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Effects of Turbine Operating Efficiency on Smolt Passage Survival

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Abstract.—We conducted a retrospective analysis of data on the relationship between operating efficiency of Kaplan turbines and direct passage survival of salmonid smolts. A review of a key report instrumental in establishing ±1% turbine efficiency rule for operating Snake and Columbia river hydroelectric stations found a weak association ($r^2 = 0.112$) but also found misspecification of the turbine efficiency data. At four Snake and Columbia river dams, manipulative studies were performed to investigate the relationship between turbine performance and smolt passage survival, as estimated with balloon-tag releases and recoveries. At all sites, peak passage survival did not coincide with the observed turbine operating efficiency peak. The difference between maximum survival and survival at peak turbine efficiency was as much as 3.2%. However, at three sites, maximum survival was within the ±1% peak efficiency operating rule. A meta-analysis that used balloon-tag survival results from 11 different hydroprojects also found no association between relative turbine efficiency at a site and smolt passage survival ($r^2 = 0.0311$, $P = 0.2640$). For the benefit of smolt survival during passage, we recommend managing turbine operations to achieve maximum passage survival rather than focusing solely on peak operating efficiency of Kaplan turbines.

Safe downstream passage of salmonid smolts through hydroprojects is a key component of the recovery plan for Pacific Northwest stocks listed under the Endangered Species Act of 1973. Improving the prospects for safe passage have included increasing the likelihood that salmonid smolts bypass the turbine units entirely, as well as increasing the likelihood of survival of smolts that pass through the turbines. In the latter case, one approach has been to restrict turbine operation to conditions that are expected to optimize passage survival. Currently, the major hydroelectric projects on the Snake and Columbia rivers must operate turbine units within ±1% of peak operating efficiency. The Biological Opinion issued by the National Marine Fisheries Service (NMFS 1994, 2000) and the 1994 Columbia River Fish and Wildlife Program, Section 5.6D.1 (Northwest Power Planning Council 1994) have similar specifications. This operating requirement is based on the belief that ‘‘turbine survival is directly related to turbine efficiency’’ (NMFS 1994) with highest survival rates occurring at peak turbine operating efficiency. However, NMFS acknowledges that, ‘‘the precise benefits of increased turbine efficiency. . . are unknown’’ (NMFS 1994). The survival relationship used to establish this policy was based on the early investigations of Long and Marquette (1967) and M. C. Bell (U.S. Army Corps of Engineers, unpublished report). Gordon (2001) provides a review of the calculations for determining turbine efficiency.

The purpose of our investigation was to reexamine the evidence presented in Bell (unpublished report) and compare it with more recent data generated by balloon-tag releases and recoveries of salmonids conducted by Normandeau Associates (1994–2000; Appendix A). The balloon-tag studies include site-specific investigations where turbine passage survival was estimated at alternative operating levels at four different hydroprojects in the Pacific Northwest. Our review concludes with a meta-analysis of 49 different balloon-tag survival estimates from 14 turbine units at 11 different hydroprojects across the country. Throughout these retrospective analyses, only Kaplan turbines

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were considered to enhance the comparability of the comparisons. We examined Kaplan turbines because 13 of the 16 major hydroprojects on the Columbia and Snake river system use Kaplan turbines for some or all of their hydroelectric production.

Historical Data

For numerous hydroelectric projects, Bell (unpublished report) compiled results on turbine passage survival of salmonid smolts and turbine operating conditions, such as head, turbine efficiency, discharge, and blade style. Despite the many comparisons performed in the Bell compendium, only at Big Cliff Dam in 1964 and 1966 was smolt survival regressed against turbine efficiency for Kaplan-type turbines. In the first year of study, a significant relationship was found ($P = 0.017$, $r^2 = 0.254$, $N = 39$). During the second year of trials, no significant relationship was found between turbine efficiency and smolt survival ($P = 0.258$, $r^2 = 0.020$, $N = 36$). Nevertheless, the combined 2-year study found a significant relationship ($P = 0.003$, $r^2 = 0.112$, $N = 75$). For turbine efficiencies ranging from 33–96%, passage survival was investigated for chinook salmon *Onchorynchus tshawytscha* smolts averaging 101 mm long. Bell (unpublished report) concluded, ‘‘There does not seem to be a smooth ascending and descending curve following the efficiency line of the turbines as might have been expected.’’ The likely reason why a curvilinear survivorship curve with turbine efficiency was not observed was because Bell used percent wicket-gate opening as a surrogate for turbine efficiency. Although percent wicket-gate opening has an effect on turbine efficiency, they are not synonymous. Nevertheless, Bell (unpublished report) concluded that, ‘‘The data offer some support, however, to the hypothesis that the best points of machine efficiency should give the best points of fish passage survival.’’ However, we believe Bell presents no valid information on the relationship between turbine efficiency of Kaplan turbines and smolt passage survival.

Site-Specific Balloon-Tag Investigations

At four Snake and Columbia river projects (i.e., Lower Granite, Wanapum, Rocky Reach, and Bonneville dams), turbine operating levels were manipulated to investigate the relationship between smolt survival and turbine efficiency. All reported survival estimates were for 1-h observed survival following the balloon-tag release and recovery trials. The field trials consisted of paired releases of smolts that were uniquely coded and equipped with uninflated balloon tags and miniature radio tags. The test fish were released into the turbine unit though an induction tube with flowing river water; controls were concurrently released in a similar manner but into the turbine discharge. The balloon tag inflates shortly after release and, in conjunction with the radio tag, facilitates recovery. The tagged fish were released one at a time to permit downstream recovery crews to retrieve the individuals and assess their survival status. Alive fish upon recovery were held in flow-through tanks to determine their 1-h postrelease survival status. Number of tagged smolts recovered alive or dead or that escaped were counted for both turbine and control release groups. Maximum likelihood estimation was used to account for recovery efficiency and to estimate the probability of turbine passage survival. Details of the balloon-tagging and release methods and estimation procedure can be found in Mathur et al. (1996). The estimates of turbine passage survival from the analysis are functions of direct mortality and do not necessarily incorporate indirect or delayed effects associated with turbine passage.

At Lower Granite Dam (Normandeau Associates and Skalski 1995; Mathur et al. 2000), a Kaplan turbine was operated at three different discharge levels of 382.3, 509.7, and 538.0 m^3/s, which respectively correspond to discharge values at the low end of the ±1% peak efficiency, at or near peak efficiency, and at an excessive flow for the blade angle that resulted in cavitation of the turbine. Turbine cavitation occurs when the flow field is disrupted, resulting in partial vacuums that collapse, causing pitting and other damage to the metal surfaces in contact with the water. Releases through the turbine ranged from 250 to 320 fish/test condition; the corresponding control releases ranged from 250 to 320 fish/trial. Spring chinook salmon smolt (mean total length = 150 mm) survival was estimated to be 0.972 ($\widehat{SE} = 0.012$), 0.953 ($\widehat{SE} = 0.013$), and 0.946 ($\widehat{SE} = 0.013$), respectively (Figure 1). This six-blade Kaplan turbine was operated at 90 revolutions/m (rpm), with a head of 29.9 m. None of the survival estimates were significantly different ($P > 0.05$). In this study, maximum observed survival did not occur at peak observed efficiency nor was survival significantly lower under cavitation mode than within ±1% of peak operating levels.

At Wanapum Dam (Normandeau Associates et al. 1996), a five-blade Kaplan turbine with a speed of 87.5 rpm was operated at four different dis-

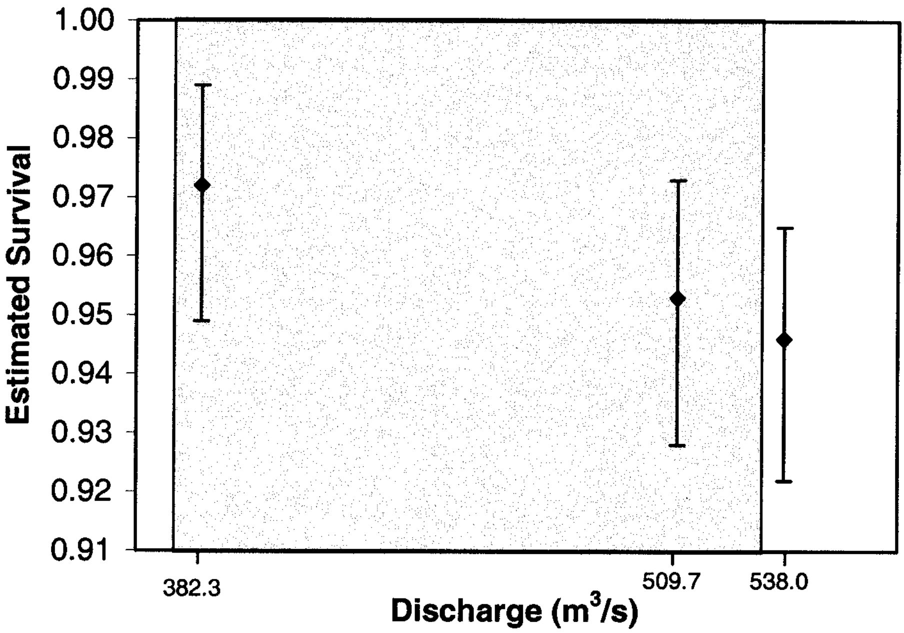

FIGURE 1.—Plots of salmonid smolt survival estimates and associated 95% confidence intervals versus discharge level for a Kaplan turbine at Lower Granite Dam, Washington, 1995. The shaded area indicates treatments that were within 1% of peak turbine efficiency.

charge levels (i.e., 254.9, 311.5, 424.8, and 481.4 m^3/s) during balloon-tag trials. Coho salmon *O. kisutch* smolts (mean total length = 154 mm) were released during these trials at two different locations, 3.0 m and 9.1 m below the turbine intake ceiling. The number of fish released through the turbine ranged from 158 to 160 per test condition; the paired control releases were 160 fish per trial. Fish released at the 9.1-m depth had consistently higher survival rates than fish released 3.0 m below the intake ceiling (Figure 2). The 3-m depth corresponds roughly to releases near the hub, whereas the 9.1-m depth corresponds to releases near the midblade, provided the fish remain in the flow lines. The release location effect ($P < 0.001$) on smolt survival was significant, as was a curvilinear trend ($P = 0.0273$) in survival rates versus discharge levels. The curvilinear survival trend with discharge is what Bell (unpublished report) anticipated but did not observe during his trials. However, the maximum observed survival did not correspond to the peak observed turbine efficiency at either release location. Moreover, the maximum observed survival occurred outside the zone of ±1% of peak efficiency (Figure 2).

At Rocky Reach Dam (Normandeau Associates et al. 1996), balloon-tag trials were performed at two different release locations within the turbine intake (3.0 and 9.1 m below the intake ceiling) and at three different turbine discharge levels of a six-blade Kaplan turbine. The turbine operated at 90 rpm with an approximate head of 28.0 m. The discharge levels for the three different turbine operating levels were 226.5, 339.8, and 453.1 m^3/s. The sample sizes for the in-turbine releases ranged from 71 to 165 fish/trial; the paired control releases ranged from 65 to 115 fish/trial. Once again, release location had an appreciable effect ($P = 0.1151$) on chinook salmon smolt (mean total length = 184 mm) survival with a nonsignificant curvilinear trend ($P = 0.1272$) as a function of discharge. Peak survival for both release locations occurred at a discharge of 339.8 m^3/s but did not coincide with peak observed turbine efficiency (Figure 3). The efficiency curve in this test had a very gentle slope, wherein all test conditions were within ±1% of peak turbine efficiency. Nevertheless, the parallelism and convex shape of the survivorship curves (Figure 3) suggest peak survival was within the range of discharge levels tested. Consequently, although peak survival did not coincide with peak observed efficiency, peak survival was within the zone of ±1% of peak efficiency.

During the winter of 1999–2000, an intensive balloon-tag study (Normandeau Assocaites et al.

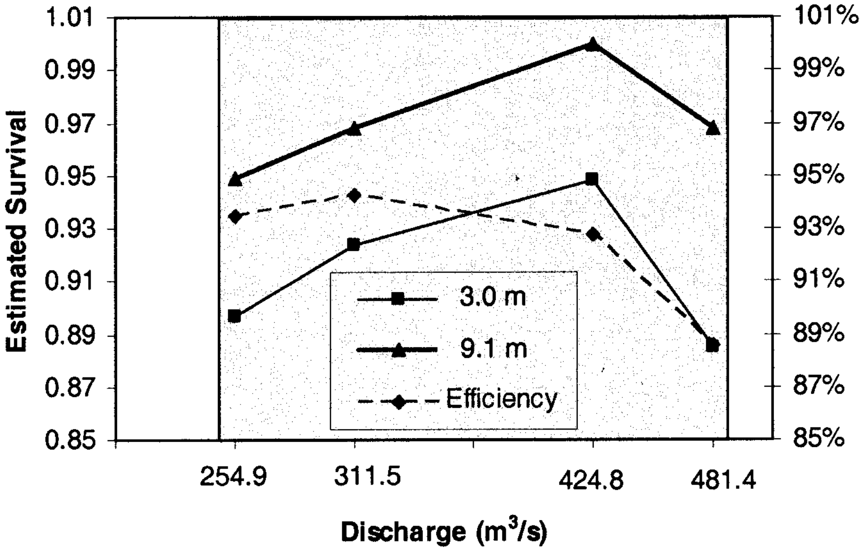

FIGURE 2.—Plots of estimated salmonid smolt survival at Wanapum Dam, Washington, in 1996 as a function of release location within the turbine intake and discharge level. Also plotted are the turbine efficiencies as a function of discharge level. The shaded area is within the zone of ±1% of peak turbine efficiency.

2000) was performed at Bonneville Dam, where at a standard Kaplan turbine, smolt survival was estimated at four different discharge levels (175.6, 198.2, 297.3, and 339.8 m^3/s) and at three different release locations (hub, tip, and mid-blade). The hub and midblade releases were 2 m and 0.9 m above the wicket gates, respectively. The tip release was 0.1 m below the wicket gate elevation. The standard five-blade Kaplan turbine ran at a speed of 75 rpm and an average head of 17.4 m. Releases through the turbine ranged from 170 to 264 fish/test condition; the paired control releases ranged from 140 to 200 fish/trial. The survivorship profiles for the tip and midblade releases show strong parallelism with both profiles showing maximum survival at 297.3 m^3/s. For the tip and midblade releases, maximum survival coincided with peak observed efficiency (Figure 4). For the hub releases, which had generally higher survival, maximum survival did not occur with peak observed turbine efficiency (Figure 4). Consequently, at Bonneville Dam, peak survival will depend on the distribution of the fish passage through the turbine unit.

Additional analyses, regressing daily survival estimates against turbine operating conditions dur-

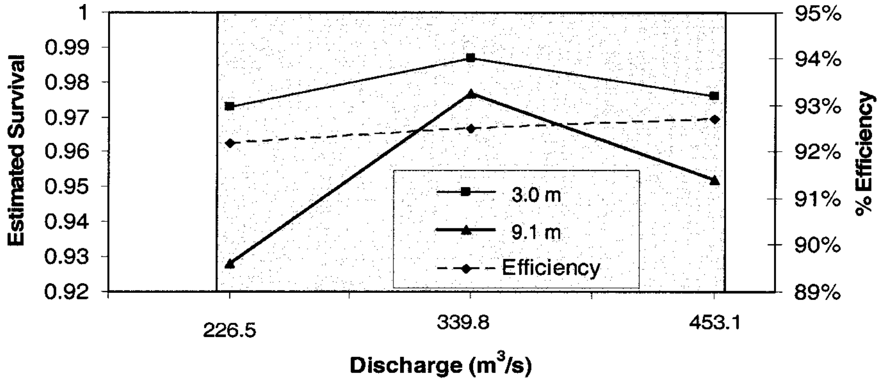

FIGURE 3.—Plots of estimated salmonid smolt survival at Rocky Reach Dam, Washington, 1996, as a function of release location within the turbine intake and discharge level. Also plotted are turbine efficiencies as a function of discharge level. The shaded area is within the zone of ±1% of peak turbine efficiency.

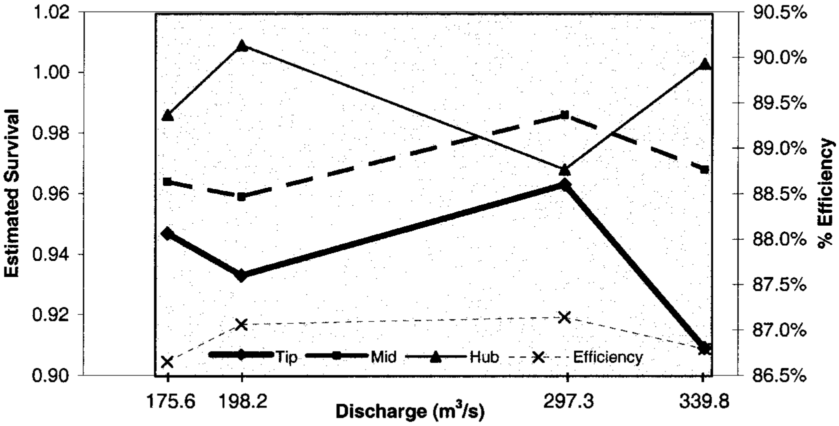

FIGURE 4.—Plots of estimated salmonid smolt survival at Powerhouse No. 1 of Bonneville Dam, Washington, 1999–2000, as a function of discharge level and release location (i.e., blade tip, midblade, or hub) within the turbine intake. Also plotted are turbine efficiencies as a function of discharge level. The shaded area is within the zone of ±1% of peak turbine efficiency.

ing the course of the 3-month Bonneville Dam study, were performed. No significant relationship was found between chinook salmon survival (mean total length = 166 mm) and turbine efficiency for smolts released at the hub ($P = 0.5892$, $r^2 = 0.0213$), tip ($P = 1.0$, $r^2 = 0$), or midblade ($P = 0.9276$, $r^2 = 0.0005$; Figure 5). Similarly, no relationships were found between smolt survival and average head, blade angle, power generation level, or discharge ($P > 0.05$) during the Bonneville Dam trials.

Cross-Study Analysis

Using survival estimates generated from balloon-tagging studies including 49 different trials, 14 different Kaplan turbine units, and 11 different hydroprojects (Appendix A), we investigated relationships between fish survival and species, size, and turbine operating conditions. Although these studies are observational, they provide an additional opportunity for examining the relationship between turbine passage survival and a wider range of conditions. This exploratory investigation between turbine efficiency and fish survival also provided little evidence to support the ±1% peak efficiency rule. Although fish size was significantly related to turbine passage survival ($P = 0.0016$, $r^2 = 0.1930$), turbine efficiency was not ($P = 0.2640$, $r^2 = 0.0311$; Figure 6). Over the range of fish sizes tested (mean total length = 82.0–342.9 mm), as fish size increased, so did turbine passage mortality. Other turbine conditions such as number of blades ($P = 0.0260$, $r^2 = 0.1011$), speed ($P = 0.0180$, $r^2 = 0.1135$), and head ($P = 0.1145$, $r^2 = 0.0522$) appear more likely to be related to fish survival than turbine efficiency. When only the data from salmonids are analyzed (Appendix A), conclusions concerning turbine efficiency remain unchanged ($P = 0.1320$, $r^2 = 0.0792$). Additional information on the relationship of blade number, rotational speed, and fish size on turbine passage survival is available in EPRI (1987).

Conclusion

The results of the Kaplan turbine studies reported by Bell (unpublished report) showed a linear trend of increased turbine passage survival with increasing turbine efficiency. This linear trend, significant in one year but not the next, was contrary to the expectations of Bell (unpublished report), who expected a curvilinear trend for survival as efficiency peaked and then waned. We contend that Bell (unpublished report) did not actually measure turbine efficiency during his experiments.

In more recent studies conducted in the Pacific Northwest using balloon-tagging and recapture, smolt passage survival demonstrated the expected curvilinear trend in survival as related to discharge volume and turbine operating efficiency. However, peak observed survival did not coincide with peak turbine efficiency at Lower Granite, Wanapum, or Rocky Reach dams. At Bonneville Dam, peak observed survival coincided with turbine efficiency for the blade-tip and midblade releases but not the hub release (Figure 4). However, the range of turbine efficiencies examined during these studies was somewhat limited. The existing turbine operating rules in the Snake and Columbia river basins do not readily permit data collection outside the ±1% narrow band of efficiency levels. Hence, inferences to turbine passage survival are limited by the very turbine operating rules we wished to test. For this reason, information outside the Pacific Northwest was also examined.

The meta-analysis using the results from 11 different hydroprojects also found no relationship between turbine passage survival and turbine operating efficiency. Although the data are quite variable and include salmonids and nonsalmonids, the regression analysis was sensitive enough to detect a relationship between fish size and turbine passage survival, as well as relationships between passage survival versus number of blaces and speed. These regression results are consistent with findings reported by EPRI (1987). Hence, none of the investigations reported in this retrospective analysis provide compelling evidence for a strong relationship between turbine operating efficiency and turbine passage survival. If a survival relationship does exist, the more recent balloon-tag studies suggest a curvilinear relationship, where peak survival is not necessarily coincident with peak turbine efficiency.

Generally, the turbine efficiency curves for Kaplan turbines have shallow slopes, such that the ±1% rule encompasses a wide range of discharge levels. In so doing, the zone of operating conditions within 1% of peak efficiency will probably also encompass the maximum turbine passage survival. As such, the ±1% efficiency rule, in the broadest sense, is a useful guide for managing turbine operating conditions for the benefit of smolt passage survival. However, there can be an appreciable difference between peak observed survival and the survival at peak turbine operating efficiency; for example, at Wanapum Dam, this difference was as much as 3.2% (9.1-m release location). This difference in survival is as great as the benefits of some other mitigation efforts under consideration at hydroprojects in the Snake and Columbia river basins (e.g., surface bypass col-

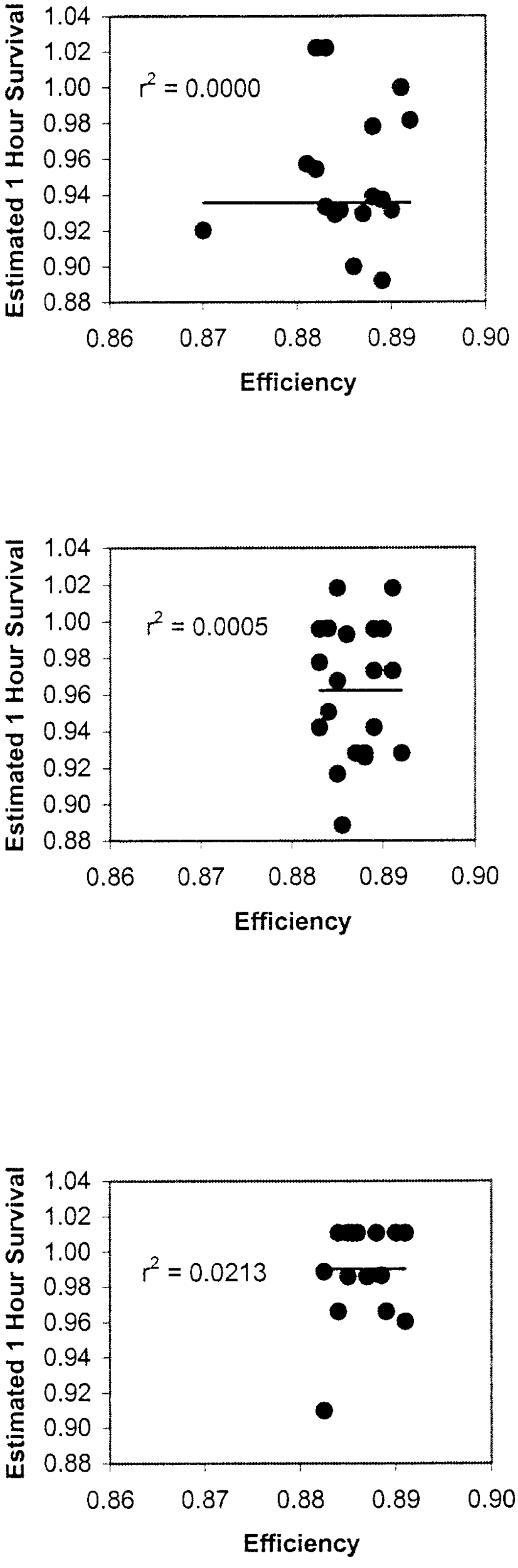

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FIGURE 5.—Scatter plots of estimated salmonid smolt survival versus turbine efficiency for the tip (top panel), mid-blade (middle panel), and hub (bottom panel) releases at turbine 5, Powerhouse No. 1, Bonneville Dam, Washington. The horizontal lines are the mean survival estimates calculated from pooling the replicate release data.

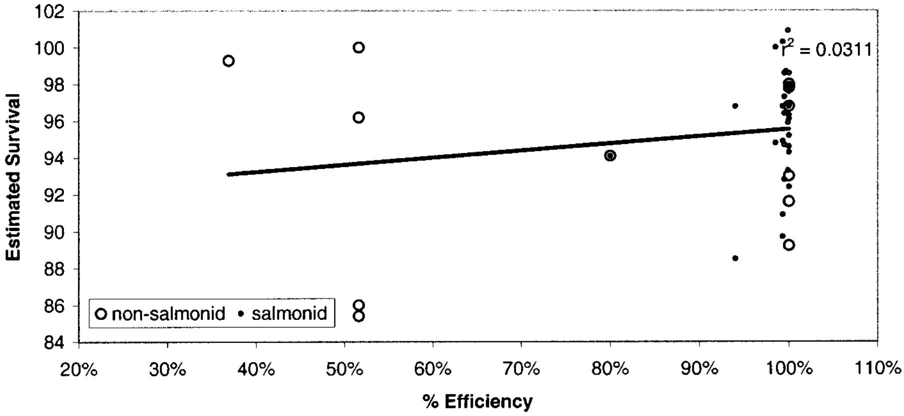

FIGURE 6.—Scatter plot of fish survival versus turbine efficiency from studies at 11 different hydroprojects. (See Appendix for details.)

lectors, diversion screens). The survival benefit in this case, however, can be more rapidly achieved, and without major new capital investment, by simply fine-tuning the turbine operations and modifying the ±1% efficiency rule. As a new generation of turbines is developed to replace existing equipment, the premise of the ±1% efficiency rule needs to be carefully reexamined so that optimal operating conditions for the fisheries resource can be better defined.

References

EPRI (Electric Power Research Institute). 1987. Turbine-related fish mortality: review and evaluation of studies. Eicher Associates, Inc. Report AP-5480 prepared for EPRI, Palo Alto, California.

Gordon, J. L. 2001. Hydraulic turbine efficiency. Canadian Journal of Civil Engineers 28:238–253.

Long, C., and W. Marquette. 1967. Research on fingerling mortality in Kaplan turbines. Bureau of Commercial Fisheries, Seattle.

Mathur, D., P. G. Heisey, E. T. Euston, and J. R. Skalski. 1996. Turbine passage survival estimation for chinook salmon smolts (*Oncorhynchus tshawytscha*) at a large dam on the Columbia River. Canadian Journal of Fisheries and Aquatic Sciences 53:542–549.

Mathur, D., P. G. Heisey, J. R. Skalski, and D. R. Kenney. 2000. Salmonid smolt survival relative to turbine efficiency and entrainment depth in hydroelectric power generation. Journal of the American Water Resources Association 36:737–747.

NMFS (National Marine Fisheries Service). 1994. Endangered Species Act section 7 consultation regarding 1994–1998 operation of the federal Columbia River power system and juvenile transportation program in 1994–1998. NMFS, Northwest Region, Seattle.

NMFS (National Marine Fisheries Service). 2000. Endangered Species Act section 7 consultation draft biological opinion on the operation of the federal Columbia River power system including the juvenile fish transportation program and the Bureau of Reclamation's 31 projects, including the entire Columbia Basin project. NMFS, Northwest Region, Seattle.

Normandeau Associates, and J. R. Skalski. 1995. Turbine passage survival of juvenile chinook salmon (*Oncorhynchus tshawytscha*) at Lower Granite Dam, Snake River, Washington. Normandeau Associates, Inc. Report for U.S. Army Corps of Engineers, Walla Walla District, Walla Walla, Washington.

Normandeau Associates, and J. R. Skalski. 1996. Relative survival of juvenile chinook salmon (*Oncorhynchus tshawytscha*) in passage through a modified Kaplan turbine at Rocky Reach Dam, Columbia River, Washington. Normandeau Associates, Inc. Report for Public Utility District 1 of Chelan County, Wenatchee, Washington.

Normandeau Associates, J. R. Skalski, and Mid-Columbia Consulting, Inc. 1996. Fish survival investigation relative to turbine rehabilitation at Wanapum Dam, Columbia River, Washington. Normandeau Associates, Inc. Report for Grant County Public Utility District Number 2, Ephrata, Washington.

Normandeau Associates, J. R. Skalski, and Mid-Columbia Consulting, Inc. 2000. Direct passage survival and condition of juvenile chinook salmon passed through an existing and new minimum gap runner turbines at Bonneville Dam, First Powerhouse, Columbia River. Normandeau Associates, Inc. report for U.S. Army Corps of Engineers, Portland District, Portland, Oregon.

Northwest Power Planning Council. 1994. 1994 Columbia River Basin fish and wildlife program. Northwest Power Planning Council, Portland, Oregon.

Appendix: Summary of Kaplan turbine balloon-tag survival studies.

TABLE A.1.—Results from balloon-tagged salmonids released and recaptured in studies at Kaplan turbines across the United States.

Location	Turbine discharge (m^3/s)	Number of blades	Runner speed (rpm)	Head (m)	Runner diameter (cm)	Relative efficiency (%)[a]	Species	Mean total length (mm)	Mean (SE) % survival to 1 h
Chalk Hill, Michigan–Wisconsin	25.5	5	100	8.8	343	1.000	Rainbow trout	220.0	89.2 (3.7)
Townsend Dam, Pennsylvania	22.7	3	152	4.9	287	0.516	Largemouth bass	101.6	100.0
	22.7	3	152	4.9	287	0.516	Largemouth bass	215.9	86.0 (4.9)
	22.7	3	152	4.9	287	0.516	Rainbow trout	139.7	96.2 (2.6)
	22.7	3	152	4.9	287	0.516	Rainbow trout	342.9	85.4 (5.1)
Hadley Falls, Massachusetts (Unit 1)	43.9	5	128	15.8	432	0.369	Shad	82.0	99.3 (5.2)
Hadley Falls, Massachusetts (Unit 1)	118.9	5	128	15.8	432	1.000	Shad	82.0	93.0 (5.9)
Hadley Falls, Massachusetts (Unit 2)	118.9	5	150	15.8	432	1.000	Shad	82.0	91.6 (4.0)
Wilder, Vermont–New Hampshire	127.4	5	112.5	15.5	274	1.000	Atlantic salmon	191.0	96.1 (1.8)
Rocky Reach, Washington (Unit 3)	453.1	6	90.0	28.0	711	1.000	Chinook salmon	145.0	94.3 (1.0)
Rocky Reach, Washington (Unit 8)	566.3	5	85.7	26.4	790	1.000	Chinook salmon	130.0	96.9 (2.6)
Wanapum, Washington (3.0 m)	254.9	5	85.7	22.7	724	0.993	Coho salmon	154.0	89.7 (2.7)
	311.5	5	85.7	22.7	724	1.000	Coho salmon	154.0	92.4 (2.3)
	424.8	5	85.7	22.7	724	0.985	Coho salmon	154.0	94.8 (2.2)
	481.4	5	85.7	22.7	724	0.940	Coho salmon	154.0	88.5 (2.6)
Wanapum, Washington (9.1 m)	254.9	5	85.7	22.7	724	0.993	Coho salmon	154.0	94.9 (2.0)
	311.5	5	85.7	22.7	724	1.000	Coho salmon	154.0	96.8 (1.7)
	424.8	5	85.7	22.7	724	0.985	Coho salmon	154.0	100.0 (1.3)
	481.4		85.7	22.7	724	0.940	Coho salmon	154.0	96.8 (1.4)
Lower Granite, Washington	594.7	6	90.0	29.9	792	1.000	Chinook salmon	147.5	94.6 (1.0)
Safe Harbor, Pennsylvania (Unit 7)	260.5	5	109	16.8	564	1.000	Shad	113.0	98.0 (1.4)
Safe Harbor, Pennsylvania (Unit 9–unvented)	226.5	7	75.0	16.8	615	1.000	Shad	111.8	97.8 (1.5)
Safe Harbor, Pennsylvania (Unit 9–vented)	226.5	7	75.0	16.8	615	1.000	Shad	117.1	96.8 (1.8)
Conowingo, Maryland	283.2	6	120	27.4	572	0.800	Shad	124.5	94.1 (4.4)
Rocky Reach, Washington (Unit 5, 3 m)	226.5	6	90	28.0	711	0.995	Chinook salmon	184.0	97.3 (1.9)
	339.8	6	90	28.0	711	0.997	Chinook salmon	184.0	98.7 (1.3)
	453.1	6	90	28.0	711	1.000	Chinook salmon	184.0	97.6 (2.3)
Rocky Reach, Washington (Unit 5, 9.1 m)	226.5	6	90	28.0	711	0.995	Chinook salmon	184.0	92.8 (4.3)
	339.8	6	90	28.0	711	0.997	Chinook salmon	184.0	97.7 (3.0)
	453.1	6	90	28.0	711	1.000	Chinook salmon	184.0	95.2 (2.3)
Bonneville, Oregon–Washington (Unit 5, tip)	175.6	5	75	17.4	711	0.995	Chinook salmon	155.0	94.7 (1.6)
	198.2	5	75	17.4	711	0.999	Chinook salmon	155.0	93.3 (1.7)
	297.3	5	75	17.4	711	1.000	Chinook salmon	155.0	96.3 (1.5)
	339.8	5	75	17.4	711	0.993	Chinook salmon	155.0	90.9 (1.9)
Bonneville, Oregon–Washington (Unit 5, mid)	175.6	5	75	17.4	711	0.995	Chinook salmon	155.0	96.4 (1.4)
	198.2	5	75	17.4	711	0.999	Chinook salmon	155.0	95.9 (1.4)
	297.3	5	75	17.4	711	1.000	Chinook salmon	155.0	98.6 (1.1)
	339.8	5	75	17.4	711	0.993	Chinook salmon	155.0	96.8 (1.4)
Bonneville, Oregon–Washington (Unit 5, hub)	175.6	5	75	17.4	711	0.995	Chinook salmon	155.0	98.6 (1.2)
	198.2	5	75	17.4	711	0.999	Chinook salmon	155.0	100.9 (7.7)
	297.3	5	75	17.4	711	1.000	Chinook salmon	155.0	96.8 (1.6)
	339.8	5	75	17.4	711	0.993	Chinook salmon	155.0	100.3 (0.6)
Lower Granite, Washington (Unit 4, mid, Intake A)	382.3	6	90	29.9	792		Chinook salmon	150	97.2 (1.2)
	509.7	6	90	29.9	792		Chinook salmon	150	95.3 (1.3)
	538.0	6	90	29.9	792		Chinook salmon	150	94.6 (1.3)
Lower Granite, Washington (Unit 4, mid, Intake B)	509.7	6	90	29.9	792		Chinook salmon	150	97.5 (1.1)
Lower Granite, Washington (Unit 4, mid, Intake C)	509.7	6	90	29.9	792		Chinook salmon	150	97.5 (1.1)
Rock Island, Washington (Unit 5, PH#1)	226.5	6	100	13.7	574		Chinook salmon	179	97.9 (1.2)
	226.5	6	100	13.7	574		Chinook salmon	179	95.7 (1.7)

[a] Relative turbine efficiency standardized to percent of maximum peak efficiency within a turbine unit; where blank, turbine efficiency measurements were not available.