Environmental Management (2007) 40:1004–1015
DOI 10.1007/s00267-007-9008-z

How Run-of-River Operation Affects Hydropower Generation and Value

Henriette I. Jager · Mark S. Bevelhimer

Received: 30 May 2006 / Accepted: 26 April 2007 / Published online: 22 September 2007

Abstract Regulated rivers in the United States are required to support human water uses while preserving aquatic ecosystems. However, the effectiveness of hydropower license requirements nationwide has not been demonstrated. One requirement that has become more common is "run-of-river" (ROR) operation, which restores a natural flow regime. It is widely believed that ROR requirements (1) are mandated to protect aquatic biota, (2) decrease hydropower generation per unit flow, and (3) decrease energy revenue. We tested these three assumptions by reviewing hydropower projects with license-mandated changes from peaking to ROR operation. We found that ROR operation was often prescribed in states with strong water-quality certification requirements and migratory fish species. Although benefits to aquatic resources were frequently cited, changes were often motivated by other considerations. After controlling for climate, the overall change in annual generation efficiency across projects because of the change in operation was not significant. However, significant decreases were detected at one quarter of individual hydropower projects. As expected, we observed a decrease in flow during peak demand at 7 of 10 projects. At the remaining projects, diurnal fluctuations actually increased because of operation of upstream storage projects. The economic implications of these results, including both producer costs and ecologic benefits, are discussed. We conclude that regional-scale studies of hydropower regulation, such as this one, are long overdue. Public dissemination of flow data, license provisions, and monitoring data by way of on-line access would facilitate regional policy analysis while increasing regulatory transparency and providing feedback to decision makers.

Keywords Ecologic valuation · Hydropower generation · In-stream flow regulation · Natural flow regime · Peaking operation · Run-of-river operation

Introduction

Aquatic species have gradually gained legal protection under United States laws regulating hydropower. The Federal Water Power Act, originally passed in 1920 (16 U.S.C. §§791-828c), established the principle of federal regulation of hydropower projects. By issuing hydropower licenses for a limited term, federal regulation was designed to prevent monopoly and protect the public interest in water use (Wright 2006). However, instream flows were not a main concern of the federal government. Rather, individual states, such as Oregon, first began to regulate stream flows to protect aquatic life (Lamb 1995). In 1986, the Electric Consumers Protection Act (ECPA; 16 U.S.C. §§ 791a-825r) amended the Federal Power Act and required the Federal Energy Regulatory Commission (FERC) to give equal consideration to environmental resources, energy conservation, and power production (Hill 1996), and nonfederal licenses began to include flow-related provisions for aquatic biota. The first 2 decades of flow regulation focused on setting minimum flows required for healthy downstream aquatic communities in tailwaters, a regulatory trend that has been followed by legislators in many other countries (Tharme 2003). With time, this centralized decision-making authority has been shifted away from the FERC and shared with a plurality of other

H. I. Jager (✉) · M. S. Bevelhimer
Oak Ridge National Laboratory, Mail Stop 6036, PO Box 2008,
Oak Ridge, TN 37831-6036, USA
e-mail: jagerhi@ornl.gov

federal and state agencies (Sensiba 1999; DeShazo and Freeman 2005).

The FERC does not publish comprehensive data describing the mitigation requirements included in their hydropower licenses, making it difficult to quantify the number of licenses with specific types of provisions for flow mitigation. The FERC generally includes conditions in hydropower licenses that require adequate instream flows to protect aquatic resources (Shupe and MacDonnell 1993). A study by DeShazo and Freeman (2005) reported that the average number of environmental conditions per license increased from 4.8 (1982 to 1990) to 12.0 (1991 to 1998). Bevelhimer and Jager (2007) reviewed the types of flow mitigations in renewed licenses. Hill (1996) reported that most applications for an original license (as opposed to a renewed license) propose to operate in run-of-river (ROR) mode.

It is generally assumed that flow restrictions cost power producers revenue and that flow restrictions protect aquatic resources. These two assumptions are usually expressed in the hydropower license and associated National Environmental Policy Act of 1969 (42 USC §§ 4321-4370d) documents. However, neither the benefits to aquatic resources nor economic costs to power producers associated with these regulations are typically studied after a license is issued. Rarely are the effects at single hydropower projects studied, which makes it difficult to generalize results to other projects on a regional or national scale. Regional- or national-scale research to assess the effectiveness of hydropower regulation is virtually nonexistent. Yet, such studies could evaluate the effectiveness of policies in terms of their effects on United States energy capacity, the economics of hydropower, and the degree environmental protection provided. In this study, we reviewed licenses in which the mode of operation changed from peaking to ROR, and asked the following questions:

1. Was the primary justification for the change in operation to benefit aquatic biota?
2. Did annual power generation decrease as a result of relicensing?
3. Did the proportion of higher-valued power generated during peak demand decrease because of relicensing?

Flexibility in the timing of water use is a primary reason for regulating rivers. Storage reservoirs provide the flexibility to use water for irrigation, hydropower, recreation, and other purposes, not just immediately after a precipitation event, but at other, drier times of the year. Many storage reservoirs are too small to carry water over from one year to the next, and it is often reasonable to assume that minimum flow requirements and changes in operational policies will not influence annual flow releases. Nevertheless, license requirements that constrain seasonal and diurnal shifting of flow can influence power generation by requiring generation units to operate at relatively inefficient flow rates. License requirements imposing minimum flows can decrease power generation if these flows are spilled over the dam rather than entrained through turbines to generate electricity or if they result in inefficient operation.

Electricity generated by hydropower projects is worth more when demand for energy is high. One advantage of hydropower compared with other sources of energy is that hydroelectric plants are capable of generating power on short notice, providing operational flexibility that is especially important during peak demand (Chatterjee and others 1998). Therefore, projects with adequate storage are often operated by storing water at off-peak times and releasing water through the turbines at peak times. This practice is referred to variously as “peaking,” “hydroshifting,” and “load-following.” Although demand varies geographically, the general definition of peak hours as those between 09:00 and 22:00 Monday through Saturday is reasonable for the regions included in this analysis (Fig. 1).

Methods

In this retrospective study, we assembled data from a variety of sources to test the three previously mentioned questions. We began with a–FERC database that includes the date of the license and operation mode before and after the license. We reviewed all hydropower licenses issued to hydropower projects by the FERC from 1988 through 2000. A total of 223 projects was relicensed during this

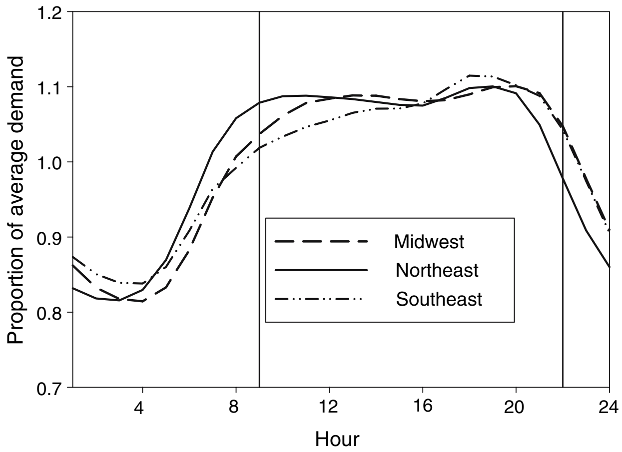

Fig. 1 Average weekday demand for three geographic regions of interest. Data are 2003 averages from the US Department of Energy Energy Information Agency. Vertical black lines bound the period of peak demand as defined for this study

period (note that some hydropower projects include multiple dams).

Reasons for License-Mandated Change to ROR Operation

First, we reviewed licenses to quantify the reasons for changes in operation. This study focuses on renewed licenses. We reviewed licenses of projects that were renewed between 1988 and 2000 by the FERC. We identified 28 of 223 projects (13%) that changed from peaking to ROR operations (Table 1) and 5 (2%) that changed to operate in ROR mode just during the spring, when target fish populations use flow as a cue for spawning (Table 2). We refer to this as "seasonal ROR" operation. The sizes of the projects, as measured by total nameplate capacity (summed over generators) ranged from 350 to 30,105 MW. We were able to obtain electronic copies of the license for all but two projects (Cavendish and Sandstone Rapids) from the FERC website (http://www.ferc.gov/docs-filing/elibrary.asp).

For 31 projects that changed operation, we determined whether operating conditions of the license actually changed as indicated in the database, and, if so, what reasons were given for changing operation. The question addressed by this summary is what the most common reasons for changing operation were and to what extent changes in operation were motivated by environmental concerns. Seven possible reasons were identified, some of which are biologic and some political in nature. These include (1) benefits of ROR flow regime for ≥ 1 anadromous fish species of concern, (2) benefits of ROR flow regime for ≥ 1 potadromous fish species of concern, (3) benefits of ROR flow regime for other, nonmigratory fishes of concern, (4) to meet the requirements for state water-quality certification, (5) to meet the requirements of a settlement agreement among stakeholders, (6) for operational reasons, and (7) for aesthetic reasons or reasons having to do with safety. More than one reason was often cited.

Effect of License-Related Flow Mitigation on Power Generation Efficiency

We conducted an intervention analysis (Box and Tiao 1975) to test for a significant effect of the license (or date of operation change) on generation efficiency, taking into account annual variations in annual flow. Quite a few projects were excluded from the study because they lacked publicly available flow-monitoring data before or after the license (Bevelhimer and Jager 2007). We obtained annual generation data for each project from a database EIA-860 maintained by the United States Department of Energy (http://www.eia.doe.gov/cneaf/electricity/page/eia860.html). Three geographic regions of interest (the Midwest, the Northeast, and the Southeast) were represented among projects with data needed for the analysis.

We used these data to test the null hypothesis that no change in efficiency in annual generation, $Y_g(t)$ occurred after the new license was issued against the one-sided alternative hypothesis that generation efficiency decreased. Annual flow, Q, was included as a covariate to remove the effects of year-to-year variation in climate. The intercept is included in the model because generation is not possible at very low flows. We tested for a significant negative effect of the license date (or the year of the change in operation) on the relationship between generation and flow by defining a step function, $I(t)$.

To account for autocorrelation, we compared a first-order autoregressive model (Equation 1) with a simpler model that did not consider autocorrelation (Equation 1 without the first term).

$$Y_g(t) = \rho Y_g(t-1) + b_0 + b_1 Q(t) + b_2 I(t)\, Q(t) + \epsilon(t),$$
$$\textit{where } I(t) = \begin{cases} 0, & t \leq \textit{license date} \\ 1, & t > \textit{license date} \end{cases} \tag{1}$$

For some projects, the autocorrelation in the autoregressive model was not significant at $\alpha = 0.1$, and Akaike's Information Criterion was higher than that in the simpler model. For these projects, we chose the simpler model.

We obtained estimates for Equation 1, with and without a repeated-measures component, by using an SAS Proc Mixed (Appendix A). Flow and intercept were treated as random effects, and year was treated as a fixed effect. Although one would not expect hydropower generation at zero flow, it is nevertheless appropriate to include an intercept in the model because generation is not possible at low flows and because assuming a linear fit through (0, 0) is a strong assumption and constraint. The slope, b_1, measures the efficiency of generation under the old license. In addition to turbine efficiency, bypass or spilled flow not run through the turbines also contributes to inefficiency and result in lower values of b_1. Parameter b_2 measures the change in efficiency after the new license. We performed a one-sided test for a significant negative effect of the license on generation efficiency, $P(b_2 \leq 0)$.

We also fitted a model (Equation 2) to all projects combined, treating project as a fixed effect and permitting separate estimates of b_1 for different projects, denoted by k, with a common intercept, b_0. This gave us an overall test of license effects across projects included in our sample:

Table 1 Twenty-eight projects that changed operation from peaking to run-of-river (ROR) mode as a result of new license provisions. US Agency acronyms used are US Geological Survey (USGS), Department of Energy's Energy Information Agency (EIA), and Federal Energy Regulatory Commission (FERC)

Hydropower project	River	State	License date	USGS downstream	USGS upstream	USGS unregulated	Annual flow (cm)	EIA plant code	Total nameplate capacity (MW) (# generators)	FERC project id
Alcona	Au Sable	MI	15-Jul-94	04137005	04137500	04136900	9912	1693	8,000 (2)	2447
Arnold Falls	Passumpsic	VT	08-Dec-94	01135500				3707	350 (1)	2399
Brule	Brule	WI	29-Aug-95	04062011	04061000	04060993	4970	1775	5,335 (3)	2431
Byllesby-Buck	New	VA	28-Mar-94	03165500^{a}	03168000	03164000	19,633	3772	21,600 (4)	2514
								3773	8,505 (3)	
Caldron Falls	Peshtigo	WI	26-Jun-97	04069500^{b}	04069500	04067958		4061	6,400 (2)	2525
Caribou Hydro	Aroostoock	VT	13-Dec-93					1513	800 (2)	2367
Cascade	Little	NC	15-Aug-94		03442440			2717	750 (2)	2541
Cavendish	Black	VT	04-Nov-94			04296000		3710	1,800 (3)	2489
Chalk Hill	Menominee	MI	07-May-97	04063000^{b} 04066030*	04066003	04063700	23,165	1776	7,800 (3)	2394
Escanaba	Escanaba	MI	13-Jul-95	04059000	04040500			7118	2,000 (2)	2506
Foote	Au Sable	MI	15-Jul-94	04137500^{c}	04137030	04136900	13,907	1705	9,000 (3)	2436
Gage	Passumpsic	VT	08-Dec-94	01135500^{b}	01135500	8,317	3713	700 (2)	2397	
High Falls	Peshtigo	WI	26-Jun-97	04069500^{b} 04068000		04067958		4065	7,000 (5)	2595
Hodenpyl	Manistee	MI	15-Jul-94	04125550^{a,b} 04124200*	04124000		9,941	1708	17,064 (2)	2599
Holyoke	Connecticut	MA	20-Aug-99	01172010^{c}	01170500	01181000	125,028	9864	2,600 (4)	2004
Hoosick Falls	Hoosick	NY	01-May-00	01334500				2489	2,000 (2)	2487
Johnson Falls	Peshtigo	WI	26-Jun-97	04069500^{b}		04067958		4067	3,520 (2)	2522
Passumpsic	Passumpsic	VT	08-Dec-94	01135500			8317	3718	700 (1)	2400
Pierce Mills	Passumpsic	VT	08-Dec-94	01135500^{b}				3721	250 (1)	2396
Pine	Pine	WI	19-Dec-95	04064500^{a}		04063700	3,532	4045	3,600 (2)	2486

Table 2 Five projects that changed from peaking to seasonal ROR operations during the spring spawning period (mid-April through June) as a result of license provisions in the three regions of interest

Project	River	State	License date	USGS downstream	Annual flow (cm)	EIA plant code	Total nameplate capacity	FERC project
Bonny Eagle	Saco, New	ME	26-Feb-98			1482	7,200 (6)	2529
Buzzards Roost	Saluda	SC	18-Dec-95	02166501	12,721	3254	15,000 (3)	1267
Essex No. 19	Winooski	VT	30-Mar-95	04290500	18,422	3737	7200 (4)	2513
Sinclair	Oconee	GA	19-Mar-96	02223000	27,896	0075, 0722	4,500 (2)	1951
Skelton	Saco	ME	26-Feb-98			1505	16,800 (2)	2527

Table 3 Four projects that (1) continued to operate in peaking mode as a result of license provisions, (2) are located in the regions of interest, and (3) have USGS flow data

Project	River	State	License date	USGS downstream	Annual flow (cms)	EIA plant code	Total nameplate	FERC project
Lloyd Shoals	Ocmulgee	GA	22-Mar-93	02210500	18,918	0712	14,400 (6)	2336
Neal Shoals	Broad	SC	18-Jun-96	02156500	35,262	3289	5,200 (4)	2315
North Georgia	Tallulah, Tugalo	SC	3-Oct-96	02181580[a]		0723	72,000 (6)	2354
						0724	16,000 (2)	
						0725	45,000 (4)	
Reusens	James	VA	18-Mar-94	02025500	36,688	3779	22,500 (5)	2376

[a] USGS flow data were only available after relicensing

$$Y_{g,k}(t) = \rho Y_{g,k}(t-1) + b_0 + b_{1,k} Q_k(t) + b_2 I_k(t) Q(t) + \varepsilon(t),$$
$$where\, I_k(t) = \begin{cases} 0, t \le license\, date\, for\, project\, k \\ 1, t > license\, date\, for\, project\, k \end{cases} \quad (2)$$

Effect of License-Related Flow Mitigation on the Timing of Flow Releases

We were interested in testing the null hypothesis that projects issued a new license and that changed operation from peaking to ROR did not change the proportion of flow during peak hours against the alternative hypothesis that the proportion decreased. We included only hydropower projects for which subdaily flow data were available both before and after relicensing. For each gage, we ordered real-time flow data from state offices of the United States Geological Survey (USGS) for years between 1985 and 2003. We obtained subdaily flow data before and after license renewal from state USGS offices for 10 hydropower projects.

We also expected the proportion of flow during peak hours below peaking projects to be much greater than that on nearby unregulated rivers. We therefore characterized the proportion of flow during peak times for two control groups: (1) gages below projects that did not change operations but continued peaking (Table 3) and (2) gages on nearby unregulated rivers. Nearby USGS gages on unregulated sections of river were identified for 4 of the 29 projects that continued peaking (Slack and Landwehr 1992).

Results

Below, we describe results for each of three questions addressed by this study.

Reasons for License-Mandated Change to ROR Operation

Improving downstream conditions for aquatic species was mentioned as a reason for changed operations for the majority (24 of 33) of licenses, and migratory fish species were present in most of the rivers involved (Fig. 2). On the East coast, diadromous fishes—including Atlantic salmon (*Salmo salar*), Atlantic sturgeon (*Acipenser oxyrhynchus*), American shad (*Alosa sapidissima*), river herring (*Alosa pseudoharengus*), and American eel (*Anguilla rostrata*)—were species of concern. In the Midwest, introduced steelhead trout (*Oncorhynchus mykiss*) and Pacific salmon,

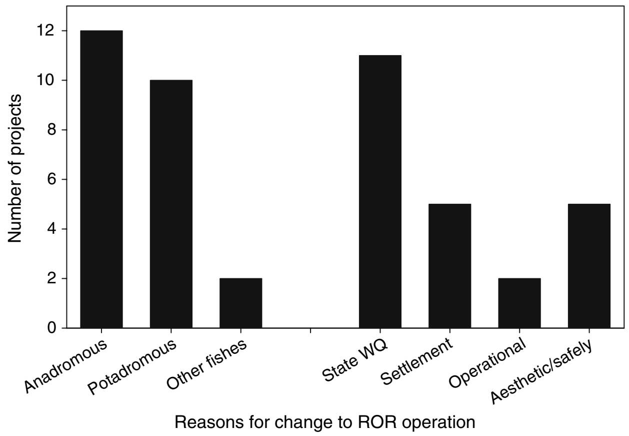

Fig. 2 Reasons listed for required change in operation from peaking to ROR or seasonal ROR. Categories are not mutually exclusive

or potadromous fishes (*e.g.*, lake sturgeon [*Acipenser fulvescens*], walleye [*Stizostedion vitreum*], northern pike [*Esox lucius*], and muskellunge [*E. masquinongy*]) were often present.

However, in a surprising number of cases, the change in operation was not motivated by environmental concerns for aquatic biota. At Spencer Mountain, the owner requested the change to ensure that wastewater treated upstream would not reach the drinking water intake immediately downstream under low-flow conditions (this license was later given up). Aesthetic considerations were frequently cited (Fig. 2). For example, ROR operation was considered to enhance the aesthetic appeal of the natural falls at Vergennes and to preserve the free-flowing nature of the scenic Au Sable River. Mitigating erosion or slumping of downstream riverbanks was cited in several cases (Prickett, Hoosick Falls, and Taftsville). Maintaining constant, full upstream reservoir levels for recreational or aesthetic reasons was cited as a reason for changing operations at Brule, Cascade, and Taftsville.

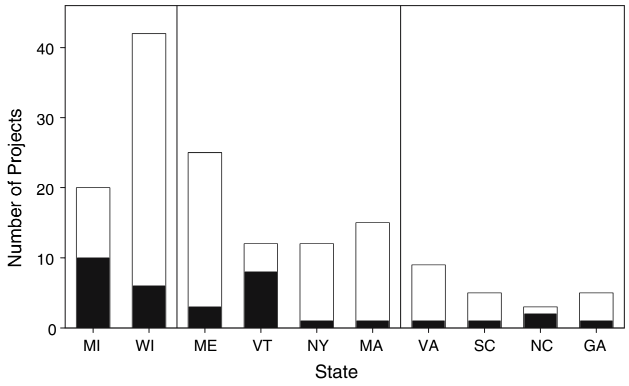

Fig. 3 Number of projects relicensed between 1988 and 2000 (white and black bars) and the subset of projects that changed operation from peaking to ROR or seasonal ROR (black bars) by state

State water-quality certification played an important role in changing project operations (Fig. 2). Under Section §401(a) of the Clean Water Act, the FERC may not issue a license for a hydroelectric project unless the state water-quality certifying agency has either issued water-quality certification for the project or has waived certification. Most of the projects that changed from peaking to ROR operation were located in a few states (Fig. 3), notably Michigan, Wisconsin, and Vermont. Projects in these states tended to occur on rivers with downstream anadromous or potadromous fish habitat in rivers flowing to the Atlantic Ocean or Great Lakes. State certification probably contributed to the ROR requirements included in settlement agreements (e.g., Alcona and Foote on the Au Sable River) and owner-requested changes in operation (e.g., Passumpsic, Skelton, Taftsville, Tippy, Vergennes, and Chalk Hill). However, numerous other projects in these states, often on the same rivers, were not required to change operations.

Effect of License-Related Flow Mitigation on Power-Generation Efficiency

In our combined analysis of all projects that changed operation, we did not detect a significant decrease after license renewal ($p = 0.2285$). Annual generation, $Y_g(t)$, showed a significant positive response to flow, Q, during prerelicensing periods ($p = 0.0210$). The autoregressive term, $\rho = 0.8254$, was highly significant ($\Pr(z>|Z|) < 0.0001$), suggesting that a repeated-measures model is appropriate. The average model fitted was $Y_g(t) = 9{,}978 + 7.78\ Q(t) - 0.2731\ I(t)\ Q(t)$. This represents a 3.5% decrease in efficiency after relicensing across projects.

We also analyzed projects separately. All but three projects showed a significant positive relationship ($b_1 > 0$) with flow (Table 4). The exceptions were Holyoke, Taftsville, and Spencer Mountain (the last showed a negative relation between generation and annual flow!).

In our analyses of 12 projects that changed operation, we detected a significant ($p < 0.05$) postlicense decrease in generation efficiency at 4 projects (Table 4). In all but 2 of the 12 projects, the sign of the coefficient, b_2, indicated a decrease in generation efficiency after the license (left and middle group in Fig. 4). The coefficients associated with the license intervention were smaller than the coefficient of flow before relicensing. The largest decrease was at Vergennes, which decreased by 91%. Among the remaining projects, changes ranged from +6% to −19% of prelicense efficiency (Fig. 4). Larger postlicense decreases were observed among three of the projects that continued peaking (four projects on the right in Fig. 4).

Table 4 Results of intervention analysis for each hydropower project, including the mode of operation after the new license, the name of the hydropower project, the first year of data included, the sample size (no of years), Akaike's information criterion (AIC) for the regression model, and estimates of four parameters, including autocorrelation (ρ), the intercept (b_0), the slope efficiency before the new license (b_1) and the effect of the license on generation efficiency (b_2), and the one-sided probability of a decrease in efficiency. For some projects, autocorrelation was not significant ($\alpha = 0.1$), and the repeated-measures model had a higher AIC than the model with no autocorrelation. For these projects, we list the preferred parameter estimates in a second line

New mode of operation	Project name	First year	N (y)	AIC	ρ	Estimated coefficients			$p\ \{b_2 <0\}$
						b_0	b_1	b_2	
ROR	Brule	1989	15	225.1	−0.6372	2,761	22.02	−2.835	0.0060
ROR	Foote	1996	17	287.0	0.2844	4,291	18.50	0.2421	0.1211
				285.9		3,953	18.75	0.2705	0.2016
ROR	Holyoke	1985	20	367.3	0.7036	5,173	0.115	0.1663	0.4785
ROR	Passumpsic	1990	12	198.6	0.5947	879	3.617	−0.6606	0.2425
ROR	Prickett	1984	19	320.1	0.5477	4,927	9.233	−0.9187	0.3218
ROR	Sandstone Rapids	1987	24	392.8	−0.1723	506	13.18	−0.7957	0.0400
				391.2		684	12.96	−0.8349	0.0830
ROR	Spencer Mountain	1986	14	255.0	−0.1575	5,554	−3.214	−0.1805	0.4433
				253.3		5,908	−3.650	−0.1681	0.4493
ROR	Taftsville	1990	12	188.6	−0.0064	173	2.615	−0.4301	0.2548
				186.6		172	2.620	−0.4316	0.2470
ROR	Vergennes	1991	14	233.2	0.3646	7,719	4.526	−4.1349	0.0039
				232.9		7,859	4.298	−4.4786	0.0001
ROR	White Rapids	1985	24	469.6	0.0743	15,898	12.31	−1.8639	0.0578
				467.6		15,438	12.61	−2.0148	0.0223
Seasonal ROR	Sinclair	1985	18	387.7	−0.2830	9,617	39.36	−3.5732	0.0117
				386.4		13,328	38.11	−3.6214	0.0138
Seasonal ROR	Essex No. 19	1985	24	486.0	0.4606	18,921	9.386	0.3184	0.8636
Peaking	Lloyd Shoals	1985	16	328.0	−0.4572	25,965	21.57	−3.511	0.0050
Peaking	Neal Shoals	1985	19	366.1	0.0049	10,652	4.157	−0.0340	0.4645
				356.1		10,631	4.163	−0.0352	0.4614
Peaking	Reusens	1985	19	391.4	0.3794	18,768	4.473	−1.5607	0.0636
Peaking	Station 2	1985	19	391.0	0.0035	17,586	7.551	−2.4427	0.0149

Effect of License-Related Flow Mitigation on the Timing of Flow Releases

Among 10 hydropower projects with flow data needed to compare flows before and after relicensing, flow during peak demand decreased, as expected, at 7 projects and increased at 3 projects. We detected a significant decrease in the percentage of flow during peak hours after relicensing at 5 projects that changed to ROR operation and 2 projects that changed to seasonal ROR operation (Figure 5). The remaining three projects showed significant increases in flow during peak hours after license renewal (Fig. 5).

We also expected the average proportion of flow during peak hours for the four peaking projects (0.470 ± 0.006) to be much greater than that of the nine unregulated sites (0.461 ± 0.0015). Although the means were significantly different (horizontal lines in Fig. 5), variation among projects is too great to permit one to classify an individual flow regime of unknown origin as either peaking or natural based on its proportion.

Discussion

This study examined three assumptions about changing from peaking to ROR operation at hydropower projects. Each of these is discussed below.

Reasons for License-Mandated Change to ROR Operation

We examined the assumption that environmental benefits motivated required changes to ROR operation. In our review of licenses, we found that changes in operation from

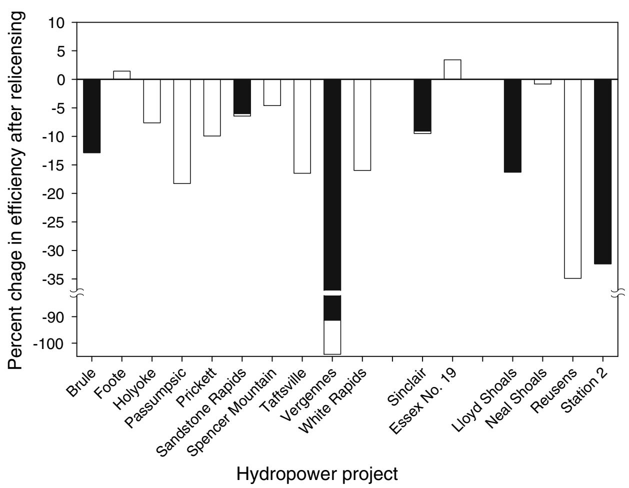

Fig. 4 Effect of new license on generation efficiency at 10 hydropower projects that changed from peaking to ROR operation (left), 2 projects that changed to seasonal ROR operation (middle), and 4 projects that continued peaking operations (right) under the terms of the revised license. Black bars indicate coefficients significantly <0 ($p < 0.05$ for a one-sided test)

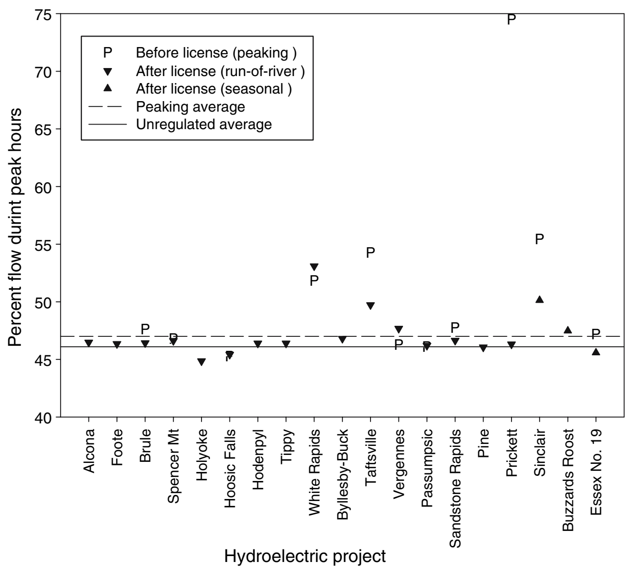

Fig. 5 Percent of flow during peak hours before (if available) and after the change from peaking to ROR operation. SE on the proportions are smaller than the symbol sizes

peaking to ROR were often proscribed to benefit aquatic resources, particularly in river systems that support migratory fish species. State water-quality certification played an important proximate role in implementing these changes.

The role of states in regulating tailwater flows has an interesting history. We noted earlier that regulation of tailwater flows began at the state level and then shifted to the federal level with ECPA legislation. In its May, 1994 "Tacoma" decision, the Supreme Court gave states the authority to set license conditions under the auspices of Section 401 of the Clean Water Act (114 S. Ct. 1900, PUD No. 1 of Jefferson County and City of Tacoma v. Washington Department of Ecology 1994). Our study supports the conclusion that state influence over license conditions has increased since that time.

Effect of License-Related Flow Mitigation on Power-Generation Efficiency

Year-to-year variation in annual flow (climate) explained the majority of variation in annual generation. We controlled for this variation by including annual flow as a covariate and focusing on efficiency. Generation efficiency did not show a significant decrease when operation changed to ROR in the majority of cases. The average effect of relicensing across projects was not significant (-9.53 MWh cms^{-1} or -0.27 MWh cfs^{-1}, which represents a 3.5% decrease in efficiency). Differences among projects in the magnitude of the intercept, b_0, and slope, b_1, are due to differences in river size and flow, differences in project head, and the number and types of turbines. We detected a significant decrease in hydropower generation per unit flow after relicensing, measured by b_2, in one quarter of the hydropower projects that changed operation. By far the largest decrease in generation efficiency was observed at one project, Vergennes. The motivation for changing operation at this particular project was to enhance the aesthetic appearance of its falls. For the remaining three quarters of projects, license modifications, including the change to ROR operation, did not have a significant negative effect. Although it was not statistically significant, this loss of efficiency postlicense could nevertheless represent a loss of generation and income to energy producers (see later).

ROR operation can increase the amount of time when generation occurs at flows that result in suboptimal turbine efficiency. Utilities owning smaller projects have less to lose in changing to an ROR mode of operation than large projects. Small projects do not generate enough energy to justify investments needed to optimize their schedules for hydropower generation, whereas at large projects, a slight change in unit loads, or a shift from peak to off-peak, can have a large effect on the value of turbine-released water. For larger projects, inefficiency can be minimized by installing double-regulated turbines (*e.g.*, Kaplan turbines), which have a flat rating curve (*i.e.*, generation is efficient at a wide range of flows; Dr. Brennan Smith, Oak Ridge National Laboratory, personal communication May 24, 2006).

We cannot be sure what the reasons were for decreased generation efficiency at the 25% of projects that showed a significant decrease because other changes could have occurred around the time that the licenses were issued. With the exception of Vergennes, the largest percentage-wise decreases in generation occurred at projects that continued peaking operation (projects on right in Fig. 3), suggesting that we should not assume that the decreases we observed were caused by the change in operation. Licenses for several of the projects in our sample acquired new minimum-flow requirements in addition to changing to ROR operation (*e.g.*, Byllesby-Buck, Pierce Mills, Passumpsic, Prickett, Taftville, Vergennes), which would decrease their generation-per-unit inflow. A summer requirement of a 4.248 cm (150 cfs) bypass flow could certainly have contributed to the large decrease at Vergennes. Of the remaining three ROR projects with significant decreases, Brule's minimum flow requirement was decreased from 2.12 to 0.425 cm (75 to 15 cfs), and we do not know if the requirements changed at Sandstone Rapids (1.416 cm [50 cfs]) or Sinclair (14.16 to 42.48 cm [500 to 1500 cfs] when not operated in ROR mode).

Effect of License-Related Flow Mitigation on the Timing of Flow Releases

The majority of projects decreased the proportion of flow during peak hours (average change was −3.6% of annual flow). Some hydropower projects in our study actually increased the proportion of flow during peak hours after relicensing. We hypothesize that these projects passed through increased flow fluctuations from upstream storage projects. Vergennes has very little storage and therefore passes through fluctuations from upstream Weybridge Dam, which apparently increased in magnitude after relicensing. Two other projects showed a significant increase in the proportion of flow during peak hours, and both are downstream of peaking projects. White Rapids on the Menominee River is below Little Quinessec Falls, and the Passumpsic project is downstream of Mio Dam and several other dams on the Passumpsic River. The project at which we observed the largest decrease was Prickett Dam on the Sturgeon River, a project that is not influenced by upstream projects. The percentage of generation during peak demand below that of Prickett Dam decreased to that of an unregulated gage upstream on the Sturgeon River (Fig. 5).

In this study, we found that a proportion of license-mandated shifts to ROR operations occurred at dams downstream of projects that continue to pass through fluctuations from upstream peaking operations. Therefore, the change to ROR operation was unlikely to yield meaningful ecologic benefits. If restoring natural flow patterns was the objective, then it might have made more sense to require owners to reregulate peaking operations from upstream dams than to require ROR operation. However, reregulation is only possible at downstream projects that have sufficient storage capacity to reshape flows. Alternatively, the change in operation could have been required of upstream storage projects. However, projects on the same river are not always owned by the same party and may not be regulated together as a group.

Economic Costs and Benefits of Changing Operation

This study was not designed to address the economic significance of changes in the amount and timing of generation that we observed, but we can provide an economic context for our results. First, our results suggest that year-to-year variation in reservoir inflows and other unknown factors contribute more economic uncertainty than the mode of operation. The total cost (or benefit) of ROR operation should account for societal values associated with hydropower production (producer value), irrigation, municipal water supply, recreation, and support of the aquatic ecosystem. The optimal timing of flows for other purposes may differ from the optimal timing of flow releases that maximize producer values. Here, we address two producer costs associated with operations: (1) decreased generation efficiency and (2) higher energy cost of fossil fuels needed to replace hydropower during peak versus. off-peak hours as well as (3) the negative costs (benefits) of environmental externalities.

The average decrease in efficiency among projects in our study was −3.6%. Only Sandstone Rapids, Foote (not shown), and one of the seasonal ROR projects (Essex No. 19) managed to increase generation -per -unit flow (Figs. 5 and 6). The average annual energy consumption of a United States household in 2005 was 11.28 MWh (US DOE [http://www.eia.doe.gov/fuelelectric.html]), so, on average, 0.406 MWh would be purchased at the higher price of fossil fuel. If this cost were passed on to rate payers (using Kotchen and others 2001 estimate of \$10.30 MWh^{-1}), our crude estimate suggests an annual increase of \$4.18 / household.

Changing to ROR operation involves the shift from generating during hours of peak demand, when energy generation is more valuable, to generating during off-peak hours, when electricity is cheaper. We note that some of the projects in our sample were more successful (*e.g.*, Prickett, Sinclair, and Taftsville) than others (*e.g.*, Vergennes and White Rapids) in reproducing a natural flow regime (Fig. 6). Therefore, power producers at projects that increased peaking operation likely profited from relicensing, whereas those at the remaining projects incurred a loss. We identified two studies that quantified losses at projects that changed operation. Harpman (1999) quantified the

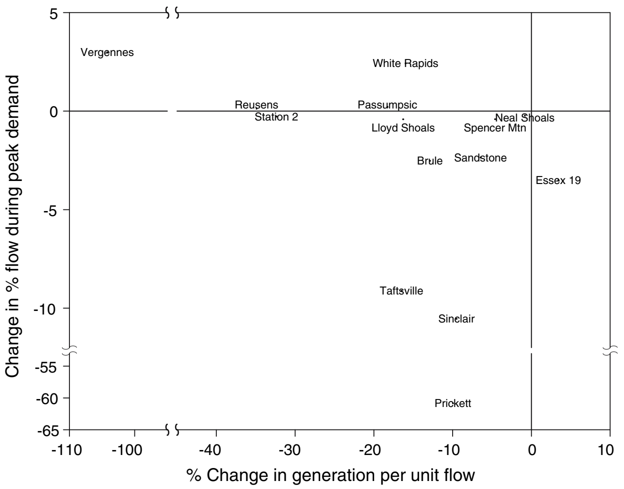

Fig. 6 License-mediated change in peaking operation and annual generation efficiency for the subset of hydropower licenses with information on both

effect of changing operation to ROR on Glen Canyon Dam on the Colorado River for a representative water year using spot market electricity values for 1995 and 1996. Shifting generation from on-peak to off-peak periods was estimated to decrease the economic value of hydroelectricity by 8.8% (Harpman 1999). Kotchen and others (2006) determined the cost of replacing peak hydropower generation at Tippy and Hodenpyle dams by purchasing energy generated by burning fossil fuels. The marginal cost of replacement thermal generation during peak hours was $10.30 per MWh greater than that generated during off-peak times ($130,000 to $180,000 y^{-1} in 2001 dollars). FERC licenses for some of our projects also provided estimates of the cost to producers. The FERC license for the Pierce Mills hydroelectric project on the Passumpsic River, Maine, provided a lower estimate for the levelized annual cost of switching to ROR operation of $2,700 or $1.67 MWh. The FERC license for the Brule project estimated that the cost of changing to ROR operation would be $93,000, or $6.37 / MWh. Therefore, the need to purchase more-expensive fossil energy can add a cost that, summed over the post-license life of the projects, results in a loss of revenue to utilities or an increased cost of energy to rate payers.

One motivation for requiring ROR operation is to restore the natural flow regime (Poff and others 1997) to benefit aquatic biota. A small number of studies have quantified the ecologic benefits of restoring a natural flow regime. Loss of rearing habitat in river margins during peaking operation is a significant concern for juvenile fish of many species. Rutherford and others (2004) found that the shift to ROR flow dramatically increased the number of Chinook salmon emigrating from the Manistee River to Lake Michigan from 100,000 to nearly 370,000 fish/Y, which resulted in lower opportunities for sports fishing /Y (see also Kotchen and others 2006). Bain (1988) found that shallow-water and slow-water fish species, which were the most abundant fishes in the unregulated river, were absent at the site that experienced the largest fluctuations in flow. Freeman and others (2001) concluded that peaking below a dam on the Tallapoosa River resulted in reproductive failure of spring-spawning fishes but not of species able to spawn after peaking operation ceased in summer.

Only one study attempted to assign monetary values to the nonproducer economic benefits of changing to ROR operation. Kotchen and others (2006) estimated that air quality and recreational fishing benefits were more than twice as large as the producer costs discussed previously. Overall, the switch to ROR was estimated to have a net economic benefit of between $500,000 and $600,000/Y when considering externalities, such as air-quality and recreational fishing benefits, in addition to replacement energy costs. One unexpected result of their study was that the change to ROR mode caused a decrease in the burning of coal and an increase in the burning of cleaner fuel oil and natural gas, leading to improved air quality and decreased greenhouse gas emissions. Under emissions trading, this benefit would likely increase in value. Nonuse values, which can be measured by determining the willingness of citizens to pay for protection of riverine populations and ecosystems, were not included in their assessment, but these can be considerable (Loomis 1998).

Regional Analysis of Hydropower Regulation

Ultimately, the level of environmental protection depends on whether policies are enforced and whether they are effective (DeShazo and Freeman 2005). Regional-scale studies of energy policy are important because they provide feedback on whether regulations are having the intended effects. Regrettably, few such studies are conducted. We found that the two largest impediments to regional-scale research of this type were (1) lack of cross-indexing between data related to hydropower facilities and that related to river flow and (2) lack of publicly available flow data. A database cross-indexing data from various United States agencies that collect data relevant to hydropower is needed that includes FERC project numbers, Energy Information Administration (EIA) plant codes, and USGS gage ids associated with each hydropower plant. A second impediment was lack of access to older (before approximately 1985) FERC licenses. However, by far the greatest impediment, which forced us to exclude many hydropower projects from our analysis, was a lack of flow data both before and after relicensing. Unfortunately, many licenses issued by the FERC have not required web-based, public access to gaging data but rather allowed the project owner (*i.e.*, utility) to keep records without providing for their dissemination to the public. In the few cases we tried, we were unsuccessful in acquiring flow data directly from project owners. We, therefore, strongly recommend that future licenses include a requirement for flow gaging by the USGS to ensure public, web-based access to flow data. In the 1994 FERC license for Foote Dam, a telemetered gage was estimated to cost 0.15¢ MWh. We also believe that agencies with responsibility for energy policy and regulation would benefit from summarizing the results of biologic and environmental monitoring collected from many isolated hydropower projects and providing these data in a usable form. Not only would this facilitate regional-scale river research, it would also increase regulatory transparency and accountability.

Acknowledgments This research was supported by the United States Department of Energy's (DOE) Energy Efficiency and Renewable Energy Office, Office of Wind and Hydropower Technologies. Oak Ridge Natural Laboratory (ORNL) is managed by UT-Battelle, LLC, for the DOE under contract DE-AC05-00OR22725. We appreciate the help provided by David Vogt (ORNL) in pointing us to energy-related data sources within the Department of Energy's Energy Information Agency. We also thank the USGS, which provided river flow data for each state. We thank Stephen Blumer (Michigan), Chandlee Keirstead (Vermont), Robert Waschbusch (Wisconsin), Ramona Traynor and Jeanne Robbins (North Carolina), Whitney Stringfield (South Carolina), Margaret Phillips (New York), Timothy Stamey (Georgia), Joel Guyer (Virginia), Linda Comeau (Massachusets), Barbara Korzendorfer (Connecticut), and Gregory Stewart (Maine). We appreciate helpful reviews by Glen Cada and Chuck Coutant. We also thank Brennan Smith (ORNL) for sharing his considerable expertise in hydropower engineering.

Appendix A

The analyses below were run using SAS$^{©}$, with and without the repeated statement, which accounts for autocorrelation. The first analysis combines all projects, and the second is fitted for each project.

All Projects Together

```
proc mixed data=gen.annual method=ML covtest noclprint=25;
   class proj_name year;
   where index(pre_oper,″Peaking″) eq 1 and
   (index(post_oper,″Run-of-River″) gt 0 or index(post_oper,″ROR″) gt 0);
   model annual_MWh = avg_cfs avg_cfs*new_license
   / solution chisq ddfm=KENWARDROGER;
   random avg_cfs / subject=proj_name type=UN;
   repeated year / subject=proj_name type=ar(1);
   title “Repeated measures model of license effect on slope, with fixed effect of project”;
   run;
```

Projects Analyzed Separately

```
proc mixed data=gen.annual method=ML covtest noclprint=25;
   class year;
   where index(pre_oper,“Peaking”) eq 1 and
   (index(post_oper,“Run-of-River”) gt 0 or index(post_oper,“ROR”) gt 0);
   model annual_MWh = avg_cfs avg_cfs*new_license
   / solution chisq ddfm=KENWARDROGER;
   random int avg_cfs / type=UN;
   /* Analyses were run with and w/out the repeated statement */
   repeated year / type=ar(1);
   by proj_name;
   title “Repeated measures model of license effect on slope, by project”;
   run;
```

References

Bain MB, Finn JT, Booke HE (1988) Streamflow regulation and fish community structure. Ecology 69:382–392

Bevelhimer MS, Jager HI (2007) Mitigation effectiveness of instream flow requirements at hydropower dams. Technical report 2006/ORNL/TM-2006/89

Box GEP, Tiao GC (1975) Intervention analysis with applications to economic and environmental problems. Journal of the American Statistical Association 70:70–79

Chatterjee B, Howitt RE, Sexton RJ (1998) The optimal joint provision of water for irrigation and hydropower. Journal of Environmental Economics and Management 36:295–313

Deshazo JR, Freeman J (2005) Public agencies as lobbyists. Columbia Law Review 105:2217–2309

Freeman MC, Bowen ZH, Bovee KD, Irwin ER (2001) Flow and habitat effects on juvenile fish abundance in natural and altered flow regimes. Ecological Applications 11:179–190

Harpman DA (1999) Assessing the short-run economic cost of environmental constraints on hydropower operations on Glen Canyon Dam. Land Economics 75:390–401

Hill J (1996) Environmental considerations in licensing hydropower projects: policies and practices at the Federal Energy Regulatory Commission. American Fisheries Society Symposium 16:190–199

Kotchen MJ, Moore MR, Lupi F, Rutherford ES (2006) Environmental constraints on hydropower: an ex-post benefit-cost analysis of dam relicensing in Michigan. Journal of Land Economics 82(3):384–403

Lamb BL (1995) Criteria for evaluating state instream-flow programs: deciding what works. Journal of Water Resources Planning and Management 121:270–274

Loomis JB (1998) Estimating the public's values for instream flow: Economic techniques and dollar values. Journal of the American Water Resources Association 34:1007–1014

Poff NL, Allan JD, Bain MB, Karr JR, Prestegaard KL, Richter BD et al. (1997) The natural flow regime. BioScience 47:769–784

Rutherford ES, Thorrold S, Woldt AP, Swank D, Godby NP (2004) Abundance, production and harvest of salmonids in the Manistee, Muskegon and Au Sable Rivers. Final Report, Michigan Department of Natural Resources, Ann Arbor, MI, 48 pp

Sensiba CR (1999) Who's in charge here? The shrinking role of the Federal Energy Regulatory Commission in hydropower relicensing. University of Colorado Law Review 70(603):603–640

Shupe SJ, MacDonnell LJ (1993) Recognizing the value of in-place uses of water in the west: an introduction to the laws, strategies, and issues. Chapter 1 *In* MacDonnell LJ, Rice TA (eds) In-stream flow protection in the West. University of Colorado School of Law

Slack JR, Landwehr JM (1992) A U.S. Geological Survey streamflow data set for the United States for the study of climate variations, 1874-1988. US Geological Survey Open-file Report 92-129, Reston, VA. Available at: http://www.pubs.usgs.gov/of/hcdn_report/.Accessed: Aug 30, 2007

Tharme RE (2003) A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. River Research and Applications 19:397–441

US Government Accountability Office (1994) Consumers could benefit from demand programs, but challenges remain. Report to the Chairman, Committee on Government Affairs, US Senate. US Government Accountability Office, Washington DC, 68 pp

Wright JD (2006) A policy analysis of the Federal Energy Regulatory Commission's hydroelectric relicensing process. Masters thesis, Humboldt State University, Redwood, CA