Identifying Promising Juvenile Salmonid Dam Passage and Survival Improvements through Simulation Modeling

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ABSTRACT
A simulation model was created to identify dam operations and configurations that provided high survivals for Juvenile salmonids migrating out of the Snake River. Regional fisheries managers sought to identify ways to operate and configure the dams and the fish transportation system (barging) to provide safe passage conditions and survival rates that met or exceeded criteria set forth in the Biological Opinion. The challenge was to determine whether a candidate operation or construction item provided the expected survival benefits when the operations and configurations of the entire system were considered. The expected influence of candidate operations and configurations was simulated to screen many millions of combinations and identify the subset that met minimum criteria. Acceptable combinations exhibited a range of survival values, construction costs, and power revenues. This approach provided a set of cost effective combinations from which a mix of survival benefits, construction costs, and power revenues could be chosen to meet stewardship goals.

Introduction

The Walla Walla District of the Corps of Engineers oversees five of the eight hydropower dams encountered by juvenile salmonids migrating out of the Snake River during their downstream migration to the Pacific Ocean. The Corps has worked with federal, state, and tribal fisheries managers who share the stewardship responsibility for anadromous salmonids to identify hydropower operations and configurations with a potential to improve fish passage conditions and survival.

Choosing which operations and construction items will yield the greatest improvement in juvenile salmon survival requires managers to evaluate a complex mix of survival benefits, construction costs, and revenue from power generation. These costs and benefits are distributed across five Walla Walla District projects and must be evaluated for several populations of fish. The evaluation must also consider how the juvenile fish transportation system alters the proportion of a population that encounters improvements at downstream dams.

To evaluate operations and construction items within the context of the entire system, Battelle and its subcontractor, Decision Support, developed a model called the Major System Improvements Analysis (MSIA) model to estimate survival benefits, construction costs, and power revenue across the Federal Columbia River Power System (FCRPS) dams. By simulating millions of combinations of operations and construction items, it was possible to identify a subset that met the survival criteria in the Biological Opinion (BiOp) (NMFS 2000). Combinations with high survivals but low construction costs or high power revenues were selected as top performers because they represent the best available balance of benefits and costs. By examining which operations and construction items were present in top-performing combinations, it was possible to identify which items contributed to high survival that also exhibited other desirable characteristics, such as cost effectiveness.

The findings demonstrate the utility of the model and the approach of evaluating alternatives in combination across the system. This approach was a rapid and efficient way to identify those combinations of operations and construction items that can meet regulatory criteria and stewardship objectives.

Objective

The objective of this project was to develop a model to identify operational alternatives and construction items that would allow the hydrosystem to meet the criteria for fish survival found in the Biological Opinion (BiOp) (NMFS 2000). To accomplish the objective, the model simulated the performance of combinations of construction items and operational alternatives. Promising construction items and operational alternatives could then be identified by their frequent occurrence in combinations with high survivals, low costs, and high revenues.

Methods

A model of fish passage and survival was created to simulate the influence of alternative operations and configurations of hydroelectric projects on the Snake and Columbia rivers. Fish passage and survival were simulated at each project and surviving fish were tracked downstream to the next project where the process would continue. The model also tracked fish through the transportation system, which allows some fish to be barged past downstream dams. Combinations that met survival criteria were analyzed further to evaluate tradeoffs among survival, construction costs, and power revenues. Combinations with high survival for a given level of construction costs and power revenues were chosen to illustrate the best available tradeoffs.

The Hydropower System

The hydrosystem encountered by migrating juvenile Snake River salmonids includes eight hydropower projects, five of which (Lower Granite, Little Goose, Lower Monumental, Ice Harbor, and McNary) are under the direction of the Walla Walla District of the Corps (see Figure 1). Though superficially similar, each project is unique in the way it is configured and operated, how fish approach, and where along the migration route it is situated. Four of the five Walla Walla projects have the capability to transport, by barge or truck, fish collected in their juvenile bypass systems. Operations during the fish migration season are specified in an annually updated Fish Passage Plan (USACE 2005), developed by regional fish managers. The plan includes detailed provisions designed to provide good fish passage conditions for the dominant species or populations in the river at a given time of year. For the purposes of this study, the system is considered to be a collection of routes configured and operated to promote good passage and survival for migrating juvenile salmonids.

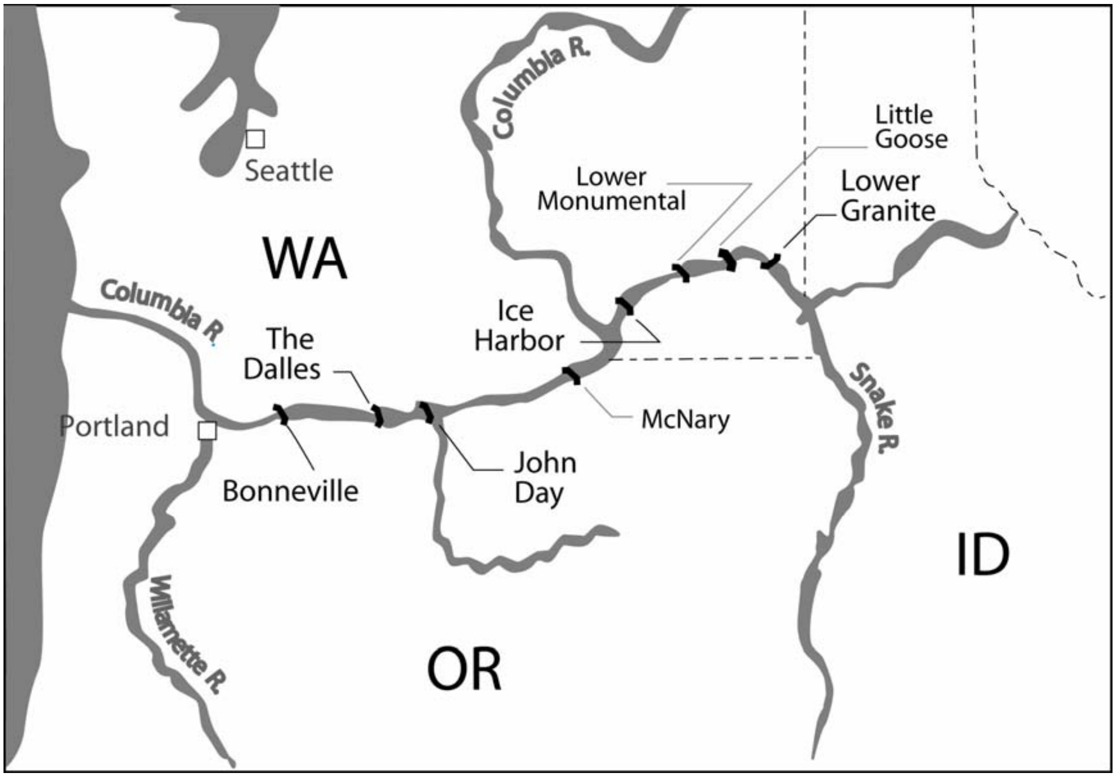

Figure 1. Dams Encountered by Snake River Salmon and Steelhead during their Migration to the Pacific Ocean.

Fish guidance screens at dams allow some juvenile salmonids entering turbine intakes to be routed into a juvenile fish facility instead of passing through the turbines. Once in a Juvenile Fish Bypass System, fish can be returned to the river or collected and transported by barge or truck for release to the river downstream of all dams. Lower Granite, Little Goose, Lower Monumental, and McNary dams have the juvenile fish facilities required to collect, hold, and load fish for transport. Ice Harbor Dam does not have the capability to transport fish.

Transporting a large proportion of migrants leaves a small proportion to encounter downstream projects and their associated passage and survival conditions. The potential of upstream transportation alternatives to influence whether downstream alternatives are effective is one reason that analyzing the system as a whole is more likely to identify the best combinations of alternatives than a project-by-project approach.

Optimization Tool (MSIA Model)

The Major System Improvements Analysis (MSIA) model was developed by Battelle and its subcontractor, Decision Support, for this project. The model simulates fish passage and survival of migrating salmon and steelhead smolts while applying alternative structural and operational modifications to the eight dams on the Snake and Lower

Columbia Rivers. Survival, construction costs, and power revenues are estimated for combinations of operational and structural alternatives.

In addition to operations, the model can simulate many proposed construction items at each project. Those items may alter fish passage routing, route specific survival, or both. Potential project enhancements to survival currently available for evaluation include divider walls, spillway improvements (modifying/relocating deflectors), new outfall locations, turbine improvements, new or modified fish facilities, extended screens, and new barges. Each of these enhancements can potentially increase survival for one or more routes. All combinations of construction items at the five projects currently amount to about 17,000,000. If these enhancements are combined with the 18,000 operational combinations, then the total number of combinations exceeds $3x10^{11}$ and could easily exceed $3x10^{15}$ if species, route flows, etc., are considered. The optimization software OptQuest©, a component of the Excel© plug-in Crystal Ball© (Decisioneering, Inc., Denver, CO, USA) was used to allow the model to simulate many combinations and identify the best performers among them.

Operational Alternatives

Operational alternatives are ways of routing water through the various structures at the dam to alter the proportion of fish going through each passage route. The proportion of fish passing a route varies according to a number of factors, including the proportion of flow going through the route, species, time of day, and others. Survival also varies among routes and may differ among species for a given route. Many of the options available to improve fish survival involve efforts to increase the proportion of fish passing routes where survivals are high.

Power is generated as water passes through turbines. Spilling water over the spillway or other non-turbine routes does not generate power. Because spillway passage often results in higher survival than does turbine passage, a trade-off arises between power generation and fish survival. Simulation results illustrate the tradeoff by showing how achieving the highest potential survival sometimes limits the potential for power generation. Conversely, the analysis illustrates how achieving the highest potential for power generation sometimes limits survival. This tradeoff could become less critical in the future as work continues on the development of fish-friendly turbine technologies.

Many factors influence the demand for power, at time scales from annual to hourly, and the supply of water varies from year to year and from spring to summer. Our model included values for the expected amount of revenue created by a given volume of water in the spring and summer and for day and night (provided by Michael J. Egge of the Northwest Division and Craig A. Newcomb of the Walla Walla District of the Corps of Engineers, June 18, 2004). This simplified representation of how supply, demand, and value for power differ through time is intended to be replaced by a detailed analysis when a limited number of combinations have been selected.

Construction Items

A broad range of construction items have been proposed to enhance the survival or routing of fish. Construction items are physical changes to the structure of the dam. Each item was expected to improve route-specific survival, fish routing, or both. Unlike most operational alternatives, construction items have a quality of permanence. Once constructed, the item is always available, although it may not have an effect under certain operational conditions. This permanence creates the need to consider the value of an item across seasons and years.

Each item is specific to a location, with the exception of barges which are used across all transport locations. Some items, such as spillway improvements, include several improvements grouped into a single item for simplicity. Items were evaluated as if they were independent, though some items may complement each other. For example, a behavioral guidance structure may direct more fish into a removable spillway weir to allow it to pass even more fish in a given volume of flow. The two items were not forced to occur together, but if they happened to perform well together, they would both be found in combinations performing well.

The Cost Engineering Branch, Engineering Division, Walla Walla District, Corps of Engineers, estimated the costs for each construction item, which includes planning, engineering, and construction management. These cost estimates are based on the scope of work, assumptions, and methodology presented in this report. Escalation, operation, and maintenance are not included. Estimates were developed as comparison type costs for use in economic studies and option selection. The cost estimates are not intended to be used for program funding estimates. A more complete evaluation of costs should be conducted for those items showing promise.

Some items may take considerable time to implement. Design and construction of major features like an RSW or BGS typically take two years to manufacture and install. Major spillway or stilling basin modifications could take several years due to the limited construction window; they must be accomplished when fish passage will not be significantly affected. Turbine replacement may take 2 to 3 years per turbine depending on the level of construction needed. Only one turbine unit can be rehabilitated at a time for several reasons. These include availability of workspace and crane equipment, the need to maintain power production, and funding limitations. Installation of six turbines at a given dam could take 12 to 15 years. These scheduling issues were not considered in the current analysis, but they should be revisited for items showing promise.

Survival Metrics

The transportation system creates a dichotomy between fish arriving downstream of Bonneville Dam in barges and those arriving as in-river migrants. Multiple survival metrics are needed to evaluate whether the survival of these two groups meets stewardship goals, both separately and in combination.

System Survival was defined as the overall percentage of fish surviving from the head of Lower Granite Pool to downstream of Bonneville Dam, regardless of whether they arrived by migrating in the river or by being transported. This metric includes both transported and in-river migrating fish.

In-River Survival was defined as the percentage of fish *migrating in river* surviving from the head of Lower Granite Pool to downstream of Bonneville Dam. This metric does not indicate the proportion of fish migrating in river. A high survival value does not indicate whether a large or small proportion migrated in river, only a higher rate of survival for in-river migrants. Transported fish do not enter into this calculation.

Neither the System Survival nor the In-River Survival metrics indicate what proportion of fish remain in the river, rather than being transported. Because some stewardship goals seek to avoid using one route exclusively, it was necessary to determine what proportion of fish migrated in the river, as opposed to being transported downstream. The Proportion In River is computed as the number of fish migrating in river arriving downstream of Bonneville Dam divided by the number of fish estimated to arrive if all fish were returned the river instead of transporting them. If transportation occurred at only one point in the model, there would be a direct relationship between the proportion transported and the proportion remaining in river. The ability to transport at more than one project, with less than 100% survival between, means survival alters the conversion between the two. It is a complex task to track where fish enter the transportation system, but the model automatically computes the proportions for each simulation. Setting a minimum criterion for the Proportion In River limits the proportion of fish transported. The number of individuals arriving in-river downstream of Bonneville Dam is a function of both the In-River Survival and the Proportion In River.

Stewardship Goal

A stewardship goal defines the desired outcome for a population. In this analysis, we are focusing on downstream migrants, and the goal is to selecting operational alternatives and construction items resulting in high values for System Survival and In-River Survival while ensuring a balance between the proportion of fish migrating in river and those being transported. This approach has been termed “spreading the risk.” Top performance under this stewardship goal required good survival through both in-river and transportation passage routes and some proportion of fish remaining in the river.

Model Runs

A model run simulated one combination of operational alternatives and construction items across the five dams for a single population in spring or summer. The outputs for a run included estimates of survival, passage routing, construction costs, and power revenue for the combination. A new run was made each time an operational alternative or construction item was changed, and a new set of outputs was created. Changes can be made manually to explore specific combinations of interest, but automation was needed to address the many combinations possible for the system. The software tool, OptQuest©, was used to automatically select combinations and capture outputs. This allowed hundreds of thousands of combinations to be simulated in a single session.

Performance Criteria

The hydropower system can be operated or configured to provide various benefits. The minimum survival levels specified in the 2000 BiOp were used as performance criteria for stewardship goals (Table 1). Only those combinations of operations and construction items meeting the minimum performance criteria were selected for analysis. Simulated In-River Survivals for steelhead and subyearling Chinook salmon fell below the BiOp criteria for all combinations. In those cases, the operations set forth in the BiOp (NMFS 2000) were simulated and the resultant survival value was used as an adjusted minimum. The adjusted minimum (shown in table in parentheses) was then applied in place of the BiOp In-River Survival criteria for steelhead or subyearling Chinook salmon when selecting combinations meeting minimum criteria. The BiOp did not specify criteria for Proportion In River, so the minimum was set at the level estimated for the operations set forth in the BiOp.

Performance was optimized by maximizing In-River Survival while requiring System Survival to meet or exceed the minimum criteria. No combination for steelhead or fall Chinook met the BiOp (NMFS 2000) standard for In-River Survival, so the adjusted value (see Table 1) was used as the minimum criteria, and the maximization sought combinations with In-River Survival approaching the BiOp (NMFS 2000) criteria.

Table 1. 2000 BiOp Juvenile Salmon Survival Criteria

	System Survival	In-River Survival (Adjusted Value) [1]	Proportion In River
Spring Chinook Salmon (yearling)	57.6%	49.6%	≥ 23.2%
Steelhead	50.8%	51.6% (44.7%)	≥ 18.9%
Fall Chinook Salmon (subyearling)	12.7%	14.3% (8.47%)	≥ 20.0%

[1] **Value for simulated BiOp conditions.**

Optimization

Optimization involves maximizing a measure of performance based upon the survival metrics. For the Spread the Risk goal, In-River Survival was maximized because all combinations fell short of the BiOp (NMFS 2000) criteria. While the single metric was being maximized, other metrics were required to meet or exceed criteria. During maximization, a combination was retained in the set of acceptable performers only if these criteria were met.

There are also tradeoffs between survival, construction costs, and power revenue. These tradeoffs are not considered when selecting combinations meeting survival standards, but it is worthwhile to evaluate the inherent tradeoffs among survival, construction costs, and power revenue for combinations exceeding the minimum criteria. The following analysis strives to illustrate the unavoidable tradeoffs as survival is maximized.

Top Performers for Survival across Net Revenue

Among combinations meeting minimum criteria, there can be a range of survival for a given level of construction costs or power revenues. It makes sense to choose combinations that offer more benefits for the same costs. In this simulation costs include construction costs as well as changes in revenue from power generation. To combine the two, net revenue was defined as the power revenue minus an annualized construction cost (represented as the payment computed for a 30-year loan at 5.625%). Combinations with the greatest survival for a given level of net revenue were considered to be Top Performers.

Top Performers are a subset of the combinations meeting the minimum criteria for survival (Table 1). Top Performers for survival have higher survival than any combination with greater net revenue. Across the range of net revenue encompassed by acceptable performing combinations, there can be several Top Performers. The trend of survival for Top Performers across the range of net revenue illustrates an unavoidable tradeoff between costs and benefits,. Top Performers were analyzed to identify operations and construction items contributing to performance.

Results

Model Results

The majority of the millions of possible combinations failed to meet the minimum survival criteria. In spite of the many combinations eliminated, hundreds of combinations met the minimum survival criteria. From these sets of acceptable performers, top performing combinations were identified that had the highest survival performance for each level of revenue.

In spring, both steelhead and yearling Chinook salmon are migrating through the system, requiring combinations to meet minimum criteria for both species. Since it was possible to meet the minimum criteria for yearling Chinook salmon in simulations, only combinations doing so were accepted. The search for the best combinations then fell to the performance of Steelhead, where simulations fell short of meeting the 2000 BiOp criteria for In-River Survival. Thousands of combinations met the minimum adjusted Steelhead In-River Survival criteria for the Spread the Risk goal (Figure 2). Top Performers (N = 32) ranged widely in both In River Survival and net revenue.

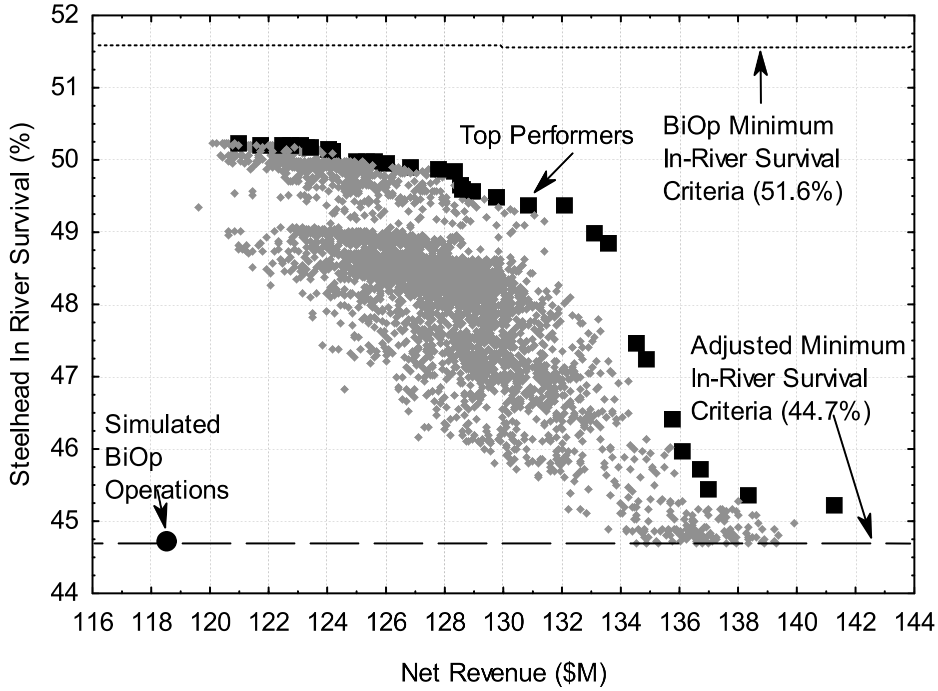

Figure 2. Steelhead In-River Survival versus Net Revenue in Spring under the Spread the Risk Goal. Black squares are Top Performers. Black circle shows simulated performance of operations recommended in 2000 BiOp.

Combinations selected as Top Performers provided higher survivals and greater net revenue than the operations specified in the BiOp (Figure 3). The bubbles in Figure 3 are larger when construction costs are higher. From this plot we see that combinations to the upper left provide small increments of survival benefit, but at a high construction cost which diminishes net revenue. Combinations to the lower right on the plot provide considerable revenue benefits, but with limited survival benefit.

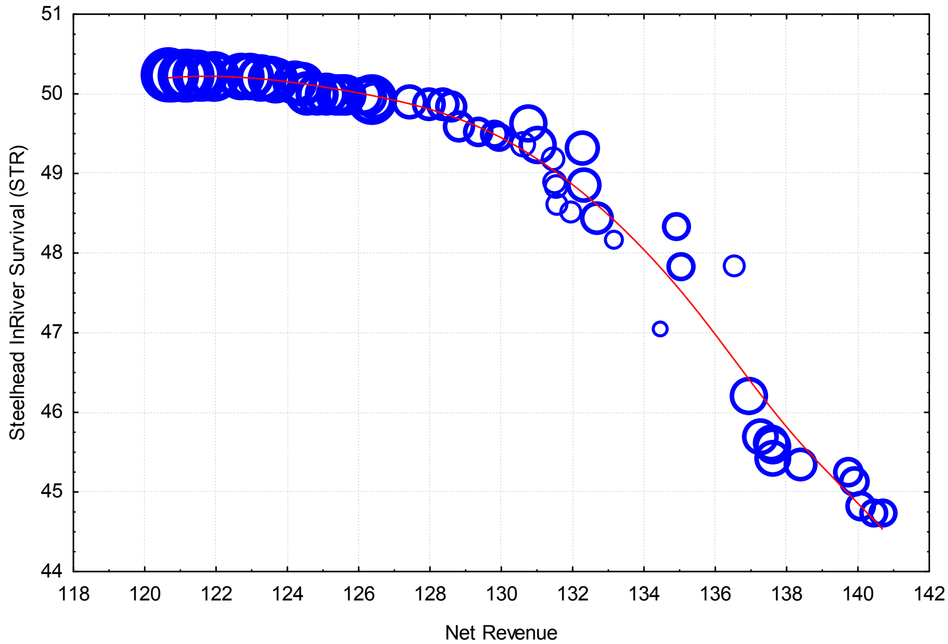

Figure 3. Top Performers for Steelhead In-River Survival versus Net Revenue in Spring under the Spread the Risk Goal. Larger bubbles indicate greater construction cost.

The set of Top Performers include the highest benefits for each level of net revenue. Examining the makeup of those combinations reveals much about what is required to achieve survival benefits. Only certain operational alternatives were included in the set of Top Performers. All included transport at the uppermost collection project, LGR. The most common operation, across combinations of construction items, included a balance between transport and allowing fish to pass without being collected. Certain high-cost construction items were absent from the set of Top Performers. Conversely, no top performers included no construction items.

The mix of cost, revenue, and survival varied widely among Top Performers (Figure 4). The highest survivals are desirable from a stewardship standpoint, but the final increments in survival come at relatively high cost. Figure 5 illustrates that a few high-cost construction items contribute the last fraction of a percent of survival. Combinations without those particular large construction items achieve nearly the same survival at lower cost and, therefore, a higher net revenue.

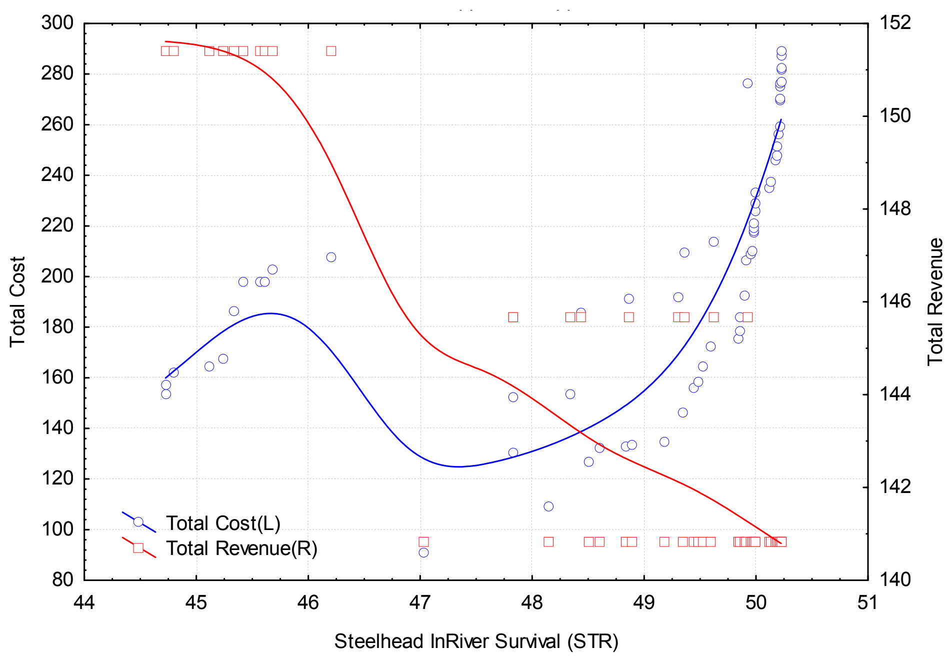

Figure 4. Total Cost and Revenue versus Steelhead In-River Survival for Top Performers

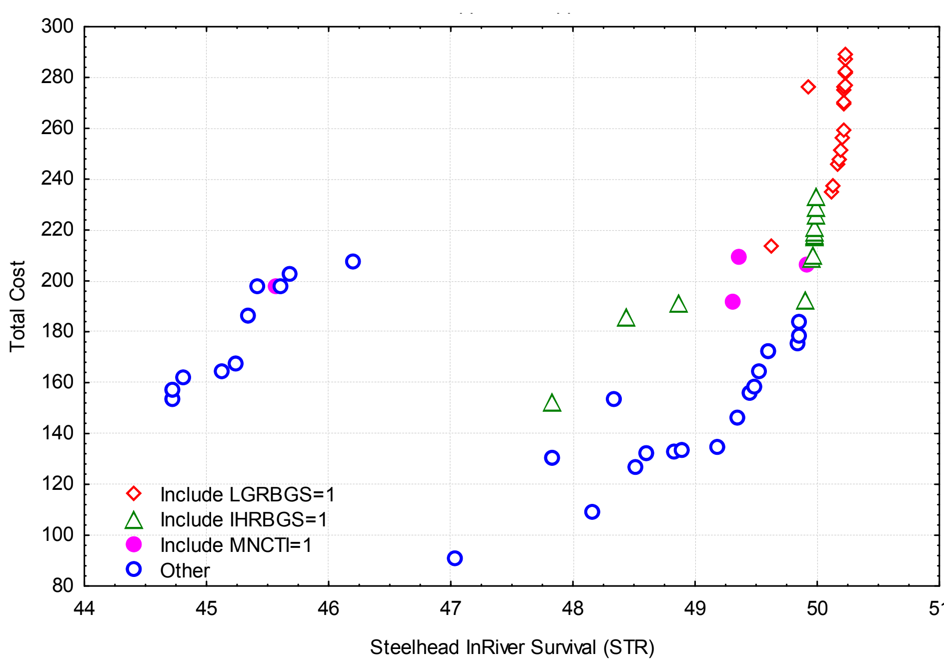

Figure 5. Total Cost Versus Steelhead In-River Survival Showing Marginal Survival Benefits of Selected Construction Items.

Another piece of information that can be extracted from the set of Top Performers is what individual operations and construction items are common or uncommon. Common items are likely both effective and cost-effective contributors to the stewardship goal. Items that are rare or absent are either less effective than another item, more costly, or both. Table 2 illustrates some construction items, highlighted in red, that are not contained in any combination that is a Top Performer. Construction items with a colored green occur in all top performers for that operation (leftmost columns indicate operations). A majority of cells colored green suggest that the construction item performs well across multiple operations.

Table 2. Operational Combinations of Top Performers for Spring Spread the Risk Goal.

LGR	LGS	LMN	IHR	MCN	LGRBGS	LGRSI	LRRTI	LGRFF	LGRBARGE	LGSBGS	LGSDW	LGSTI	LGSFF	LGSNO	LGSBARGE	LMNBGS	LMNDW	LMNSI	LMNTI
RWT	BP	BP	RW	RWT	0.	0.85	0.54	0.15	0.62	0.	0.69	0.38	0.38	0.62	0.85	0.	0.54	0.92	0.31
RWT	BP	BP	RW	RW	0.	0.5	0.	0.	1.	0.	0.5	1.	0.	0.5	0.	0.	0.5	0.5	0.5
RWT	BP	RWT	RW	RWT	0.	0.	1.	1.	1.	0.	0.	1.	0.	1.	1.	0.	1.	1.	0.
RWT	BP	RWT	RW	RW	0.	0.	0.	1.	1.	0.	0.5	0.5	1.	1.	0.	0.	1.	0.	0.

Discussion

Numerous combinations of proposed alternative operations and construction items intended to improve fish passage and survival through the Snake and Columbia River hydrosystem were evaluated. The model developed in this effort organized the available information and examined the implications of information within the context of the system as a whole. A fundamental and important advance was the incorporation of automation to transform the model into an efficient tool for tackling the complexity arising when choosing among many alternatives. This advance was critical because it enabled the system to be evaluated and optimized as a whole, rather than as a series of individual dams.

Simulation modeling revealed operational alternatives and construction items likely to meet minimum acceptable survival criteria. Incorporating construction costs and net revenue emphasized inherent tradeoffs between survival and power revenue and assured Top Performers were cost effective, given their revenue level. Each combination in a set of Top Performers represents a specific result for survival and net revenue and the resulting curve illustrates the unavoidable tradeoff. Input from regional managers will determine what point along the curve provides the best combination of survival and net revenue.

Conclusions

The alternatives proposed for operating or configuring the hydropower system created a bewildering number of possible combinations. The simulated performance of most combinations fell short of minimum BiOp criteria, leaving a still numerous set of combinations meeting the minimum adjusted criteria and each provides a different mix of costs and benefits. Focusing on Top Performers with the highest survival for a given level of net revenue illustrated the trade-offs between survival and net revenue.

Examining the Top Performers provided insights into what items were contributing most to performance. Higher cost items were generally not favored in the selection of Top Performers unless they provided a benefit not available elsewhere at a lower cost.

The use of optimization provided a fast and effective way to narrow the range of possibilities to a manageable set. The set of Top Performers are the likely choices, given that they provide the most benefit for a given cost. The final mix of benefits and costs is left to the stewards of the resource, but this process enables that decision to be based on the best possible information.

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