during the remainder of the year. The natural supplies to the lakes are large relative to the range of flows on the connecting channels, which are remarkably constant. This fact will have an effect later upon our results, since changes in a given lake will be absorbed by other lakes only after a long period of time. If there is a long-run change in the water supply to the lake (i.e., a diversion), the outflow is adjusted in such a way that the system will reach a new equilibrium after a period of time, with a new steady state lake level and flows in the connecting channels.

Consumptive water use in the Great Lakes basin will continue to grow as the population and economy expand. In addition, there will be periodic pressures to increase water diversions, particularly from the Chicago diversion, when lake levels are high or river levels are low. However, the future demand for Great Lakes water involves many uncertainties. If the earth warms up and the upper midwest becomes drier, then demand could be greatly expanded. In contrast, abundant rains could slow the growth in demand to a trickle. Given this uncertainty, this study focuses on the supply side and assumes that there will be demand for whatever amount is supplied at $100 per ac. ft. This price for water is on the low side for most water uses except for agriculture which cannot pay much more than $50 per ac. ft.

COST OF WITHDRAWALS

The major cost of most new diversions or withdrawals is the fixed costs. For example, fixed costs of diverting 10,000 cfs from Lake Superior to the Missouri River Basin were estimated at $10 billion while the annual variable costs were estimated at $10 million. The fixed costs for a relatively small Lake Erie diversion were estimated to be $3.2 billion (DeCooke et al, 1984 and Banks, 1982). For this model the fixed costs for new water diversions or withdrawals are based on the Superior-Missouri River and the Lake Erie transfers amortized over an infinite time horizon. The operating and maintenance costs are fixed per 1 thousand cfs costs.

Because of the complexity of the system, a hydrologic response model (HRM) is used to estimate the external effect of water withdrawals from the Great Lakes system (Quinn, 1978, Hartmann, 1988). The changes in Lake Superior's hydrologic component are accounted for in the lower lakes by passing the change, according to the Lake Superior regulation plan, through the St. Mary's River flow, which is part of the HRM. Lake Ontario is not considered, however, in the HRM, since it does not affect anything upstream due to Niagara Falls. Changes in Lake Ontario levels are derived using the Lake Ontario regulation plan algorithm (plan 1958-D), adjusted by the effect of the upper lakes. These three simulation models account for the whole system and result in monthly lake levels and water flows in the connecting channels.

The key external cost components in this analysis are the effect on the industries that use the water as a stock; commercial navigation and hydropower production. In order to simplify the analysis, it was assumed that these costs are quadratic relative to lake levels. That can be thought of as a Taylor expansion only over the first two arguments. Before describing the method used to obtain these costs, several additional assumptions should be mentioned. In order to gain insight into these two industries, it was assumed that the current diversions and consumptive use remain the same. In other words, the effect of withdrawing water is in addition to the existing withdrawals. Moreover, with respect to the commercial navigation, it was assumed that the demand for shipped goods is totally elastic, while the supply is totally inelastic. That is, all the costs incurred by lower lake levels will fall on the shipping industries. Further research is needed, however, with respect to whether goods can be shipped in alternative ways, and whether part of the cost can be shifted to the consumers. With respect to the hydropower production, it was assumed that the demand function is totally inelastic, but cannot be totally supplied by hydropower generations. That is, every power capacity loss due to lower lake levels (and lower outflows in the connecting channels) will result in shifting to higher cost modes. The difference between these costs is the loss to consumers, which in this case is within the system (Great Lakes states and provinces).

Navigation on the Great Lakes: Reduced lake levels will increase the cost to the shipping industries, since ships will have to carry less; and in order to ship the same quantity, they will have to make more trips. These additional trips are the loss to the shipping industry. It is implicitly assumed that all the other factors of production are smoothly adjusted to changing lake levels, thus the only factor responsible for the loss is the reduced lake levels.

The loss for the shipping industry was estimated by calculating monthly trip hours for each state for every lake that the state has access to. The data was taken from Water Borne Commerce of the United States (WCUS), 1977-1986. Almost 200 million short tons are shipped on the lakes annually. The hourly cost was used to attach cost to the number of trip hours. In order to obtain the cost in terms of losses, the base cost was set at the highest lake levels during the period January 1980 to December 1986, and a value of zero cost was attached to it. The cost then was adjusted to be the additional cost due to reduced lake levels. This additional cost (loss) vector was regressed on lake level change for that period without a constant.

(1) $$Loss_{i,L,t} = a\,(DLL_{L,t}) + b\,(DLL_{L,t})^2.$$

Where: $NLOSS_{i,L,t}$ = loss to player i on lake L at time t (navigation).
$DLL_{L,t}$ = decreased lake level at Lake L at time t and;
a,b = coefficients to be estimated.

Hydropower Production on the Great Lakes: Unlike commercial navigation, hydropower is affected directly by the outflow in the connecting channels. But this outflow is, in turn, determined by the lake level. As mentioned above, substitutes do exist for hydropower, but they are more expensive.

Three major areas produce hydroelectric power: upper Michigan at the Sault Ste. Marie Locks (Michigan and Ontario), the Niagara River Falls to Lake Ontario (Ontario and New York) and the St. Lawrence River, which is the outflow from Lake Ontario (Ontario and Quebec). The distribution is much more concentrated than the one for commercial navigation. In addition, there are fewer states that produce hydropower, and most of them are located downstream. This is a classic situation in which economic efficiency problems occur because of interdependencies.

Data was collected for the different plants on the relationship between the energy loss and the flows in the connecting channels, as well as the lakes elevation between 1980 and 1988 (N.Y.P.A., 1989, Ontario Hydro, 1987 and Hydro Quebec, 1988). However, only the lake level variable is included in the cost equation, since lake levels and outflows in the connecting channels are highly correlated. The loss is calculated as the difference between hydropower and the best alternative source existing for that state, multiplied by the energy loss for that month. The loss equation can be written as:

$$(2) \quad PLoss_{i,L,t} = c\,(DLL_{L,t}) + d\,(DLL_{L,t})^2$$

Where:
- $PLoss_{i,L,t}$ = power loss to player i on lake L at time t.
- $DLL_{L,t}$ = decreased lake level L at time t.
- c,d = cost coefficients to be estimated.

GAME THEORY MODEL

Much attention has been given to analyzing different market structures by looking at the dynamics that arise from the interaction amongst different parties. Game theory provides a method for looking at such dynamic interactions and is particularly useful for resource extraction problems, where there are interactions over time among a finite number of players. Some useful applications of this theory to natural resources where common property or open access is a problem include: Levhari and Mirman (1981) for the fisheries, Reinganum and Stokey (1985) for oligopoly extraction of nonrenewable resources, Eswaran and Lewis (1984) for renewable resources, and Negry (1989) for groundwater mining.

In applying the theory to the Great Lakes problem, we start with the following transition equation:

(3) $S_{t+1} - S_t = f(y_{1t}, y_{2t}, \ldots, y_{nt})$

Where S_t is the state variable, y_{it} is the (1xn) control vector for the n players for period t. Player i faces the following objective:

(4) $$Z_i = \sum_{t=0}^{\infty} \beta^{t} J_{it}(S_t, y_{1t}, \ldots, y_{nt}) \quad 0<\beta<1 \quad \forall_i \in N.$$

Where J_i is the payoff function for player i, at time t,β is the discount factor and Z_i is the discounted objective function. Player i tries to maximize (2) subject to (1) where S_o is given and y_i is nonnegative. While the constraints described above can be estimated, we need a constraint on the way each player j (where j≠i) chooses a strategy. This constraint is not obvious, since we are dealing with expectations and not with stocks of resources. Alternative assumptions on what player i _expects_ player j to choose, y_{jt}, will complete the game's characteristics and determine the equilibrium. Two commonly used assumptions are found in the literature of dynamic games. First is an open-loop in which players decide at the beginning of the game on a strategy path _given_ the other player's expected strategy path. This path is called an _open-loop Nash equilibrium_, if for _each_ player, the path that they choose is the optimal one, given the paths that the other players choose is also optimal. Thus, none of the players have an incentive to change their strategy, either in the beginning of the game or during the game. Formally defining an open-loop Nash equilibrium, we get the following extractions vector set:

(5) $$Z_i\left[S_o, (y_1^*)_{t=0}^{\infty}, \ldots, (y_n^*)_{t=0}^{\infty}\right] \geq Z_i\left[S_o, (y_1^*)_{t=0}^{\infty}, \ldots, (y_{i-1}^*)_{t=0}^{\infty}, (y_i)_{t=0}^{\infty}, (y_{i+1}^*)_{t=0}^{\infty}, \ldots, (y_n^*)_{t=0}^{\infty})\right] \quad \forall (y_i) \in Y.$$

Where $\{y_i\}_{t=0}^{\infty}$ is any other feasible strategy vector for player i. In other words, the extraction path will be optimal to every player because we assume that the other players will not change their strategies. Necessary conditions for this equilibrium can be derived by solving n current value Hamiltonians. The current value Hamiltonian for player i is the following:

(6) $H_i = J_i\ (\cdot) + \lambda_i\ f(\cdot),$

where λ is a costate variable vector attached to the stock. The necessary conditions are:

(7) $\frac{\partial J_i(\cdot)}{\partial y_i} = \lambda_i \frac{\partial f(\cdot)}{\partial y_i} \quad \forall_t$

(8) $\lambda_{i,t+1} - \lambda_{i,t} = r\lambda_i - \frac{\partial H_i}{\partial S_t}$

(9) $S_{t+1} - S_t = f(y_1, y_2, \ldots, y_n)$

where r is the interest rate. These conditions are also sufficient, provided the concavity of the Hamiltonian in S and y. Since our problem is of an infinite horizon, the transversality conditions are:

(10) $\lim_{t \to \infty} \beta^t\ \lambda_t \geq 0$ and;

(11) $\lim_{t \to \infty} \beta^t\ S_t\lambda_t = 0$

Conditions (8) and (9), together with the concavity of the Hamiltonian, are sufficient for an optimum.

Starting from (6), we get the following:

$$(12) \quad \lambda_i = \sum_{t=\bar{t}}^{\infty} \beta^t \frac{\partial J_{i,\bar{t}}}{\partial S_{\bar{t}}} \quad \forall \bar{t}$$

Substituting in (5), we get:

$$(13) \quad \frac{\partial J_i}{\partial y_i} = \lambda_i \quad \forall t$$

Solving the extraction path involves solving difference equations, but if we are interested in the steady state of the system, we know that in the steady state, $\lambda_{ss} = \lambda_{t+1} = \lambda_t$, thus:

$$(14) \quad \lambda_t = \frac{\partial J_{i,t} / \partial S_t}{r}$$

which is the value of the stock to player i in a steady state. The steady state extraction rate is then obtained from the steady state costate variable.

The problem with an open-loop equilibrium is its strong assumption that players solve the game at the beginning of the game, where the solution is a <u>vector</u> of extraction paths. While the game's equilibrium is consistent at t=0, it relies on non-credible future behavior, which is not necessarily in the interest of player i to fulfill. A more reasonable assumption is that players do not commit themselves only to a time profile of actions, but to a time-state profile, which results in a <u>decision rule</u>. The decision rule includes the extraction as a function of the given state at the current time. This kind of equilibrium will be called <u>closed-loop</u> (or feedback) equilibrium. A closed-loop equilibrium is subgame perfect, which means that when the game is played by the decision rules of the players, a Nash equilibrium is reached at every stage of the game. Thus, the game is time consistent by definition. The discounted objective function for player i is now written:

$$(15)\quad Z_i = \sum_{t=o}^{\infty} \beta^t J_i(S_t, y_{1t}, \ldots, y_{nt}) \qquad \forall i \in N$$

But unlike the open-loop case y_j, where $j \neq i$ is also a function of the state variable, i.e.,

$$(16)\quad y_{i,t} = g_i(S_t) \qquad \forall i \in N, \ \forall t$$

the Nash equilibrium now will have the property that no player will have an incentive to change the decision rule <u>given</u> the other player's decision rule, thus:

$$(17)\quad Z_i \left[y_1(s)^*, \ldots, y_{i-1}(s)^*, y_i(s)^*, y_{i+1}(s)^*, \ldots, y_n(s)^* \right] \geq$$

$$Z_i \left[y_1^*(s), \ldots, y_{i-1}(s)^*, y_i(s), y_{i+1}(s)^*, \ldots, y_n(s)^* \right] \qquad \forall i \in N, \ \forall y_i(s)$$

The current value Hamiltonian for player i will be:

$$(18)\quad H_i \left[S_t, y_1(s), \ldots, y_n(s) \right] = J_i \left[s_t, y_1(s), \ldots, y_n(s) \right] +$$

$$\lambda i f \left[S_t, y_1(s), \ldots, y_n(s) \right] \qquad \forall t, \quad \forall i \in N$$

The Nash equilibrium will satisfy the following necessary conditions (Starr and Ho, 1969):

$$(19)\quad y_i = g^*(S) \text{ maximize } H_i(S, g_1^*(S), \ldots, y_i, \ldots g_n^*(s)) \quad \forall t\ ,\ \forall i \in N$$

$$(20)\quad S_{t+1} - S_t = f(y_1, y_2, \ldots, y_n) \quad \forall_t$$

$$(21)\quad \lambda_{t+1} - \lambda_t = r\lambda_t - \frac{\partial H_i}{\partial S} - \sum_{\substack{j=1 \\ j \neq i}}^{17} \frac{\partial H_i}{\partial y_j} \cdot \frac{\partial g_j^*}{\partial S} \quad \forall_t,\ \forall i \in N,\ \forall j \neq i \in N$$

Equations (17) and (18) have the same structure as in the open-loop Nash equilibrium. The summation term in (19) is the basis for the difference between the two concepts. This interaction term indicates the effect that player i has on the decision rule of player j's Hamiltonian. Intuitively, the explanation is that: player i, by knowing how he or she can influence player j's extraction, will take it into account in his or her maximization conditions. When player i derives the canonical equation with respect to the stock, he or she notices that S_t is not only in his or her Hamiltonian, but in the others as well. Moreover, the sign of $\partial g_j^* (S)/\partial S$ will probably be positive, thus players will extract less when the stock level goes down. This in turn will offset the losses incurred by player i from driving the stock down. Therefore, in equilibrium the stock level as well as the shadow price will be lower in a closed-loop as compared to the open-loop equilibrium. In a common property or open access resource model, where property rights are not well-defined, the closed-loop equilibrium seems more appropriate. Notice that y_i and λ_i are not functions of time any more, but functions of the stocks. That is, the decision rules are with respect to <u>stocks</u> without importance to the <u>time</u> that these stocks are reached.

It should be mentioned at this point that open-loop and closed-loop do not always differ. Whenever a player <u>cannot</u> manipulate the stock or <u>doesn't want</u> to manipulate it, there will not be any change between the two concepts. In the common property literature, it applies to the two endpoint solutions, namely, the open access and social planner solutions. In the open access, it is assumed the players are too small to affect the stock, while in the social planner's problem, it is not in his or her interest to manipulate the stock. When the number of players is finite, the two concepts give rise to different equilibrium values

Finally, it is important to realize that a closed-loop equilibrium is a Nash equilibrium in the sense of a given decision rule, but not in the context of an extraction path. Therefore, the feedback solutions are not the usual Nash solutions, but rather non-Nash ones. This occurs because players know that their action will have an effect on their rivals' action, which implies that the conjecture variation is no longer zero. Additionally, it is the only conjecture variation that is consistent with profit maximization, since players will always do whatever is in their interest to do (i.e., profit maximization). Other conjecture variations, while sometimes more attractive, are harder to justify on the grounds of some maximization behavior in a noncooperative sense (see Mason et al., 1988 and Runge, 1986).

IMPLEMENTING THE MODEL

The parties involved in this game are eight states and two provinces. The eight U.S. states are: Minnesota, Wisconsin, Michigan, Illinois, Indiana, Pennsylvania, Ohio and New York, while the two Canadian provinces are Ontario and Quebec. Thus, we have potential conflicts not only between states and provinces, but also between countries. Moreover, there are states that have access to more than one lake. In general, the system has 4 state variables (the lakes), 10 players (states and provinces) and 17 decision variables (number of players with access to each lake).

In the Great Lakes game, player i on Lake L faces the following problem:

$$\text{(22)}\quad \underset{y_{i,L}}{\text{Max}} \quad \pi_{i,L} = \sum_{L=1}^{4} \sum_{t=0}^{\infty} \beta^{t} \left[y_{i,L,t}(P\text{-}VC) - NLoss(LL_{L,t}) - PLoss\ (LL_{L,t}) \right]$$

s.t.

$$\text{(23)}\quad DLL_{L,t} = \sum_{K=1}^{4} \sum_{i=1}^{17} y_{i}e_{k,L} \qquad \forall_{K,L} = 1,2,3,4 \quad \forall_{i} = 1,\ldots,17$$

$$\text{(24)}\quad LL_{t=0} = \overline{LL} \quad \forall L = 1,2,3,4$$

Here, $e_{k,L}$ is the cross lake coefficient. That is, the effect on all lakes of a given lake level reduction. This is a 4x4 matrix with unit diagonal components (that is, the effect of a lake on itself was normalized to 1). While y_i for every player results in a revenue that is directly related to the quantity sold, the costs are determined not only by player i, but by the others as well.

The following current value Hamiltonian is:

$$\text{(25)}\quad H_{i,L} = \left[y_{i,L}(p\text{-}Vc)\text{-}NLoss(LL)\text{-}PLoss(LL) \right] + \lambda_{i,1} \left(\sum_{k=1}^{4} \sum_{i=1}^{17} y_{i,L}e_{k,L} \right) + \mu_{i,L}\, y_{i,L}$$

where $\mu_{i,L}$ is the costate variable associated with the nonnegativity constraint. The associated Kuhn-Tucker condition for this variable and $y_{i,L}$ should be satisfied in equilibrium (Knapp, 1983).

$$\text{(26)}\quad \mu^{*}_{i,L}\, y^{*}_{i,L} = 0\ ;\quad y^{*}_{i,L} \geq 0\ ;\quad \mu^{*}_{i,L} \geq 0.$$

The other first order necessary conditions are the usual ones:

$$\frac{\partial H_{i,L}}{\partial y_{i,L}} = 0 \tag{27}$$

$$\lambda_{i,L} = r\lambda_{i,1} - \frac{\partial H_{i,L}}{\partial LL} \tag{28}$$

and the transition equation (23).

In practice, what we require is that the decisions of the states will be constrained to diversions out of the lake and not diversions into the lake. Whenever $y_{i,L}$ equals zero, there will be a positive costate variable, $\mu_{i,L}$ which is the effect on player i of a unit of water diverted <u>into</u> the lake.

The fixed costs are not included in the necessary conditions. The outcome, however, is supposed to cover the amortized value of the fixed cost. If it does not, then the project is assumed not to be built.

As mentioned above, there are 10 players and 17 decision variables. That means that some of the players have more than one lake that they have access to and therefore have more than one decision variable. Thus, whenever players in this game choose a strategy, they take only part of the other strategies as givens. The strategies that affect their payoffs are taken into account when they set their first order conditions for profit maximization. In that case, the associated condition looks like:

$$NMB_{i,L} = \lambda_{i,L} + \sum_{\substack{k=1 \\ k \neq L}}^{4} \lambda_{i,K} \tag{29}$$

where NMB is the net marginal benefit for player i on lake L.

Finally, it is important to understand that the water body dealt with is a large one. The results of withdrawing water will reach its full impact only after about 15 years (DeCooke et al., 1984). Moreover, the diversion from different lakes have an additive effect. In that case, we can separate the effects lake by lake. A strategy which is the steady state one will have a costate variable associated with it, which is a combination of two components--the effect up to 15 years, and the effect 15 years and beyond.

Let the loss function for an industry i be:

$$(30)\quad \text{Loss}_i = \alpha_{1,i}\,\gamma_L y + \alpha_{2,i}(\gamma_L y)^2 \qquad \forall i = 1,2$$

Note that i represents industries and not players, and r is the effect of the level of diverting ltcfs. If we assume that it takes 180 months to get to the steady state, the present value of losses to industry i should be:

$$(31)\quad \text{PVLoss} = \begin{cases} \left[\alpha_{1,i} g_i y + \dfrac{2\alpha_{1,i}\gamma_i y}{(1+r)} + \ldots + \dfrac{180\alpha_{1,i}\gamma_L y}{(1+r)^{179}}\right] + \alpha_{2,i}\gamma_L^2 y^2 + \dfrac{\alpha_{2,i}(2\gamma_L)^2 y^2}{(1+r)} + \ldots + \dfrac{\alpha_{2,i}(180\gamma)^2 y^2}{(1+r)^{179}} & \text{for } t<180 \\[2ex] \dfrac{\dfrac{180\alpha_{1,i}\gamma_L y + \alpha_{2,i}(180\gamma_L)^2 y^2}{r}}{(1+r)^{180}} & \text{for } t \geq 180 \end{cases}$$

or, after some algebraic manipulation:

$$(32)\quad \text{PVLoss}_i = \left(\alpha_{1,i}\gamma_L y \left[\sum_{t=0}^{179} t(1+r)^{1-t}\right] + \alpha_{2,i}\gamma_L^2 y^2 \left[\sum_{t=1}^{180} t^2(1+r)^{1-t}\right]\right)$$

$$+ \left(\frac{180\alpha_{1,i}\gamma_L y + \alpha_{2,i}(180\gamma_L)^2 y^2}{r(1+r)^{180}} \right)$$

where y is the sum of all diversions adjusted by the cross lake affects and each player treats his rivals' decisions as givens.

The closed loop equilibrium is calculated by, again, solving a system of equations. This time, the coefficients are different, since players take into account their effect on other players. The effect of other players extractions on player i himself is implicitly taken into account by solving the set of equations simultaneously. Recall that every player other than i has a decision rule that depends on stock. That is:

$$(33)\quad y_j = g_j^* \left[S(y_i, \ldots, y_i, \ldots, y_n) \right]$$

player i, resets his first order condition based on this information. With respect to player j he gets:

$$(34)\quad \frac{\partial g_j^*}{\partial y_i} < 0$$

However, there are several players, thus:

$$(35)\quad \sum_{j \neq i} \frac{\partial g_j^*}{\partial y_i} < 0$$

(35) is the "manipulation affect". Every player on the system manipulates the stock according to (35), since he <u>thinks</u> that he will increase his profit. The inefficiency increases because every body thinks so. Equation (32) for the closed-loop solution becomes:

$$(36)\quad \text{PVLoss}_i = \left[\alpha_{1,i} \gamma_L \cdot \sum_{i=1}^{n} g_i^* \cdot \left(g_1^*(y_1, \ldots, y_n) + \ldots + g_n^*(y_1, \ldots, y_n) \right) \right] \cdot$$

$$\cdot \left[\sum_{t=0}^{179} t(1+r)^{1-t} \right] + \alpha_{2,1} \gamma_L^2 \cdot \left[\sum_{i=1}^{n} g_i^* \left(g_1^*(y_1, \ldots, y_n) + \ldots + g_n^*(y_1, \ldots, y_n) \right) \right] \cdot$$

$$\cdot \left[\sum_{t=1}^{180} t^2 \, (1+r)^{1-t} \right] \Big) +$$

$$\left(\frac{180\alpha_{1,i}\gamma_L \cdot \sum_{i=1}^{n} g_i^* \left[g_1^*(y_i,\ldots,y_n)+\ldots+g_n^*(y_1,\ldots,y_n)\right] + \alpha_{2,1}(180\gamma_L)^2 \cdot}{} \right.$$

$$\left. \frac{\left[\sum_{i=1}^{n} g_i^* \left[g_1^*(y_1,\ldots,y_n) +\ldots+g_n^*(y_1,\ldots,y_n)\right]\right.}{r\ (1+r)^{180}} \right)$$

The equilibrium is, thus, computed in two stages. In the first stage, each player faces the following problem: departing from the open loop equilibrium, how much more can he extract without affecting his cost and thus, increasing his profit? The answer is to increase the extraction as long as it will not affect the lake level. This, in turn, depends on the reaction of the other players to his action. The second stage is reached when all the first order conditions are solved together after adjusting the coefficients of the derivative of the payoff matrix (Hessiqan) according to the manipulation affect. When players are <u>not identical</u>, it is possible that players will divert <u>less</u> than in open loop after taking into account their rivals' <u>closed-loop</u> strategies. It is so because only on the second stage, players actually are taking into account that not only are they playing a closed loop strategy, but that all of the other players are doing the same.

RESULTS

Based on the physical and hydrological data, as well as the economic indicators, it is possible to construct the following games: 1) Social Planner's Game (a 1-player game); 2) U.S. vs. Canada - Open-loop (a two-country game); 3) U.S. vs. Canada - Closed-loop (a two-country game); 4) Ten Players - Open-loop; and, 5) Ten Players - Closed-loop.

The best regression estimates for the impacts of reduced lake level include only the squared term for the decreased lake level. In general these results were as good or better than a regression which includes both reduced lake level and the quadratic term for it. Since we wanted to keep one functional form, we chose to concentrate on the reduced square term (Table 1). The cross lake affects are given in Table 2 (these are ratios for the total affect) while the inner lake affect for the first 15 years is given in Table 3.

Game 1 (Social Planner's Game): The social planner's game is set up so the discounted net benefit of the whole basin, subject to hydrological and nonnegativity constraints, are maximized. It is *as if* all the lake uses in the basin are under one ownership and all the impacts of diverting lake water are taken into account. Table 4 gives the solution for 0.4% real monthly interest rate. The socially optimal diversion is to increase the Chicago diversion by 0.71 tcfs and to build a new project on Lake Ontario to divert 10.55 tcfs. Since the present value of the project benefits minus annual variable costs is larger than the fixed cost ($3,200 million), the project passes the economic efficiency test. These discounted benefits are for an infinite time period, with a constant stream of monthly benefits. This means, of course, that at higher discount rates and/or lower water prices, benefits would drop relative to costs and diversions would be less economic. Surprisingly, a significant part of the supply is being taken from a lake which produces an important part of the hydroelectric power in the basin. However, withdrawals from this lake do not affect the upper lakes. In contrast, taking water from the upper lakes will result in a chain effect that will cost more than can be compensated for by revenues generated.

Games 2 and 3 (U.S. vs. Canada: Open-loop/ Closed-loop): In the two country games there is no difference between the open-loop and the closed-loop solutions (Table 5). The reason is that only the U.S. "wins" in the open-loop game, thus they have no incentive to further drive down the lake levels because Canada is already not diverting. Canada could influence the U.S. by extracting water, but they will lose even more than the U.S. for every inch the lakes drop. Thus, the best strategy for Canada is to play 0 in both games while the U.S.'s best strategy is to divert 44 tcfs from Lake Ontario. The U.S. gains about $31 billion (excluding fixed costs), while Canada loses more than $90 billion. The total social loss of $61,457 million versus $7,981 million benefit for the social optimum solution, clearly indicates the inefficiency of moving from a one player to a two player game or solution. This is all based on the highly unlikely assumption that the U.S. could divert and sell as much water as it wanted at $100/ac. ft. However, the important lesson to be gained is the distribution of benefits and costs and how they influence the decision.

Games 4 and 5 (Ten Players - Open-loop/Closed-loop): All the diversions in these games are above Lake Ontario (Table 6). These diversions increase the losses imposed on the whole basin. The incentive to increase the amount of water diverted from the Great Lakes as well as a shift in the location of the diversion results from the location of states around the lakes and the distribution of costs and benefits of diversions. Lake Erie is a big problem. While a significant part of the hydropower facilities is located in the outflow from the lake, certain states such as Pennsylvania, are affected very little by reduced lake levels. This difference in cost incidence of large diversions causes very large losses for New York and the two Canadian provinces.

It is important to note that, while there are several states that are diverting water (4 in the open-loop game and 5 in the closed-loop game), only Pennsylvania "wins" while all the others have a negative present value of benefits. This is exactly the essence of the "tragedy of the Commons." States divert water not because they will gain something but because they will lose less by doing so. The difference in the losses results because if they do not divert, some other state will. If the difference in losses is larger than the fixed cost, the state gains from building it.

The open-loop and the closed-loop solution is the additional amount of water diverted from Lakes Superior and Michigan-Huron. This difference is a function of the cost of impacts on various states as well as the hydrological relationships among the lakes. The major difference is a diversion from Lake Superior (the Wisconsin part) as well as the doubling of the diversion from Lake Michigan-Huron by Illinois and Indiana. The "tragedy" increases since everybody tries to manipulate the stock (lake levels). The results suggest that the open-loop equilibrium under estimates the true social loss by 34%. The difference in benefits for binding agreements to limit state diversions are quite large and can prevent about one-third of the externality involved in managing the lakes by states and provinces as compared to the social planner.

SUMMARY AND POLICY IMPLICATIONS

Different market structures can give rise to totally different supply patterns of water from the Great Lakes. The lakes are characterized by different types of users. This fact is the core reason for conflicting incentives, which result in large losses if lake diversions are not regulated. The fact that the big users of water as a stock are located downstream, can result in large losses if downstream water rights are ignored.

Neither Ontario nor Quebec have an incentive to extract large amounts of water. Thus, the incentive to reach an agreement to restrict water withdrawals rests mainly with the two Canadian provinces and the States of New York and Michigan.

Formulating the game as an open-loop game does not account for the "strategic externality," which basically is a weak assumption. Players generally do not necessarily have a strong incentive to remain in their original strategies if it is not in their best interest. Thus the closed-loop game is more realistic for open access resources or what some call the Commons. The benefits of managing an open access resource become higher when the possibility of "feedback" strategies is recognized through the open-loop game.

Finally, it should be mentioned that more research is needed with respect to the demand side, which is ignored in this study. The incorporation of the demand, however, is much more difficult than the supply because of data problems. The inadequate demand estimates resulted in diversions from Lakes Ontario, Erie and Michigan-Huron that are unrealistically large. What the results really show is that small water diversions or withdrawals from certain lakes, either for use inside or outside the basin, might pass the economic efficiency test. Yet because of the unequal distribution of benefits and costs of water diversions among states, several states and the U.S. federal government may have economic incentives to promote socially inefficient diversions. In addition, more research is needed on other types of expectation formation, other than the open- and closed-loops (Mason, et al., 1988). The best expectations are those that could be verified in reality, which is very difficult to do.

Table 1

Cost Coefficients for Water Diversion or Withdrawals
(for Losses in Millions $/in drop in Lake Level)

	Superior		Michigan-Huron		Erie		Ontario	
	Navigation	Hydropower	Nav.	Hydro.	Nav.	Hydro.	Nav.	Hydro.
MN	.0036	-	-	-	-	-	-	-
WI	.0015	-	.0012	-	-	-	-	-
MI	-	.007	.007	-	.0025	-	-	-
IL	-	-	.0028	-	-	-	-	-
IN	-	-	.0027	-	-	-	-	-
OH	-	-	-	-	.0050	-	-	-
PA	-	-	-	-	.0004	-	-	-
NY	-	-	-	-	.0004	.033	.00014	.02
ONT	.0015	.0061	.0027	-	.00046	.033	.0011	.02
Q	-	-	-	-	-	-	.0022	.0368

Table 2

Cross Lake Coefficients (ratio) for Water Diversion or Withdrawals

diver- \ affects sion from\ upon	Superior	Michigan-Huron	Erie	Ontario
Superior	1.00	1.32	.92	1.08
Michigan-Huron	0.31	1.00	.69	.72
Erie	0.15	0.38	1.00	1.02
Ontario	0	0	0	1.00

Table 3

Monthly Inner Lake Affect for Water Diversion or Withdrawals

(for the first 180 months, in inches per 1tcfs)

Superior	Michigan-Huron	Erie	Ontario
.0033	.0045	.0032	.0008

Source: IJC (1981).

Table 4
Social Planner's Solution

	Diversion (tcfs)	Lake Level Δ (inches) in Steady State	PV of Net Benefits (million $)
Superior	-	.13	-5.36
Michigan-Huron	0.71	.58	984.71
Erie	-	.28	-113.99
Ontario	10.55	1.59	7115.80
Total:	11.26	-	7981.16

Table 5

U.S. vs. Canada: Open-loop and Closed-loop Equilibria

	Diversion (tcfs) Open-Loop / Closed-loop	Lake Level Δ (inches) Open-loop / Closed-loop	PV of Net Benefits (Million $) Open-loop / Closed-loop
SUP:	-	0	-
U.S.	0	-	0
Canada	0	-	0
M-H:	-	0	-
U.S.	0	-	0
Canada	0	-	0
Erie:	-	0	-
U.S.	0	-	0
Canada	0	-	0
Ont:	-	6.33	-
U.S.	43.95	-	31,360
Canada	0	-	-92,817
Total:	43.95	6.33	-61,457

Table 6
The Ten Players Game

	Diversion (tcfs)		Lake Level Δ (inches)		PV of Net Benefits Million $	
	Open-Loop	Closed-loop	Open-loop	Closed-loop	Open-loop	Closed-Loop
SUP:						
MN	0	0	21.98	34.99	-274.10	-694.59
WI	0	8.11	-	-	-126.90	-151.46
MI	0	0	-	-	-53.30	-135.06
ONT	0	0	-	-	-160.66	-407.11
M-H:	-	-	83.28	127.75	-	-
MI	0	0	-	-	-1001.82	-1800.47
WI	0	0	-	-	-131.15	-262.67
ONT	0	0	-	-	-295.08	-694.46
IL	21.12	42.7	-	-	-55.61	31.86
IN	21.12	42.7	-	-	-55.61	31.86
Erie:	-	-	108.60	131.63	-	-
ONT	0	0	-	-	-69,781.48	-105.432.51
MI	0	0	-	-	-4647.35	-7,021.66
OH	11.39	11.58	-	-	-800.33	-1,207.35
PA	148.02	150.55	-	-	772.90	841.08
NY	0	0	-	-	-69,716.42	-105,334.21
ONT:	-	-	27.79	33.93	-	-
NY	0	0	-	-	-51,079.67	-76,127.00
ONT	0	0	-	-	-53,514.42	-79,755.67
Q	0	0	-	-	-98,913.00	-147,415.67
Total:	201.64	255.64	-	-	-349,834.00	-525,535.09

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