Environmental Constraints on Hydropower: An Ex Post Benefit-Cost Analysis of Dam Relicensing in Michigan

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ABSTRACT. *We conduct a benefit-cost analysis of a relicensing agreement for two hydroelectric dams in Michigan. The agreement changed daily conditions from peaking to run-of-river flows. We consider three categories of costs and benefits: producer costs of adapting electricity production to the new time profile of hydroelectric output; benefits of reductions in air pollution and greenhouse gas emissions; and benefits of improved recreational fishing. The best estimates suggest that the aggregate benefits are more than twice as large as the producer costs. The conceptual and empirical methods provide a template for investigating the effects of an environmental constraint on hydroelectric dams.* (JEL Q43, Q57)

I. INTRODUCTION

A reallocation of river resources toward environmental purposes has been underway in the United States for several decades. This trend is evident in public policies designed to reduce the environmental impacts of hydroelectric dams. Several federal laws—including the Grand Canyon Protection Act (1992), the Northwest Power Act (1980), and the Central Valley Project Improvement Act (1992)—instruct managers at specific water projects to impose environmental constraints on hydroelectric operations. A more general mandate comes from the Electric Consumers Protection Act (1986), which instructs federal regulators to "balance" hydropower and the environment at all projects licensed by the Federal Energy Regulatory Commission (FERC). Moreover, species recovery measures implemented under the Endangered Species Act (1973) affect hydroelectric operations in several major river basins.

This paper considers the question of whether environmental constraints on hydroelectric dams are desirable from an economic perspective. Specifically, we conduct an ex post benefit-cost analysis of a FERC relicensing agreement for two hydroelectric dams on the Manistee River in Michigan. Under terms of the 1994 agreement, daily stream flow conditions on the Manistee returned to run-of-river (ROR) flow after 70 years of peak-flow operations.[1] Federal regulators mandated the switch to ROR flows based on the assumption that it would improve habitat conditions for fish species in the Manistee River and Lake Michigan (FERC 1994a). Biological research confirms that the switch in regime did have the assumed effect. By lowering water temperature and increasing substrate in the riverbed, the switch to ROR

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[1] ROR flow tracks natural stream flow, with water releases from the dam approximately equal to water flows into the reservoir above the dam on a continuous basis. Peak (or "peaking") flow maximizes water flow through the turbines during periods of peak electricity demand.

flow dramatically increased the number of Chinook salmon emigrating from the Manistee River to Lake Michigan—from below 100,000 to nearly 370,000 fish per year (Rutherford et al. 2004).

Our analysis considers three categories of costs and benefits related to the switch to ROR flow on the Manistee River: (1) electricity production costs, (2) air quality benefits, and (3) recreational fishing benefits. First, we develop a model to estimate the costs of replacement power that the electric utility must generate to compensate for the change in hydropower production at the dams. Prior to the switch, the dams were operated to maximize power production during periods of peak electricity demand. New constraints on peak-period water releases thus created a need for peak replacement power from thermal power plants, and the cost of electricity production increased as a result. With our model, we show how estimates of these producer costs can be derived using publicly available data from state and federal agencies.[2]

Second, we estimate the economic benefits that arise from changes in air pollution emissions. With the flow constraint at the Manistee River dams, the need for thermal (replacement) power increases during peak periods, but decreases during off-peak periods. Thermal power during peak periods is generated with relatively "clean" fossil fuels (fuel oil and natural gas) as the marginal sources, while thermal power during off-peak periods is generated with coal. Thus, the net effect of generating the replacement power is a decrease in air pollution and greenhouse gas (GHG) emissions. We apply benefit transfer methodology to estimate the air quality benefits associated with the emission reductions. These benefits were unanticipated, as regulators did not include changes in air quality as a category of environmental impacts in their analysis of the environmental constraint at the Manistee River dams (FERC 1994a).[3]

Third, we estimate the recreational fishing benefits associated with the policy-induced increase in the production of Chinook salmon. Chinook salmon is an introduced species in the Great Lakes, yet it has become a major sport fish in Lake Michigan and its tributaries. A distinct element of our research is that we value actual changes in resource conditions, not predicted or hypothetical changes. In particular, output from a salmon population model (the increase in salmon numbers) serves as an input to the recreational fishing model (increases in salmon catch rates). The increases in catch rates are valued using a random-utility travel cost model of recreational fishing in Michigan (Lupi et al. 2001).[4]

[2] In related research, models have been used to estimate the cost of environmental constraints on hydropower operations at Glen Canyon Dam on the Colorado River (Harpman 1999), Flaming Gorge Dam on the Green River (Edwards, Flaim, and Howitt 1999), and at the four dams on the lower Snake River (Huppert 1999). In Section 3, we discuss how these models relate to our approach here.

[3] Previous research has found that replacement power generated from fossil fuels can increase or decrease emissions relative to baseline hydropower operations. With flow constraints at Glen Canyon Dam, the need for thermal power follows the pattern of the Manistee River dams, i.e., increasing during peak periods and decreasing during off-peak periods (Harpman 1999). Thus, the net effect is a decrease in air pollution and GHG emissions (U.S. Department of the Interior 1995). In contrast, in the Columbia River basin, estimated air pollution and GHG emissions would increase in response to most environmental constraints on hydropower operations (U.S. Department of Energy 1995). There, the time pattern of hydroelectricity production is not the primary adjustment. Instead, hydroelectricity production decreases substantially under most scenarios, with turbines removed from service or hydraulic head severely reduced. In these cases, the thermal power required as replacement power increases pollution emissions.

[4] Other research on the benefits of constraining hydropower, in contrast, has studied recreational fishing benefits of higher hypothetical salmon catch rates on the Penobscot River in Maine (Morey, Rowe, and Watson 1993), use values for lowering reservoir levels in the Columbia River basin (Cameron et al. 1996), and nonuse values for improving environmental conditions on the Elwha River and the Colorado River (Loomis 1996; Welsh et al. 1995). Moreover, several other studies focus generally on the economic value of instream flow (e.g., Berrens et al. 1998; Duffield, Neher, and Brown 1992;

We report a range of estimates of the annual costs and benefits that result from the switch to ROR flow on the Manistee River. The best point estimates find that aggregate benefits range from $806,156 to $985,080 per year and producer costs are $310,612 per year. These results suggest that economic surplus increased as a consequence of the environmental constraint on the Manistee River.

The paper makes four contributions to the literature. First, the analysis considers several categories of benefits and costs, and it is ex post.[5] The vast majority of related research on benefit-cost analysis concentrates on a single category of benefit or cost; rarely do studies conduct a thorough treatment of several benefit-cost categories. The need for ex post analysis, moreover, has been identified by the National Research Council (NRC) as a priority area in water resources research (NRC 2001). Second, we integrate ecological and economic analyses to estimate recreational fishing benefits. The integration translates riverine ecosystem functions into an ecosystem service, which is a methodology that follows another NRC recommendation for a richer approach to valuing ecosystem services (NRC 2005). Third, we provide the first estimates of the benefits or costs associated with changes in air pollution and GHG emissions that arise from an environmental constraint on hydroelectric dams. While air pollution effects of such constraints have been estimated, we are unaware of another study that estimates the economic value of the change in emissions. Fourth, the research provides a template for FERC's economic analysis of hydroelectric dam relicensing. FERC has regulatory authority for more than 1,000 projects in the United States, yet it routinely fails to estimate the benefits and/or costs of nonmarket goods and services in its analyses for relicensing proceedings.[6] Thus, the treatment of recreational fishing and pollution emissions demonstrates how FERC could assess hydropower-environment tradeoffs, and thereby implement its legislative mandate to "balance" hydropower and the environment.

The next section of the paper provides background on hydropower-environment tradeoffs on the Manistee River. Section 3 analyzes the costs of changes in electricity output. Section 4 analyzes air quality benefits of those same changes. Section 5 integrates ecological and economic models to estimate recreational fishing benefits. Section 6 summarizes the benefits and costs, and Section 7 makes concluding remarks.

II. BACKGROUND

When unconstrained, hydropower operations maximize the value of power by storing water when electricity demand is low and releasing water through turbines when demand is high. Two general peak-flow patterns are consistent with this approach. One is seasonal, in which high volumes of spring runoff are stored for release during summer when air conditioning increases demand. The second pattern is daily, in which water is stored over-

Loomis and Cooper 1990; Loomis and Feldman 1995), or on the value of changes in catch rates due to other causes (e.g., Lupi, Hoehn, and Christie 2003).

[5] The analysis is ex post by considering three effects of the switch to ROR flow on the Manistee River. Specifically, the estimates of producer costs and air quality benefits rely on our key modeling tool, which provides estimates of the change in peak-period hydroelectric production due to the switch from peaking to ROR flow. Data on hydroelectric production, along with estimates of the marginal cost of thermal electric production and marginal damage cost of air pollutants, are also from the period after the switch to ROR. Finally, the estimates of recreational fishing benefits rely on estimates of the increase in natural production of chinook salmon due to the switch to ROR.

[6] See Moore, Maclin, and Kershner (2001) for a general assessment of FERC's shortcomings in the application of economic principles and methods. Other federal water-resource agencies (U.S. Army Corps of Engineers, Bureau of Reclamation, and Natural Resources Conservation Service) are required to apply the *Economic and Environmental Principles and Guidelines of Water and Related Land Resources Implementation Studies* (U.S. Water Resources Council 1983). Yet, FERC is not required to apply these economic methods even though it regulates hydropower operations.

night and then released the next day during daily peak demand. River systems managed for hydropower exhibit one or both of these patterns.

The imposition of an environmental constraint inherently reduces the value of a river as a power producer. Environmental constraints can affect either the seasonal or daily flow patterns in order to improve the natural habitat of a river. Requiring "flushing" flows during spring runoff is an attempt to restore native habitat or to cue migratory behavior of anadromous species like salmon. Requiring higher daily flows during off-peak periods seeks to improve habitat by relieving the stress of low flows on fish species. In general, environmental constraints on hydropower typically involve reproducing some, or all, of the river-flow patterns that pre-dated the dam.

The Manistee River is a major tributary of Lake Michigan (Figure 1), with a drainage area of roughly 1,780 square miles and average discharges of 2,084 cubic feet per second.[7] A large electric utility, Consumers Energy Company, operates two hydropower dams on the river. Tippy Dam has 20.1 megawatts of generating capacity and operates with a normal volume of 1,100 acre-feet in its reservoir. Hodenpyl Dam has 17.0 megawatts of capacity and operates with a normal volume of 1,665 acre-feet. The dams were constructed in 1920 and were historically operated in a daily peaking mode under conditions of a FERC license. In peaking mode, daily flows on the Manistee River alternated between levels exceeding a ten-year flood during high-flow episodes and, at the other extreme, levels corresponding to a drought condition during low-flow episodes (Rozich 1998).

A 1994 FERC relicensing agreement established ROR flows as the official operating condition for both dams in new 40-year licenses.[8] In the relicensing process, stakeholders agreed that, "the major adverse impacts from Consumer's Power's [former name] hydroelectric operations are the result of a peaking mode of operation on downstream riverine habitat" (FERC 1994d, 61,369). The Final Environmental Assessment anticipated that converting to a ROR mode would improve habitat conditions below Tippy Dam, where Chinook salmon (*Oncorhynchus tschawytscha*) and steelhead trout (*Oncorhynchus mykiss*) use the river for spawning and nursery grounds (FERC 1994a). Tippy is the lowest dam on the river and has no facilities for fish passage.

As we will see, the costs and benefits of switching to ROR flows at both dams are the result of changes in the timing of both hydro- and thermal-electricity production, and of measurable improvements in fish habitat. The next three sections consider the different categories of costs and benefits.

III. PRODUCER COSTS OF SWITCHING TO RUN-OF-RIVER FLOW

The change from peaking to ROR modes on the Manistee River shifts the timing of daily hydroelectricity production at the river's two dams: less hydroelectricity is generated during the peak period of electricity demand, and more is generated during the off-peak period. This shift implies that Consumer's Energy must adjust the timing of its thermal electricity generation in order to maintain the same levels of combined (thermal plus hydro) peak and off-peak production. In this section, we develop a model to estimate the producer cost associated with the switch from peaking to ROR management.

Our approach draws on three studies of environmental constraints on hydroelectricity production. Following Harpman (1999) and Huppert (1999), we compare a historical production regime to a new regime with an environmental mandate as a way to estimate the costs for a benefit-cost analysis. Furthermore, mirroring the approach of Edwards, Flaim, and Howitt (1999) and Huppert (1999), we estimate

[7] The factual information reported in this paragraph comes from four government documents (FERC 1994a, 1994b, 1994c, 1994d).

[8] In anticipation of the FERC relicensing agreement, Consumers Energy had converted the management of both dams to ROR flows starting in 1989.

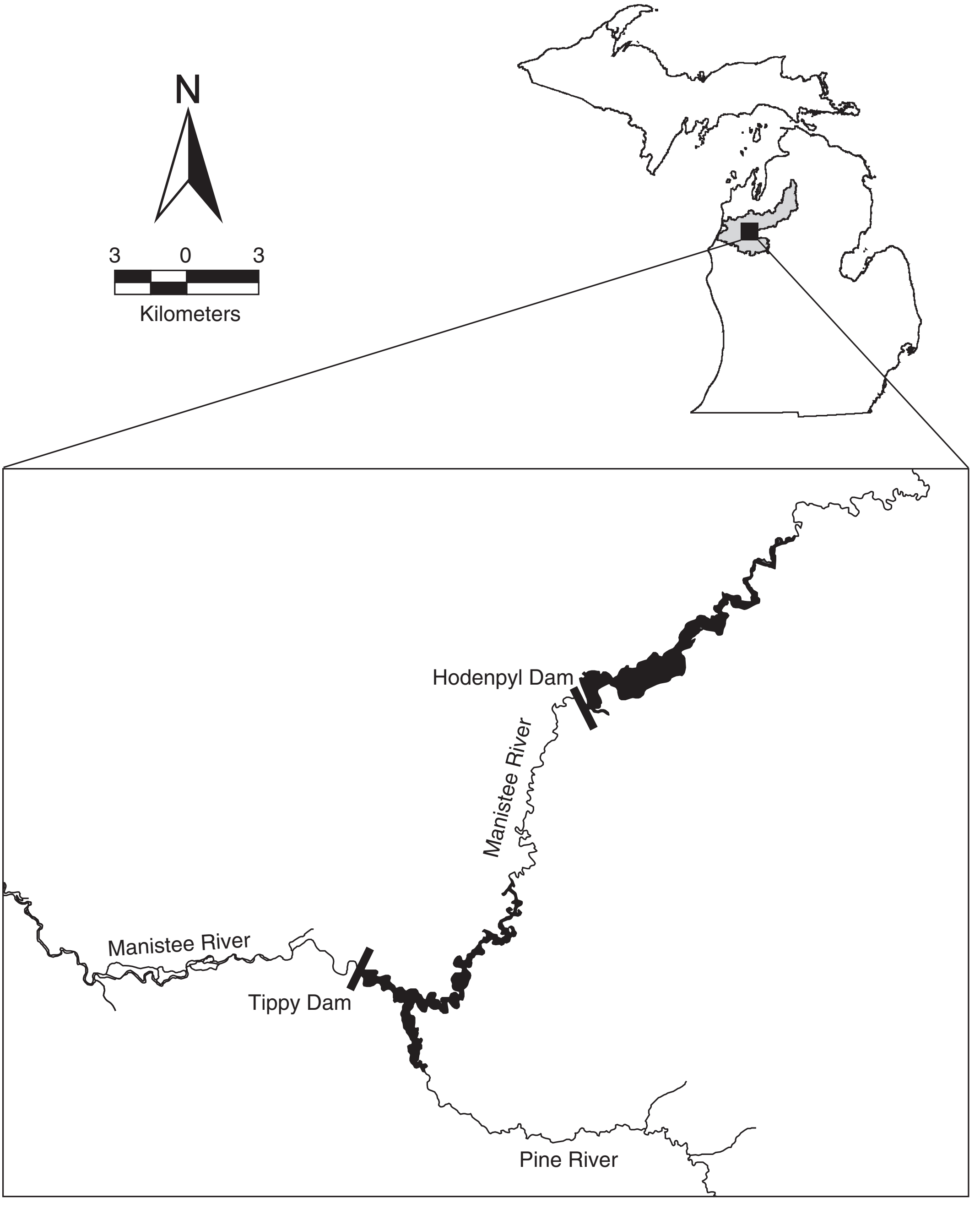

FIGURE 1
Manistee River, Michigan

producer costs while holding total electricity production (thermal plus hydro) constant, thereby applying the replacement cost method of analysis. In contrast to the existing studies, our model is simpler because of a natural feature of the Manistee River: the Manistee has notoriously stable streamflow because it is primarily a groundwater-fed system rather than a system dominated by land-surface runoff (Rozich 1998). In particular, the Manistee does not receive spring runoff from mountain snowpack, unlike many rivers in the western United States. Several simplifying assumptions are reasonable because of the stable streamflow.

We begin with specification of the production function for annual hydroelectricity generation at a dam. Let $Q_H = aV$, where Q_H is annual hydroelectricity production, V is the volume of annual river flow, and a is a positive constant that converts river flow into electricity production. The linear relationship between river flow and electricity generation is consistent with the production technology at the Manistee River dams, given that the dams produce electricity with a fixed hydraulic head.[9] Linearity of the production function implies that peak and off-peak flows are perfect substitutes in the production of annual hydroelectricity. Thus, we can decompose river flow into peak (p) and off-peak (o) flows such that $V = v^p + v^o$. Now letting q_H^k for $k = p,o$ denote annual peak and off-peak hydroelectricity production, we can write

$$q_H^k = av^k = Q_H \frac{v^k}{V}. \quad [1]$$

This equation expresses either peak or off-peak production in terms of total production multiplied by the respective proportional flow. Equation [1] will be useful for deriving cost estimates later in this section.

We now specify a variable cost function for an electricity producer that operates (existing) thermal and hydroelectric power plants. Annual variable costs, C, can be written as

$$C = c_T^p q_T^p + c_T^o q_T^o + c_H q_H^p + c_H q_H^o, \quad [2]$$

where c denotes (constant) marginal costs,[10] q denotes electricity production, subscripts distinguish between thermal (T) and hydro (H), and superscripts continue to distinguish between peak (p) and off-peak (o) time periods. Note that c_H does not vary between peak and off-peak periods because the marginal cost of operating the dam does not vary by time-of-day. The same restriction does not apply to thermal electricity, as c_T^p and c_T^o will depend on the different energy inputs used to produce peak and off-peak thermal electricity (Ellerman 1996).

Our task is to compare the change in variable costs that occurs as a result of the change in management from peaking to ROR mode. Conceptually, we can accomplish this for a particular dam using the variable cost function. Letting $\hat{C}$ and $\overline{C}$ denote the variable costs under peaking and ROR modes, respectively, the change in variable costs can be written as $\Delta C = \overline{C} - \hat{C}$.[11] We know that total hydroelectric production (peak plus off-peak) remains constant between management regimes.[12] Thus, there is no change in the costs of hydroelectric production, and the change in

[9] Hydraulic head is the vertical distance that water falls when producing electrical energy. It is a variable in the production function for hydroelectricity, yet it becomes a constant in the case of fixed hydraulic head (Woods and Wollenberg 1996). The Manistee River dams have fixed hydraulic head, which follows from the stable flow of the Manistee River throughout the year and the fact that the reservoir heights vary by less than one foot, even when the dams are operating in a peaking mode.

[10] The assumption of constant marginal cost is made because we consider relatively small changes in quantity.

[11] Throughout the paper, we use the notation of hats to denote peaking flow and bars to denote ROR flow. This notation makes it straightforward to keep the distinction in mind, as a graph of peaking flow would be peaked, while a graph of ROR flow would be horizontal.

[12] This follows because of the linear production function, and it is consistent with FERC's (1994d) observation that the change from peaking to ROR mode will retain "essentially all the energy output and a significant portion of the peaking capacity of these plants" (p. 61,369). Formally the implication is that $\hat{q}_H^p + \hat{q}_H^o = \overline{q}_H^p + \overline{q}_H^o$.

variable costs can be written as a function of the change in thermal generation:

$$\Delta C = c_T^p(\bar{q}_T^p - \hat{q}_T^p) + c_T^o(\bar{q}_T^o - \hat{q}_T^o). \quad [3]$$

We can simplify equation [3] further by relying on the replacement cost approach, which assumes that total electricity production during peak and off-peak times remains constant. Since there is no change in hydro production, no change in total production means that the change in peak thermal production must be offset exactly by the change in off-peak thermal production, implying that $\bar{q}_T^p - \hat{q}_T^p = \hat{q}_T^o - \bar{q}_T^o$. It follows that equation [3] simplifies to

$$\Delta C = (c_T^p - c_T^o)(\bar{q}_T^p - \hat{q}_T^p). \quad [4]$$

As a final step, it is useful to recognize that no change in the combined peak production implies that the change in peak thermal production must be offset exactly by the change in peak hydro production, implying that $\bar{q}_T^p - \hat{q}_T^p = \hat{q}_H^p - \bar{q}_H^p$. Thus, letting $\Delta q = \hat{q}_H^p - \bar{q}_H^p$, which is the magnitude of the shift in hydro production, we can write equation [4] as

$$\Delta C = (c_T^p - c_T^o)\Delta q. \quad [5]$$

This expression has an intuitive interpretation. The shift from peaking to ROR mode creates a decrease in peak hydro production (Δq). The cost of this decrease is the cost of replacement thermal electricity ($c_T^p \Delta q$). The shift to ROR also implies an increase in off-peak hydro production equal to the same quantity. This implies a decrease in the cost of off-peak thermal production ($c_T^o \Delta q$). The net effect on variable costs is therefore the shifting quantity multiplied by the difference in marginal costs between peak and off-peak thermal production.

We now turn to the empirical estimates of equation [5] for both the Tippy and Hodenpyl dams on the Manistee River. The first step is to derive estimates of Δq for each dam. Using the definition of Δq and equation [1], we have the following identity:

$$\Delta q = Q_H(\hat{v}^p - \bar{v}^p)/V. \quad [6]$$

Our estimates of V are based on the stable mean water flows that are reported above each of the dams (FERC 1994b, 34-35). Converting the reported mean flow rates into an annual estimate yields V = 56,039,472,000 cubic feet per year (cfy) for Tippy Dam and V = 39,577,680,000 cfy for Hodenpyl Dam.

Now consider the annual peak flow variables in equation [6], $\bar{v}^p$ and $\hat{v}^p$. In each day, 10 hours are considered peak and 14 hours are considered off-peak (Rozich 1998). Under ROR mode, therefore, peak flows at each dam are calculated as simply $\bar{v}^p = \frac{10}{24}V$, where we use the estimate of V for the respective dam. The calculation of $\hat{v}^p$ requires a few more steps. Prior to relicensing and the switch to ROR, the official operating mode for these two projects was a "minimum flow—peaking mode" (FERC 1994a, 11–12) that is, the legal requirement of a minimum stream flow limited the amount of water that could be apportioned to peak times. Assuming the utility company was solving a cost-minimizing hydro-thermal coordination problem (Edwards, Flaim, and Howitt 1999), the optimal apportionment during peaking mode would have been to satisfy the minimum flow requirement during off-peak times and allocate the remaining flow to peak times. The legal minimum flows below the two dams are 871 cfs for Tippy and 492 cfs for Hodenpyl (FERC 1994a, 11–12). Satisfying these minimums during the off-peak times and allocating the remaining flow during peak times implies that $\hat{v}^p$ = 40,016,556,000 cfy for Tippy Dam and $\hat{v}^p$ = 30,526,848,000 cfy for Hodenpyl Dam.[13]

The final variable in equation [6] is Q_H. Our estimates come from reports on each dam's hydroelectricity generation that the utility company is required to file with public agencies (FERC 1996–2001; Michigan Public Service Commission 1990–1995). Because generation varies some-

[13] For perspective, peak-period output in peaking mode is 74% of total output, while peak-period output in ROR mode is 42% of total output (with total output constant between modes).

TABLE 1
ANNUAL PRODUCER COST OF SWITCHING FROM PEAKING TO ROR MODE, 1990–2001

	Foregone Peak Production, Δq	Marginal Cost Differential of Thermal Generation, $c_T^p - c_T^o$	Annual Producer Cost, ΔC
Tippy Dam			
Mean	17,708.2	1.03	176,115
(Std. Dev.)	(1,564.9)	(0.60)	(93,958)
Hodenpyl Dam			
Mean	13,634.7	1.03	134,497
(Std. Dev.)	(1,863.2)	(0.60)	(68,305)

Notes: Hydroelectricity production is in megawatt-hours per year. Marginal cost differential is in cents per kWh. Producer cost is in dollars per year reported in 2001 dollars.

what year-to-year at the dams, we consider the 12 years of data from 1990 to 2001. The mean estimate for the Tippy Dam is $Q_H =$ 59,541.1 megawatt-hours per year, and the mean estimate for the Hodenpyl Dam is $Q_H =$ 38,445.8 megawatt-hours per year.

Combining these different variables, we report estimates of Δq for both dams in the first column of Table 1. Based on the variability that arises from Q_H, we also report standard deviations.

Having derived estimates of Δq for each dam, the next step for estimating the change in variable costs in equation [5] is to consider $c_T^p - c_T^o$. Under the Public Utility Regulatory Policy Act of 1978 (PURPA), electric utilities are required to report their "avoided cost" of electricity generation during peak and off-peak periods. Avoided cost under PURPA is defined as the cost that the utility would forego by purchasing a kilowatt-hour (kWh) from a private producer, rather than by generating the electricity itself. It thus serves as a measure of the utility's short-run marginal cost of electricity generation. Since thermal generation is the source of marginal production, we use the reported avoided costs to estimate the marginal cost of thermal electricity generation. We obtained monthly PURPA data for the years 1990 through 2001 from the Michigan Public Service Commission (2003). Reported in 2001 dollars, the peak marginal cost estimates c_T^p range from 1.92 to 5.24 cents per kWh, while the off-peak marginal cost estimates c_T^o range from 1.37 to 2.59 cents per kWh. It is always the case that peak marginal cost exceeds off-peak marginal cost.[14] We report the estimates of the mean difference $c_T^p - c_T^o$ in the second column of Table 1. These estimates do not differ between the two dams.

We can now use equation [5] to solve for ΔC, which is the change in producer costs that results from the switch from peaking to ROR mode at each of the two dams. The mean estimates of ΔC for 1990–2001 are reported in the third column of Table 1. Adding the cost estimates for both dams, we estimate the mean increase in producer costs to be $310,613 per year. Using the standard deviations, we also estimate a 95% confidence interval that ranges from $219,132 to $402,094 per year.

IV. AIR QUALITY BENEFITS

We established in the previous section that the switch from peaking to ROR mode caused a shift of thermal electricity from off-peak to peak times of day. We now consider the air quality benefits that arise from

[14] These differences depend primarily on the different energy inputs used to produce peak and off-peak electricity (Ellerman 1996). We will see in the next section that the difference here is due to increased use of fuel oil and natural gas to generate electricity during peak times.

this change in the profile of thermal electricity production. As we will show, the change to ROR mode causes a decrease in the burning of coal and an increase in the burning of fuel oil and natural gas. A consequence of the change in the mix of fossil fuels is a decrease in air pollution and greenhouse-gas (GHG) emissions. We consider five conventional pollutants (nitrogen oxides, particulates, sulfur dioxide, lead, mercury) and three GHGs (carbon dioxide, methane, nitrous oxide). After quantifying changes in emissions, we apply benefit-transfer methodology to estimate the social benefits.

Our conceptual approach is straightforward. Again, the task is to analyze the effects of the change from peaking to ROR mode at the two dams. We simplify the analysis here by considering the two dams simultaneously. Let $\hat{E}_i$ and $\overline{E}_i$ denote the emissions of pollutant i under peaking and ROR modes, respectively. The difference in emissions of pollutant i between the two modes is $\Delta E_i = \overline{E}_i - \hat{E}_i$. Since we are considering relatively small changes in electricity generation, we assume a linear relationship between changes in thermal electricity generation and changes in emissions. Specifically, we model the relationship as

$$\begin{aligned} \Delta E_i &= m_i^p(\overline{q}_T^p - \hat{q}_T^p) + m_i^o(\overline{q}_T^o - \hat{q}_T^o) \\ &= (m_i^p - m_i^o)\Delta q, \end{aligned} \qquad [7]$$

where $m_i^k > 0$ for $k = p,o$ denotes the marginal effect on emissions of pollutant i from either peak or off-peak thermal electricity generation, and the notation for quantities of power production follows from the previous section but now represents choices that account for both dams simultaneously.[15] An important feature of equation [7] is the way that the marginal effect on emissions differs between peak and off-peak periods. The difference is motivated by the fact that utilities often use different fuel mixes to meet peak and off-peak demand.[16] For example, as we discuss in more detail below, Consumers Energy burns coal to generate its baseload capacity of thermal electricity, but burns fuel oil and natural gas to generate the added capacity during periods of peak electricity demand.[17] Note that since $\Delta q > 0$, equation [7] implies that $\Delta E_i < 0$ if $m_i^p < m_i^o$ that is, emissions will decrease with the switch to ROR if the marginal effect of thermal generation on emissions is lower during peak periods than during off-peak periods.

After estimating emission changes for each pollutant, the next step is to determine the associated social benefits. Let $b_i < 0$ denote the marginal social benefit of emissions of pollutant i.[18] The constant marginal social benefit is justified on the basis that we are considering relatively small changes in emissions. It follows that the social benefit of the change in emissions of pollutant i can be written as $B_i = b_i \Delta E_i$. Note that $B_i > 0$ whenever there is a reduction in the emissions of pollutant i. Now, substituting equation [7] into the social benefit expression yields

$$B_i = b_i(m_i^p - m_i^o)\Delta q. \qquad [8]$$

With equation [8] for each pollutant, the social benefits of the change in *all* emissions is simply $\Sigma_{i=1}^n B_i$ for all n pollutants.

We now turn to the data used to implement the conceptual framework. The results of the previous section provide an estimate of the shift in mean thermal generation that occurs as a result of the switch to ROR at both the Tippy and Hodenpyl dams. Summing these results from Table 1

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[15] In other words, Δq represents the annual shift of thermal electricity generation from off-peak to peak periods at *both* dams.

[16] The economic approach to fuel choice in electricity generation is based on minimizing capital, fuel, and operating costs (Ellerman 1996).

[17] For Consumers Energy, natural gas and fuel oil are used solely to fuel plants that add peak capacity and are not used in baseload capacity. In other words, coal is the only fossil fuel for baseload capacity, and thus all fossil-fueled off-peak generation is coal-fired (Consumers Energy Company 2006).

[18] Note that $-b_i > 0$ implies that the marginal social benefit of an emission *reduction* is positive.

implies a combined shift of 31,342.9 megawatt-hours per year. This is the estimate of Δq for use in equation [8].

The first step in establishing m_i^p and m_i^o for each pollutant is to determine emission rates for thermal generation by different fuel sources. We obtain these parameters from Ecobilan's Tool for Environmental Analysis and Management (TEAM) model, which is a life-cycle assessment engineering model (Ecobilan 1996). In Appendix Table 1, we report these parameters in terms of emissions per megawatt-hour of electricity generation from coal, fuel oil, and natural gas.[19]

The next step is to determine the fuel mix that Consumers Energy Company uses to produce its off-peak and peak thermal electricity. We use the coal parameters listed in Appendix Table 1 as the estimates for m_i^o, as only coal is used for thermal, off-peak generation. The use of both fuel oil and natural gas for thermal, peak generation creates the need to estimate their shares. To derive estimates for m_i^p, we collected data on Consumers Energy's actual use of fuel oil and natural gas between the years 1990 and 2001.[20] With these data, we compute total BTUs from fuel oil and natural gas, and the annual share of this total contributed by the two fuels. We then use the shares of each fuel to calculate a weighted average of the emissions columns for fuel oil and natural gas in Appendix Table 1. Finally, averaging these results over the different years provides our estimates of m_i^p for each pollutant.[21]

The first column of Table 2 reports our estimates of the difference $m_i^p - m_i^o$ for each pollutant. The fact that the difference is negative for all pollutants follows because the marginal emissions from coal (the off-peak fuel) is greater than from fuel oil and natural gas (the peak fuels). Now, multiplying this difference by Δq (i.e., 31,342.9 megawatt hours) yields estimates of the annual change in emissions for each pollutant, ΔE_i. These estimates are reported in the second column of Table 2. The negative sign for all pollutants implies that emissions declined with the change from peaking to ROR flows.

The final step for calculating the benefits of the change in emissions is to quantify the marginal damage costs ($-b_i$) of each pollutant. We follow the methodology of benefit transfer, which involves the use of existing estimates of the economic value of a nonmarket good in order to estimate the economic value of the same (or related) good in a different context (Rosenberger and Loomis 2003). The literature on the environmental costs of electricity generation contains well-developed estimates of the marginal damage costs of conventional air pollutants (Smith 1996). The literature on the economics of climate change reports estimates of the marginal damage costs of GHG emissions. Recognizing that benefit transfers are inherently associated with a degree of imprecision, we report low and high marginal damage scenarios when possible. The marginal damage costs that we use for the different scenarios and pollutants are reported in Appendix Table 2. Formally, the costs listed in the table are interpreted as $-b_i$.

[19] Other facility characteristics – such as age, stack height, and equipment features—can affect air pollution emissions and damage costs (Banzhaf, Desvousges, and Johnson 1996; Rowe, Lang, and Chestnut 1996). Information on these characteristics of Consumer Energy power plants was not included in the study.

[20] Consumers Energy's use of fuel oil and natural gas for electricity generation has risen steadily since 1991, from about 2,300 billion BTUs in 1991 to over 15,500 billion BTUs in 2001 (FERC 1991–2002). Fuel oil is burned at several of the company's primarily coal-fired plants to meet daily peak demand (Carlson 1999; Consumers Energy Company 1999). Since 1993, natural gas has also been used to meet daily peak demand (Berquist 1998). The natural gas share increased steadily after 1993 and reached 63% in 2001. In 1999, additional peak load capacity from natural gas fired duct burners was added at a third major plant (Michigan Public Service Commission 1999).

[21] Consumers Energy operates with five power plants that are fueled by natural gas and/or fuel oil. If these plants have different efficiencies in electricity production, the least efficient plants would be brought online last during a period of peak demand. This would tend to make marginal pollution emissions exceed average emissions for these fuel sources, yet we use only a single average value for emissions from these plants.

TABLE 2

MEAN ANNUAL EMISSION REDUCTIONS AND AIR QUALITY BENEFITS, 1990–2001

	Mean Difference between Off-Peak and Peak Emissions, $m_i^p - m_i^o$	Mean Change in Emissions, ΔE_i	Air Quality Benefits (B_i)	
			Low ($)	High ($)
Carbon dioxide	−2.758E-01	−8643.80	20,832	151,785
Lead	−6.752E-07	−0.021	10	44
Mercury	−2.490E-08	−0.001	0	0
Methane	−4.837E-06	−0.152	10	45
Nitrogen oxides	−3.079E-03	−96.496	6,367	14,797
Nitrous oxide	−2.434E-05	−0.763	557	5,015
Particulates	−5.615E-04	−17.598	14,363	49,378
Sulfur dioxide	−5.486E-03	−171.939	25,617	25,617
Total	–	–	67,756	246,680

Notes: Difference between off-peak and peak emissions reported in tons per megawatt-hour of generation. Emission reductions reported in tons. Air quality benefits ($/year) reported in 2001 dollars and rounded to the nearest dollar.

Estimates for the marginal damage costs of nitrogen oxides, particulates, and lead are taken from a major study of air pollution externalities of electricity generation in Minnesota (Banzhaf, Desvousges, and Johnson 1996).[22] The damage estimates are based on health effects and are therefore sensitive to the population size in affected areas. The Minnesota study develops results for three different population scenarios: rural, metropolitan fringe, and urban. We use results from the rural and metropolitan fringe scenarios, as the plants operated by Consumers Energy generally fit the population characteristics of these scenarios. The midpoint of the confidence interval in the rural scenario serves as the low estimate, while the midpoint of the confidence interval in the metropolitan fringe scenario serves as the high estimate.

The estimate of the marginal damage cost of mercury emissions comes from a study of air pollution externalities from electricity generation in New York State (Rowe, Lang, and Chestnut 1996).[23] Because the study provides one estimate, $50.34 per ton, our marginal damages remain constant between the low- and high-damage scenarios.

We treat sulfur dioxide differently than the other pollutants because of the tradable permit market that was established by Title IV of the Clean Air Act. With the permit market in place, the benefits of a reduction in sulfur dioxide are not avoided marginal damage costs, but avoided marginal abatement costs (Burtraw and Toman 1997). This follows because aggregate emissions of sulfur dioxide will not change, yet less abatement will be necessary. To estimate the avoided marginal abatement cost we use the average permit price between 1995 and 2001 (USEPA 2004). The price is $148.99 per ton, and it does not vary between our low- and high-damage scenarios.[24]

The estimates of the marginal damage costs from GHGs—carbon dioxide, methane, and nitrous oxide—are taken from

[22] The Minnesota study was conducted with a specific focus on making the results transferable to other locations and contexts. A study of New York State (Rowe, Lang, and Chestnut 1996) provides an alternative source of marginal damage costs for nitrogen oxides, particulates, and lead. Relative to the Minnesota study, the New York study has higher estimates (when evaluated at the mid-point of the Minnesota scenarios' confidence intervals); therefore, we use the Minnesota study results as more conservative estimates.

[23] The Minnesota study does not estimate marginal damage costs of mercury.

[24] Other studies provide more recent estimates of efficient fees for SO_2 and NO_x (Banzhaf, Burtraw, and Palmer 2004) and the marginal benefits of SO_2 and NO_x emission reductions (Burtraw et al. 2003). We do not apply their results in the benefit transfer as their studies pertain to post-2001, while our analysis ends in 2001.

Fankhauser (1994, 1995). The estimates account for uncertainty and are originally reported as a confidence interval. We use the lower bound of the interval as our low-damage estimate and the upper bound as our high-damage estimate (Appendix Table 2).[25]

The final step is to multiply the avoided marginal damage costs for each pollutant by the estimated change in emissions in order to estimate B_i for all i pollutants. These results are reported in the last two columns of Table 2 for the low- and high-damage scenarios. After summing the results across all pollutants, the low and high estimates for the air quality benefits are \$67,756 and \$246,680 per year. In the low scenario, reductions in carbon dioxide, particulates, and sulfur dioxide account for the vast majority of the benefits. In the high scenario, reductions in carbon dioxide account for a much greater share of the benefits than in the low scenario, with the difference reflecting the uncertainty about the economic impacts of climate change. In both scenarios, the benefits of reductions in lead, mercury, and methane are negligible.

V. RECREATIONAL FISHING BENEFITS

This section considers the recreational fishing benefits of switching from peaking to ROR modes on the Manistee River dams. We begin with an ecological analysis of the effects on habitat and natural reproduction of Chinook salmon. These estimates of river-based production of juveniles (smolts) are used to predict increases in Lake Michigan and Manistee River fish populations. We then use the results of the ecological analysis as an input for the economic model of recreational fishing. The increase in lake and river fish populations are assumed to increase catch rates, and we estimate the economic benefits of the increased catch rates using the Michigan Recreational Angling Demand Model (Lupi et al. 2001).

In general, our analytical method links aquatic ecosystem functions (spawning/nursery habitat for wild fish and water temperature regulation through river flow regime) with their service flows (fish populations and recreational fishing). We thus provide a case study of the aquatic ecosystem functions-goods-valuation framework that was developed recently in an NRC study (NRC 2005, Chapter 3).

Ecological Effects of Switching to ROR Flows

Ecological research has investigated the effects on Chinook salmon and steelhead trout from the switch to ROR flows on the Manistee River (Rutherford et al. 2004; Woldt and Rutherford 2002). These studies translate ROR-induced increases in parr survival into numbers of fish emigrating into Lake Michigan during the smolt life stage and, ultimately, numbers at age of adult.[26] The switch in management regime was found to affect the population of Chinook salmon, but it did not affect the population of steelhead trout.[27] We thus only include Chinook salmon in the analysis.

[25] Fankhauser's (1994, 1995) estimates of carbon dioxide's marginal damage costs are within the range of other estimates reported in the literature (e.g., Ayers and Walter 1991; Nordhaus and Yang 1996; Peck and Teisberg, 1992).

[26] The parr life stage is the juvenile stage spent in the stream prior to migration. The smolt life stage encompasses migration to Lake Michigan. The adult life stage is spent in Lake Michigan before individuals return to spawn and die in tributary streams.

[27] The different results between species are attributed to the length of time spent in the parr stage. Because steelhead parr spend an average of two years in the stream (compared to 1–2 months for salmon), their survival appears to be adversely affected by the relatively high temperatures (>20°C) of water released from Tippy Dam during summer months (Woldt and Rutherford 2002). This occurs because Tippy Dam is a top-draw dam, so water released from its reservoir is heated by sunlight before release. Laboratory experiments indicate that survival of steelhead parr decreases dramatically at temperatures above 19°C (Horne, Rutherford, and Wehrly 2004).

The change from peaking to ROR flow improved spawning and nursery habitat conditions for salmonids below Tippy Dam, which is the stretch of the Manistee River where adult salmon return to spawn. Habitat quality is measured by river substrate composition, with quality increasing as the percentage of cobble and gravel in the substrate increases. Flow stabilization increased the average percentage of cobble and gravel in the substrate closest to the dam from 50% to 70%. This change in substrate composition is attributed to reduced erosion of sand from river banks due to the ROR flow stabilization (Rutherford et al. 2004). Cobble and gravel substrates provide optimal habitat for spawning adult salmon and for survival, feeding, and growth of juvenile salmon (e.g., Fausch and Northcote 1992).

Field estimates of wild salmon smolts emigrating to Lake Michigan were obtained as follows. Parr abundance and survival rates were estimated in spring, summer, and fall by electrofishing randomly selected shoreline sites (Woldt and Rutherford 2002). Smolt emigration was measured using a combination of techniques: electrofishing pre-smolt stages, trapping smolts in a 2.4-diameter-auger smolt trap downstream of the nursery area, and mark-recapture experiments that compared ratios of wild and hatchery adult spawners with known numbers of marked hatchery smolts stocked in previous years (Rutherford et al. 2004). Estimates of smolts were made for conditions before and after the change to ROR flow. "Before" conditions were from 1979, while "after" conditions were from 1992–1994 and 1997–1998. Salmon smolt production varies widely with water discharge, so the point estimate in 1979 was compared to smolt production predicted from a smolt-discharge regression relationship for post-ROR years in the Manistee River. For chinook salmon smolts, estimated emigrants increased over 270%, from below 100,000 in 1979 (under peaking flow) to nearly 370,000 for a similar discharge (under ROR flow).

Based on these estimates of increased survival and recruitment of wild smolts from the Manistee River, we estimate the percentage increase in the total population (hatchery plus wild fish) of salmon in Lake Michigan.[28] We use a fishery population model for Lake Michigan chinook salmon (Madenjian et al. 2002; Rutherford 1997) to estimate numbers at age of adult resulting from increased wild smolt production. The model starts with the number of wild and hatchery smolts emigrating from the nursery habitat, and it accounts for losses due to natural mortality, fishing mortality, and spawning emigration to tributaries. We develop three cases for Lake Michigan chinook salmon based on the mean and a 95% confidence interval around the mean. The estimates are based on the 270% increase in chinook salmon smolt production in the Manistee River. The low, medium, and high cases for the increase in the Lake Michigan population of chinook salmon are 1.66%, 3.63%, and 4.84%.

The adult fish population also increased in the Manistee River itself, as fish return there to spawn.[29] The best available point estimate for the ROR-induced population increase in the river is 61.6% (Rutherford et al. 2004). This estimate accounts for strays that will migrate to other streams due to imperfect fidelity.[30] In parallel with the lake estimates, we derive low, medium, and high case scenarios for the river. Here again, we rely on the results from

[28] Over 30% of chinook salmon caught in Lake Michigan originate through natural reproduction in Lake Michigan tributaries. Hatchery operations are responsible for the remainder of the salmon population. We assume that stocking policy of hatchery fish is exogenous to natural reproduction in the Manistee River. This is reasonable based on our conversations with fishery managers in the Michigan Department of Natural Resources.

[29] In the steady state, fish populations increase simultaneously in both Lake Michigan and the Manistee River. Adult chinook salmon return to spawn in the Manistee River after spending three years, on average, in Lake Michigan.

[30] While some fish stray to other rivers, we did not consider changes to any fall runs other than the Manistee River because specific estimates of these increases are not available.

the population model and assume the proportional differences between the river estimates are the same as those for the lake estimates. Thus, low, medium, and high cases for the increase in the Manistee River population of chinook salmon during the fall runs are 28.2%, 61.6%, and 82.1%.

Estimating Recreational Fishing Benefits

The changes in Lake Michigan and Manistee River salmon populations provide the starting point for our analysis of the recreational fishing benefits. We assume our estimates for the population change translate directly into changes in catch rates. That is, we assume low, medium, and high increases in lake catch rates of 1.66%, 3.63%, and 4.84%, and we assume low, medium, and high increases in river catch rates of 28.2%, 61.6%, and 82.1%.

The benefits of the increased catch rates are estimated with the Michigan Recreational Angling Demand Model, which is a repeated random utility model that applies the travel cost method.[31] The model uses data describing where and how often anglers go fishing in Michigan. The data were collected in a telephone panel survey that followed anglers during the 1994-1995 fishing season. The 1,902 panel members were recruited by identifying potential anglers from screening interviews of 6,342 randomly selected Michigan residents. The data set includes details on 5,425 fishing trips taken by panel members.

The structure of the model, which is a four-level nested logit, reflects the broad array of fishing opportunities available to the state's anglers. Trips are differentiated by trip durations (single versus multiple day trips), by water body fished (Great Lakes, inland lakes, rivers/streams), and by species targeted ("warm" species such as bass, perch, and walleye, versus "cold" species such as salmon and trout). Thus, for both single- and multiple-day trip types, seven distinct fishing activities are classified: Great Lakes warm, Great Lakes cold, inland lake warm, inland lake cold, river and stream warm, river and stream cold, and river anadromous runs.[32] The model divides the fishing season into a series of choice occasions. The four-levels of nesting consist of the participation decision, trip length, trip type, and site choice as the bottom level of the nesting structure. In all, the model contains over 850 fishing opportunities in each choice occasion, and this set of opportunities is available for over 60 occasions for each sampled angler.

Chinook salmon are available in two of the seven fishing activities in the model: the Great Lakes cold and the river anadromous runs. For the former, site characteristics include catch rates for chinook salmon, coho salmon, steelhead and lake trout. For the latter, site characteristics include catch rates for chinook salmon, coho salmon and steelhead.

We apply the model to simulate the effects of higher catch rates for chinook salmon, using the lake and river catch rates that are reported above. The chinook salmon catch rates are adjusted for Lake Michigan sites in two types of trips: the single- and multiple-day portions of the Great Lake cold fishing trip types. Likewise, chinook salmon catch rates are adjusted at the Manistee River for the single- and multiple-day portions of the fall anadromous run fishing trip type. The model contains roughly 80 parameters that are statistically estimated. While we do not report details of the estimation here, it is worth mentioning that the key parameters in the simulation (travel costs and all chinook salmon catch rate variables) have

[31] Random utility models (RUMs) use data on individual trips to explain anglers' fishing site choices and to relate these choices to the costs and characteristics of alternative fishing sites (Morey 1999). Anglers' choices reveal their relative preferences for site characteristics and travel costs, i.e., the anglers' willingness to incur costs for different site characteristics. Through this linkage, RUMs can value changes in site characteristics such as catch rates.

[32] "Anadromous runs" refer to Great Lakes trout and salmon on migratory runs up a river.

TABLE 3

RECREATIONAL FISHING BENEFITS FROM CATCH-RATE INCREASES FOR CHINOOK SALMON

	Baseline Days of Use (days/yr)	Change in Days of Use from Catch-Rate Increases		
		Low	Medium	High
Fishing trip types				
Anadromous runs	663,000	2,000	6,000	9,900
Great Lakes cold	922,000	5,900	12,900	17,100
All other types	10,526,000	−7,700	−18,500	−26,300
Recreational fishing benefits ($/yr)		301,900	738,400	1,068,600

Notes: The catch-rate increases for Great Lakes cold are 1.66% (low), 3.63% (medium), and 4.84% (high). For anadromous runs on the Manistee River, they are 28.2% (low), 61.6% (medium), and 82.1% (high). All other types of fishing include warm-water fisheries in the Great Lakes, inland lakes and rivers, and cold-water fisheries in inland lakes and rivers of Michigan. Benefits are reported in 2001 dollars.

the anticipated signs and are all significantly different from zero with $p < 0.001$.

Table 3 presents the estimated changes in fishing trip days and consumer surplus per year for the three cases, along with the baseline number of fishing days. The numbers on fishing trip days suggest that the increases in salmon catch rates are generating a substantial substitution toward chinook salmon fishing; that is, the higher catch rates are attracting anglers from other fishing activities to salmon fishing. The estimated increases in consumer surplus (in 2001 dollars) to Michigan-resident anglers are: $301,900 for the low case, $738,400 for the medium case, and $1,068,600 for the high case. The consumer-surplus estimates reflect the increases in total annual statewide use value to Michigan-resident anglers fishing in Michigan during the April to October season.

VI. NET BENEFITS

Table 4 summarizes our estimates of the annual costs and benefits of switching from peaking to ROR modes at the Tippy and Hodelpyl dams on the Manistee River in Michigan. Producer costs increase because of the need for the utility to generate more peak electricity and less off-peak electricity at thermal power plants. Our mean estimate of these costs is $310,612 per year, and the 95% confidence interval around the mean ranges from $219,132 to $402,094. The first category of benefits arises from the reductions in air pollution emissions due to the changed profile of thermal electricity generation. We report a range of the social benefits that arise from the emission reductions: the low estimate is $67,756 per year, and the high estimate is $246,680. The second category of

TABLE 4

SUMMARY OF ANNUAL COSTS AND BENEFITS

Costs	$
Thermal electricity production	310,612
	[219,132–402,094]
Benefits	
Emission reductions	[67,756–246,680]
Recreational fishing	738,400
	[301,900–1,068,600]

Notes: Costs and benefits are reported in 2001 dollars. Numbers in brackets indicate the range of estimates. The range of estimates for the costs of thermal electricity production and recreational fishing benefits are based on 95% confidence intervals. Numbers not in brackets are point estimates. There is no point estimate for benefits of emission reductions.

benefits accrues to recreational anglers. The change to ROR flows improved chinook salmon habitat, and the result has been a population increase within both Lake Michigan and the Manistee River. Based on commensurate increases in the catch rates, our best estimate of the use-value benefits to anglers is $738,400 per year, but we also report low and high estimates from a 95% confidence interval that range from $301,900 to $1,068,600.

The general finding, based on our best estimates, is that the benefits exceed the costs of the switch from peaking to ROR flows on the Manistee River. Even ignoring air quality benefits entirely, the best estimate of the annual benefits to recreational anglers is more than twice the annual costs to the electric utility. The best estimate of the recreational fishing benefits even exceeds the upper bound of the 95% confidence interval for the producer costs by more than $300,000. In the extreme case, where we consider the upper bound of the confidence interval for producer costs and the lower bound of the confidence interval for recreational fishing benefits, the inclusion of air quality benefits suggests that the net benefits are close to breakeven, or still positive. Using the low estimate for air quality benefits, the net benefits are −$32,438, which is close to a breakeven result. Using the high estimate for air quality benefits, the net benefits are clearly positive, at $146,486. Thus, the only case in which net benefits are not clearly positive is the case in which we use the highest cost estimates and lowest benefit estimates and even in this case, the net benefits are close to breakeven. We therefore interpret our results as suggesting that the net benefits of switching from peaking to ROR flows are non-negative and most likely positive.

VII. CONCLUSION

This paper conducts an ex post benefit-cost analysis of an environmental constraint that was imposed on two hydropower dams on the Manistee River in Michigan. The constraint—to maintain river flow in a ROR (natural) mode rather than a peaking mode—was set in a FERC license that imposed new operating conditions for the dams. The best estimates suggest that the air quality and recreational fishing benefits are more than twice as large as the producer costs. Imposition of the constraint therefore appears to have passed the benefit-cost criterion of positive net benefits. While the analysis is useful for understanding the welfare implications of the specific policy in Michigan, some general insights follow as well.

The National Research Council has emphasized the need for ex post analysis in water resources research (NRC 2001) and, as well, for the integration of ecological and economic perspectives in valuing ecosystem services (NRC 2005). This paper provides an example of both recommended approaches. The ex post nature of the analysis implies that benefit estimation is based on actual, rather than forecasted, changes in conditions. Here we have taken advantage of publicly available data on electric utilities to derive estimates of the producer costs and changes in air quality benefits. We have also combined original ecological research on changes in salmon populations with a random-utility travel cost model to estimate recreational fishing benefits. Our hope is that the conceptual and empirical methodology will prove useful for other researchers conducting similar analyses. The results also point to important categories of benefits and costs that should be considered when conducting ex ante studies.

The benefits of reductions in air pollution and GHG emissions were an unanticipated consequence of the switch to ROR flows. Hydropower is commonly advanced as a "nonpolluting" source of energy, and conventional wisdom holds that operational constraints on hydroelectric dams will reduce the production of clean energy. Our analysis suggests, however, that replacing daily peak flows with ROR flows actually lowers pollution emissions in this case, and the estimated benefits of these emissions reductions are substantial.

Although these are the first estimates of air quality benefits from an environmental constraint on hydropower, the results suggest that future studies should not ignore this potentially important category of impacts, especially when changes in emissions are likely to occur in or near highly populated areas.

Our study focuses on 1990–2001, yet the benefits and costs of the relicensing event (and the switch to ROR flow) will continue until the current license expires in 2034. Realistically, conditions underlying the economic effects will change over time (conditions such as the marginal cost of electricity production and the demand for recreational fishing). Already, the marginal benefits to the utility of reducing SO_2 and NO_x emissions have increased considerably. The SO_2 market price rose rapidly during 2004 and 2005 to a level of $1,578 per ton in December 2005 (Cantor Environmental Brokerage 2006). This figure contrasts with the study's estimated marginal benefit of SO_2 reduction, $149 per ton. NO_x prices exceeded $2,000 per ton for almost all of 2004 and 2005, which contrasts with the study's high estimate for marginal benefit of NO_x reduction, $153 per ton. NO_x prices are now indicators of marginal benefit to the utility, as NO_x emissions are now capped at the state level and traded on an interstate market in the eastern United States, including Michigan (USEPA 2005).[33] Clearly, the estimated benefits of switching to ROR flow would likely be much higher if estimated for the last few years, and these higher benefits would strengthen the finding that the net benefits are positive. Yet the general point is simply that the estimated benefits and costs may change over time in ways that our analysis does not assess.

While we considered two categories of nonmarket benefits, we did not account for other possible benefits. For example, the change to ROR (natural) flows likely affects other ecological services besides natural production of chinook salmon. We did not examine the nature or value of these services. Moreover, we only measured use values, and not nonuse values. For the increased production of salmon, we do not know the sign or magnitude of possible nonuse values. Although chinook salmon are neither native to nor endangered in Lake Michigan, they do play an important role in controlling the abundance of other non-native species. Since we study a marginal change in their local population, changes in nonuse values may not be substantial in our case. Nevertheless, it is important to acknowledge that nonuse benefits may be more important, if not pivotal, in other contexts.

In conclusion, resource managers and regulators have an ongoing need for economic analysis of hydropower-environment tradeoffs in the allocation of river resources. This is especially true for the Federal Energy Regulatory Commission, which has licensing authority over 1,011 hydropower projects and operates with a legal mandate to balance hydropower and the environment in project (re)licensing. Despite this mandate, FERC often falls short in its application of contemporary methods of social benefit-cost analysis. Thus, there is a need for case studies of how to conduct economic analysis of hydropower-environment tradeoffs when it comes to the regulation of hydropower projects throughout the United States. The intent of this paper has been to provide such a study.

APPENDIX

The appendix contains two tables: a table on pollution emissions by fuel source (Table A.1) and a table on marginal damage cost by pollutant (Table A.2).

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[33] An interesting note is that, by internalizing externalities, pollution permit markets might provide an incentive for the electric utility to switch to ROR flow as a profit opportunity rather than as a response to a regulatory constraint. For example, at an SO_2 price of $1,578 per ton and an NO_x price of $2,000 per ton, the annual SO_2 and NO_x emission reductions of the switch carry a value of over $450,000 per year. This compares favorably to producer cost: the upper bound of the 95-percent confidence interval for the cost of the switch is $402,094 per year.

TABLE A.1
EMISSIONS BY FUEL SOURCE OF THERMAL ELECTRICITY GENERATION

Pollutant	Coal	Fuel Oil	Natural Gas
Carbon dioxide	1.134E-00	9.140E-01	6.522E-01
Lead	6.752E-07	0.0	0.0
Mercury	2.490E-08	0.0	0.0
Methane	1.336E-05	1.041E-05	1.555E-06
Nitrogen oxides	5.275E-03	1.990E-03	2.959E-03
Nitrous oxide	4.868E-05	2.434E-05	2.434E-05
Particulates	8.540E-04	3.673E-04	1.614E-05
Sulfur dioxide	1.060E-02	6.497E-03	3.228E-06

Notes: Emissions are reported in tons per megawatt-hour of generation. The data are taken from Ecobilan's TEAM model copyright © 1996. All conversions, except lead and mercury, are based on nation-wide electric utility data. Conversions for lead and mercury are taken from data specific to emissions from electricity generation in the North American Electric Reliability Council (NERC) East Central Area Reliability (ECAR) region, in which lead and mercury emissions are assumed to arise solely from coal.

TABLE A.2
LOW AND HIGH ESTIMATES OF THE MARGINAL DAMAGE COSTS OF DIFFERENT POLLUTANTS ($-b_i$)

Pollutant	Low ($)	High ($)
Carbon dioxide	2.41	17.56
Lead	489.33	2,100.27
Mercury	50.34	50.34
Methane	68.34	293.30
Nitrogen oxides	65.98	153.34
Nitrous oxide	729.52	6,572.95
Particulates	816.16	2,805.86
Sulfur dioxide	148.99	148.99

Notes: Marginal damages are reported in 2001 dollars. All estimates are reported in damages per ton of pollutant. The sources of all estimates are reported in the text.

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