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ARTICLE

A management strategy evaluation of the commercial sockeye salmon fishery in Bristol Bay, Alaska[1]

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Abstract: Bristol Bay, Alaska, is home to the largest sockeye salmon (*Oncorhynchus nerka*) fishery in the world, harvesting an average of 25 million fish with an ex-vessel value exceeding US$100 million annually. Daily fishing effort is adaptively managed to achieve stock-specific escapement goals. Traditional methods for defining these goals relied on stock–recruitment analysis; however, this approach often ignores three fundamental sources of uncertainty: estimation error, implementation uncertainty, and time-varying recruitment dynamics. To compare escapement goal alternatives, we conducted a management strategy evaluation that simulated time-varying recruitment across production regimes and replicated the daily in-season management process. Results indicate (*i*) implementation uncertainty can be reasonably approximated with simple rules reflecting fishery managers' daily decision process; (*ii*) despite implementation uncertainty, escapement goals are likely to be realized or exceeded, on average; and (*iii*) management strategies targeting escapement levels estimated by traditional methods to produce maximum sustainable yield may result in lower catch and greater variability in fishing opportunity compared with a strategy with defining high and low escapement goals that are targeted depending on assessed run size, which may maximize future catch while reducing the frequency of extremely low harvests.

Résumé : La baie de Bristol, en Alaska, est le lieu de la plus importante pêche au saumon sockeye (*Oncorhynchus nerka*) du monde, avec une production annuelle moyenne de 25 millions de poissons d'une valeur au débarquement de plus de US$100 millions. L'effort de pêche journalier est géré de manière adaptative pour permettre l'atteinte d'objectifs d'échappement propres au stock. Si les méthodes traditionnelles d'établissement de ces objectifs reposent sur l'analyse du recrutement au stock, cette approche ne tient pas compte, dans bien des cas, de trois sources fondamentales d'incertitude, à savoir l'erreur d'estimation, l'incertitude associée à la mise en œuvre et la dynamique de recrutement variable dans le temps. Afin de comparer différents objectifs d'échappement, nous avons réalisé une évaluation des stratégies de gestion qui simule le recrutement variable dans le temps pour différents régimes de production et reproduit le processus de gestion journalière durant la saison. Les résultats indiquent que (*i*) de simples règles reflétant le processus décisionnel journalier des gestionnaires de la pêche peuvent produire une approximation raisonnable de l'incertitude associée à la mise en œuvre, (*ii*) malgré l'incertitude associée à la mise en œuvre, les objectifs d'échappement sont susceptibles d'être atteints ou dépassés en moyenne et (*iii*) des stratégies de gestion qui visent des niveaux d'échappement estimés par des méthodes traditionnelles pour produire le rendement équilibré maximal peuvent se traduire par des prises plus faibles et une plus grande variabilité des possibilités de pêche qu'une stratégie qui comprend des objectifs d'échappement élevés et faibles utilisés tour à tour selon l'effectif de la montaison évalué, ce qui pourrait maximiser les prises futures tout en réduisant la fréquence de productions extrêmement faibles. [Traduit par la Rédaction]

Introduction

Fisheries management can be made more effective through systematic analysis of management alternatives, where the likelihood and relative risk of potential outcomes are quantified while accounting for both biological and management uncertainty. Management strategy evaluation (MSE) (Smith et al. 1999) is now widely used across species, ecosystems, and regions globally to assess and compare alternative policy choices and their robustness with to scientific uncertainty and natural variation (Punt et al. 2016). A full MSE involves two fundamental components: engagement with the stakeholder community to identify manage-

ment objectives and value functions for comparing outcomes, and the development of simulation frameworks for modeling the feedback loop between the management structure and underlying biological dynamics of the population or group of populations under evaluation (Bunnefeld et al. 2011). By directly confronting and quantifying the true sources of uncertainty in the biology of the target species, how we observe populations over time, and implementation of fishery management, MSE frameworks directly model the feedbacks between population dynamics and harvest, providing decision makers with better information on which to base harvest policy (Punt et al. 2016; Rademeyer et al. 2007; Smith et al. 1999).

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Fig. 1. Map of Bristol Bay, Alaska. Crosshatched areas describe boundaries of terminal fishing districts, and gray labels indicate river systems of origin for stocks included in the simulation. The Wood, Alagnak, and Naknek Special Harvest Areas are located just upstream of each respective river mouth. Map created with shape files from the Alaska Department of Fish and Game Anadromous Waters Catalogue, as well as US Geological Survey National Hydrography Dataset and National Elevation Dataset.
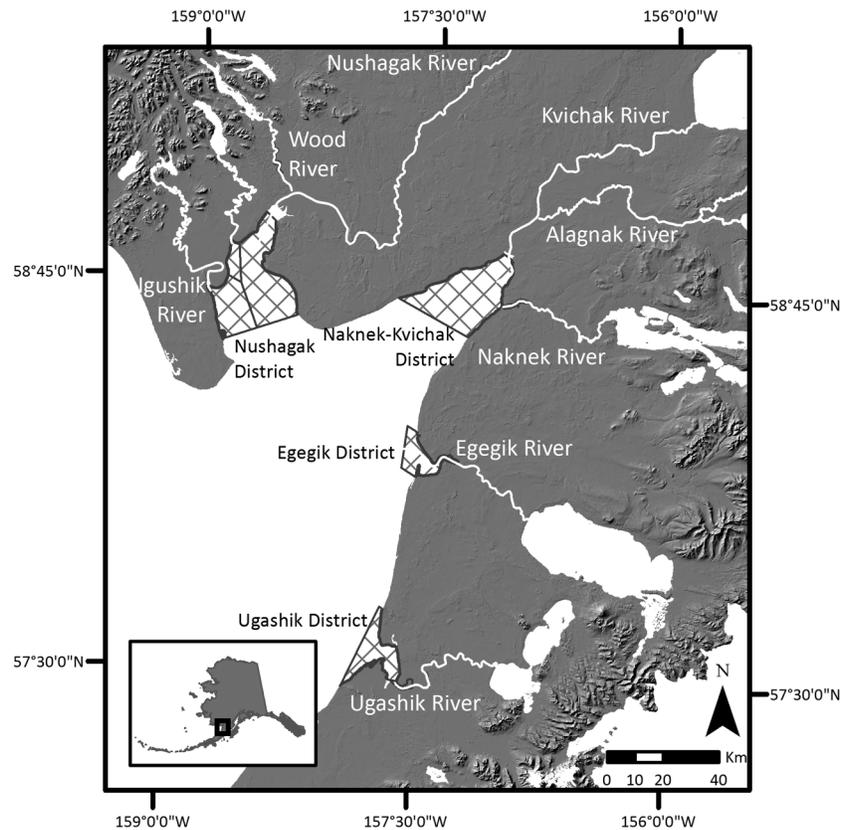
Despite increasing use in marine fisheries management, the closed-loop simulation–estimation methods embodied in MSE have seen much less frequent application in salmon fisheries management (for examples, see Link and Peterman 1998; Dorner et al. 2009; Steiner et al. 2011; Winship et al. 2013). This is particularly surprising given that more complete data are often available for salmon stocks when compared with most marine species, including either direct enumeration of the spawning stock size or reliable indices of abundance and extensive time series of age composition.

The commercial fishery in Bristol Bay, Alaska (Fig. 1), is the largest producer of sockeye salmon (*Oncorhynchus nerka*) worldwide with an average annual harvest of 25 million salmon since 1980 and a 2017 harvest of 37.7 million salmon with an ex-vessel value of US$209.9 million. This fishery operates through active in-season regulation of fishing effort in terminal fishing districts by emergency order (Clark et al. 2006). Terminal fishing districts encompass the mouth of one or more river systems and are intended to harvest only the target stock or stocks during their return migration to their natal river(s). Fishing effort is regulated to achieve annual escapement goals or target spawning stock sizes that have proven to maintain consistent yield over time and where possible produce maximum sustainable yield (MSY). Within the state of Alaska, escapement goals are typically presented as a range, with a lower and upper bound that may also include an explicit midpoint target.

Previous evaluations of fisheries harvest control rules have suggested that this type of constant-escapement strategy generally outperforms alternatives when the objective is to maximize cumulative yield, mean annual yield, or long-term profits (Deroba and Bence 2008). However, under certain conditions this may not be the case. For example, Walters and Parma (1996) found that if interannual variation in recruitment is autocorrelated, constant-escapement policies resulted in inferior harvest outcomes relative to constant fishing mortality control rules. Specifically, dynamic programming analysis indicated that imposing constant harvest rates performed very close (within 15%) to potential management performance with perfect information about future recruitment variation. Further, when imperfect information on population size is available to management, Engen et al. (1997) found alternative harvest control rules (i.e., proportional threshold harvesting) outperform constant-escapement policies for some fish life histories with respect to time to extinction and mean annual yield.

The common practice within the State of Alaska for evaluating alternative escapement goals or management strategies has been to fit Ricker-type models to reconstructed stock–recruitment data using maximum-likelihood or Bayesian methods. Fitted models are then used to simulate total run size and harvestable surplus or catch, across a range of potential escapements including the spawning abundance expected to produce maximum sustainable yield (S_{msy}) (Fair et al. 2012). However, this approach does not account for the uncertainty in future yield or optimal spawning stock size arising from three processes. First, it does not account for stochastic variation in future recruitment and the resulting impact on potential harvest in the fishery, which is important because stakeholders are often interested in the variability of catch as well as the average (Steiner et al. 2011). Second, many of the Bristol Bay sockeye stocks show evidence of past transitions among regimes with differing productivity (Adkison et al. 1996; Peterman et al. 2003). However, previous escapement goal evaluations have treated these shifts as random process variation, ignoring the autocorrelated and episodic nature of Bristol Bay

sockeye salmon production dynamics. Finally, although active in-season management has proven effective in capturing value from, and ensuring sustainability of, the Bristol Bay fishery, managers cannot always precisely achieve escapement goals. Referred to as implementation uncertainty in the management process, resulting differences between management targets and realized outcomes have been demonstrated to have substantial impacts on the perceived value of management alternatives (Cass et al. 2003; Dorner et al. 2009; Kell et al. 2005; Rosenberg and Brault 1993).

Several factors contribute to implementation uncertainty and influence fishery managers' ability to accurately realize escapement goals. Daily fishing effort is adjusted based in part on pre-season expectations and in part on comparisons of cumulative escapement to daily targets derived from the average inshore arrival distribution of each stock. As a result, management performance is sensitive to deviations from average inshore run timing and interannual variation in run size (Adkison and Cunningham 2015), as well as errors in preseason run size forecasts and delays in the availability of in-season information. The accuracy of annual preseason forecasts for the abundance of returning salmon are correlated with implementation uncertainty. Over-forecasts are associated with under-escapement events and vice versa, and the ratio of realized escapements to target escapement are positively correlated with overall run size (Bocking and Peterman 1988). Given that in-season management decisions largely rely on comparison of current cumulative escapement with daily escapement targets, real-time escapement information is necessary for the efficient prosecution of the fishery. In practice, however, current escapement information does not account for fish in transit between the commercial fishing district and upriver escapement enumeration sites. This results in escapement data only being available after a time lag determined by migration distance and variation in fish movement, but on average between 1 and 5 days for different Bristol Bay river systems.

Implementation uncertainty also results from decisions involving implicit and explicit trade-offs by fishery managers and those in the fishing industry. These trade-offs affect the ability of the fishery to capture very large daily and annual returns. Fishery managers must deal with mixed-stock harvest and regulatory constraints on fishing time designed to share harvest opportunity among different harvester groups (i.e., drift- and set-net operations). Furthermore, due to the mixed-stock nature Bristol Bay's terminal fishing districts (Cunningham et al. 2018), complex in-season management decisions are necessary to allocate fishing effort amongst districts and fishing areas within districts, to ensure that seasonal escapement goals for all river systems are met. Fishery managers will, unless otherwise directed by regulations set out by the Alaska Board of Fisheries, generally err on the side of ensuring escapement to the weakest constituent stocks(s) within a district. At the same time, fish processing companies must decide each year how much to gear up prior to the fishing season to handle expected harvest volumes. It is inefficient for processors to gear up for infrequent but very large annual returns, nor is it efficient to accommodate infrequent but very large daily harvest volumes (Bue et al. 2008; Wang et al. 2019). When daily catches exceed tendering and processing capacity within a district or for Bristol Bay as a whole, processors suspend buying temporarily, and otherwise-harvestable fish are added to the escapement, which increases implementation uncertainty. Despite substantial evidence that implementation uncertainty exists and is considerable, the assumption that escapement goals will be perfectly achieved in the future has been assumed in past escapement goal analyses of this system (see Dorner et al. 2009 for an exception).

The purpose of this MSE was to evaluate performance of four existing or proposed harvest strategies for the Bristol Bay, Alaska, commercial fishery, utilizing closed-loop Monte Carlo simulations that accounted for estimation uncertainty in stock–recruitment model parameters, autocorrelated and regime-driven shifts in population

productivity, and implementation uncertainty in the management and harvesting processes. Three of the four strategies evaluated represent constant escapement type harvest control rules (Deroba and Bence 2008), while the fourth strategy targeted higher escapement goals closer to theoretical optima (S_{msy}) in years where a simple in-season assessment predicted larger run sizes. These closed-loop simulations were used to specifically address three questions regarding management of the fishery:

1. Are the alternative escapement goals likely to be achieved given implementation uncertainty associated with mixed-stock terminal fishery management, small delays in escapement information, interannual variation in run timing and distribution, and occasional constraints on harvesting capacity?
2. Are higher escapement goals estimated to produce MSY likely to result in higher run sizes, given process variation in recruitment and periodic shifts in population productivity?
3. Which management strategies are likely to maximize future harvest while minimizing the frequency of low catch years that result in hardship for salmon harvesters and processors?

Wang et al. (2019) document the economic modeling component of the MSE presented here with a focus on how different escapement goal policies influence the revenue from the harvest by considering processing capacity, market factors, and product value from different annual harvest levels. In this paper, we focus on the performance of management alternatives in meeting biological objectives and resulting harvest outcomes and factor economics in only so far as they affect daily harvest capacity and therefore realized escapement.

Methods

Alternative management strategies for the Bristol Bay fishery were compared by simulating outcomes using an MSE simulation framework composed of a linked biological operating model and management simulation model, subject to a range of uncertainties. The biological model was designed to capture the variability in realized recruitment based upon previous analyses of spawner–recruit data by Cunningham et al. (2015). This operating model simulated transitions between high and low productivity regimes observed for many Bristol Bay stocks and process variation in recruitment while propagating the estimation uncertainty in stock–recruitment model parameters through the simulated population dynamics. Conversely, the management model captured the implementation uncertainty in the management process resulting from the difficulty inherent in the daily regulation of fishing effort across multiple fishing districts, with independent escapement goals, based upon lagged escapement information and uncertainty in the arrival timing of sockeye to fishing districts and occasional limits to daily harvests created by processing limits. Together the biological and management models were used to simulate future stock-specific run sizes, catches, and realized escapements across a 100-year time horizon. Forward simulations, given a specific harvest policy, were replicated 500 times to propagate process, implementation, and estimation uncertainty through to predicted outcomes. Each of the replicate simulations of the 100-year time series was repeated for each of four alternative management strategies describing current management, theoretical optima from previous analyses, and alternatives proposed by stakeholders.

Management strategies

Four alternative management strategies were evaluated for the Bristol Bay fishery, each specifying annual escapement (spawning abundance) goals for the eight major sockeye salmon populations (Fig. 1). These strategies were based on extensive consultation with the study's stakeholder Advisory Panel (AP). The AP was made up

Table 1. Alternative management strategies for the Bristol Bay commercial sockeye salmon fishery.

| Stock | Escapement goals (thousands) | | | | | |
| | Current SEG (status quo)[a] | Proposed SEG[b] | BEG[c] | TR-based EG[d] | | |
				Lower goal	Upper goal	Total run breakpoint
Igushik	225	300	291	225	430	720
Wood	1100	1300	1550	1100	1500	3200
Nushagak	590	700	801	590	825	1200
Naknek	1100	1450	1858	1100	1900	3300
Egegik	1100	1450	5242	1100	1750	4700
Ugashik	850	1000	2602	850	1600	2500

Note: Values are the midpoint escapement targets for the four management strategies in thousands of sockeye salmon. Kvichak and Alagnak escapement targets did not vary across of the management strategies.

[a]Sustainable escapement goals in place at the time of this analysis (prior to 2015 season).

[b]Sustainable escapement goals proposed by ADF&G in 2012.

[c]Biological escapement goals as estimated by Fair et al. (2012) to produce maximum sustainable yield (MSY) based on a time-invariant Ricker model.

[d]Total run-based escapement goals. Lower and upper escapement goals are targeted based on the comparison of a midseason assessment of run size with the total run breakpoint. If the run size projection exceeds the total run breakpoint, the upper goal is selected; otherwise, the lower goal remains the target.

of individuals from the harvesting and processing sectors in Bristol Bay and research and management agency staff (Alaska Department of Fish and Game, ADF&G). Strategies had to be implementable within the existing constraints of the regulatory framework and provide reasonable opportunities to improve upon biological and economic yield from the status quo escapement goals. Three of four management strategies specified constant escapement type harvest control rules, while the fourth strategy implemented a harvest control rule with variable escapement goals depending on estimated run size in a given year (Table 1).

The first trial management strategy (hereinafter Current SEG) targeted the midpoints of the "current" sustainable escapement goal (SEG) ranges for Bristol Bay stocks (Baker et al. 2006) that were in place at the time of the MSE process (2014–2015): the status quo. The second strategy (Proposed SEG) specified that managers would target the midpoints of revised SEGs that were proposed by the ADF&G in 2012 (Fair et al. 2012). The third strategy (BEG) used the biological escapement goals estimated by Fair et al. (2012) for each stock. These BEGs were equal to the escapement levels estimated to produce maximum sustainable yield (S_{msy}) when time-invariant Ricker stock–recruitment models were fit to available data. Stock-specific BEG targets were between 29% and 377% higher than the status quo (Current SEG). Proposed SEGs struck a balance between the status quo and the theoretical optimum (BEG) targets and were only 18%–33% higher than the Current SEGs (Table 1).

The fourth and final management strategy was a "total run-based escapement goal" (TR-based EG) with variable escapement goals based on predicted total run size and was developed in collaboration with the stakeholder AP. To model this strategy, two escapement goals were defined for each stock, and the decision of which to target in a given season depended on a midseason assessment of the total run size. For the TR-based EG strategy, the simulated manager targeted the lower-tier goal for a given stock at the beginning of the season; however, if an in-season assessment of run size exceeded a specified total run threshold, the seasonal escapement target was shifted upward to the higher escapement goal (Table 1).

At the time of this MSE, no changes were proposed to management of the Kvichak and Alagnak stocks, so their escapement goals were defined at the status quo. However, as these stocks are harvested together with the Naknek stock in the Naknek–Kvichak fishing district (Cunningham et al. 2018), their realized catch and escapement was expected to be influenced by alternative management strategies for the Naknek stock. Across all strategies examined, we simulated the current TR-based EG for the Kvichak River. The Kvichak River escapement goal is set at 50% of a preseason forecast and that of a midseason run size assessment based on cumulative catch and escapement to date, subject to an overarching 2–10 million constraint (i.e., never less than 2 million or more than 10 million escapement). As the Naknek–Kvichak District is managed to meet Kvichak and Naknek escapement goals, the simulated escapement and total return to the Alagnak River did not influence in-season management in our model.

Biological operating model

Recruitment models

The biological operating model of the MSE framework was intended to capture the uncertainty in future recruitment to the eight major Bristol Bay stocks (Fig. 1). Recruitment is defined as the total production from a specific brood year escapement (spawning abundance) and is calculated as the total return abundance of salmon observed as catch or escapement in subsequent years. To simulate the spawner–recruit dynamics for each of these river systems, we fit several types of Ricker (eq. 1) spawner–recruit models to data reconstructed by Cunningham et al. (2018) for years 1963–2016.

$$
\begin{aligned}
R_{y,p} &= S_{y,p} \exp\left[\alpha_p\left(1 - \frac{S_{y,p}}{\beta_p}\right) \right] \exp(\varepsilon_{y,p}) \\
\varepsilon_{y,p} &\sim \text{Normal}\left(0, \sigma_p^2\right)
\end{aligned}
\tag{1}
$$

In this parameterization of the Ricker (1954) model, $\exp(\alpha_p)$ describes maximum productivity (recruits per spawner) in the absence of density-dependent compensation for each population p, β_p describes equilibrium (unfished) abundance, and σ_p represents the standard deviation of lognormally distributed process uncertainty.

Three variants of the Ricker model were fit to data for the Bristol Bay stocks and used to simulate future trends in recruitment. A time-varying (hidden Markov) version of the Ricker model was used for the Kvichak, Naknek, Egegik, Ugashik, Wood, and Igushik stocks; a time-invariant Bayesian Ricker model was used for the Alagnak stock; and a maximum likelihood version of the time-invariant Ricker model was used for the Nushagak stock. Time-varying recruitment models were used where possible given the nonstationary production dynamics for these systems previously described by Peterman et al. (2003). The choice of recruitment approximation was based on the availability of prior

information on equilibrium abundance and estimation model convergence (Cunningham et al. 2015).

The hidden Markov Ricker model assumes that the form of the stock–recruitment relationship has alternated between productive and unproductive states over time, and estimates separate parameters for each of these two regimes. Transition between these production regimes is modeled as a first-order Markov process, where future regime occupancy is conditioned on the regime occupied in the previous brood year and with the probabilities for transitioning among regimes estimated from the data.

In practice, this means expected recruitment from each brood year (y) is modeled as a mixture of two separate spawner–recruit relationships, with the probability that any particular year belongs to the high or low productivity regime depending on the observed regime in $y - 1$ (eq. 2):

$$
\begin{aligned}
R_{y,p} &= S_{y,p} \exp\left[\alpha_{\lambda_{y,p},p}\left(1 - \frac{S_{y,p}}{\beta_{\lambda_{y,p},p}}\right)\right] \exp(\varepsilon_{y,p}) \\
\varepsilon_{y,p} &\sim \text{Normal}\left(0, \sigma^2_{\lambda_{y,p},p}\right) \\
\lambda_{y,p} &\sim \text{Bernoulli}(\gamma_{y,p,r}) \\
\gamma_{y=1,p,r} &= \omega_{p,r} \\
\gamma_{y,p,r} &= \pi_{i=\lambda_{y-1,p},j=r,p}
\end{aligned}
$$

(2)

This dependency allows the conditional probability of remaining within a productivity regime or transitioning to another to be estimated, and permits simulation of future regime occupancy.

In the hidden Markov model (eq. 2), the values of Ricker parameters ($\alpha_{\lambda_{y,p},p}$, $\beta_{\lambda_{y,p},p}$, $\sigma_{\lambda_{y,p},p}$) for a population p depend on the regime or state ($\lambda_{y,p}$) occupied in brood year y. The regime $\lambda_{y,p}$ occupied in each brood year depends on the population-specific probability of regime occupancy ($\gamma_{y,p,r}$) and is drawn from a Bernoulli distribution in each posterior sample. The regime occupancy probability in the first brood year is equal to the regime-specific (r) initial state probability $\omega_{p,r}$ that is estimated from the data. In all subsequent brood years, the regime occupancy probability is equal to the transition probability matrix ($\pi_{i,j,p}$), which governs the likelihood of regime occupancy, conditioned upon the previous year's regime, for each population. In $\pi_{i,j,p}$, i represents the regime from which one is transitioning, and j represents the production regime to which one is transitioning (eq. 3).

$$
(3) \qquad \pi_{i,j,p} = \begin{bmatrix} p_{i=1,j=1} & p_{i=1,j=2} \\ p_{i=2,j=1} & p_{i=2,j=2} \end{bmatrix}
$$

Diagonal elements of this matrix describe the probability of remaining in the same regime, while the off-diagonal elements describe the probability of state transitions. The prior distribution for the row elements of $\pi_{i,j,p}$ was Dirichlet with scale parameters (2,2) based on the fact that each row of the transition matrix represents a separate multinomial distribution. This Dirichlet prior results in a broad normal distribution with expected value of 0.5 for remaining in the same regime and transitioning to the other.

Informative prior distributions for the equilibrium population size parameters ($\beta_{r,p}$) were derived from paleolimnological data collected from nursery lakes of the Bristol Bay river systems (Rogers et al. 2013, Schindler et al. 2005, 2006). Nitrogen isotopes from lake sediments were used to reconstruct time series of sockeye salmon abundances before the advent of commercial fishing and escapement enumeration. The resulting informative priors were normally distributed with mean equal to the top 20% of reconstructed abundances and a coefficient of variation (CV) of 0.5 (see Cunningham et al. 2015 for further detail).

Table 2. Average age composition proportions ($P_{p,a}$) used to allocate recruitment across age classes.

Stock	1.2	1.3	2.2	2.3
Igushik	0.23	0.67	0.06	0.04
Wood	0.46	0.47	0.05	0.03
Nushagak	0.10	0.82	0.04	0.03
Kvichak	0.24	0.10	0.59	0.07
Alagnak	0.29	0.53	0.10	0.09
Naknek	0.18	0.44	0.18	0.19
Egegik	0.08	0.15	0.45	0.32
Ugashik	0.28	0.31	0.28	0.13

The hidden Markov model did not converge when fit to stock–recruitment data from the Alagnak system, so the stock–recruitment relationship for this population was approximated by a single-regime Bayesian Ricker model with the same paleolimnological prior on β. Paleolimnological data were unavailable for the Nushagak River population; therefore, a maximum likelihood Ricker model was fit to those data. For both the Alagnak and Nushagak populations, estimated stock–recruitment model parameters and uncertainty were used to simulate future recruitment.

Forward simulation

The eight salmon populations were simulated forward in time from 2014 to 2113, tracking the abundance of the four age classes comprising the majority of salmon returns 1.2, 1.3, 2.2, and 2.3 ($x.y$ denotes a fish that spent x years in fresh water followed by y years in the ocean before returning to spawn). The observed escapements to each river in years 2008–2013 were used to initialize these simulations. Future recruitments were simulated using the population-specific Ricker parameters drawn from respective joint posteriors from Bayesian stock–recruitment models, thus propagating correlation among parameters. For Nushagak River, whose stock–recruitment model was fit by maximum likelihood, parameters were drawn from a normal distribution with mean equal to the point estimates for each parameter and assuming a CV equal to the average of parameter-specific posterior CVs across the other populations. In addition to propagating estimation uncertainty in recruitment model parameters, process uncertainty in future recruitments was incorporated by multiplying expected recruitment by a lognormal random deviate, with variance equal to that estimated for each population.

To simulate production uncertainty arising from periodic shifts among production regimes, we generated a 100-year time series of future regime states independently for the six populations to which the hidden Markov model was fit (i.e., Kvichak, Naknek, Egegik, Ugashik, Wood, and Igushik rivers). The presence of a stock in either the high or low productivity regime in each year was determined by generating random jumps between regimes based upon the previously estimated transition probabilities for each population ($\pi_{i,j,p}$). An initial random state was drawn for each stock with equal probabilities of occupying the high and low productivity regime. Future productivity states were simulated by drawing a random value from a uniform (0,1) distribution and comparing it with the probability of remaining in the current state i and the probability of transitioning to the other state (production regime) j, depending on the state in brood year y (eq. 3). This process was repeated until a full matrix of production states for each of the six hidden Markov populations.

The full age structure of each population was simulated by allocating future recruitment ($\hat{R}_{y,p,s}$), of population p in simulation s, across age classes, and therefore return years, based on the average age composition of returning fish to each river system (Table 2). The number of fish returning ($A_{t,p,s,a}$) in calendar year t aggregates expected recruitment across age classes and brood years for each population.

(4) $\quad \begin{aligned} A_{t,p,s,a} &= \hat{R}_{y,p,s} P_{p,a} \\ t &= y + \phi_a \end{aligned}$

These annual returns were calculated by multiplying the simulated recruitment from a brood year y by the average observed age composition proportions for each stock across years ($P_{p,a}$) and applying the correct year offset (ϕ_a) for each age class to determine the calendar year of maturation (eq. 4).

Returning adult sockeye ($A_{t,p,s,a}$) were then subject to harvest mortality as calculated by the daily management model (detailed below). The simulated spawning abundance $\hat{S}_{t,p,s}$ is the number of returning adults less the simulated catch $C_{t,p,s,d}$, summed across ages and days d, respectively, for each calendar year, population, and simulation (eq. 5).

(5) $\quad \hat{S}_{y=t,p,s} = \sum_{a=1}^{4} A_{t,p,s,a} - \sum_{d}^{\text{days}} C_{t,p,s,d}$

Management simulation model

The Bristol Bay commercial fishery is prosecuted in four primary terminal fishing districts (Fig. 1) located at the mouth of one or more salmon producing river systems (the Togiak fishing district was not included in these analyses given its spatial segregation and independent management). We simulated the difficulties inherent in a fishery manager's decisions regarding the daily regulation of effort in these districts to replicate the implementation uncertainty inherent in the in-season fishery management process. Simulation of fishery manager behavior required several pieces of information. First, the average arrival distribution for each stock was necessary to create daily cumulative escapement targets for the seasonal escapement goals under each management strategy. These daily targets were the criteria upon which the simulated manager decides whether to open a commercial fishing district on each day. Second, transit times between commercial fishing districts and escapement enumeration sites on each river were necessary to account for the time lag before in-season escapement information is available to the simulated manager. Finally, stock-specific harvest for each commercial fishing district, section, and special harvest area were derived from run reconstructions by Cunningham et al. (2018), who used age and genetic composition of catch information to estimate harvest rates in natal fishing districts and interception rates in non-natal fishing districts. To condition our management simulation model, these harvest rates were later tuned through an iterative process of comparing simulated escapement outcomes with observed escapements for years 1963–2008, years for which daily run reconstructions were available from Branch and Hilborn (2010). Given our purpose of simulating daily in-season management, it was necessary to partition returning adult sockeye in each year (from the biological model) into discrete daily "packets" of fish arriving in Bristol Bay. These daily packets, or arrival groups, were tracked forward in time across spatial stages, through fishing districts and upstream migration, and past escapement enumeration sites, similar to "box-car" models developed by Starr and Hilborn (1988). The arrival of sockeye to fishing districts in Bristol Bay does not strictly follow a normal distribution (Branch and Hilborn 2010), being often right-skewed with large daily deviations from the expected arrival distribution. The arrival process in each year was simulated by selecting a year at random from the years for which daily arrivals by stock had been reconstructed (Branch and Hilborn 2010) and converting these to the proportion $P_{t,p,s,d}$ of the seasonal total arriving on day d. The annual abundance of arriving individuals ($A_{t,p,s,a}$) was then multiplied by the daily proportions ($P_{t,p,s,d}$) to calculate the number of fish entering the fishing district on each day of the simulation as $E_{t,p,s,d} = P_{t,p,s,d} \sum_a A_{t,p,s,a}$. In this way the simulated inshore arrival of fish

Table 3. Matrix of harvest rate by fishery option and population ($h_{f,p}$) for the west side of Bristol Bay.

Fishery option (f)	Igushik	Wood	Nushagak
1. None	0.0%	0.0%	0.0%
2. Nushagak and Igushik sections	44.0%	60.0%	80.0%
3. Nushagak section only	20.0%	60.0%	80.0%
4. Igushik section only	30.0%	0.0%	0.0%
5. Wood River Special Harvest Area	0.0%	80.0%	0.0%
6. Wood River Special Harvest Area and Igushik section	30.0%	80.0%	0.0%

captured the observed interannual variation in both the shape of the arrival distribution and arrival timing.

Bristol Bay fishery managers open and close fishing areas on a daily basis. Here we refer to the area or combination of fishing areas open to fishing effort on a given day as a fishery option (f). If fishing option f were selected on day d of the season, then a fraction ($h_{f,p}$) of stock p was harvested (Tables 3 and 4). The catch on a given day is therefore $C_{t,p,s,d} = E_{t,p,s,d} u_{t,p,s,d}$, where $u_{t,p,s,d}$ is equal to the harvest rate $h_{f,p}$ depending on the fishery option selected by the simulated manager on any given day. Daily catch was subject to infrequent processing capacity constraints described by Wang et al. (2019); if daily catch was greater than processing capacity, the foregone harvest was counted as escapement. Fish were assumed to reside in fishing districts and be available to harvest for 2 days during the return migration, based on insights from fishery managers and bounded by the difference in timing between observed peaks in district catches and subsequent upstream escapement. Therefore, the number of fish leaving the fishing district ($L_{t,p,s,d}$) on day d is the number that entered the fishing district minus the harvest on each of the preceding days of residency k:

(6) $\quad L_{t,p,s,d} = \sum_{k=1}^{2} (E_{t,p,s,d-k} - C_{t,p,s,d-k})$

Daily escapement at the enumeration site on day d ($S_{t,p,s,d}$) was the number of fish leaving the fishing district l days before (l being the lag time between departure from the fishing district and reaching the counting site): $S_{t,p,s,d+l} = L_{t,p,s,d}$. Lag times in days between the fishing district and escapement enumeration sites were as follows: Igushik 4, Wood 1, Nushagak 2, Kvichak 3, Alagnak 2, Naknek 1, Egegik 5, Ugashik 2.

Simulation of the in-season management decision process depended upon two key components. The first is the matrix of population-specific harvest rates by fishery option ($h_{f,p}$) that describes the realized harvest rate for each population when commercial fishing effort is allowed in a specific commercial fishing district or combination of districts. The management model for the west side of Bristol Bay included the Nushagak and Igushik sections and Wood River Special Harvest Area. In total, six alternative fishery options were available to the simulated west side manager, including options for no open areas and various combinations of different fishing areas (Table 3). Given that the east side of Bristol Bay is composed of three commercial fishing districts harvesting a mixture of stocks (Cunningham et al. 2018), the management model for this side was more complex and comprised the Naknek–Kvichak, Egegik, and Ugashik districts, as well as the Naknek River Special Harvest Area. In total, nine alternative fishery options were available for in-season management, with differing harvest rates imposed on each of the populations on the east side of Bristol Bay (Table 4). For fishery options in which multiple fishing areas are open, in each of which fish of population p are harvested or intercepted, the total harvest rate for that population is one minus the product of district-specific survival rates:

Table 4. Matrix of harvest rate by fishery option and population ($h_{f,p}$) for the east side of Bristol Bay.

Fishery option (f)	Kvichak	Alagnak	Naknek	Egegik	Ugashik
1. None	0.0%	0.0%	0.0%	0.0%	0.0%
2. Naknek–Kvichak District only	50.0%	45.0%	50.0%	5.2%	2.0%
3. Egegik District only	5.1%	3.7%	6.5%	95.0%	10.1%
4. Ugashik District only	0.6%	0.6%	0.4%	3.4%	60.0%
5. Naknek–Kvichak and Egegik Districts	52.5%	47.0%	53.3%	95.3%	11.9%
6. Naknek–Kvichak and Ugashik Districts	50.3%	45.3%	50.2%	8.4%	60.8%
7. Egegik and Ugashik Districts	5.7%	4.3%	6.9%	95.2%	64.0%
8. Naknek–Kvichak, Egegik, and Ugashik Districts	52.9%	47.3%	53.4%	95.4%	64.8%
9. Naknek River Special Harvest Area	0.0%	0.0%	90.0%	0.0%	0.0%

$h_{f,p} = 1 - \Pi_{i \in f} (1 - H_{i,p})$, where $H_{i,p}$ is the harvest rate of population p in district i when open.

The second key component of the simulated in-season management process was the decision rules governing which fishery option was selected on each day. During each day of the season, the cumulative escapement to each river system was compared with the daily target cumulative escapement expected at that point in the season. The status of each stock, with respect to the daily target, was recorded and formed the criteria upon which the optimal fishery option was selected. For example, if Egegik and Ugashik stocks were ahead of their in-season escapement targets through a particular date, while Kvichak and Naknek stocks were not, a fishery option would be selected wherein both the Egegik and Ugashik districts would open, but not the Naknek–Kvichak District (i.e., Table 4, option 7). Under option 7, the Egegik and Ugashik stocks would be harvested at high rates in their respective districts, but non-zero harvest rates would also be imposed on the Kvichak, Alagnak, and Naknek stocks as a result of interception in the two open districts (Table 4).

In-season management of the Kvichak River across all four alternative strategies reflected the rolling escapement goal currently in place. For the Kvichak River system, an initial preseason escapement goal ($PEg_{t,s}$) was set at 50% of a preseason forecast for the total Kvichak run ($PF_{t,s}$). The preseason forecast was equal to the true run size in that year t of simulation s plus lognormally distributed error proportional to that observed for the University of Washington Fisheries Research Institute preseason forecast:

$$
(7) \quad
\begin{aligned}
PF_{t,s} &= \sum_{a=1}^{4} (A_{t,p=\text{Kvichak},s,a}) \exp(\varepsilon_{PF}) \\
\varepsilon_{PF} &\sim \text{Normal}(0.02, \ 1.24^2) \\
PEg_{t,s} &= 0.5 PF_{t,s}
\end{aligned}
$$

At the midpoint of the season, a new midseason escapement goal is set at 50% of the run size projected by a simple in-season assessment, and daily escapement targets were updated accordingly. The in-season assessment used cumulative catch plus escapement though the historical median date for Kvichak returns to project total run size. Both the initial and midseason escapement goals for the Kvichak River were subject to lower and upper bounds of 2 and 10 million sockeye, respectively, as per the existing regulations.

The TR-based EG strategy followed a similar in-season assessment procedure to update daily escapement targets. At the beginning of each season, daily cumulative escapements targets were set so as to achieve the lower goal (Table 1). On the date during which 50% of seasonal catch plus escapement has historically been observed for each population (the average midpoint MP_p of the arrival distribution), an in-season estimate of run size was made based on the observed cumulative catch and escapement through that date:

$$
(8) \quad IF_{t,p,s} = 2 \cdot \sum_{d=1}^{MP_p} E_{t,p,s,d}
$$

If the in-season run size forecast ($IF_{t,p,s}$) exceeded the specified total run breakpoint, the seasonal escapement goal was moved to the higher specified goal (Table 1), and daily cumulative escapement targets were updated accordingly.

Tuning the management simulation model

To determine whether the management model accurately reflected the outcome of the in-season decision process by real Bristol Bay fishery managers, we assessed the efficacy of our simulated fishery manager. Efficacy of the simulated manager was evaluated by running the model retrospectively for years 1963–2008, given the escapement goals in place and daily inshore arrivals in each year, for each of the eight model populations. The seasonal escapement total achieved by the simulated manager was then compared with the true observed escapement in each year to assess the extent to which the management simulation model was accurately emulating the behavior of fishery managers. This comparison was used to tune the population-specific harvest rates by fishery ($h_{f,p}$) to achieve the highest possible agreement between simulated and observed management outcomes and ensure the correct level of implementation uncertainty was introduced.

Performance metrics

Metrics for evaluating the performance of alternative management strategies were developed by the stakeholder AP in collaboration with the study team. The majority of performance metrics identified by the AP concerned magnitude and variability of future harvest opportunity. Resulting performance metrics quantified the expected level of future catch as well as the expected variability in catch resulting from variation in population productivity and uncertainty associated with the management process. There was generally an interest in evaluating outcomes at both the stock level and aggregated for Bristol Bay as a whole and a desire to quantify catch outcomes relative to expectations under the status quo (Current SEG) strategy. The AP also highlighted the risk associated with years of detrimentally low catch, and the frequency of these events across the 100-year simulation was developed as a performance metric.

Results

Simulated management model

Efficacy of the simulated management model in emulating past management outcomes was evaluated by comparing escapements achieved by the simulated manager with the observed escapements for 1963–2008. To ensure outcomes were comparable, we set escapement goals provided to the simulated manager in each year equal to the goals that were in place in each previous year. Figure 2 displays the observed escapement (x axis) compared with

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Fig. 2. Comparison of escapement outcomes from the management simulation model with observed escapements to the major Bristol Bay river systems for 1963–2008. Management model escapement targets were equal to escapement goals in place in each year. The true observed escapement in millions of sockeye is on the *x* axis, and escapements achieved by the management model are on the *y* axis. Points falling on the 1:1 line indicate that the management simulation model exactly reflected the true management outcome in that year.
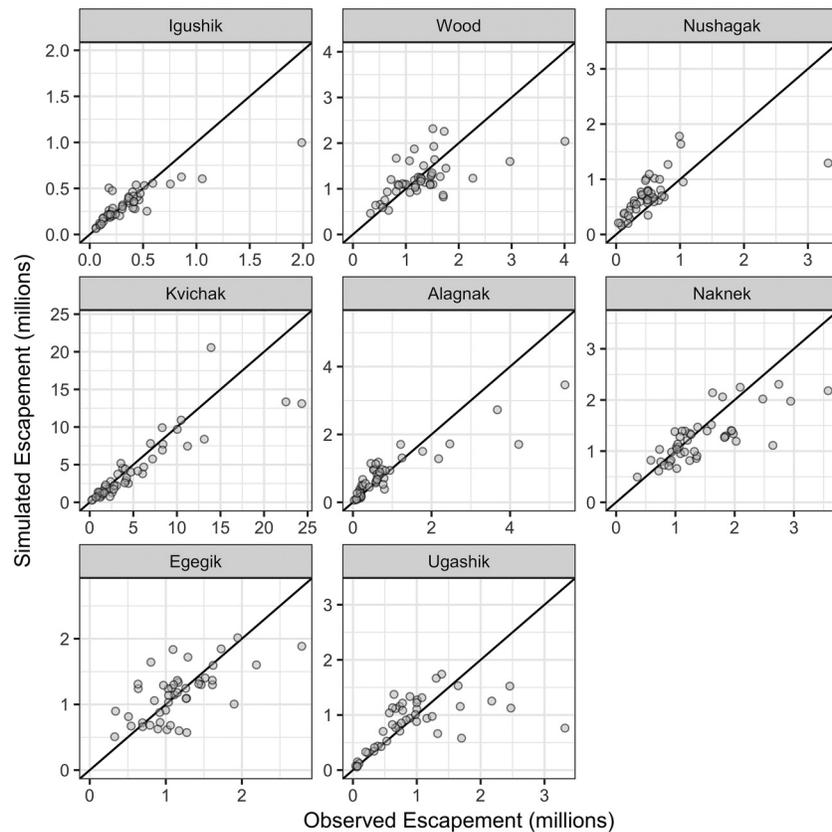
the escapement achieved by the management model (*y* axis) when provided with the same data and targets, after harvest rates were manually tuned. Population-specific comparisons indicate no significant biases in management outcomes, save a slight tendency of the management model to achieve higher than observed escapements to the Nushagak River (Fig. 2). However, comparisons for the Alagnak, Naknek, and Ugashik stocks indicate a slight tendency for the management model to under-escape relative to historical observations in years of high run size. Overall, differences between simulated and observed management outcomes were small after only moderate tuning of harvest rates, and results are likely robust to these slight differences.

Management strategy comparison

Are alternative escapement goals likely to be achieved?

Simulation analysis suggests that alternative escapement goals are likely to be met, with median escapements predicted to exceed goals by some amount under all strategies. Across river systems, higher median escapement is expected under the BEG strategy with escapement goals based on the substantially higher S_{msy} estimates from Fair et al. (2012), although substantial variation in escapements across all strategies examined is predicted (Fig. 3). This pattern in realized escapements was most pronounced for the Naknek, Egegik, and Ugashik stocks, which is largely due to the greater disparity between Current SEGs and the BEGs for these stocks (Table 1).

While realized escapements are predicted to exceed goals across rivers and management strategies, results suggest the ability to precisely attain escapement goals is higher for single-stock fisheries than mixed-stock terminal fisheries. Across management strate-

gies, median predicted escapement to the Egegik and Ugashik rivers that are harvested in single-stock fisheries was closer to the specified targets. Conversely, realized escapements for the Igushik, Wood, and Nushagak rivers that are fished in the same mixed-stock fishing district are predicted to exhibit greater variability in realized escapement relative to the midpoints of the escapement goals specified under each strategy (Fig. 3; Table 1).

The estimated median escapement to the Kvichak River differed across management strategies, despite the fact that the Kvichak is managed in the same way across scenarios. The median value for predicted escapement to the Kvichak is 5.3 million sockeye higher for the BEG strategy than for the scenario modeling Current SEGs. Differences in realized Kvichak escapement across management strategies results from mixed-stock constraints on fishing effort in the Naknek–Kvichak District, due to the necessity of reducing exploitation rates on the Naknek stock to achieve its higher escapement goal under the BEG strategy.

In addition to differences in the median expected escapement under alternative management strategies, differences in the shape and modality of expected escapements were found (Fig. 3). The management strategy implementing variable escapement goals (TR-based EG) produced bimodal distributions of escapement across years and simulations. Given that total run breakpoints for this strategy were set at the median observed run size (1956–2014 return years), it was expected that both the upper and lower goals would be targeted in proportion to whether an overall increase in total run size was observed across the time frame of simulation. Bimodal escapement patterns were observed for the Naknek, Egegik, Ugashik, and Wood rivers under the TR-based EG management strategy, while expected escapement for all other

Fig. 3. Distribution of predicted escapement in millions of sockeye to the eight major Bristol Bay river systems across replicate 100-year simulations under each management strategy. The point, thick line, and thin line describe the median, 50%, and 90% intervals, respectively, for each prediction. Crossed targets show the midpoint escapement goals under each management strategy. Escapement goals are not shown for the Kvichak River because of its harvest rate-based management procedure.
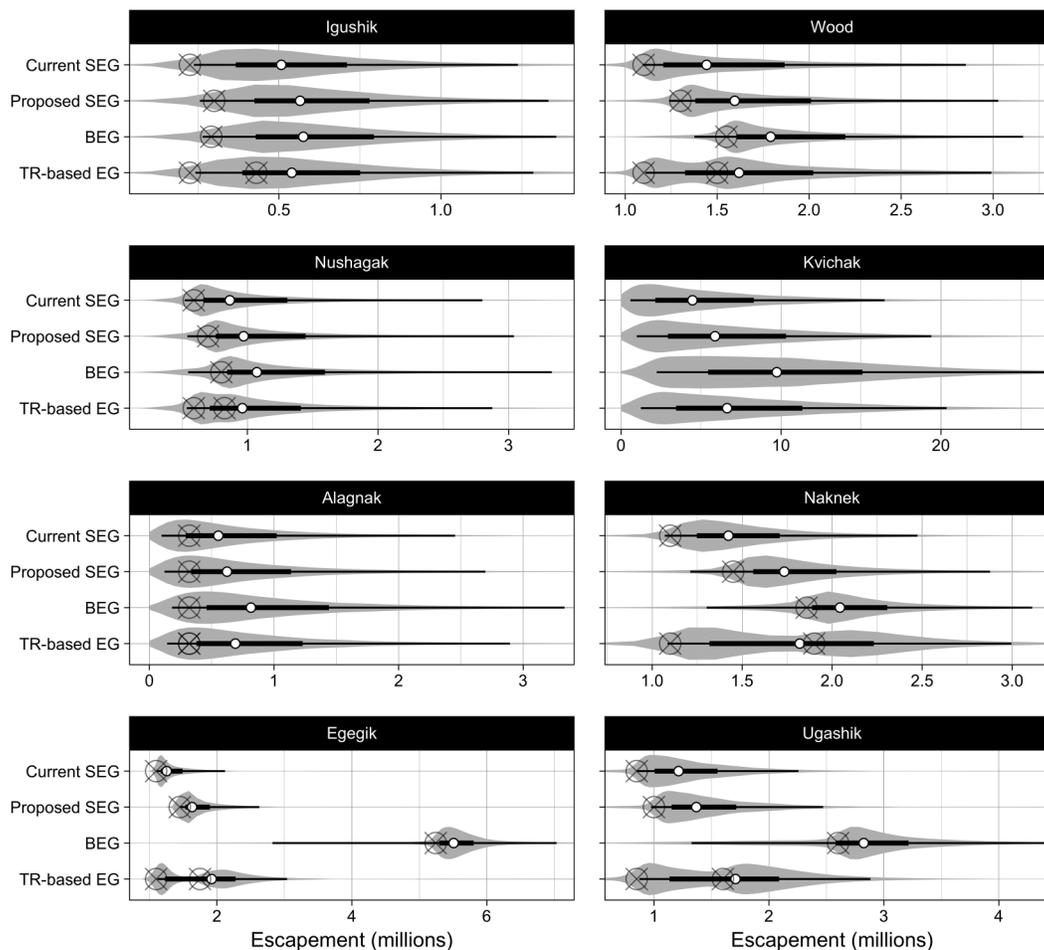
management strategies appear right-skewed but unimodal. This suggests that independent of the implementation uncertainty associated with in-season management, the TR-based EG management strategy is resulting in differences in realized escapement across years. However, it is unclear whether these high and low escapements truly coincide with years of large and small run size for these populations or whether the uncertainty in the in-season assessment process swamps the potential benefit of this strategy through a mismatch between total run-based goals and true run sizes. Overall, simulations suggest that alternative escapement goals are likely to be achieved and often exceeded on average across populations, although the difficulty in their implementation leads to high variation in realized escapement among years.

Are higher escapement goals estimated to produce MSY likely to result in higher run sizes?

The median value for predicted future sockeye run size is greatest under the BEG strategy and lowest for the scenario based upon Current SEGs for Kvichak, Egegik, and Naknek river systems (Fig. 4). These findings suggest that for these three systems, increases in realized escapement are likely to result in some increase in median return size. For all other populations, the predicted future median run size is similar across management strategies. Despite some differences in median run size across management strategies, these differences are on average small relative to the expected variation in production across years and

simulations. Results suggest that future shifts in production regimes across the 100-year time series, combined with process variation in recruitment and estimation uncertainty in the true value of stock–recruitment parameters, generally results in similar predictions for the magnitude of future run sizes independent of the management strategy adopted (Fig. 4).

Which management strategies are likely to maximize future harvest?

The distribution of predicted catches across the replicate 100-year simulations indicates that substantial variability in future harvest for all stocks is expected across management strategies, when the full range of biological and management uncertainties are considered (Fig. 5). However, some differences in median expected catch and distribution of catch are predicted. The BEG management strategy is predicted to result in lower median catch in the future, relative to the Current SEG strategy (status quo) for most populations. This is particularly pronounced for the Nushagak, Egegik, and Ugashik populations, where a high probability of low and zero catches is expected (Fig. 5). The highest median future catch for the Nushagak population is predicted to be achieved under either the Current SEG or TR-based EG strategies, under the Proposed SEG or TR-based EG strategies for the Egegik population, and under the Current SEG or Proposed SEG strategies for the Ugashik population. The distribution of predicted future catches from the Igushik and Naknek populations appears very similar

Fig. 4. Distribution of predicted run size in millions of sockeye for the eight major Bristol Bay river systems across replicate 100-year simulations under each management strategy. The point, thick line, and thin line describe the median, 50%, and 90% intervals, respectively, for each prediction.
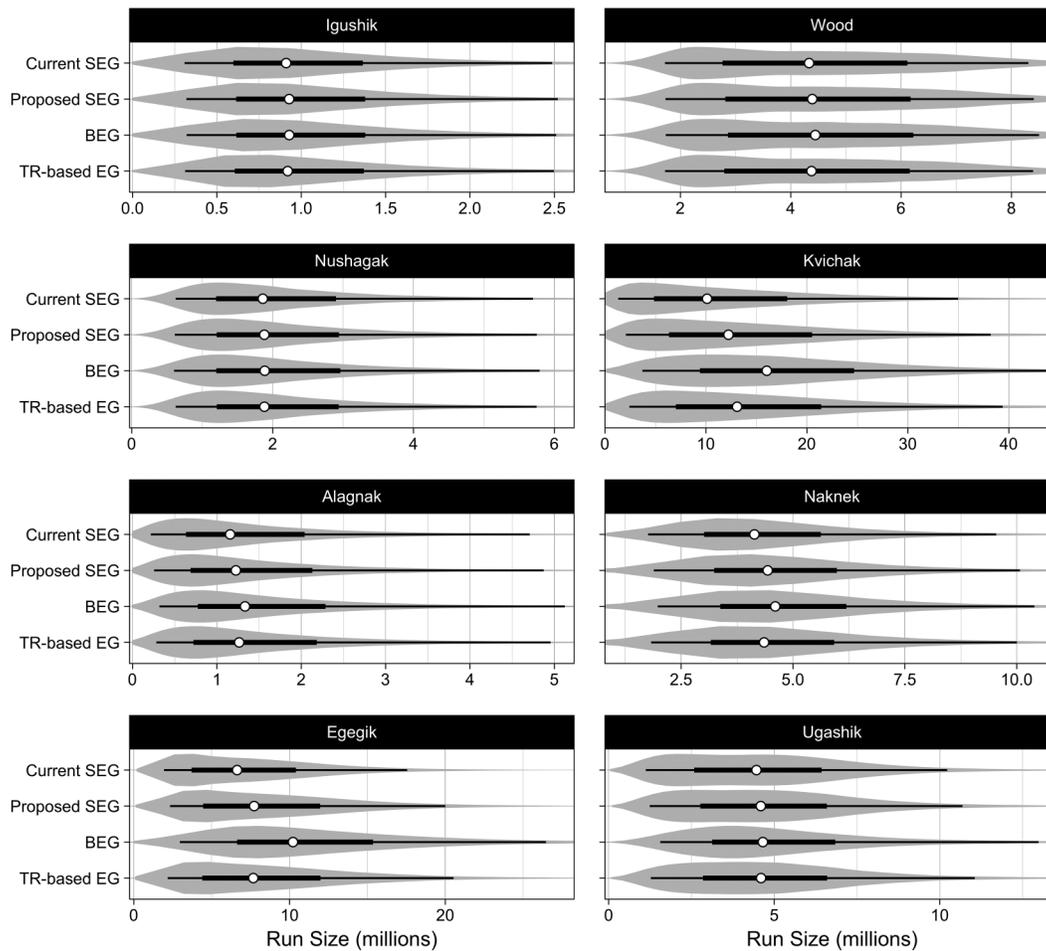

under all management strategies explored. Although not managed differently across management strategies, resultant differences in escapement from mixed-stock interactions lead to slight differences in the distribution of expected catch from the Kvichak population among strategies, with Current SEGs expected to yield the lowest future catch. For no river system did the management strategy based on BEGs (escapement levels estimated by Fair et al. (2012) to produce MSY) outperform other strategies, given both variation in recruitment and implementation uncertainty.

When the distribution of predicted future escapement, run size, and catch were aggregated at the scale of Bristol Bay as a whole, some differences from stock-level results were observed (Fig. 6). Consistent with results at the stock level, expected escapement was higher for the BEG management strategy when compared with the Current SEGs. Median Bristol Bay escapement under the TR-based EG strategy was also higher than that expected under both the Current SEG and Proposed SEG management strategies. Similar patterns in the relative magnitude of future run sizes were also predicted, independent of whether aggregated at the Bristol Bay level or at the stock level. The BEG strategy is expected to result in the highest median future run size, followed by relatively equal run sizes for the Proposed SEG and TR-based EG strategies, and the lowest expected Bristol Bay run size under the Current SEG strategy (Fig. 6). In contrast with some stock-level results (Fig. 5), the expected median future catch is highest under either the Proposed SEG or the TR-based EG strategies when aggregated at the Bristol Bay level in each year (Fig. 6).

Although similar to stock-level results, expected differences in catch were small relative to the variation in these predictions.

As part of this MSE for the Bristol Bay commercial fishery, stakeholders were asked to identify alternative output metrics for consideration. The stakeholder group identified the percent difference in expected future catch between the status quo (Current SEG) and alternative management strategies, as well as the expected proportion of future years where catch fell below 5, 10, and 15 million sockeye salmon as quantities of interest. Figure 7 displays the percent increase, or decrease, in catch expected under the Proposed SEG, BEG, and TR-based EG strategies, relative to predictions from the Current SEG strategy across the 100-year time series and replicate simulations. For all populations with the exception of the Kvichak River, the BEG strategy is expected to result in a net decrease in catch relative to predictions under the Current SEG strategy. The magnitude of this predicted catch difference under the BEG strategy is greatest for the Ugashik and Nushagak stocks, with an estimated median reduction in catch of 33.9% and 20.8%, respectively (Fig. 7). Conversely, results indicate that relative to expected future catch under the status quo management strategy (Current SEG), the Proposed SEG and TR-based EG strategies are predicted to result in 17.2% and 9.5% higher median future catches from the Egegik population, respectively. Comparison of the predicted median difference in future catch between the TR-based EG and Current SEG strategies indicates relatively small differences (<1% difference) for all populations, with the exceptions of Egegik (9.5% higher) and Kvichak (10.5%

Fig. 5. Distribution of predicted catch in millions of sockeye for the eight major Bristol Bay river systems across replicate 100-year simulations under each management strategy. The point, thick line, and thin line describe the median, 50%, and 90% intervals, respectively, for each prediction.
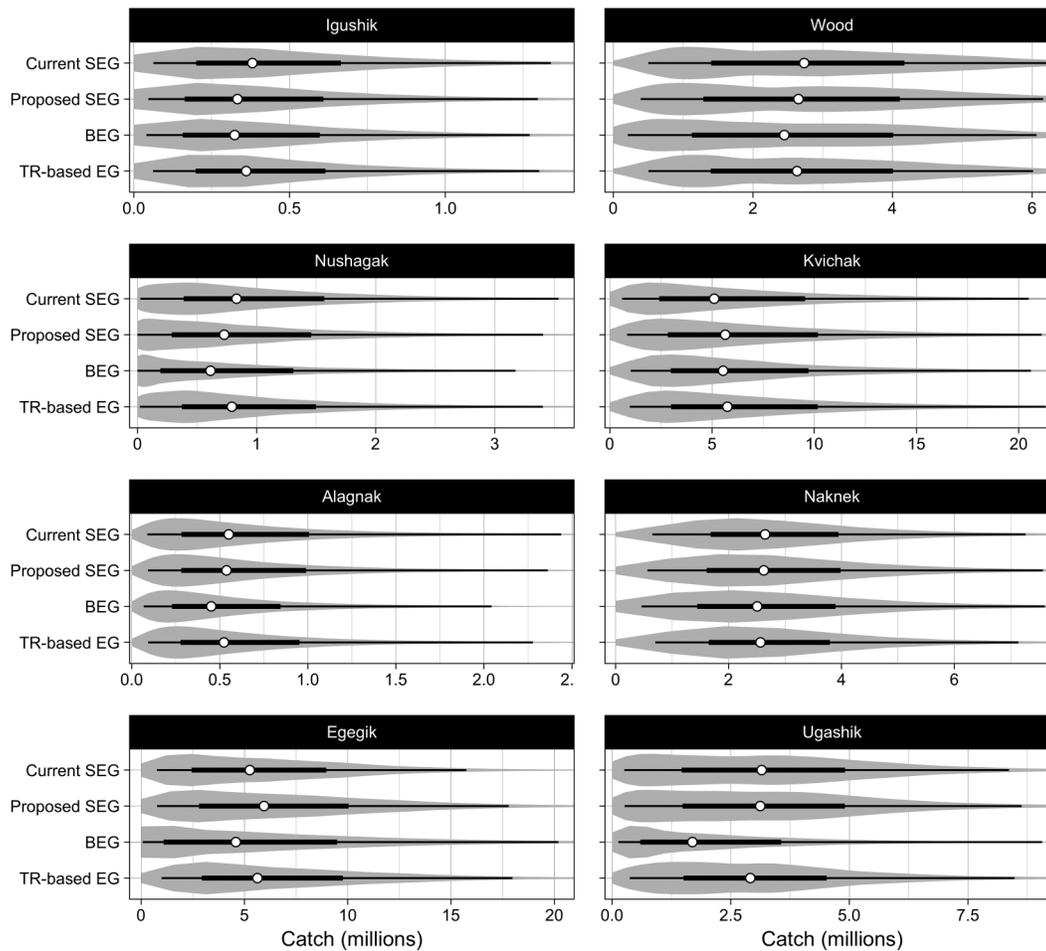
higher) populations ([Fig. 7]). As noted previously, the expected differences in future catch among management strategies is on average small relative to the variation in these predictions.

Which management strategies will minimize the frequency of low catch years that result in hardship for salmon harvesters and processors?

Quantifying differences among management strategies in the frequency of years with small catches that jeopardize the economic sustainability of commercial fishery harvesters and processors was identified as a priority by stakeholders. [Figure 8] illustrates the predicted proportion of years in each 100-year time series in which total Bristol Bay catches are predicted to be less than 5 million, 10 million, and 15 million sockeye. Results indicate that for all management strategies, the median expectation for the percentage of years with Bristol Bay catch less than 5 million sockeye is at or near zero. However, the 50% probability interval for the BEG strategy indicates that observing 1 of 100 years with catch below 5 million sockeye may be expected with a probability of 0.5 (50% chance). Results further indicate that for the Current SEG, Proposed SEG, and TR-based EG strategies, Bristol Bay catches less than 10 million sockeye are expected in 2% of years, while catches below this level are predicted to occur in 5% of years under the BEG strategy. The frequency with which Bristol Bay catches less than 15 million sockeye are expected to be observed in the future indicates that catches at this level or below will occur in approximately 9% of years under the Proposed SEG strategy and

11%–12% of years under either Current SEG or TR-based EG strategies ([Fig. 8]). Bristol Bay catches of 15 million or below are expected to be observed significantly more frequently under the BEG management strategy in approximately 18%–19% of years in the future. Taken together, these results suggest that the frequency of small Bristol Bay catches is significantly increased under the higher escapement goals established by BEG management strategy.

Discussion

This research originated with a request by the Alaska Board of Fisheries for scientists and stakeholders to examine the effects of implementation error and economics on escapement goal setting in the Bristol Bay sockeye salmon fishery. To assess the performance of alternative proposed escapement goals, we conducted an MSE in collaboration with a group of stakeholders representing the harvesting, fish processing, and management communities. The AP provided valuable information and feedback to the study team related to the economics and management of the fishery, and it developed implementable management strategies for the study team to examine. Stochastic closed-loop simulations conducted as part of this MSE indicated that (*i*) despite implementation uncertainty escapement goals were likely to be achieved or slightly exceeded on average, (*ii*) higher escapements mandated under the BEG strategy targeting S_{msy} as estimated from past analyses were likely to result in higher future returns but with large variability in future production, and (*iii*) the larger run sizes

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Fig. 6. Distribution of predicted total escapement, returns, and catch for Bristol Bay as a whole in millions of sockeye across replicate 100-year simulations under each management strategy. The point, thick line, and thin line describe the median, 50%, and 90% intervals, respectively, for each prediction.
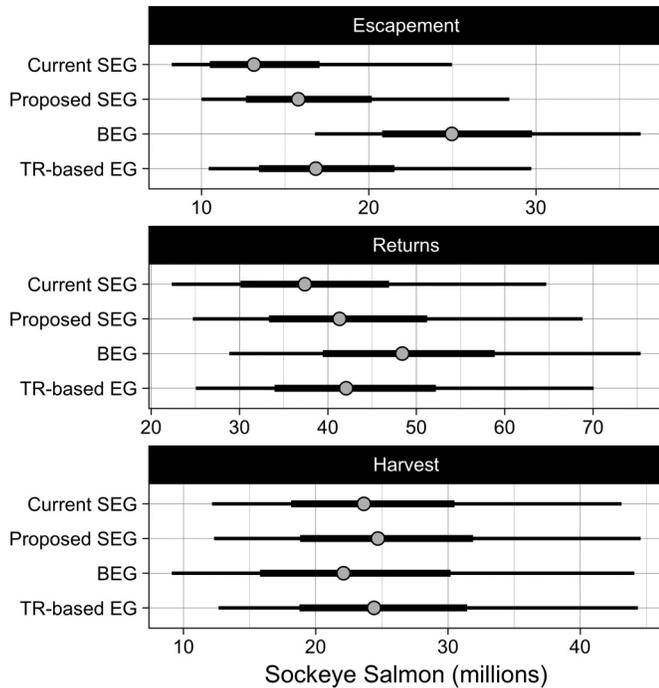

Fig. 7. Percent difference in catch between the Current SEG (status quo) and the Proposed SEG, BEG, and TR-based management strategies for the eight major Bristol Bay river systems across replicate 100-year simulations. The point, thick line, and thin line describe the median, 50%, and 90% intervals, respectively, for each prediction. A value of −50 indicates a 50% reduction in expected catch relative to the Current SEG management strategy.
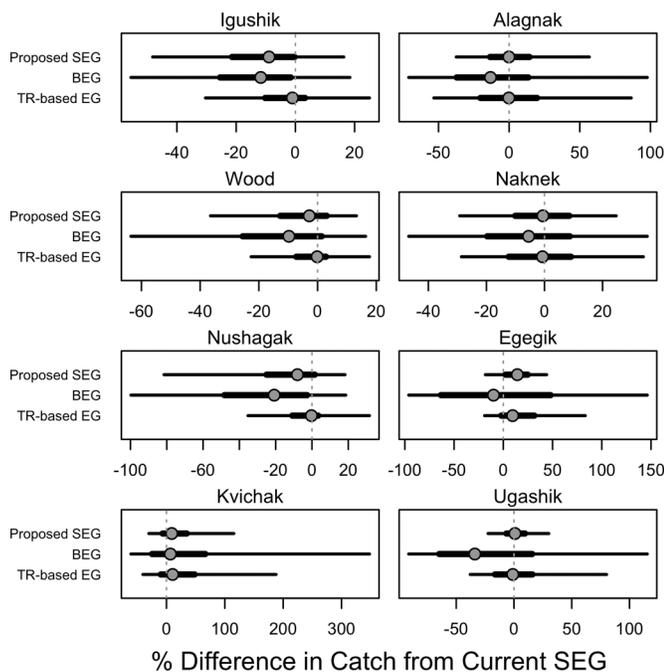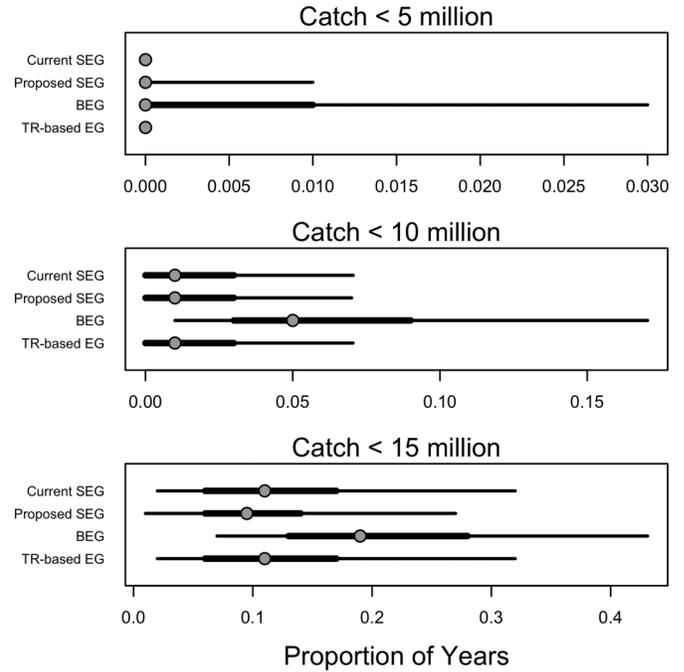

Fig. 8. Predicted proportion of years in which total Bristol Bay catch will be less than 5, 10, and 15 million sockeye across replicate simulations under each strategy. The point, thick line, and thin line describe the median, 50%, and 90% intervals, respectively, for each prediction.

expected under the BEG strategy are not large enough to offset the increase in escapement required for most stocks, and the highest future catch is expected under either the TR-based EG or Proposed SEG strategies. However, the combination of implementation uncertainty in the management process, periodic shifts in population productivity observed at long time scales, and stochastic interannual variation in recruitment all result in significant variation in predicted future run size and potential harvest. Based on these analyses, the AP made a unanimous recommendation to the Alaska Board of Fisheries to implement TR-based EG ranges for the stocks originally under consideration. The changes were simple and mimic the TR-based strategy modeled here; the lower ends of the recommended ranges for each stock were set at the lower end of the Current SEG and the upper ends were set at the upper ends of the Proposed SEGs, thereby widening the management target compared to the Current and Proposed SEGs. Further, the AP recommended regulatory guidance that in years with below-average runs, management should target escapements within the lower half of the overall range and in the upper half of the range during large runs. In 2015, the Alaska Board of Fisheries and the ADF&G adopted the AP-recommended regulatory language and escapement goals.

Implementation uncertainty was modeled by creating a simulated manager that opened and closed terminal fishing areas on a daily basis. Although governed by relatively crude decision rules, this simulated manager was able to achieve seasonal escapements in remarkably close agreement with what was observed in the past when presented with the same in-season information (Fig. 2). This relative agreement in management outcomes between the simulated manager and past observations provided confidence that the simulation model was incorporating the correct level of implementation uncertainty with respect to achieving seasonal escapement goals.

The challenge associated with in-season management of these fisheries was captured in this analysis by varying the timing and distribution of salmon arriving in fishing districts and replicating

the delay in information available to the simulated manager. Variation in arrival timing and the distribution of salmon arrivals resulted in realistic bias in the comparison of current escapement to daily targets and bias in midseason run size predictions used to update the Kvichak escapement goal across all strategies and escapement goals for all stocks under the TR-based EG strategy. Without directly simulating the inherent challenges in in-season management process, it is unlikely our analysis would have accurately assessed the relative performance of the alternative management strategies.

The simulation approach to integrating implementation uncertainty presented here contrasts with the empirical methods more commonly employed in MSE for salmon fisheries. Both Dorner et al. (2009) and Collie et al. (2012) utilized empirical relationships between target escapement goals and realized escapements in the past to incorporate "outcome uncertainty" or the combined effect of variation in catchability, physical and biological dynamics, and noncompliance in evaluation of salmon management alternatives. While previous research has highlighted both the magnitude of this uncertainty in sockeye salmon management (Holt and Peterman 2006) and the potential implication of ignoring its effect (Holt and Peterman 2008), the nuances of biology, information available to management, and the ability of the management structure to effectively control fishing effort suggest that approaches to quantifying implementation or outcome uncertainty are likely to be region- and fishery-specific. Given the success of the simulation-based approach to approximating the management process presented here in replicating past performance, we advocate for consideration of this as an alternative to empirical methods for incorporating implementation uncertainty in fishery MSE, independent of species, if successful in replicating past fishery outcomes. Furthermore, a simulation-based approach to incorporating implementation uncertainty may provide greater opportunity to explore the utility of integrating additional sources of information in the management process.

Bristol Bay fishery managers have access to several additional pieces of in-season information that were not provided to our simulated manager and may be responsible for observed differences in outcomes during the retrospective performance tests (Fig. 2). Fishery managers often estimate the number of fish in transit between fishing districts and escapement enumeration sites from in-river test fisheries or aerial surveys. Managers also have an index of abundance for Bristol Bay sockeye salmon from the Port Moller Test Fishery (Flynn and Hilborn 2004), which captures fish during the homeward migration 5–10 days before arriving inshore. While availability of this auxiliary information may be responsible for the differences in management performance observed during testing, it is difficult to describe empirically how district managers incorporate this information in their decision process and as a result this information was left out of our management simulation model by necessity. However, future research to quantify exactly how this additional information influences in-season management decisions would be useful in improving our approximation of the management process and in quantifying the value of those data.

The BEG strategy targeted S_{msy}, or the spawning stock sizes estimated by Fair et al. (2012), to produce MSY. MSE simulation results indicated that despite the predicted increase in escapement for most stocks under this management strategy, it is expected to result in the lowest catch among strategies for many stocks (Figs. 5 and 7) and higher frequency of years with detrimentally low catch for Bristol Bay as a whole (Fig. 8). There are several reasons for this outcome, most importantly that the increase in run size achieved by these increased escapements, if present, was not sufficient to offset the increased management burden (Fig. 4). This may have resulted from the higher escapements under the BEG strategy pushing some populations beyond the spawning stock size producing maximum yield during periods of higher

recruitment associated with high productivity regimes, resulting in foregone yield. As the BEG strategy is based upon the spawning stock sizes estimated by Fair et al. (2012) to produce S_{msy} under the assumption of a time-invariant production, this is perhaps not surprising.

Future stock–recruitment analyses to identify biological escapement goals (i.e., S_{msy}) for salmon populations may benefit from directly estimating production regime transitions as we have done, and using the estimated transition probabilities to quantify future regime occupancy and identifying management targets that maximize yield across future productivity states. More generally, the sensitivity of results presented here to regime-shift behavior combined with the observed ubiquity of periodic shifts in productivity for many fish species globally (Vert-pre et al. 2013) highlights the necessity of incorporating temporal trends in recruitment dynamics within MSE. Time-varying production dynamics have already been included in MSEs for a wide range of species, including Gulf of Alaska walleye pollock (*Gadus chalcogrammus*) (A'mar et al. 2009), salmon (Collie et al. 2012; Dorner et al. 2009; Hawkshaw and Walters 2015), and snow crab (*Chionoecetes opilio*) (Szuwalski and Punt 2012), among others, and should be explored as part of the MSE process for other species in the future.

Results of this MSE suggest that for the Bristol Bay commercial salmon fishery, the highest total future yields and lowest frequency of extreme low catch years may be achieved under the Proposed SEG or TR-based EG management strategies, but that median differences in these expected outcomes are largely overshadowed by the high level of variation and uncertainty in biology and management implementation. Not only are the higher escapement goals under the BEG management strategy not expected to increase harvest potential, they are expected to result in more years with extremely low harvest and more variability in catch overall. The increase in catch variability expected under the BEG strategy results in part from increased variation in recruitment but also from processing capacity limitation in years of extremely large catch in industry-imposed harvest limits (Wang et al. 2019). Furthermore economic analyses by Wang et al. (2019) suggest that Bristol Bay salmon processors are unlikely to increase capacity in response to infrequent years of large run size and potential harvest and are therefore unlikely to capture value from larger but more variable returns under the BEG management strategy.

Harvest control rules of the constant escapement form have been repeatedly demonstrated to maximize long-term average catch (Ricker 1958), but result in higher variability in yield than either constant fishing mortality rate or constant catch control rules (Deroba and Bence 2008) due to the frequency of fishery closures (Lande et al. 1997; Lillegard et al. 2005). Furthermore, when recruitment varies over time in an autocorrelated manner, constant fishing mortality rate policies have been found to achieve nearly the same yield as constant-escapement policies (Walters and Parma 1996). More recently, Hawkshaw and Walters (2015) used dynamic programming to identify an optimal harvest control rule for a mixed-stock salmon fishery and found the preferred rule to be a mixture of constant escapement and constant exploitation policies, where the exploitation rate followed a smooth curve between zero and an upper limit or "conservation constraint" when the population was above a minimum stock size. While all of the management strategies explored in our analysis are of the constant-escapement form, the TR-based EG strategy that attempts to increase spawning stock size during years of high return was found to outperform a strategy that targeted the theoretical optimum (S_{msy}) in every year (BEG strategy). This type of tiered constant escapement strategy was intended to maximize potential recruitment during periods of high population productivity while reducing conservation costs in years of low productivity. However, it is important to note that the TR-based EG strategy can only be reliably evaluated when the potential for error in

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assigning the high and low escapement targets is considered, as we have done here.

The MSE simulation framework presented here could be further extended in several ways. First, the simulation framework did not model covariation in recruitment dynamics across populations, either in terms of process variation (recruitment deviations) or for regime transitions. This was a necessity given that stock–recruitment models were fit to data from each population separately, rather than within a hierarchical framework that would permit estimation of these cross-correlations. Although it should be noted that minimal correlation in past regime occupancy patterns was observed across populations, with the exception of changes associated with the shift in the Pacific Decadal Oscillation (Mantua and Hare 2002), so the results presented here are likely robust to the simplifying assumption of independent future regime state occupancy in our simulations. Second, we did not attempt to incorporate the auxiliary information available in-season to fishery managers by the Port Moller Test Fishery or aerial surveys of fishing districts or rivers. In practice, fishery managers spend a portion of their time quantifying fish abundance from the air and talking to both pilots and fishermen to obtain additional information. However, the exact extent to which managers rely on this information is unknown, and both its reliability and impact on decisions is difficult to quantify. Finally, the fishery was assumed to be unselective with respect to the age of returning salmon. In reality, Cunningham et al. (2018) found selectivity to generally increase with ocean age; however, this is unlikely to influence our results given the range of uncertainties already incorporated.

MSE provides a way to quantify the likelihood of potential outcomes from alternative potential management measures and the level of associated risk (Rademeyer et al. 2007; Smith et al. 1999), and MSE has seen increased recognition and use for applied management of aquatic (Punt et al. 2016) and terrestrial (Bunnefeld et al. 2011) systems and species. A major component of constructing MSE frameworks is quantifying and propagating a range of biological and management uncertainties and variation within the system through the simulation process to predicted outcomes (Holland 2010). In this way, MSE provides major benefits over traditional methods for setting harvest policy in salmon fisheries that rely only on the modeling of stock–recruitment data and ignore implementation uncertainty. Stakeholder involvement and the integrated economic component of this MSE (Wang et al. 2019) helped to illuminate important economic implications of escapement goal policies in Bristol Bay that reinforced conclusions from the biological result presented here.

The expanded use of MSE approaches, incorporating stakeholder participation, in salmon fisheries within the state of Alaska and elsewhere should be considered, where sufficient time, resources, and personnel are available to develop and test simulation and estimation models. Finally, this study demonstrated how the full MSE process, involving iterative collaboration between the study team and fishery stakeholders, provides benefits to researchers through direct feedback, insights, and additional information to aid the analysis. Ultimately, this collaboration provided the basis for building consensus and understanding within the stakeholder community and among regulators to affect positive change in the management of the fishery.

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