Balancing fish-energy-cost tradeoffs through strategic basin-wide dam management

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Abstract

Dam management often involves tradeoffs among hydropower generation capacity, environmental impacts, and project costs. However, our understandings of such tradeoffs under a full range of dam management options remain limited, which hinders our ability to make sound and scientifically defensible dam management decisions. In order to assess the scope for theoretical tradeoffs, a dynamic model of hydropower production, important fish populations, and project costs was developed using the system dynamics modeling technique. Three dam management options were investigated the likely outcomes from: dam removal, fishway installation (e.g., pool-and-weir, Denil, and fish lift), and no action. The model was applied to the Penobscot River located in Maine, US as a proof of concept, where recent actions (i.e., dam removal and fishway construction) have been undertaken. We modeled theoretical influence of these actions on four significant sea-run fish (alewife, American shad, Atlantic salmon, and sea lamprey) by developing an index of spawner population potential based on population models for each species. Optimal dam management solutions may maximize spawner population potential and energy production to 60-65% of maximum achievable values while limiting the project cost to $17 million (44% of the maximum value). Our results demonstrate that basin-scale management strategies may increase the migratory fish restoration while preserving hydropower generation capacity. Diversification of management options (e.g., combination of fishway installations, dam removals, and generation capacity) may increase the efficacy of strategic fish-energy-cost tradeoffs.

Keywords:

Basin scale dam management; fish-energy-cost tradeoffs; sea run fish population; hydropower generation; multi-objective optimization; system dynamics modeling

1. Introduction

Ensuring critical services provided by dams (e.g., hydropower generation, water supply, flood control, recreation) while sustaining healthy, functioning ecosystems is one of the grand challenges of dam management and decision-making. Environmental impacts induced by dams (e.g., alteration of natural flow regimes and sediment transportation, blockage of fish migration) and their cascading social and economic problems (e.g., revenue loss in the fishing industry) have been increasingly being recognized over the recent decades (Bunn and Arthington, 2002; Gehrke et al., 2002; Liermann et al., 2012; Poff et al., 2007; Ziv et al., 2012). In response, dam operations have been increasingly regulated to meet minimum environmental flows for protection of wildlife habitats and downstream recreational uses (Olden and Naiman, 2010; Richter and Thomas, 2007). Additionally, fish conservation and restoration has become a required part of hydropower facilities' relicensing process under the regulations of the Federal Energy Regulatory Commission (FERC) (Emerson et al., 2012; Schramm et al., 2016). Hydropower operators are generally required to provide safe, timely, and effective fish passage. Efforts to mitigate these effects on migratory fish populations have included a wide range of engineered fish passage structures. Such structures are not guaranteed solutions and vary greatly in efficacy (Bunt et al., 2012; Noonan et al., 2012). More comprehensive improvement, such as dam removal may also be used to address impacts. All of these solutions and environmental constraints usually lead to reductions in hydropower generation or other dam services in order to accommodate operation (Edwards, 2003; Kuby et al., 2005; Roy et al., 2018; Song and Mo, 2019; Song et al., 2019).

Operator responsibilities may also include safety issues associated with operation. In the US, over 60,000 dams will outlive their design lifespan by the late 2030s, posing a significant public safety risk if not repaired and maintained (O'Connor et al., 2015; USACE, 2016). Rehabilitation cost of the aged dams has been estimated to be a minimum of US$ 70 billion (Silva et al., 2019). Decision support that allows maximizing services provided by dams, while minimizing their environmental impacts and cost is therefore imperative.

Energy generation, fish restoration, and cost are three major considerations influencing hydropower dam decision-making (Neeson et al., 2015; Opperman et al., 2011; Ziv et al., 2012).

Depending on the type and context of dam management actions, tradeoffs among these three objectives often exist. The most costly dam management actions do not necessarily yield the best fish restoration or hydropower outcomes. Optimal solutions that balance fish-energy tradeoffs may be impractical when cost is considered. For example, fishway installation has been suggested as an effective way to balance fish-energy tradeoffs (Wild et al., 2018), but its upfront cost can be as much as two times of the dam removal cost (American Rivers, 1999; Strassman, 2011). In fact, such tradeoffs can vary significantly by river basin and by dam because the assemblage of dams can have synergistic influences on a river and its aquatic communities.

To optimize these tradeoffs, numerous studies have noted the importance of basin scale or even multi-basin scale management as opposed to the traditional individual-based dam management (Neeson et al., 2015; Opperman et al., 2011; Roy et al., 2018). Fish-energy tradeoffs related to dams have been widely studied under diverse management options, including construction (Wild et al., 2018; Ziv et al., 2012), removal (Kuby et al., 2005; Null et al., 2014; Roy et al., 2018), fishway installation (Kuby et al., 2005; Song et al., 2019), or turbine shutdown (Eyler et al., 2016; Song et al., 2019; Trancart et al., 2013) at individual or basin scales. These studies highlight the advantages to managing dams at a larger scale but fall short of assessing the costs and operational efficacy for those that make the ultimate decision of what scale to work (e.g., the operators) and the decision-making incentives for management (in FERC). Besides, most previous tradeoff studies generally examined only a single type of management actions. For example, Ziv et al. (2012) studied energy-fish-biodiversity tradeoffs under new dam construction scenarios in the Mekong River Basin. Null et al. (2014) analyzed tradeoffs between fish habitat gains and water supply losses under dam removal scenarios in California's Central Valley. Roy et al. (2018) also put emphasis on strategic dam removal and its influence on a wide array of tradeoffs at three watersheds in the New England region. To our knowledge, Song et al. (2019) is the only study that has investigated the potential combinations of multiple dam management actions including dam removal, fishway installations, and turbine shutdowns for basin-scale dam management. The results of the study suggested that the optimal outcomes in hydropower generation and fish biomass may only be achieved when all three management actions are integrated. Therefore, a thorough investigation and analysis of the fish-energy-cost tradeoffs associated with a full range of dam management options are pivotal to help support the making of sound and scientifically defensible decisions.

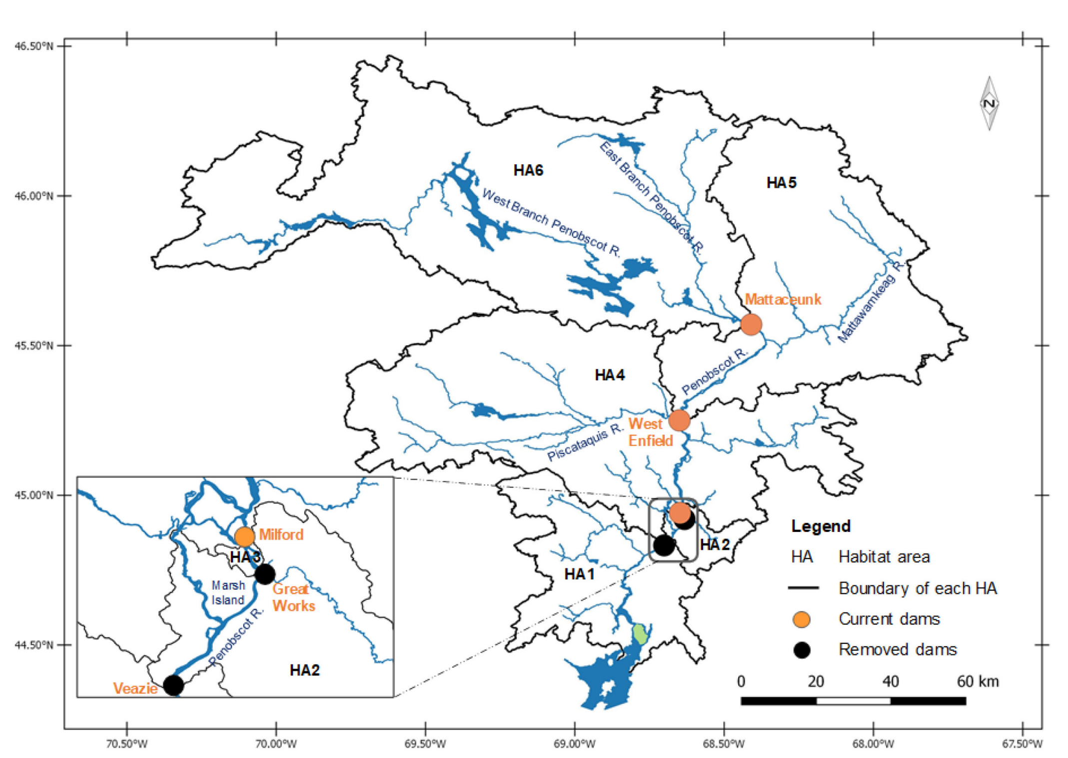
This study has three policy-relevant objectives. First, we detail a comprehensive analysis of fish-energy-cost tradeoffs under multiple dam management options, including dam removal and fishway installations on a basin scale. Second, we compare various dam management strategies using production possibility frontier curves to provide insights into the optimal strategies to balance energy-fish-cost tradeoffs. Third, we develop a dynamic modeling framework for basin-scale dam decision-making. This framework can be scaled and generalized to any region or river basin. It can also be used to facilitate dam negotiation process and engage stakeholders whose expertise and knowledge background may vary widely.

To achieve these objectives, a system dynamics model (SDM) was developed to simulate fish-energy-cost tradeoffs in dam decision-making. SDM is a computational method using a set of linked differential equations to dynamically simulate interactions within and among complex systems over a certain time period (Forrester, 1997; Sterman, 2001). It is a powerful tool to study multidisciplinary responses and tradeoffs of an action by capturing feedback loops and time delays among physical and biological components in a system (Cheng et al., 2018; Song et al., 2019). SDM has been previously applied to simulate dynamic hydropower productions (Bosona and Gebresenbet, 2010; Sharifi et al., 2013), fish populations by considering different mortality sources at individual fish life cycle stages (Barber et al., 2018; Ford, 2000; Stich et al., 2018), and energy-fish tradeoffs under various dam management scenarios (Song and Mo, 2019; Song et al., 2019). However, it has not been applied to investigate dam-related fish-energy-cost tradeoffs at a basin scale. We use five hydropower dams located in the main stem of the Penobscot River, Maine to demonstrate the modeling framework. One of the nation's most innovative and collaborative restoration projects, the Penobscot River Restoration Project (PRRP), has completed in 2016 with the goal of balancing hydropower and fisheries restoration through removing lowermost dams, installing fishways, and installing hydropower capacity on non-powered dams (Opperman et al., 2011). Three hypotheses were tested in this work. (1) There are dam management strategies that maximize fish restoration potential, while minimizing hydropower loss and cost. (2) Basin-scale dam management strategies outperform individual dam management strategies in terms of balancing energy and fish outcomes. (3) Diversifying dam management options can improve energy, fish, and cost outcomes in dam decision-making.

2. Materials and methods

2.1. Proof of concept

The Penobscot River basin is a hotspot for both hydropower production and wild diadromous fish restoration. Hydropower in this basin alone accounts for around 22% of the total installed capacity in Maine (Kleinschmidt Group, 2015). These hydropower dams (as well as non-hydropower dams) have been implicated as the main reason for the substantial decline of native diadromous fish species (e.g., Atlantic salmon) with high commercial, ecosystem, and recreational values (NRC, 2002; Trinko Lake et al., 2012). To explore the fish-energy-cost tradeoffs associated with various dam management scenarios, we chose to study five hydropower dams located on the main-stem of the Penobscot River as a proof of concept. We note that two of the most downstream dams (Veazie and Great Works) have been removed in 2012 and 2013, respectively, as part of the PRRP (Opperman et al., 2011). The remaining three dams, from downstream to upstream, are the Milford Dam (with a Denil fishway and a fish lift), the West Enfield Dam (with a pool-and-weir fishway) and the Mattaceunk Dam (with a vertical slot fishway). Currently, the West Enfield Dam is undergoing relicensing process and Mattaceunk Dam is dealing with transitions from an annual to a subsequent license. Detailed information of the current condition of relevant dams on the Penobscot River is provided in Figure 1. This approach excludes several major tributaries of the Penobscot River and does not consider the complex fish passage paths near Marsh Island (Stich et al., 2014). We note that the results from this research are intended to demonstrate the efficacy of such an approach, rather than being prescriptive for this watershed.



Dams (distance to ocean)	Year	Dam height (meters)	Dam length (meters)	Installed power capacity (MW)	The maximum turbine release capacity ($\times 10^6$ m^3/d)	Rated head (meters)	Fish upstream passage facility	License expiration date
Mattaceunk (rkm 175)	1939	14	357	21.6	18.2	11.9	Vertical slot fishway	Annual license
West Enfield (rkm 114)	1894	14	296	13.0	22.0	7.9	Pool-and-weir fishway	05/31/2024
Milford (rkm 73)	1906	10	426	8.0	17.2	5.8	Denil fishway and fish lift	03/31/2038
Great Works (rkm 69)	1900	6.1	331	7.6	21.1	5.3	Removed	N/A
Veazie (rkm 55)	1912	10	257	9.3	13.6	7.3	Removed	N/A

Figure 1. Map of the study area illustrating the locations of the five hydropower dams located in the mainstem of the Penobscot River, Maine along with project information for the studied dams.

Our fish population modelling efforts were restricted to four of the twelve native diadromous fish species found in this system (Saunders et al., 2006) based on their high commercial, recreational, cultural, and ecological values: alewife (*Alosa pseudoharengus*), American shad (*Alosa sapidissima*), Atlantic salmon (*Salmo salar*), and sea lamprey (*Petromyzon marinus*). These four species may also undertake long distance migrations that historically distributed them throughout the reaches being modeled. Other species such as sturgeon (*Acipenser oxyrinchus* and *A. brevirostrum*), tomcod (*Microgadus tomcod*), smelt (*Osmerus mordax*) tend to exploit the lower river reaches making them less appropriate for this tradeoff simulation. Passage improvements for the catadromous eel (*Anguilla rostrata*) are less congruent with general fishway design and instead rely on climbing behaviors (Geffroy and Bardonnet, 2012; Jellyman, 1977; Watz et al., 2019). These fish also have a coastwide population structure (Jessop and Lee, 2016) making them less amenable to modeling within a single river system. Our four selected anadromous species spend most of their lives in the ocean to grow, but return to freshwater to spawn. Alewife (Barber et al., 2018), American shad (Bailey and Zydlewski, 2013), and Atlantic salmon (Fleming, 1998) have high rates of repeat spawning (iteroparity) over the course of their lifetime whereas sea lamprey spawn only once (semelparous) before death (Weaver et al., 2018).

Management scenarios. We assumed the baseline (worst) fish condition of each dam is complete obstruction of fish. Previous studies have shown that the effectiveness of fishways in facilitating fish upstream passage varies markedly based upon the types and numbers of fishway installed as well as the types of fish species (Bunt et al., 2012; Noonan et al., 2012). To capture these diversities, we simulated the installation of three widely adopted fishways: pool-and-weir fishway, Denil fishway, and fish lift (Table 1). It is not uncommon to have multiple fishways installed on a single dam. In this study, we assume up to two fishways can be installed on a dam simultaneously. Therefore each dam has a total of eight potential management options (1) install pool-and-weir fishway, (2) install Denil fishway, (3) install fish lift, (4) install pool-and-weir and Denil fishways, (5) install pool-and-weir and fish lift, (6) install Denil and fish lift, (7) dam removal, and (8) no action. To provide a complete picture of the accumulated effects of multiple dams, we analyzed all possible permutations of the studied five dams (8^5 = 32,768 scenarios). When two fishways were installed, fish passage was assumed to be additive such that:

$$P_{Total} = P_{Fishway1} + P_{Fishway2} * (1 - P_{Fishway1})$$

representing the most optimistic outcome of using two structures.

Table 1. Description, passage rate, and capital cost of the studied fishways

Fishway	Description	Fishway upstream passage rate (%)								Capital cost per vertical meter (2019$ million/m)*	
		Alewife		American shad		Atlantic salmon		Sea lamprey			
		Mean	Ranges	Mean	Ranges	Mean	Ranges	Mean	Ranges	Mean	Ranges
Pool-and-weir	A series of small pools to create a long and slopping channel for fish to travel around the dam	36	6-73 (Bunt et al., 2012; Gahagan and Elzey, 2016; Nau et al., 2017; Sullivan, 2017)	19	0-70 (Beasley and Hightower, 2000; Bunt et al., 2012; Groux et al., 2017; Haro and Castro-Santos, 2012; Haro and Kynard, 1997; Sullivan, 2004)	48	0-100 (Bunt et al., 2012; Gowans et al., 2003; Holbrook et al., 2009; Lundqvist et al., 2008; Noonan et al., 2012)	18	1-35 (Castro-Santos et al., 2016; Haro and Kynard, 1997; O'Connor et al., 2003; Pereira et al., 2017)	0.178	0.01-0.215 (Nieminen et al., 2017) and historical data provided by collaborators from NOAA recreation center
Denil	A series of baffles with a relatively steep slope to reduce flow velocities	43	1-97 (Bunt et al., 2012; Haro et al., 1999; Nau et al., 2017; Stokesbury et al., 2015)	15	7-61 (Haro et al., 1999; Slatick, 1975)	76	12-100 (Holbrook et al., 2009; Noonan et al., 2012; Nyqvist et al., 2017a)	20	Passage efficiency estimate	0.190	0.132-0.296 (Nieminen et al., 2017) and historical data provided by collaborators from NOAA recreation center
Fish lift	An elevator to carry fish over a barrier	70	Passage efficiency estimate	35	6-67 (Groux et al., 2017; Larinier and Travade, 2002; Moser et al., 2000; Sprankle, 2005)	55	36-67 (Gowans et al., 2003; Noonan et al., 2012)	60	Passage efficiency estimate	0.237	0.057-0.287 (Porcher and Larinier, 2002)

*Capital costs include design, permitting, and construction. The historical cost data was adjusted to $2019 USD with an inflation rate of 3% (Kotz, 2003)

2.2. Fish-energy-cost model

Six basin-scale objectives were chosen to evaluate candidate dam management scenarios: spawner population potential of four primary sea-run fish species (number of spawners), annual hydropower generation (GWh/year), and project cost ($2019 million). These measures were simulated using an integrated SDM model, consisting of age-structured fish population models, an energy model, and a cost model (Figure 2). SDM model was built in Vensim® DSS and runs on a daily time step.

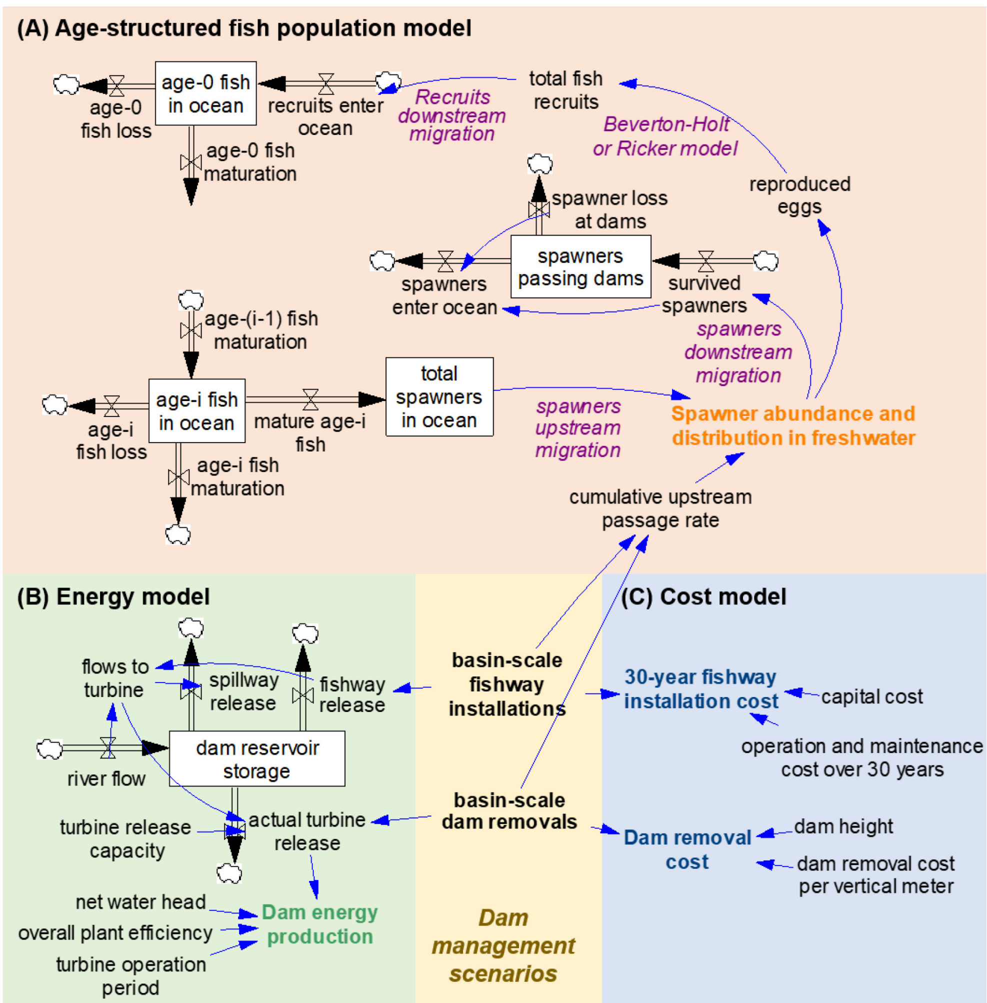


Figure 2. A simplified version of the integrated SDM model illustrating the key variables and connections of (A) age-structured fish population model, (B) energy model, and (C) cost model. The performances of fish population, hydropower generation, and cost are closely linked with dam management options on a basin scale. The complete model is provided in the supporting information as a Vensim® file.

The age-structured fish population model simulates spawner population potential of four fish species in the freshwater that are ready to spawn each year by keeping track of their growth, mortality, maturity, iteroparity, timing and period of migration at each life stage throughout the whole life span. The stabilized fish population potential was used in analysis. The model was run over a 150-year time horizon to ensure stabilization. These models are modifications of four extant fish population models with alewife (Barber et al., 2018), American shad (Bailey and Zydlewski, 2013), Atlantic salmon (Nieland et al., 2015), and sea lamprey (Weaver et al., 2018). While the life histories of these species differ, we used a generalized format to account for the spawner potential under each scenario. The life cycle of each fish species starts from egg deposition in the freshwater, to recruit production in the freshwater, juvenile and post-spawners (excluding sea lamprey) seaward migration, the growth/maturity of fishes in the ocean, and spawning runs. Egg production each year was simulated as a product of the number of females that survived to spawn and their fecundity. Recruit production was determined by the carrying capacity of habitats and the spawner-recruit relationship. The Berverton-Holt spawner-recruit curve was adopted to simulate the recruit production of alewife (Barber et al., 2018) and Atlantic salmon (Nieland et al., 2013), while the Ricker spawner-recruit curve was used for American shad (Bailey and Zydlewski, 2013) and sea lamprey (Dawson and Jones, 2009).

For juvenile and post-spawn adults, seaward migration may require pass dams through spillways, turbine facilities, or fish bypass systems. The ratio of fish utilizing each route to pass a dam was assumed to be proportional to water being released through each route (Nyqvist et al., 2017b). Turbine mortality rate for all fish species was assumed to be 10% when passing each dam (Haro and Castro-Santos, 2012), while mortality rates of the other two migration routes were assumed to be zero as they are generally benign (Muir et al., 2001).

In the ocean, the number of fishes that can reach sexual maturity was determined by the ocean mortality rate and the probability of maturation (Table B1 in the supporting information). Sexually mature females (i.e., spawners) swim to the freshwater to spawn. The number of spawners reaching a habitat area (HA_j) was determined by the cumulative upstream passage rate of dams downstream of HA_j as well as the dispersal rule described by Equations 1. We included the long-term blockage effect of dams that restricts fishes' motivation to seek habitats that were suitable for spawning but no longer accessible.

$$\begin{cases} S_{HA_j} = \left(\frac{A_j}{A} + \left(D_{HA_j} - \frac{A_j}{A}\right) \times \left(1 - P_j\right)\right) \times S, & \frac{A_j}{A} < D_{HA_j} \\ S_{HA_j} = D_{HA_j} \times S, & \frac{A_j}{A} \geq D_{HA_j} \end{cases} \quad \text{Equation 1}$$

where A_j and A are the size of habitat area j, HA_j and the total habitat area in the basin, respectively. j is a habitat area index which goes from 1 to 6, with 1 indicating the most downstream habitat area and 6 indicating the most upstream habitat area as segmented by dams. Habitat area sizes differ amongst the four fish species. The value of A_j and A for alewife and Atlantic salmon were obtained from (TNC, 2016) and (Nieland et al., 2015), respectively. The total habitat area, A, of American shad was calculated based upon Atlantic salmon total habitat area, assuming the ratio of the two is linearly proportional to the ratio between the two fish species' migration ranges within the Penobscot river basin (786 and 11,569 km for shad and salmon, respectively) (Trinko Lake et al., 2012). This is because both fish species have similar preference of free-flowing river as their habitats (Greene et al., 2009; NMFS and USFWS, 2005). Once shad total habitat area was calculated, it was then allocated to the six river segments created by the five dams based upon the stream length of each segment to calculate HA_j (Trinko Lake et al., 2012). Sea lamprey habitat areas were assumed to be in the same size as Atlantic salmon's due to lack of field data as well as the similarity of preferred spawning habitat and migration range between the two species (Trinko Lake et al., 2012). P_j is the upstream passage rate of the dam located at the upstream of HA_j, dimensionless, the values of which are provided in Table 1. For a dam installed two fishways, the combined upstream passage rate, $P_{j,ab}$, was calculated based upon the passage rate of the two individual fishways, $P_{j,a}$ and $P_{j,b}$ using Equation 2. S_{HA_j} and S are the numbers of spawners in HA_j and the whole basin, respectively. D_{HA_j} is a dispersal factor calculated by Equation 3. D_{HA_1} equals 1.

$$P_{j,ab} = P_{j,a} + \left(1 - P_{j,a}\right) \times P_{j,b} \quad \text{Equation 2}$$

$$D_{HA_j} = \left(D_{HA_{j-1}} - \frac{A_{j-1}}{A}\right) \times P_{j-1} \quad \text{Equation 3}$$

The descriptions and governing equations of each life stage, as well as the value of input parameters were provided in the Appendix A of the SI. Particularly, this model captured the cumulative upstream and downstream impacts of all five dams on the distribution and population of spawners in the basin. Thus, it is capable to project relative changes in spawner population potential under various dam management alternatives.

The energy model simulates daily hydropower generation (MWh) by each of the five dams, which was calculated as a product of daily turbine release (m^3/s), net water head (meters), turbine operation period (hours), plant overall efficiency (assumed to be 0.85), water density (1000 kg/m^3), and gravitational acceleration (9.8 m/s^2) (Adeva Bustos et al., 2017; Hadjerioua et al., 2012; Singh and Singal, 2017). Daily stream flow data during the period of January 2001 to December 2015 at two nearby U.S. Geological Survey (USGS) stream gages (01034500 and 01034000) were used to estimate the river flows at the five studied dams using the drainage-area ratio method (Song et al., 2019). This 15-year data period was repeated 10 times for the modelled 150-year time horizon. Turbine release was determined by the relative values of three variables: river flow goes to turbine (the difference between river flow and flow demanded by fishway), the maximum turbine release capacity, and the minimum turbine release capacity (assumed to be 40% of the maximum capacity) (Table A1 of the SI). Net water head of each dam was assumed to be its rated head obtained from (Amaral et al., 2012). Turbine operation period was assumed to be 24 hours per day. The energy model has been validated using a 15-year (January 2001 to December 2015) hydroelectricity dataset obtained from the U.S. Energy Information Administration (EIA, 2018; Song et al., 2019). Annual hydropower generation (GWh/y) was calculated as the average annual energy production over 15 years.

The cost model calculates total project costs related to fishway installation and dam removal. The revenue from hydropower generation was excluded due to its significant positive correlation with the energy generation estimated through the energy model. Fishway installation cost includes capital investment and operation and maintenance (O&M) cost over a 30-year planning horizon. This time period was chosen based upon the typical FERC license period for non-federal owned hydroelectric dams (Madani, 2011). Capital investment of fishway installation was estimated as a product of the dam height and the unit capital cost per vertical meter rise of the dam height (Table 1). The unit capital cost per vertical meter rise of the dam height for different fishways were obtained mainly from Nieminen et al. (2017) and Porcher and Larinier (2002). Annual O&M cost was estimated to equal 2% of the capital cost of a particular fishway

(Nieminen et al., 2017). Dam removal cost is a one-time investment which was simulated by multiplying the dam height with the average dam removal cost per vertical meter rise of the dam height ($ 0.173 million/meter (Maclin and Sicchio, 1999)).

2.3. Performance measures

Fish index is an indicator we created to represent the overall abundancy and diversity of the four fish species under consideration. The fish index was calculated using Equation 4.

$$Fish\ index = \sum_{i=1}^{4} \frac{P_{ia}}{P_{im}} \quad \text{Equation 4}$$

where i is a fish species index; P_{ia} is the spawner population potential of species i under a certain dam management alternative; P_{im} is the maximum spawner population potential of species i that the pristine river could support. We assume the value of P_{ia} under the scenario of removing all dams equals to the value of P_{im}. This approach administered equal value to each species.

Pearson correlation coefficients were used to quantity the correlations among various dam management options and the performance of the six basin-scale objectives described in Section 2.2. The Pearson correlation coefficients measure the linear association between two normally distributed random variables (Schober et al., 2018). It is a number between -1 and 1 that indicates the magnitude and direction of the association. A Pearson correlation coefficient between variable X and Y is calculated by Equation 5.

$$r = \frac{\sum_{i=1}^{n}(X_i-\overline{X})(Y_i-\overline{Y})}{\sqrt{\sum_{i=1}^{n}(X_i-\overline{X})}\sqrt{\sum_{i=1}^{n}(Y_i-\overline{Y})}} \quad \text{Equation 5}$$

The magnitude of the association for the absolute value of r was interpreted using Cohen's recommendation where 0~0.3 be interpreted as a weak correlation, 0.3~0.5 as a moderate correlation, and greater than 0.5 as a strong correlation (Cohen, 1988). The existence of a strong association does not imply a causal link between the variables.

The Pareto-optimal frontier defines the set of solutions for which none of the objectives can be improved in value by any other feasible solutions without worsening at least another objective value (Abbass et al., 2001; Almeida et al., 2019; Roy et al., 2018). To analyze tradeoffs between fish index, energy generation, and project cost under all dam management scenarios, we plotted the Pareto frontier with respect two out of the three criteria using the *geom_frontier()* function from the KraljicMatrix package in R. In addition, we determined the Pareto frontier that optimizes all three objectives using the *nondominated_points()* function from the 'emoa' package in R.

2.4. Sensitivity analysis

We performed a Monte Carlo simulation for a dam management scenario that resembles the current condition of dam management in the Penobscot River (two dam removal and fish elevator construction) to understand the effects of parameters' uncertainties on spawner populations, hydropower generation, and project costs (Cheng et al., 2018; Sterman, 1984; Ventana, 2002). As installation of vertical slot fishway is not considered in this study, we assume the Mattaceunk dam has a pool-and-weir fishway given the similarities of the two fishways in fish passage performance and construction cost. The tested parameters, values, and ranges associated with fish population model and cost model can be found in the Appendix B of the SI. Sensitivity analysis of the energy model was not carried out as we simulated hydropower generation is linearly related to associated variables (e.g., turbine release, net head, turbine operation period). The Monte Carlo simulation was repeated for 1,000 times.

3. Results and discussion

3.1. Fish-energy-cost tradeoffs of dam decision-making

The parallel coordinate plot in Figure 3 presents the key performance tradeoffs among the six objectives of interest: hydropower generation, project cost, and population potential of four primary sea-run fish species. Each vertical axis represents performance of the six objectives. The six objectives are oriented such that their performance improves moving vertically upward on each axis. Each polyline represents one of the 32,768 dam management scenarios and performance is designated by the points at which it intersects each vertical axis. The steepness of the diagonal lines between two adjacent axes displays the degree of conflict between the two objectives. The polylines are color-coded to represent the value of fish index which increases with colors changing from red to blue. The Pearson coefficient (*r*) among the six objectives as well as between the management options at each dam and the performance of six objectives at a 5% significance level is shown in Figure 4.

Energy and fish tradeoffs. Figure 3 shows a notable tradeoff between hydropower generation and the fish index, as only dark and light red polylines (low fish index) occupy the top 20% of the energy axis while the dark blue polylines (high fish index) are uniformly concentrated in the lower half of the energy axis. More specifically, preserving 95% of the installed capacity (405 GWh/y) accompanies 70~90% reduction of the fish index as compared to its maximum potential. On the other hand, preserving 95% of the fish index results in a 77% reduction of the installed hydropower generation capacity. Balanced management solutions can only be found where both energy and fish are around 60~66% of their maximum values, as indicated by the cyan polylines above 250 GWh/y of the energy axis. These balanced solutions are associated with removing any two of the three most downstream dams while installing at least one fishway at the remaining dams. On the other hand, certain dam management actions may result in both low energy generation and fish populations (e.g., red polylines under 140 GWh/y). These outcomes mainly stem from management actions that only involve upstream dams while the most downstream dam(s) remains impassible. As shown in Figure 4, removing the two most upstream dams display moderate negative correlations with energy ($r = -0.6 \sim -0.5$) and negligible correlations with fish ($r \approx 0$).

Cost and fish tradeoffs. The dark blue polylines (>80% of the maximum fish index value) are crowded in the area where project costs range from $9.3 to $23.6 million. The fish index increases with the increase of project cost until it reaches a threshold of nearly $24 million. Additional investment does not further increase fish index or even has an adverse effect on it. This is associated with management actions taken at upstream dams where the majority of fish population does not reach their immediate downstream habitat area (Song et al., 2019). This also occurs in management scenarios where fishway installation was chosen over dam removal. This is because fishway construction has a higher cost, but inferior performance in fish restoration, compared to dam removal (Magilligan et al., 2016; Nieminen et al., 2017). This explanation is demonstrated by the Pearson coefficients that indicate dam removals and fishway installations have a negligible negative ($r = -0.2 \sim -0.1$) and positive ($r = 0.1 \sim 0.4$) correlations with cost, respectively. In contrast, both options have positive correlations with the fish index ($r = 0.1 \sim 0.3$).

Energy and cost tradeoffs. Tradeoff between energy and cost is less substantial. The optimal solution in terms of both energy and cost is when all dams are preserved for power generation. Any other management actions tend to decrease energy and increase project costs as fishways are installed or dams are removed. The extent of decreased energy generation and increased project cost are closely related to the number of managed dams and the implemented options. In general, it is more cost effective to have fewer dams, further upstream with more generation capacity in terms of fish, cost, and energy management.

Fish-energy-cost tradeoffs. A total of 243 out of the 32,768 dam management alternatives were identified as Pareto-optimal solutions, which simultaneous optimizes hydropower generation, project cost, and fish index. Among these dam management scenarios, project costs are in the range between \$16.1 to \$24.3 million (44% to 66% of the maximum cost) if maximizing energy and fish index to 60~65% of their maximum values. Only one of these scenarios comes with a project cost of lower than \$17 million. This scenario involves removing the most downstream dam, installing Denil and fish lift fishway at the second dam, removing the third dam, install Denil fishway at the upstream two dams.

Tradeoffs among fish species. Relatively strong positive correlations (r = 0.7~0.9) present across the four fish species, except for the correlations between Atlantic salmon and American shad (r = 0.5) as well as Atlantic salmon and sea lamprey (r = 0.5). A lower correlation indicates potential conflicts in terms of restoration outcomes for different fish species. The three studied fishways, pool-and-wire fishway, Denil fishway, and fish lift, are considered effective in facilitating upstream passage of Atlantic salmon. However, American shad and sea lamprey may not effectively pass these fishways. Therefore, installing one or two of the three fishways may not simultaneously increase population potentials of all fish species. It is interesting to note that installation of the Denil fishway at the third dam can be negatively correlated with the population of American shad (r = −0.1). Furthermore, the installation of Denil or pool-and-weir fishway at the second or the third dam can be negatively correlated with the sea lamprey population potential (r = −0.1). This is linked to the low passage rates of the two fishways for American shad and sea lamprey as well as the severe turbine kills when post-spawn adults and juveniles migrate downstream. In this condition, fishways may work as ecological traps and potentially cause a further collapse of the regional fishery (Pelicice and Agostinho, 2008).

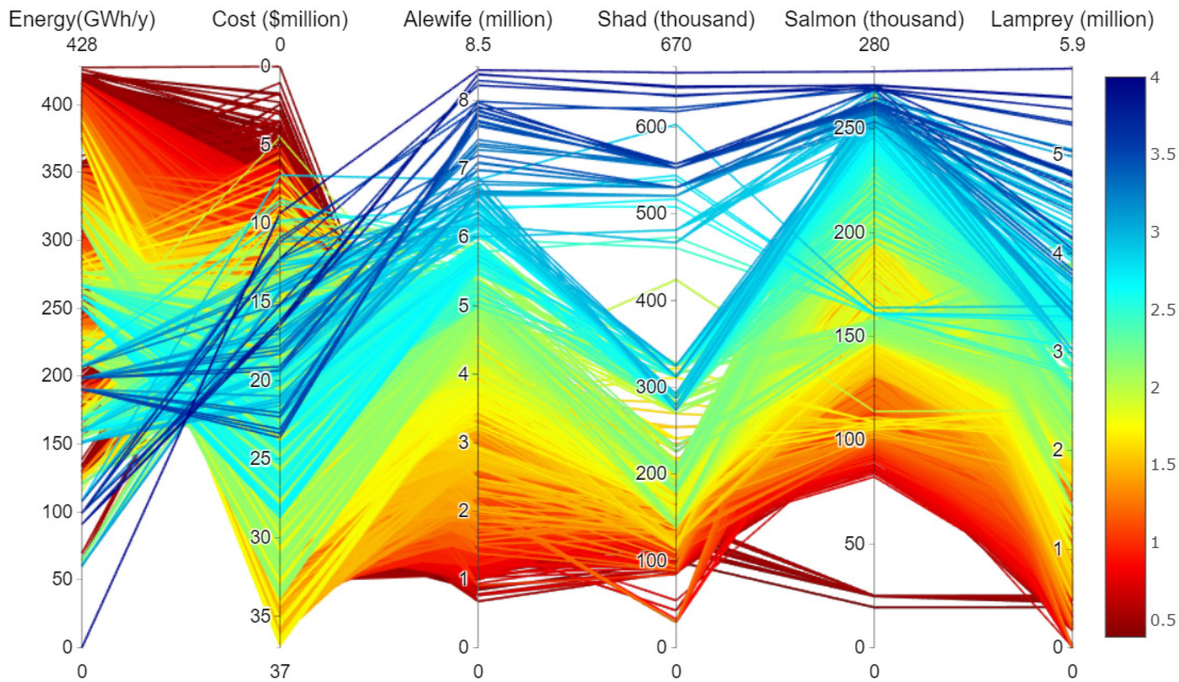


Figure 3. Parallel coordinate plot of tradeoffs among seven objectives for all basin-scale dam management scenarios in the Penobscot River. Each y-axis indicates one objective. The arrow indicates the preferred direction of all objectives. Each polyline is one dam management scenario which color-coded by the value of fish index.

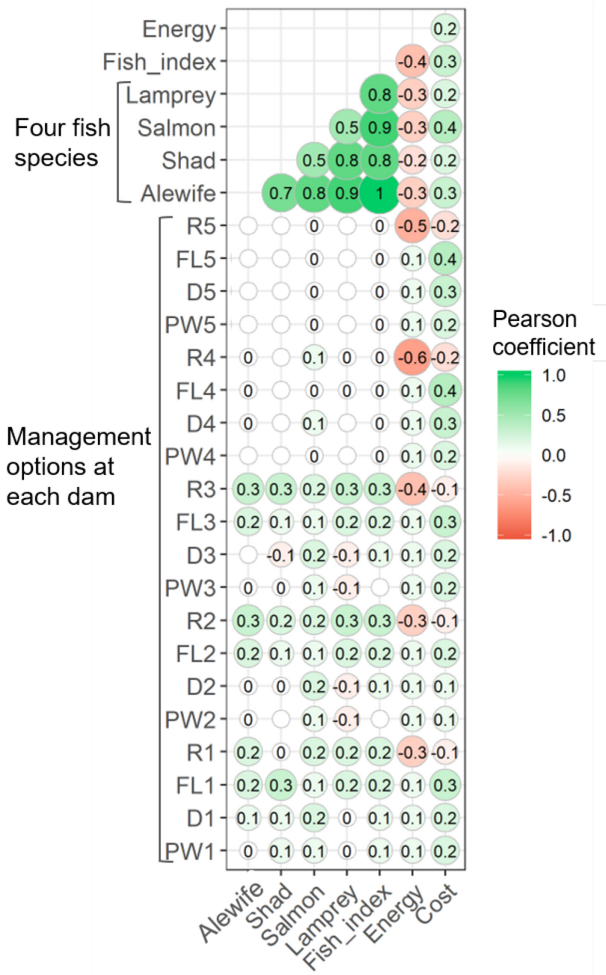


Figure 4. Pearson coefficient among management options at each dam and the performance of six objectives at the 0.05 level. Some of the cells are blank, meaning that the correlation detected is not considered to be significant. PW stands for pool-and-weir fishway, D for Denil fishway, FL for fish lift, and R for removal. The number following these initials refers to the studied five dams, among these 1 to 5 refer to dams from downstream to upstream: the Veazie, Great Works, Milford, West Enfield, and Mattaceunk Dam.

3.2. The effectiveness of dam management strategies

Given the dense nature of cloud of potential dam management scenarios showing in the parallel coordinate plot in Figure 3, we projected the performances of fish index, energy, and project cost onto two-dimensional scatter plots to get further insight into their inherent tradeoffs as well as to determine the Pareto-optimal frontier.

3.2.1. Individual vs. basin-scale dam management strategies

Figure 5 is a comparison of the fish-energy tradeoff performances between individual dam management strategies (scenarios that only include management action at one out of the five dams) and basin-scale strategies (scenarios that have management action at least two dams). While the individual dam management strategies are likely to preserve a high percentage of the hydropower generation capacity, our results show that basin-scale management strategies can significantly improve fish index while preserving a similar amount of hydropower generation capacity. This shows that the basin-scale management can more effectively balance fish-energy tradeoffs than individual management as our second hypothesis stated. It also indicates the importance of strategically managing dams on a basin scale to achieve balanced outcomes between two competitive interests. For individual dam management strategies, scenarios that lead to increase of fish index are associated with managing the most downstream dam. This finding highlights the importance of prioritizing the enhancement of fish passage performance of the most downstream dam to recover migratory fish species.

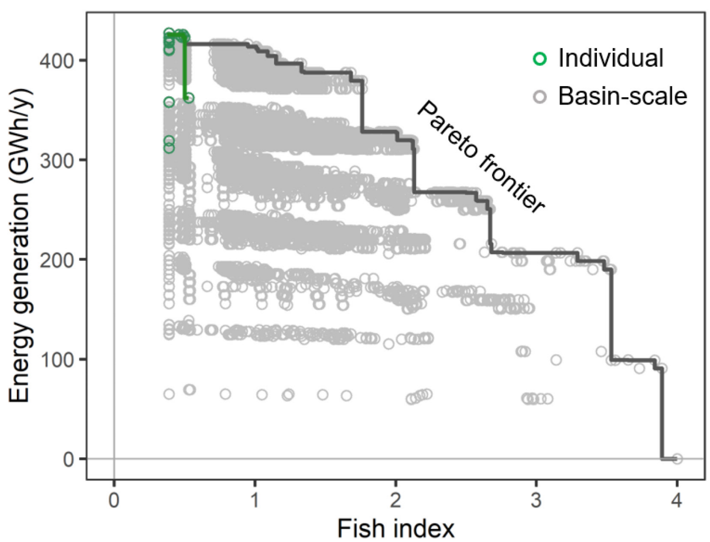


Figure 5. Fish-energy tradeoffs under individual (green circles) and basin-scale (grey circles) dam management scenarios. Each point corresponds to a polyline in Figure 2.

3.2.2. Single vs. diversified management options

The impacts of single and diversified management options for basin-scale dam management were analyzed by dividing all scenarios into four groups: (1) no action for all five dams, (2) only implement fishway installations, (3) only implement removals, (4) integrate fishway installations and removals. For fishway installations, we further separated them into two groups: management options with only 1 fishway allowed at each dam versus management options with up to 2 fishways allowed at one dam.

From a fish-energy perspective (Figure 6 (a)), management scenarios that only involve fishway installations (yellow and orange circles) are mostly effective in terms of preserving hydropower generation capacity. However, they have limited benefit in terms of fish restoration. This is because of the relatively low upstream passage performance for fish that need to ascend sequential dams, even though each dam has a high upstream passage rate (Song et al., 2019; Sweka et al., 2014; Winemiller et al., 2016). For example, only 33% spawners can reach their spawning habitat areas located on the upstream of five dams even if each dam's upstream passage rate is 80% (relatively high). It is notable that none of the management scenarios that only involve dam removals (red circles) reside on the Pareto frontier curve. This indicates that dam removal alone cannot optimize both energy generation and fish restoration. On the other hand, dam management scenarios that integrate fishway installations and dam removals (light and dark blue circles) occupies the majority of the "turning point" of the Pareto frontier curve, indicating optimal solutions simultaneously maximize energy and fish populations. From a fish-cost perspective (Figure 6 (b)), the Pareto-efficient scenarios are those with the least cost at each level of fish index. Although management scenarios that only involve dam removals are the cheapest solutions, management scenarios that integrate fishway installations and removals can achieve similar level of fish index with a slightly higher cost. This finding is also applicable to an energy-cost perspective (Figure 6 (c)). Taking all three aspects into consideration, we conclude that diversifying dam management options have the highest potential in balancing fish-energy-cost tradeoffs.

Allowing multiple fishways to be installed on a single dam also has a significant effect on the fish-energy-cost outcomes. For management scenarios that only involve fishway installations, allowing installation of two fishways on each dam can increase the possibility of improved fish index up to a value of 1.8, while preserving a similar amount of hydropower generation capacity. However, this comes at a cost of higher project investment. This is because the performance of fishways typically differs among species (Noonan et al., 2012). For example, pool-and-weir and Denil fishways have high passage rates for Atlantic salmon but low passage rates for American shad, alewife, and sea lamprey (Table 1). Fish lifts generally perform well for the upstream passage of most fish species. Therefore, installation of multiple fishways at one dam may facilitate upstream migration of multiple species. Similarly, for the scenarios that integrate fishway installations and dam removals, allowing installation of multiple fishways on a single dam can also markedly increase the value of fish index while preserving a similar amount of energy as compared with scenarios that only install one fishway. These findings further confirm that diversifying dam management options by allowing tailored fishway design and installations targeting multiple fish species can further benefit the optimization of the fish-energy-cost outcomes.

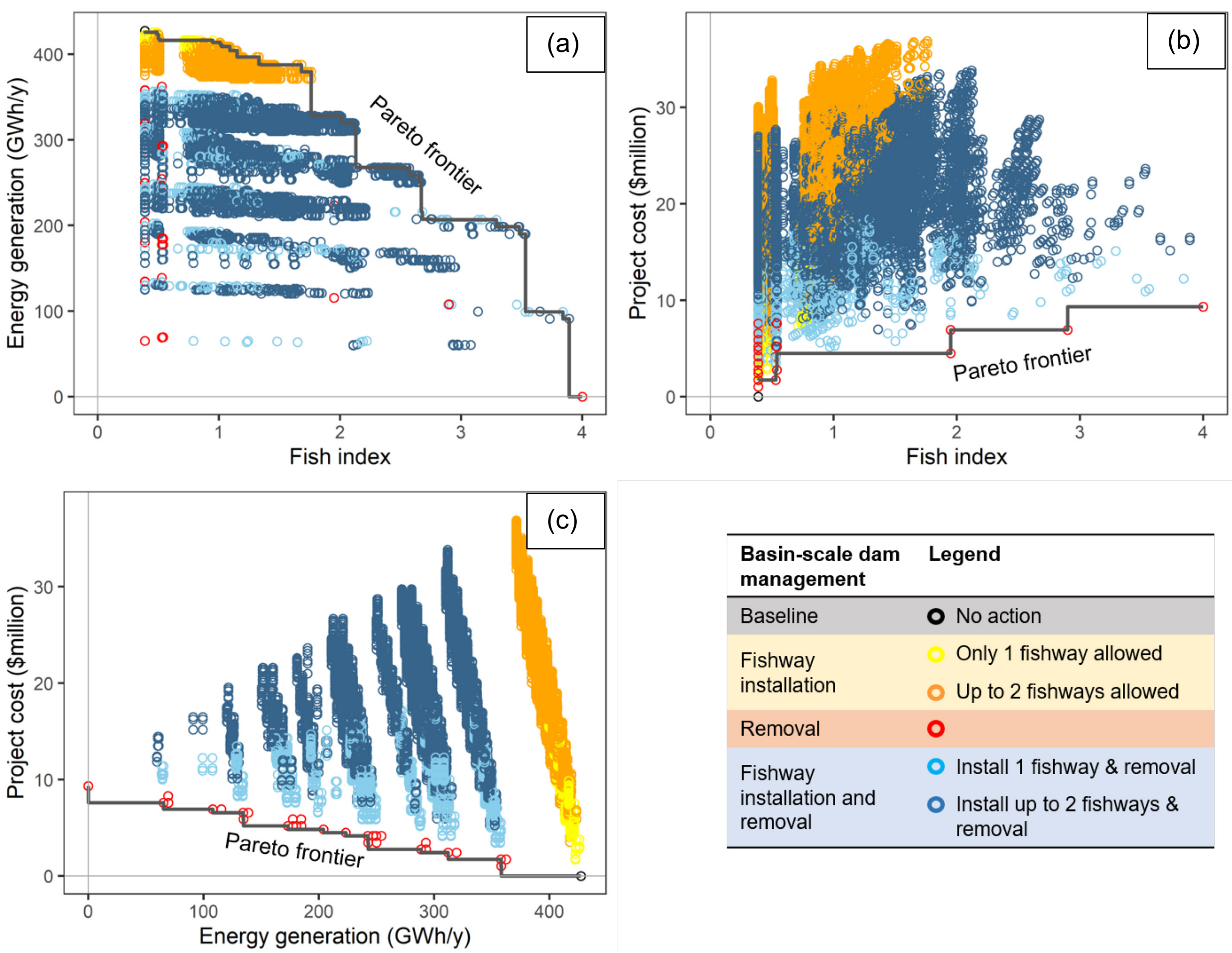


Figure 6. Tradeoffs among fish index, energy generation, and project costs for all basin-scale dam management scenarios of five main-stem dams in the Penobscot River basin. Each point represents a basin-scale dam management scenario.

3.3. Sensitivity analysis

Figure 7 presents trajectories of fish spawner population potential associated with 50%, 75%, 95%, and 100% likelihood for the tested scenario in response to changes of input parameters. Spawner population potentials of alewife, American shad, Atlantic salmon were found to change at a range of 0~13.9 million, 0~0.9 million, and 42~386 thousand, respectively, with a 100% confidence in the studied river basin. The results also show that spawner population potential of these three species reach equilibrium under all scenarios. This phenomenon can be explained as an outcome of the necessary biological process of density dependence, usually in early life history (Quinn and Collie, 2005). It has to be noted that these equilibriums are a result of the simplified mathematical assumptions for testing theoretical sensitivities, while there are numerous uncertain and stochastic factors that can result in population potential variations in reality. The equilibrium of sea lamprey spawner population potential is sensitive to parameters' uncertainty. With a 50% confidence, sea lamprey spawner population potential stabilize at a range of 0~7million. Otherwise, it presents a regular oscillation every 9 years which is consistent with one life cycle of sea lamprey. This is a mathematical result of the Ricker curve, a density dependent spawner-recruit curve presented (Myers, 2001). This curve determines that recruits of sea lamprey are reduced at high spawner population levels and increase at low population levels. For project cost, it is in the range of $7.4~$34.4 million with a 100% confidence.

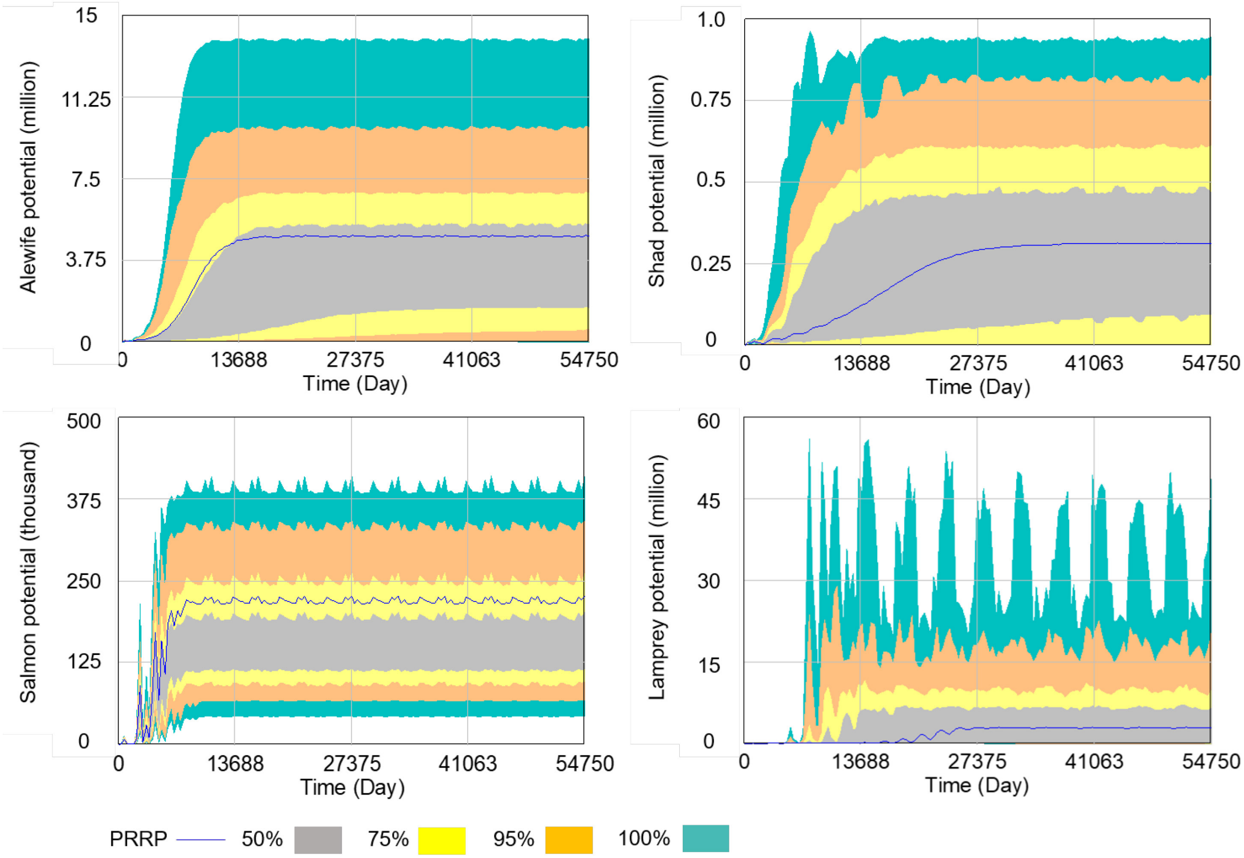


Figure 7. Monte Carlo simulation of the age-structured fish population model, presenting trajectory spawner population potential of (a) alewife, (b) American shad, (c) Atlantic salmon, and (d) sea lamprey in response to changes of input parameters.

4. Conclusion and policy implications

This dynamic modeling framework utilizing the system dynamics modeling technique was developed in this study to examine various dam management options. Using the Penobscot River as a testbed, it was found that it is possible to maximize fish potential and hydropower generation to 60-62% of their highest achievable values while limiting the project cost to $17 million (44% of the highest possible project cost). Our results also show that basin-scale management strategies can significantly improve fish index while preserving a similar amount of hydropower generation capacity as compared to management strategies that only focus on individual dams. It also has to be noted that the monetary values discussed in this study are 'costs' for in-situ dam management, but they can also be considered as 'investments' for a healthier ecosystem. Future work may include monetized values of ecosystem services for a more comprehensive cost-benefit analysis.

This integrated basin scale approach we describe is distinct from the current practice where dam decisions are often made in isolation and are primarily based upon the interests of the individual dam owners (Graf, 2001; Moran et al., 2018). Our results clearly demonstrate the advantage of dam management at a basin-scale for simultaneously optimizing energy, fish, and cost outcomes. This further highlights the importance of engaging a broad range of stakeholders who can influenced by dam decisions, especially those that have been rarely engaged in the decision-making process (Fearnside, 2015; Siciliano et al., 2015). Incorporating stakeholder inputs in the FERC hydropower relicensing process could be an important initial step in achieving this goal. When the dam management is done from a basin scale, diversification of management options (e.g., combination of fishway installations and dam removals) as well as implementation of fishways targeting multiple fish species can better balance fish-energy-cost tradeoffs.

Real-world decision-making may involve more criteria than those that have been considered in this study, such as flood control, recreation, water supply, sediment contamination/accumulation, and environmental release constraints. The modeling framework developed in this study may be extended to involve additional criteria that might be of interest to the stakeholders and decision makers. It may also be extended spatially and temporally to other river basins to address specific real-world challenges. Such an approach is not intended to make a decision, but rather to inform those upon whom that responsibility rests. Specifically, these models can be used to facilitate the discussions among stakeholders and decision-makers for consensus building in pursuit of the best possible economic, environmental, and social outcomes. Although this modeling framework applied historical stream flow data, it can also be extended to incorporate the influence of climate change on dam management.

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