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FOR THE GREAT LAKES BASIN

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ABSTRACT: The five Great Lakes can be classified as a common property 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 affects the water levels in the entire system. This, in turn, adversely affects 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 will be implemented to describe this situation. There will be several games 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) will be compared to 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 will be 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 commons.

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

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 considered to be the largest fresh water body in the world (20X of the world's fresh water stock, and

95% of the American continent's). Lake Superior is considered the first 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 the alternative of using the water for purposes outside the lakes and basin.

We can dichotomize the value of the water to a decision maker to flow and to stock uses. While the flow value occurs only to the party that withdraws water from a given point on the lakes, that is not necessarily true with respect to the value 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 one of the players depends not only on his actions, but on the other players' actions as well. 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 he uses for his own purposes.

This study concentrates only on the two major industries that will lose because of reduced lake levels: commercial navigation and hydropower production. Lake shore properties were not included because water diversions tend to decrease the lake levels, while the damage occurring to shore property owners tends to be related to high lake levels. Other uses of water, i.e., fishing, recreation and wildlife, were found to be less sensitive, and thus will not change the result by much (IJC. 1981).

It is important to understand why game theory should be adopted here. After all, we could perform several cost-benefit analyses, but this would be a redundancy, as these have already been done for several diversion proposals (David, et al., 1988, IJC. 1981). The core issue here is that, as long as there are a finite number of parties involved in this process, the change in lake level 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 cost-benefit analysis is not the "end of the Game", and thus, the results from this analysis will not be accurate.

Once we construct the game, the question is what kind of equilibria we are looking for. The dynamic game theory makes a distinction between an open-loop and a closed-loop equilibria (Clemhout and Wan, 1979). The different between those two equilibria is not only in the value of the variables, but in the environment that they try to describe.

A model of dynamic games is presented in the next section. The study area will be described in section 3 and the results of the different games will be described in section 4. The conclusion and policy implications will conclude the paper.

THE THEORETICAL MODEL

Much attention has been given for analyzing different market structures by looking at the dynamics that arise from the interaction amongst different parties. Game theory becomes important in such a case. This theory is particularly useful for resource extraction problems, where interactions over time between a finite number of players are the reality. Some useful applications of this theory to natural resources where common property is the 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 general, we have a transition equation which is assumed to be:

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

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

$$(2)\quad \sum_{t=0}^{\infty} \beta^{t} \cdot J_i\,(S_t,\, y_{1t},\ldots,y_{nt}) \quad 0<\beta<1 \quad \forall i \in N.$$

Where J_i is the payoff function for player i, and is the discount factor. Player i tries to maximize (2) subject to (1) and with S_0 given and non-negative y_i. While the constraints described up to this point can be estimated, we need also a constraint of the way by which player j (where j#i) chooses his strategy. This is very subtle, since we are dealing here with expectations and not with stocks of resources. Alternative assumptions on player i expect player j to choose y_{jt} will complete the game's characteristics and thus, will determine the equilibrium. Two commonly used assumptions are used in the literature of dynamic games. The first one is an open-loop in which players decide at the beginning of the game on a strategy path given the other player's strategy path. This path is called an open-loop Nash equilibrium, if for each player, the path that he chooses is the optimal one, given the paths that the other players choose is optimal, as well. Thus, no player has an incentive to change his strategy, either in the beginning of the game or through the game. Formally defining open-loop Nash equilibrium, we get: the extractions vector set is a Nash equilibrium if:

$$(3)\quad J_i(y_1^*,y_2^*,\ldots,y_{i-1}^*,y_i^*,y_{i+1}^*,\ldots,\ y_n^*) \geq J\ (y_1^*,y_2^*,\ldots,y_{i+1}^*,y_1,y_{i+1}^*,\ldots y_n^*) \qquad \forall y_i$$

Where y_i is any other feasible strategy vector for player i. In other words, a strategy of 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 written:

$$(4)\quad H_i = J_i\ (\cdot) + \lambda_i \cdot f(\cdot),$$

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

$$(5)\quad \frac{\partial J_i(\cdot)}{\partial y_i} = 0$$

$$(6)\quad \lambda_{i,t+1} - \lambda_{i,t} = r \cdot \lambda_i - \frac{\partial H_i}{\partial S_t}$$

$$(7)\quad S_{t+1} - S_t = f(y_1, y_2, \ldots, y_n)$$

Where r is the interest rate, these conditions are also sufficient, provided the concavity of the Hamiltonian is S and Y. Since our problem is of an infinite horizon, the transversality conditions are:

$$(8)\quad \lim_{t\to\infty} \beta^t \lambda_t \geq 0 \quad \text{and;}$$

$$(9)\quad \lim_{t\to\infty} \beta^t S_t \lambda_t = 0$$

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

Starting from (6), we get the following:

$$(10)\quad \lambda_i = \sum_{t=\bar{t}}^{\infty} \beta \cdot \frac{\partial J_{i,\bar{t}}}{\partial S_{\bar{t}}} \qquad \forall \bar{t}$$

Substituting in (5), we get:

$$(11)\quad \frac{\partial J_i}{\partial y_i} = \lambda_i \qquad \forall t$$

Solving the extraction path involves some differential equation solving methods, but if we are interested in the steady state of the system, we know that, in the steady state, $_{ss}$ - $_{t+1}$ - $_{t}$, thus:

$$(12)\quad \lambda_t = \frac{\frac{\partial J_{i,t}}{\partial S_t}}{r}$$

which is the value of the stock to player i in a steady state. From the steady state costate variable, we can also get the steady state extraction rate.

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 vector of extraction path. While the game's equilibrium is consistent at t-0, it is not necessarily time consistent at future dates. A more reasonable assumption is that players do not commit themselves only to time profile of actions, but to a time-state profile, which results in a decision rule. The decision rule includes the extraction as a function of the given state at the current time. This kind of equilibrium will be called closed-loop (or feedback) equilibrium. A closed-loop equilibrium is subgame perfect, which means that if we play the game by the decision rules of the players, we will get a Nash equilibrium for every stage of the game. Thus, the game is time consistent by definition. The discounted objective function for player i is now written:

$$(13)\quad \sum_{t=o}^{\infty} \beta^t J_i(S_t,\ y_1, \ldots,\ y_n) \qquad \forall i \in N$$

but not like in the open-loop case y_j, where j i is also *a* function of the state variable. That is:

$$(14)\quad y_{i,t} = g_i(S_t) \qquad \forall i \in N,\ \forall t$$

The Nash equilibrium now will have the property that no player will have an incentive to change his decision rule given the other player's decision rule, thus:

$$(15)\quad J_i\left\{ y_1(s)^*, \ldots, y_{i-1}(s)^*,\ y_i(s)^*,\ y_{i+1}(s)^*, \ldots, y_n(s)^* \right\} \geq$$

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

The current value Hamiltonian for player i will be:

$$(16)\quad H_i\left[S_t, y_1(s), \ldots, y_n(s) \right] = J_i\left[s_t, y_1(s), \ldots, y_n(s) \right] + \lambda i \cdot f\left[S_t, y_1(s), \ldots, y_n(s) \right] \qquad \forall t \qquad \forall i \in N$$

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

$$(17)\quad y_i = g^*(S) \text{ maximize } H_i(S, g_1^*(S), \ldots, y_i, \ldots g_n(s)) \qquad \forall t,\ \forall i \in N$$

$$(18)\quad S_{t+1} - S_t = f(y_1, y_2, \ldots, y_n) \qquad \forall t$$

$$(19)\quad \lambda_{t+1} - \lambda_t = r \cdot \lambda_t - \frac{\partial H_i}{\partial S} - \sum_{\substack{j=1 \\ j \neq i}}^{n} \frac{\partial H_i}{\partial y_j} \cdot \frac{\partial g_j^*}{\partial S} \qquad \forall t,\ \forall i \in N,\ \forall j \neq i \in N$$

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 goes in the following way: player i, by knowing that he can influence player j's extraction, will take it into account in his maximization conditions. When player i derives his canonical equation with respect to the stock, he notices that S_t is not only in his 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 to player i by driving the stock down. We can expect, therefore, that in equilibrium the stock level as well as the shadow price will be lower in a closed-loop equilibrium. In a common property resource model, when property rights are well defined, the closed-loop equilibrium seems more appropriate to represent the reality.

It should be mentioned at this point that open-loop and closed-loop do not always differ. Whenever a player cannot manipulate the stock or doesn't want 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 free access and social planner solution. In the free 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 interest to manipulate the stock. When the number of players is a finite one, do the two concepts give rise to different equilibrium values?

Finally, it is important to realize that a closed-loop equilibrium is a Nash one in the sense of a given decision rule, but not in the context of a given extraction path. Therefore, we would argue that 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 actually 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 ground of some maximization behavior in a non-cooperative sense (see, for example: Mason, et al., 1988 and Runge, 1986).

THE GREAT LAKES GAME

The Great Lakes system consists of a series of five major lakes which are connected by four channels. Lakes Superior and Ontario are completely regulated, while lakes Michigan-Huron and Erie are not. The system has a surface water area of 5,475 cubic miles. Lake Superior is the furthest to the west. 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 fact 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 which are well documented. Two diversions (Long Lake and Ogoki) divert water into Lake Superior by Ontario. Water is taken out from 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. This adds up to approximately w tcfs in the total Great Lakes basin. Table 1 represents the major dimension components of the Great Lakes system.

TABLE 1: PHYSICAL AND HYDROLOGIC FACTORS OF THE GREAT LAKES

	Superior	Michigan/Huron	Erie	Ontario
Physical Components:				
Water surface area (sq.m.)	31,700	45,500	9,910	7,340
Volume (c.m.)	2,900	2,030	116	393
Depth (ft.)	600.4	578.7	570.4	244.8
Hydrologic components:				
Water In (tcfs):				
- Run-off from land draining	50	90	25	34
- Precipitation on Lake	74	109	26	19
- Inflow	0	78 (b)	187 (c)	205 (e)
- Diversions	5 (a)	0	0	7 (f)
Water out (tcfs):				
- Evaporated from lake	51	87	26	14
- Outflow	780 (b)	187 (c)	205 (e)	251 (g)
- Diversions	0	3 (d)	7	0

Source: IJC (1981)

NOTES:
(a) Long-lake Ogoki diversion.
(b) Sault-St. Marie's river
(c) St. Clair and Detroit river.
(d) Chicago Diversion.
(e) Niagara river.
(f) Welland Canal (from Erie to Ontario).
(g) St. Lawrence river.

It is noteworthy that the Lakes are in their natural regimes in general. Stated differently, water in equals water out on the average. 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 lowering 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 consistent. 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. It should be mentioned that the problem here is of a renewable resource, even though the system is already in equilibrium (i.e., water in - water out). 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.

Because of the complexity of the system, a hydrologic response model (HRM) was developed to estimate the effect of either deterministic or stochastic changes in the natural unregulated portion of the system (Quinn, 1978, Hartmann, 1988). The changes in Lake Superior's hydrologic component are accommodated for the lower lakes by passing the change, according to Lake Superior regulation plan, on 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 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 here a conflict 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 player's accesses to the lakes).

The stock affect when withdrawing water from the lake is not similar to the affect of a groundwater aquifer. The direct marginal costs do not change as much as the impact upon commercial navigation hydropower production industries on the lakes. Therefore, the cost function with respect to the maintenance and operation costs were assumed to have a constant marginal cost (DeCooke et al., 1984). The fixed cost of this kind of project are the major cost component. For Lake Superior, water diversion of 10,000 cfs to the Missouri River basin, the fixed costs were found to be 26.6 billion dollars, and the variable annual costs are 15.6 million dollars. For Lake Erie, however, the fixed costs are only 3.2 billion dollars. We will assume that the fixed costs are amortized over an infinite amount of time. This amortized cost should be covered by the net social benefits from the project.

The water price is assumed to be constant. This is by no means a weak assumption, but in the current situation, seems, to be the reasonable one. The emphasis of this research is on the supply side, which gives rise to the interesting interactions between players, which are few, and the affect of one upon the other can be well documented. The demand side, however, contains a lot of competing uses and, assuming an aggregate demand function for a player, would be not much more accurate than assuming a constant price. We will assume a price of $100 for an acre-foot which is reasonable, except for agricultural uses that cannot pay this amount of money under the current conditions. However, water diversions will probably occur because of more binding water constraints, thus it might be reflected in higher agricultural product prices.

The most interesting cost components in this analysis are, of course, the effect on the industries that use the water as a stock, namely commercial navigation and hydropower production. In order to simplify the analysis, it was assumed that these costs are quadratic in the lake levels. That can be thought of as a Taylor expansion only over the first two arguments. Before we describe the way we get these costs, we should mention some additional assumptions. In order to gain the most sensitive insight into these two industries, it was assumed that the current situation of the diversions and consumptive use remains the same. In other words, the effect if withdrawing water is in addition to the existing situation. Moreover, with respect to the commercial navigation, it was assumed that the demand for shipped goods is totally elastic, while the supply to 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 generation modes. The difference between these costs is lost to the consumers, which, in this case, are within the system (Great Lakes states and provinces).

Navigation on the Great Lakes According to the assumptions listed above, reduced lake levels will affect the shipping industries, since ships will have to load less in order to ship the same quantity, thus making more trips. This additional number of trips is 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 level.

The loss for the shipping industry was calculated in the following way: monthly trip hours were calculated for each state for every lake that the state has access to. The data was taken from WCUS (1977-1986). There are close to 200 million short tons that are shipped on the lakes annually. These monthly trip hours were calculated in several steps. First, the carrying capacity of a given port on a given lake was divided by the average number of short tons for this port. Then the destination of the ships were used in order to get the mileage required for these ships. The annual data in the SCUS was converted to monthly data according to the distribution of the shipping season (ILER, 1981). The number of miles required was then divided by the average travel speed to get the number of hours required. The hourly cost was then used in order to attach the cost to the number of hours. Reduced lake level affect the carrying capacity through what is called the immersion factor. The loss is determined by the additional trips (hours) due to lower lake levels. Hourly operating cost, vessels capacity and speed, were taken from ILER (1981). Distances were taken from the U.S. Army Corps of Engineers branch in Buffalo, New York. In order to get the costs in terms of losses, it was decided that the base cost is the one for the highest lake levels during that period, and value of zero cost was attached to it. The costs then were adjusted to be the additional costs due to reduced lake levels. This additional costs (losses) vector was regressed as lake level change for that period without a constant.

$$(20) \quad Loss_{i,L,t} = a \cdot (DLL_{L,t}) + b \cdot (DLL_{L,t})^2 .$$

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 on the connecting channels. But this outflow is, in turn, determined by the lake levels. As mentioned above, substitutes do exist for hydropower, but they are more expensive.

Three major areas produced hydroelectric power: upper Michigan on Sault St. Mary's river (michigan and Ontario), the Niagara River Falls to Lake Ontario through the Niagara Falls (Ontario and New York) and the St. Lawrence River, which is the outflow from Lake Ontario (Ontario and Quebec). The distribution, as we can see, is much more biased than the one for commercial navigation is. Not only that, there are fewer states that produce hydropower, but most of them are located downstream. This is a classical situation for efficiency problems.

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

$$(21) \quad PLoss_{i,L,t} = c \cdot (DLL_{L,t} + d) \cdot (DLL_{L,t})^2$$

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.

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

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

s.t.

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

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

Here, $e_{k,L}$ is the cross lake coefficient. That is, the affect of all lakes on a given lake level reduction. This is a 4x4 matrix with unit diagonal components (that is, the affect 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 as we see are determined not only by player i, but by the others as well.

The following current value Hamiltonian which corresponds to this problem is:

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

$$+ \mu_{i,L} \cdot y_{i,L}$$

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

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

The other first order necessary conditions are the usual ones:

$$(27)\quad \frac{\partial H_{i,L}}{\partial Y_{i,L}} = 0$$

$$(28) \quad \dot{\lambda}_{i,L} = r\cdot\lambda_{i,1} - \frac{\partial H_{i,L}}{\partial LL}$$

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 $y_{i,L}$ will be equal to zero, there will be a positive costate variable, which is the affect on player i of a unit of water diverted into the lake.

The fixed costs were not included in the necessary conditions. The outcome, however, was supposed to cover the ammortized value of the fixed cost. If it couldn't do it, the project was assumed not to take place.

Finally, two more comments. 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 a player in this game chooses a strategy, he takes only part of the other strategies as givens. The strategies that affect his payoffs are taken into account when he sets his first order condition for profit maximization. In that case, the associated condition looks like:

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

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 taking 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 affects lake by lake. A strategy which is the steady state one will have a costate associated with it, which is combined out of two component. The effect up to 15 years, and the effect 15 years from now until infinity.

Let the loss function for an industry i be:

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

Note that here i represents industries and nott players, and r is the effect of the level of diverting 1tcfs. If we assume that it takes 180 months to get to the steady state, the present value of the losses to industry i should look like:

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

or, after **some** algebraic manipulation:

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

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

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

RESULTS

Given the physical and hydrological data, as well as the economic indicators, •it is possible to construct five games, upon which we will concentrate here. These five games are: 1) Social-planner's Games (a 1-player game); 2) U.S. vs. Canada -

Open-loop (a two countries game); 3) U.S. vs. Canada - Closed-loop (a two countries game); 4) Ten Players - Open-loop; and Game 5, Ten Players - Closed-loop. As you can see, these games concentrate on. both open- and closed-loop solutions.

Since, in general regressions only, the squared reduced lake levels gave better coefficients, it was decided to use only that variable. The cost estimates are given in Table 2. The cross lake affects are given in Table 3 (these are ratios for the total affect), and the inner lake affect for the first 15 years are given in Table 4.

Game 1 (Social Planner's Game): Here we have only one player that tries to maximize the discounted net benefit of the whole basin, subject to hydrological and non-negativity constraints. The social planner solves the problem as if he owns all the industries in the basin. He takes into account all the consequences of diverting water from a given lake. Table 5 gives the solution for 0.4% monthly interest rate. As can be seen from the table, the socially optimal diversion is to increase the Chicago diversion by 0.71 tcfs and to build a new project on Lake Ontario, which will divert 10.55 tcfs. Since the present value of the net benefit of the project is larger than the fixed cost (3,200 million dollars), the project should be built. Notice that these discounted net benefits are for an infinite amount of time, given the same monthly steady stream of benefits. 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, this lake does not affect the upper lakes. Taking water from the other lakes will simply result in a chain effect that will cost more than can be compensated for by revenues generated.

Game 2 (U.S. vs. Canada: Open-loop): Here the two countries take into account the stock affect, but do not take into account that their actions can influence their rivals'. The results are given in Table 6. The present value of the net benefits are negative, but notice that is U.S. is now better off than in the social planner's case. The fact that Canada diverted water from Lake Ontario is the essence of the commons. When the stock is being reduced for some reason, there are two opposite effects. One thing that happens is that the player faces a new situation where the value of the assets (stock level) has been depreciated and thus, he will move to use the water as a "flow" instead of "stock". The other affect is opposite in sign, and has the following interpretation: it is beneficial to divert less water, as the opportunity cost of diverting water has been increasing. The magnitude of these two affects will determine the direction in which the equilibrium will move.

Game 3 (U.S. vs. Canada: Closed-loop): As discussed before, the closed-loop equilibria tries to solve the inconsistency problem that arises from the fact that each player will make a decision based upon the stock level at the time of which he has to decide. Intuitively, each player asks the following question: "Given that we start from the open-loop equilibrium, and I extract slightly more of" the resource, I can anticipate that some players will not overuse the resource as its shadow price increased." Therefore, the stock will go up again by some magnitude. Here, the players are not identical, a fact that can change the type of solution; if the players were identical, all would act in the same way in equilibrium. In our example, the additional manipulation actions taken by players generally result in other players extracting less, or, finding it too expensive, not at all. An example can be seen in Table 6 for the closed-loop solution. By driving Lake Ontario levels down, the U.S. pushed Canada out of the game. An open-loop solution would result in Canada remaining in the game, even if it is not in her interest to do so under a particular lake level. It can be seen that the manipulation affect clearly aggrevated the inefficiency involved in the Commons. Canada looses three times as much as in the open-loop,, while the U.S. gains only twice what she gained in the open-loop.

Game 4 (Ten Players - Open-loop): As can be seen from Table 7, the solution this time is entirely within the upper lakes. This fact will increase, of course, the inefficiency involved. Although this is a result of the increase in the supply of water from the Great Lakes, it is mainly caused by the location that the water is supplied from. Lake Erie is the big problem here. While a significant part of the hydropower facilities is located in the outflow from the lake, there are also states such as Ohio and Pennsylvania that are not affected much by reduced lake levels. This constrast is the source for very large losses to Ontario and New York due to a large diversion, which is upstream from the falls.

Game 5 (Ten Players - closed-loop): The important change here is the shift of diversion from Lake Erie to Lake Michigan-Huron. The Wisconsin port on Lake Michigan-Huron can manipulate downstream states like Pennsylvania much more, the vice versa. The result, hwoever, is an increase of the supply from the 43 tcfs in the open-loop, to 159 tcfs in the closed-loop. The inefficiency, however, is increasing by eight times. Not only is the inefficiency difference larger between the closed-loop to the open-loop, there is also a big difference between the 2 players game to the 10 players game. This has important policy and political implications.

Summary and Policy Implications

We can clearly see different market structures give rise to totally different supply patterns of water from the Great Lakes. This common property resource is characterized by different types of users. This fact is the core reason for conflicting goals, which result in a quite large inefficiency loss without regulating the lakes. The fact that the big users of water as a stock are located downstream, combined with the fact that these users are the main ones (i.e., hydropower production), will result in large losses without well defined property rights.

Canada, as can be seen from the results, is a passive player. Neither Ontario nor Quebec extract water in most cases. Thus, the incentive to reach to an agreement lies mainly in the Canadian side.

Formulating the game as an open-loop game does not account for the "strategic externality", which basically is not a reasonable assumption. Players do not necessarily have the incentive to remain in their original strategies if it doesn't pay off to do so. Not counting this component can result in an underestimated social loss, which can get up/down to about 75Z of the inefficiency in this case.

The benefits of managing the Commons becomes, therefore, bigger than we can count for both kind of externalities.

Finally, it should be mentioned that more research is needed with respect to the demand side, which was ignored in this study. The incorporation of the demand, however, is much more vague than the supply because of data problems. Also, more research is needed on other types of expectation formation, other than the open- and closed-loops (Cornes and Sandier, 1988). The best expectations are those that could be verified in reality, which is very difficult to do.

Table 2 - Cost Coefficients

(for Losses in Millions $ per Inch
Decreased from Lake Level)

	Superior		M-H		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	.45	.00014	.02
DNT	.0015	.0061	.0027	-	.00046	.45	.0011	.02
Q	-	-	-	-	-	-	.0022	.0368

Table 3 - Cross Lake Coefficients (ratio)

[diver- \ affects sion from\ upon	S	MH	E	O
S	1.00	1.32	.92	1.08
M-H	0.31	1.00	.69	.72
E	0.15	0.38	1.00	1.02
O	O	O	O	1.00

Table 4 - Inner Affect

(for the first 180 months,
in inches per itcfs).

SUP	M-H	E	ONT
.0033	.0045	.0032	.0008

Source: IJC (1981).

Table 5: Social Planner's Solution

	Diversion (tcfs)	Lake Level A (inches)	PV of Net Benefits (m$)
SUP	-	.13	-5.36
M-H	0.71	.58	984.71
Erie	-	.28	-113.99
ONT	10.55	1.59	7115.80
Total:	11.26	-	7981.16

Table 6 - U.S. vs. Canada:
Open-loop and Closed-loop Equilibria

	Diversion (tcfs)		Lake Level A (inches)		PV of Net Benefits (M$)	
	Open-Loop	Closed-loop	Open-loop	Closed-loop	Open-loop	Closed-loop
SUP:	-	-	.51	0	-	-
U.S.	0	0	-	-	-60	0
Canada	0	0	-	-	-21	0
M-H:	-	-	2.24	0	-	-
U.S.	2.76	0	-	-	3,637	0
Canada	0	0	-	-	-53	0
Erie:	-	-	1.10	0	-	-
U.S.	0	0	-	-	-930	0
Canada	0	0	-	-	-792	0
Ont:	-	-	3.58	6.33	-	-
U.S.	17.16	43.95	-	-	14,419	31,360
Canada	5.72	0	-	-	-21,606	-92,817

Table 7 - The Ten Players Game

	Diversion (tcfs)		Lake Level A (inches)		PV of Net Benefits (M$)	
	Open-Loop	Closed-loop	Open-loop	Closed-loop	Open-loop	Closed-Loop
SUP:						
MN	0	0	10.97	27.63	-17,074	-108,287
WI	13.27	0	-	-	11,696	-45,118
MI	0	0	-	-	-3,320	-21,056
ONT	0	0	-	-	-10,007	-63,468
M-H:	-	-	25.74	120.1	-	-
MI	0	0	-	-	-18,272	-395,126
WI	0	134.95	-	-	-3,132	123,556
ONT	0	0	-	-	-7045	-152,406
IL	5.06	6.8	-	-	-136	-148,411
IN	0.	0	-	-	-7309	-152,406
Erie:	-	-	32.45	66.22	-	-
ONT	0	0	-	-	-9,379,365	-77,819,595
MI	0	0	-	-	52,054	-431,890
OH	0	0	-	-	-10,911	-86,378
PA	24.21	17.15	-	-	33,485	-17,400
NY	0	0	-	-	-9,370,620	-77,747,110
ONT:	-	-	6.14	17.22	-	-
NY	0	0	-	-	-700	-235,190
ONT	0	0	-	-	-734	-246,400
Q	0	0	-	-	-1,356	-455,432
Total:	42.54	158.9	-	-	-18,836,754	-158,002,118

REFERENCES

Clemhout, S. and H. Y. Wan, Jr., 1979. "Interactive Economic Dynamics and Differential Games." Journal of Optimization Theory and Applications. 27(1):7-30.

David, M. H., E. F. Joeres, E. D. Loucks, K. W. Potter and S. Rosenthal, 1988. "Effects of Diversions on the North American Great Lakes." Water Resource Bulletin. 24(1):141-148.

DeCooke, B. G., J. W. Bulkley and S. J. Wright, 1984. "Great Lakes Diversions: Preliminary Assessment of Economic Impacts." Canadian Water Resources Journal. 9(1):1-15.

Hartmann, H. C., 1988. "Potential Variation of Great Lakes Water Levels: A Hydrologic Response Analysis." NOAA Technical Memorandum ERL GLERL-68.

Hydro Quebec, 1988. Development Plan 1988-1990, Horizon 1997. Unabridged version.

International Joint Commission, 1981. Great Lakes Diversions and Consumptive Uses.

International Lake Erie Regulation Study Board (ILER), 1981. Lake Erie Water Level Study. Report to the IJC.

Knapp, K.C., 1983.. "Steady State Solutions to Dynamic Optimization Models with Inequality Constraints". Land Economics 59(3): 300-304.

Levhari, D. , and L. J. Mirman, 1980. "The Great Fish War: An Example Using a Dynamic Cournot-Nash Equilibrium." Bell Journal of Economics. 11:322-334.

Mason, C. F., T. Sandier and R. Cornes, 1988. "Expectations, the Commons and Optimal Group Size." Journal of Environmental Economics and Management. 15:99-110.

Negry, D. H., 1989. "The Common Property Aquifer as a Differential Game." Water Resources Research. 25(1):9-15.

New York Power Authority, 1989. Monthly Generations for the Niagara and St. Lawrence Projects. Mimeo, U.S. Army Corps of Engineers District, Buffalo.

Ontario Hydro, 1987. Meeting Energy Future Needs. Draft Demand/Supply Planning Strategy. Report 666 sp, System Planning Division.

Quinn, F. H., 1978. "Hydrologic Response Model of the North American Great Lakes." Journal of Hydrology. 37:295-307.

Reinganum, J. F. and N. L. Stokey, 1985. "Oligopoly Extraction of a Common Property Natural Resource: The Importance of the Period of Commitment in Dynamic Games." International Economic Review. 26(1):161-173.

Runge, C. F., 1986. "Common Property and Collective Action in Economic Development." World Development. 14:623-635.

Starr, A. W. and Y.C. Ho, 1969. "Nonzero-sum Differential Games." Journal of Optimization Theory and Application. 3(3):184-206.

Task Force on Water Diversion and Great Lakes Institutions, 1985. Final Report and Recommendations: Great Lakes Governors Task Force on Water Diversion and Great Lakes Institutions. Council of Great Lakes Governors, Madison, Wisconsin.

Water Borne Commerce of the United States (WCUS), 1977-1986. Part 3, Waterways and Harbors-Great Lakes. Dept. of the Army Corps of Engineers, Water Resources Support Center.