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Considerations for using spawner reference levels for managing single- and mixed-stock fisheries of Atlantic salmon

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The probability of achieving the spawning requirement objective of Atlantic salmon (*Salmo salar* L.) is defined by the stochastic properties of small numbers and biological characteristics of the stock. The uncertainty in achieving the spawning escapement objective is greater for small stocks than for large ones, such that measures of annual performance are more variable for small stocks. Summing individual river spawner requirements into a regional requirement reduces the probability of meeting the objectives simultaneously in all rivers. Variations in productivity among stocks, when not accounted for, can result in under-escapement in areas of lower productivity. The impact of mixed-stock fisheries can be most important for small stocks, and especially if these are of low relative productivity. Increasing the regional spawner requirement in an attempt to compensate for lower productivity may alleviate the problem somewhat, but it is not a guaranteed solution to the challenge of protecting all stocks, specifically those of low productivity in mixed-stock fishery situations. Each mixed-stock fishery situation can be evaluated on a case-by-case basis using Monte Carlo techniques.

Keywords: Atlantic salmon, management, mixed-stock fishery, reference points, uncertainty.

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Introduction

Fisheries management worldwide generally follows standard approaches. Decisions are taken after consideration of the information on the state of the resource. The information includes, but is not limited to, the following: abundance of the resource prior to exploitation (forecast), expected biological characteristics of the fish in the fishery (e.g. age structure, weight at age, proportion female), stock composition of the fish in the fishery (number of stocks or populations exploited by the fishery), and reference points that define the desired state of the resource or the fishery (spawner abundance reference levels, or optimal fishing rates). With this information, managers can decide the level of exploitation consistent with the reference points, which are universally defined to ensure the maintenance of stock abundance. Specifically, limit reference points define states of the resource to be avoided with a high probability (Potter, 2001). Therefore, the use of limit reference points requires that the probability of respecting those limits be taken into account.

Atlantic salmon (*Salmo salar* L.) fisheries in eastern Canada are managed on the basis of a fixed escapement policy that considers all fish in excess of the requirement to be surplus and available for harvest (CAFSAC, 1991b). This limit reference point has been called the conservation level (CAFSAC, 1991a), and is established on the basis of a rate of egg deposition that will produce optimal freshwater production. The rate is weighted by area estimates of freshwater habitat available for juvenile production, and the egg requirements are translated to the number of salmon required to achieve that egg deposition, using the average biological characteristics of the stock (O'Connell *et al.*, 1997). Reference points have also been defined for salmon rivers in France, and in England and Wales (Prévost and Porcher, 1996; Milner *et al.*, 2000).

Management of salmon fisheries must consider the probability of obtaining at least the number of fish required to achieve the egg depositions equivalent to the reference point for each stock. More than 2000 rivers with spawning runs of Atlantic salmon empty into the North Atlantic, and each is considered to have individual stocks (Crozier *et al.*, 2003). With few exceptions, Atlantic salmon stocks consist of relatively small numbers of spawning adults, in the order of 100s to 1000s for most rivers (Chaput, 1998; Chaput and Prévost, 1999). Atlantic salmon are exploited both in homewater freshwater fisheries as single-stock units, and in high seas marine fisheries, such as at West Greenland, as mixed-stock complexes. Several hundred rivers within eastern North America, and minimally an equal number of rivers in the eastern North Atlantic, produce salmon that could potentially be exploited in the high seas fisheries at West Greenland. Management advice for the high seas fisheries at West Greenland has to date been based in part on summing the individual river spawning requirements into a continental requirement (ICES, 2003). Although the consequences to individual stocks of mixed-stock fisheries have been documented previously (Hilborn, 1985), the uncertainties associated with summing individual river reference points for the management of mixed-stock fisheries have not been quantified.

This paper examines the factors, unrelated to management performance or derivation of the reference points (life cycle processes), that affect the uncertainty of achieving spawning escapement reference points (hence referred to as conservation levels, CL). The description of uncertainty is relevant for fisheries on individual stocks, and more so for mixed-stock fisheries managed as regional or continental complexes. Specifically for individual stocks, the probability of exceeding the limit reference points is shown here to be determined by the size of the stock, its average biological characteristics (the proportion female in this example), and its annual variation in biological characteristics (specifically the proportion female). For the mixed-stock fishery example, I illustrate how the probability of exceeding the conservation limit of the individual stocks singly and simultaneously depends upon the number and the relative productivities of the stocks within the mixed-stock fishery. Two case studies of aggregations which could be used for mixed-stock fisheries management are presented, the first based on a grouping of 17 rivers in Wales, and the second based on an aggregate of 15 monitored rivers in the eastern North Atlantic that have river-specific estimates of productivity (average recruitment per spawner at CL).

Material and methods

The issues addressed in this paper apply generally to fisheries management, but for illustrative purposes, the management of Atlantic salmon is considered. Altantic salmon management can be pictured within the general life cycle of the animal, with fisheries occurring at two points:

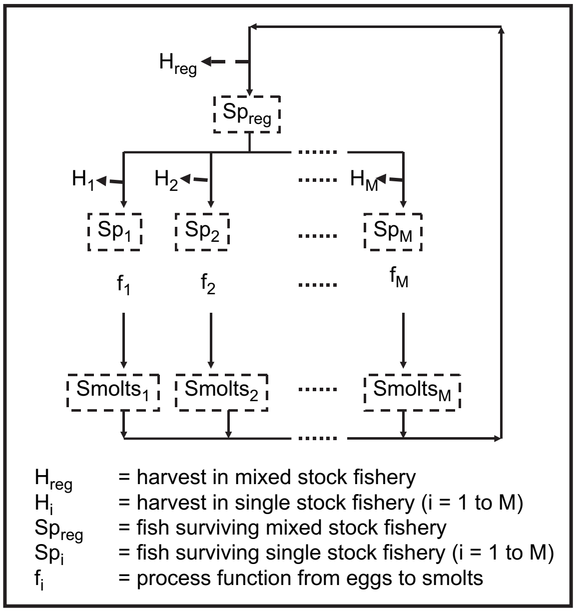

Figure 1. Simplified life history chart for Atlantic salmon, indicating fishery control points (H_{reg}; H_i), and survivors from fisheries points (Sp_{reg}; Sp_i) used to assess status and management performance.

first when the animal is at sea and stocks are mixed, and second when the fish are in their home rivers and the fisheries exploit single stocks (Figure 1). For simplification, stocks are exploited in either mixed-stock or single-stock fisheries, but never both. Management endeavours to ensure that there is a high probability that the number of fish that survive the fisheries is greater than the limit reference point (Potter, 2001). As only females contribute eggs, fisheries should be managed to ensure that the required number of females survive the fishery.

For these purposes, let $CLegg_i$ be the point estimate of the limit reference point in the currency of eggs for river i (e.g. CAFSAC, 1991a; Prévost *et al.*, 2003), and $CLfem_i$ be the point estimate of the limit reference point in currency of female fish for river i. Then

$$CLfem_i = CLegg_i \times \overline{fecundity_i}^{-1}$$

where $\overline{fecundity_i}$ is the average number of eggs per female for river i. Let CL_i be the point estimate of the limit reference point in currency of fish for river i, such that

$$CL_i = CLfem_i \times \overline{prop.\ female_i}^{-1}$$

where $\overline{prop.\ female_i}$ is the average proportion female in river i.

Let Sp_i and $Spfem_i$ be the number of fish and the number of female fish from stock i, respectively, that survive the fishery (Figure 1). Assume the proportion female and the fecundity of the fish in the stock being exploited to equal the average biological characteristics (proportion female and fecundity) of the stock used to translate the currencies of the limit reference point from eggs to fish. For simplicity, it is also assumed that natural mortality of fish between the time of the fishery and spawning is negligible. Under these assumptions, and if the fishery harvests are controlled such that $Sp_i = CL_i$, then there is a 50% chance that $Spfem_i > CLfem_i$. The question to consider is how much larger must Sp_i be relative to CL_i to ensure with a high probability that $Spfem_i > CLfem_i$?

In the mixed-stock fishery example, the management practice to date has been to sum the individual river spawner requirements into regional and continental spawner requirements (Potter, 2001; ICES, 2003; Prévost *et al.*, 2003), such that

$$CL_{reg} = \sum_{i=1}^{M} CL_i \quad \text{for M stocks in the fishery.}$$

Under assumptions similar to the single-stock fishery defined above, and if the mixed-stock fishery harvests are controlled such that the number of fish surviving the fishery (Sp_{reg}; Figure 1) equals CL_{reg}, then there is a 50% chance that $Spfem_i > CLfem_i$ for any individual stock. The question to consider is how much larger than CL_{reg} must Sp_{reg} be to ensure with a high probability that $Spfem_i > CLfem_i$ for all stocks (i = 1 to M) exploited in the mixed-stock fishery?

The probability of meeting or exceeding the spawner requirements for a given number of fish that survive the fisheries can be described using binomial and multinomial distributions (Gelman *et al.*, 1995; Hilborn and Mangel, 1997). A binomial distribution is used to represent the number of successes in a sequence of Bernoulli (two possible outcomes) trials for a given probability of success. For large n (trials), the binomial distribution is approximately normal (Gelman *et al.*, 1995). A multinomial distribution is the multivariate generalization of the binomial distribution, i.e. more than two outcomes. For the case of a single stock, the fish that survive the fishery are either male or female. The probability that a given number of females (Z) will occur within a specified group of fish (N) is described by the binomial distribution

$$\Pr(Z = k) = \frac{N!}{k!(N-k)!} p^k (1-p)^{N-k}$$

where Z is the success ($Spfem_i$), k the objective ($CLfem_i$), N the number of trials (i.e. fish that survive the fishery, Sp_i), and p is the probability of success (i.e. proportion female in the stock, p_i).

The binomial distribution has certain properties. The expected number of successes (E{Z}, females) is the product of the number of trials (N, fish surviving the fishery) and the probability of success (proportion female). The mode is $(N + 1) \times p$ (Gelman *et al.*, 1995). For a large N, the mode is approximately equal to the mean. Variance is a function of the number of trials and the probability of success ($VAR\{Z\} = N \times p \times (1 - p)$). For a fixed N, the variance is maximum when p = 0.5. The coefficient of variation (uncertainty) is inversely related to N and p, such that the CV decreases as N and/or p increase, i.e.

$$\left(CV(Z) = \sqrt{\frac{1-p}{N \times p}} \right)$$

For the case of one river, exact probabilities of meeting or exceeding the spawner requirements ($\Pr(Z \geq k)$) can be calculated directly from the binomial function.

For the mixed-stock fishery example (M stocks present in the fishery), a multinomial distribution is used because there are more than two possible outcomes (i.e. a fish surviving the mixed-stock fishery will be either male or female of one of the M stocks). The probability of a given set of outcomes (Hilborn and Mangel, 1997) is:

$$\Pr(Z_1 = k_1, Z_2 = k_2, \ldots Z_M = k_M) = \frac{N!}{k_1!k_2!\ldots k_M!} p_1^{k_1} p_2^{k_2} \ldots p_M^{k_M}$$

where $Z_1, Z_2, \ldots Z_M$ are the successes ($Spfem_i$, i = 1 to M), $k_1, k_2, \ldots k_M$ are the objectives per stock ($CLfem_i$, i = 1 to M), N is the number of trials (fish surviving the mixed-stock fishery, Sp_{reg}), $p_1, p_2, \ldots p_M$ are the probabilities of successes (i.e. the probability that a fish is from stock i and that it is female), i.e.

$$\frac{CL_i}{\sum_{i=1}^{M} CL_i} \times p_i, \quad i = 1 \text{ to } M$$

For the single-stock example, the effect of stock size (CL), proportion female (p), and annual variation in proportion female (CV′p) are described. CV′p was modelled as a triangular distribution, with the most likely value (p) within a minimum ($(1 - CV'p) \times p$) and maximum ($(1 + CV'p) \times p$) range.

For the mixed-stock fishery example, the factors considered were the number of stocks in the mixed-stock fishery, M = 3, 5, and 10 stocks, with the other parameters set at $CL_i = 1000$ fish (i = 1 to M), $p_i = 0.8$ (i = 1 to M), and CV′p = 0.1. The individual stock abundances of fish surviving the fishery are in direct proportion to the relative sizes of the stocks. Thus,

$$Sp_i = Sp_{reg} \times \frac{CL_i}{\sum_{i=1}^{M} CL_i}$$

The effect of different productivities was illustrated with example relative productivities (recruits per spawner) of 0.8, 1.0, 1.0, 1.0, and 1.2 for five rivers, with the other parameters set at $CL_i = 1000$ fish (i = 1 to 5), $p_i = 0.8$ (i = 1 to 5), and CV′p = 0.1. The relative productivities

($rel.prod_i$) in this case refer to the recruitment (male and female) expected at a spawning stock equal to CL_i. Thus,

$$Sp_i = Sp_{reg} \times \frac{CL_i}{\sum_{i=1}^{M} CL_i} \times \frac{rel.prod_i}{\sum_{i=1}^{M} rel.prod_i}$$

In the case of a multinomial distribution for which more than one stock is considered simultaneously (and for which the sum of a large number of probabilities must be calculated), or when including annual variations in the biological characteristics of a single stock or for multiple stocks, the probabilities can be conveniently approximated using Monte Carlo techniques. A binomial random variable was simulated using N (Sp_i or Sp_{reg}) independent standard uniforms, with Z equal to the number of uniform deviates $\leq p$ (Gelman *et al.*, 1995). For a multinomial distribution, a sequence of binomial draws was performed. In all, 10 000 Monte Carlo simulations were performed for each Sp_i (single stock) or Sp_{reg} (mixed stock) level. The uncertainty in achieving $CLfem_i$ relative to levels of Sp_i or Sp_{reg} is described as the proportion of the 10 000 Monte Carlo simulations for which $Spfem_i \geq CLfem_i$.

Case study 1: Aggregation of 17 Welsh rivers

Reference levels and biological characteristics data for salmon from 17 rivers in Wales (UK) are from Wyatt and Barnard (1997) and Anon. (2000); they are summarized in Table 1. The case study considers the effects of river size, differences in p among rivers, and annual variation in p, on the simultaneous and individual river achievement of $CLfem_i$ for the 17 rivers. Input values for CL_i and p_i are also listed in Table 1. Annual variability in the proportion female in individual rivers was assumed as $CV'(p) = 0.1$. Relative productivities were assumed to be similar among stocks, and there is no exchange of fish among the rivers.

Case study 2: Aggregation of monitored rivers in the Northeast Atlantic

The second case study considered the probability of achieving the spawning requirements simultaneously in the 15 monitored rivers in the Northeast Atlantic (NEAC) used in the Bayesian Hierarchical stock recruitment analysis described by Crozier *et al.* (2003) and Prévost *et al.* (2003). This case study considers the combined effects of stock size and the relative productivities on the simultaneous achievement of $CLfem_i$. The spawning requirements (CL_i) and relative productivities (defined by h_{opt} = exploitation rate at CL_i) are summarized in Table 2. The egg requirements for individual stocks were translated to fish, assuming for all 15 stocks an age structure of 80% one-sea-winter (1SW) and 20% multi-sea-winter (MSW) salmon, and sex ratios of 50% 1SW females and 80% MSW females. These biological characteristics do not reflect true individual stock values, but are used here for exemplification only. No annual variation in biological characteristics and no exchange of fish among the stocks were considered.

Table 1. Atlantic salmon biological characteristics and spawner requirements for 17 Welsh rivers, arranged north to south. Data are from Wyatt and Barnard (1997) and Anon. (2000).

	Spawning requirement			Biological characteristic	
River	Eggs (millions) $CLegg_i$	Fish CL_i	Females $CLfem_i$	Fecundity	Proportion female
Dee	15.3	5 093	2 842	5 384	0.558
Clwyd	2.62	968	507	5 165	0.524
Conwy	0.85	276	153	5 549	0.554
Ogwen	1.07	336	209	5 131	0.621
Seiont	0.61	171	109	5 602	0.636
Dwyfach/fawr	1.07	329	201	5 313	0.612
Glaslyn	0.61	190	115	5 327	0.602
Dwyryd	0.23	70	44	5 209	0.627
Mawddach	1.77	537	320	5 536	0.595
Dysynni	0.88	294	177	4 964	0.603
Dyfi	5.57	1 927	1 029	5 414	0.534
Teifi	11.89	3 571	1 957	6 076	0.548
Cleddau	2.56	751	446	5 737	0.594
Taf	2.31	882	451	5 117	0.512
Tywi	15.7	4 912	2 623	5 985	0.534
Tawe	2.36	762	436	5 413	0.572
Wye	34.5	9 990	5 335	6 467	0.534
Region total	99.9	31 061	16 954		

Table 2. Atlantic salmon spawner requirements, productivity parameters, and characteristics of 15 NEAC monitored rivers (after Crozier *et al.*, 2003). h_{opt} is the exploitation rate at optimum (optimum is the point at maximum sustainable yield), R_{opt} is the recruitment rate at optimum, and CL_i (S_{opt} in Crozier *et al.*, 2003) is the spawner requirement at optimum. Productivity is the reciprocal of $1 - h_{opt}$. Spawners at CL_i are based on assumed life history characteristics of 80% 1SW, 20% MSW salmon, sex ratios of 50% female 1SW salmon and 80% female MSW, and 3000 eggs per female fish.

River	Wetted area (1 000 m^2)	SR parameters (eggs per m^2)			Productivity	Spawners CL_i	Recruits at CL_i
		h_{opt}	R_{opt}	$CLegg_i$			
Nivelle	321.0	0.38	0.92	0.57	1.62	60	98
Oir	48.0	0.21	1.77	1.41	1.26	23	28
Frome	876.4	0.45	4.84	2.65	1.83	773	1 414
Dee	6 170.0	0.60	3.27	1.32	2.47	2 721	6 720
Burrishoole	155.0	0.63	17.19	6.44	2.67	333	888
Lune	4 230.0	0.47	4.91	2.61	1.88	3 676	6 926
Bush	845.5	0.74	11.55	3.06	3.78	862	3 255
Mourne	10 360.6	0.77	4.91	1.11	4.41	3 847	16 956
Faughan	882.4	0.80	41.25	8.21	5.03	2 414	12 133
Girnock Burn	58.8	0.53	6.96	3.27	2.13	64	136
North Esk	2 100.0	0.43	17.18	9.84	1.75	6 885	12 027
Laerdalselva	704.0	0.49	27.88	14.13	1.97	3 316	6 543
Ellidaar	199.7	0.63	120.50	44.21	2.73	2 943	8 021
Midfjardara	2 140.0	0.50	6.91	3.48	1.99	2 481	4 929
Vesturdalsa	271.0	0.71	2.47	0.735	3.41	65	223

Results

The steepness of the probability profile relative to increasing numbers of fish surviving the fisheries is inversely related to the uncertainty of achieving the spawner requirement. The probability profiles described are specific to the parameters used (i.e. CL_i, p, CV′p), but any combination of these as well as additional parameters can be modelled.

Regardless of the size of the stock (CL), the proportion female (p) and the variation in proportion female (CV′p), there is a 50% chance of meeting or exceeding the $CLfem_i$ when the number of fish surviving the fishery (Sp_i) equals CL_i (Figure 2). The probability profiles become steeper (less uncertain) with increasing CL_i. The uncertainty in the proportion of $CLfem_i$ achieved is inversely related to CL_i (Figure 3). This is a consequence of the property of the binomial function for which the coefficient of variation is inversely related to N. The effect of the proportion female on the probability profiles is consistent with the variance property of the binomial function; the variance is greatest when the proportion female is 0.5 (Figure 2). For stocks with female proportions close to 0.5, proportionally more fish must escape the fishery to exceed $CLfem_i$ with high probabilities (> 75%) than for stocks with a sex ratio biased towards female fish. The proportion of $CLfem_i$ achieved is also more variable for p = 0.5 than for p = 0.8 (Figure 3).

The incorporation of annual variability in biological characteristics (in this case, proportion female) results in more uncertainty of meeting or exceeding CL_i (Figure 2). As annual variation increases, the probability profiles become shallower such that more fish must survive the fisheries to achieve a consistently high (> 75%) probability of meeting the spawning requirements. There is greater uncertainty in the proportion of $CLfem_i$ achieved with increasing variation in the proportion female (Figure 3).

The number of fish that must survive the mixed-stock fishery (Sp_{reg}) to achieve simultaneously $CLfem_i$ for all stocks increases with the number of stocks in the fishery (Figure 4). In the example presented, when Sp_{reg} equals 110% of CL_{reg}, there is a 97% chance of meeting or exceeding $CLfem_i$ for any individual stock. The probabilities decline to 91%, 84%, and 67% for simultaneously achieving $CLfem_i$ in the complex of 3, 5, and 10 rivers, respectively (Figure 4).

The relative productivities of stocks exploited within the mixed-stock fishery have important consequences on the probability of achieving $CLfem_i$ in the individual stocks, and simultaneously in all stocks. The more productive stocks can achieve $CLfem_i$ at lower levels of Sp_{reg} than stocks of average and low productivity (Figure 5). At levels of Sp_{reg} equal to 125% of CL_{reg}, there is a 50% chance of simultaneously achieving $CLfem_i$ in all five rivers (Figure 5). The probability profile for simultaneous achievement of $Spfem_i$ for all stocks within the mixed-stock complex is defined entirely by the probability profile of the low productivity stock (i.e. in Figure 5, the low productivity stock probability profile is identical to the simultaneous profile).

Case study 1: Aggregation of 17 Welsh rivers

This case study considers the effects of stock size, differences in p among stocks, and annual variation in p

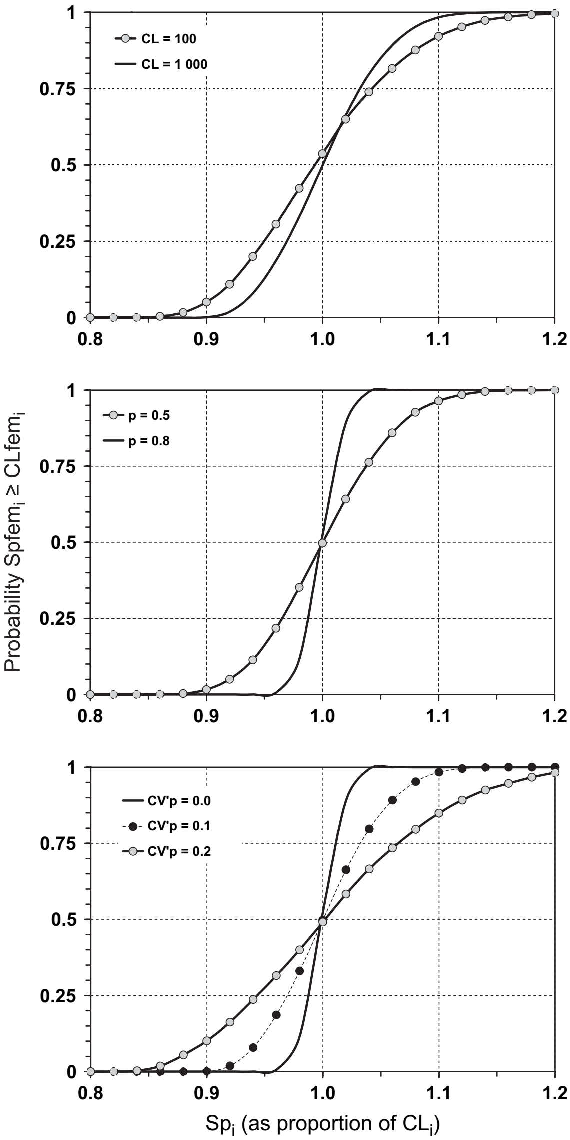

Figure 2. Monte-Carlo-derived probability profiles of achieving the individual river spawning requirement for two stock sizes (upper), two stocks differing in proportion female (middle), and a single stock with annual variation in proportion female (bottom). Parameters for the simulations are: upper panel − p = 0.8, CV′p = 0.1; middle panel − CL = 1000, CV′p = 0.1; lower panel − CL = 1000, p = 0.8.

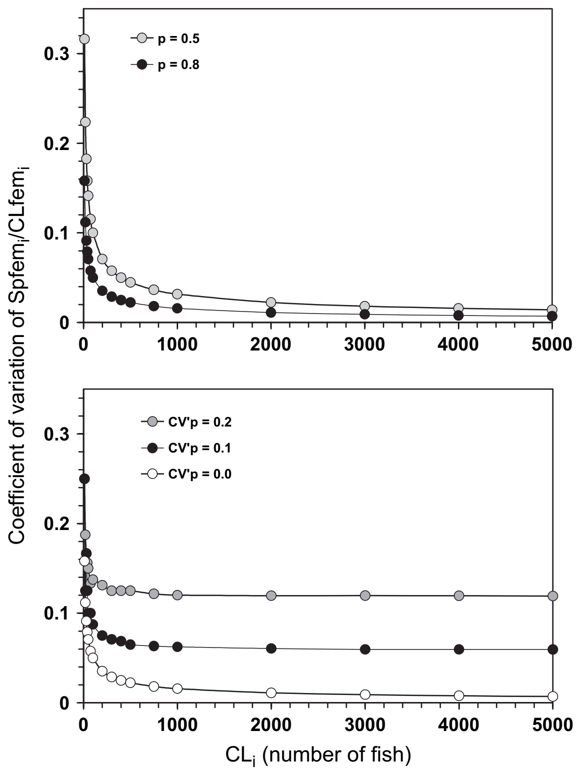

Figure 3. Uncertainty (coefficient of variation) in the proportion of $CLfem_i$ attained as a function of stock size and proportion female (upper), and relative to annual variation in proportion female (lower). Parameters for the simulations are: upper panel − CV′p = 0.1; lower panel − p = 0.8.

on the simultaneous attainment of $CLfem_i$ for 17 Welsh rivers. For those rivers, the total egg requirement is some 100 million eggs, equivalent to 31 061 spawners (Table 1). The smallest river is the Dwyryd, with a spawner requirement of 70 fish (44 female spawners), and the largest is the Wye, with a 34.5-million egg requirement equivalent to 9990 fish (5335 females). The inter-river proportion female in the returns to this region varied between 0.51 and 0.64 (Table 1).

When 31 061 fish survive the mixed-stock fishery, there is a 50% chance that about half the stocks will receive an under-escapement relative to their requirement (Figure 6). For a 50% chance of meeting or exceeding $CLfem_i$ in all 17 stocks simultaneously, Sp_{reg} must be between 110% and 115% of CL_{reg} (Figure 6). The smaller the stock, the more variable its performance in terms of the proportion of $CLfem_i$ achieved (Figure 7). The association between the uncertainty in performance and the size of the stock is described by a power function with an exponent of −0.5 (the coefficient of variation of the binomial distribution equals the square root of the reciprocal of N). The uncertainty decreases rapidly with increasing CL_i, and therefore, small stock performance would not be a good index of the status of the resource of a larger region (Figure 7).

Case study 2: Aggregation of monitored rivers in the Northeast Atlantic

The case study of the 15 monitored rivers of the Northeast Atlantic considers the effect of aggregating a large number of stocks differing in size and relative productivity within

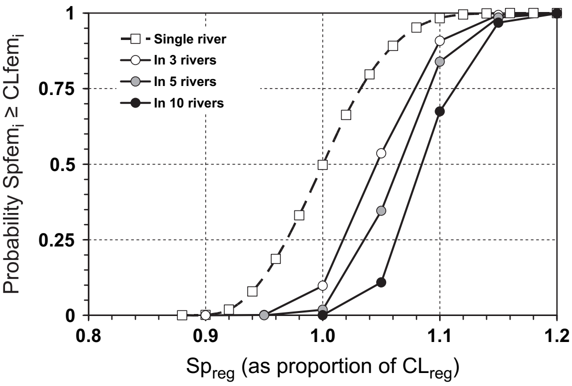

Figure 4. Monte-Carlo-derived probability profiles of simultaneously exceeding CLfem$_i$ in all rivers within a complex of 3, 5, and 10 rivers of similar individual stock size (CL$_i$ = 1000 fish).

a continental complex. Stock size (CL$_i$) varies from 23 fish to just below 7000, and relative productivity varies between 1.3 and 5.0 (Table 2). The smallest river (Oir) also happens to be the least productive, whereas the most productive rivers are of intermediate size (Table 2).

When Sp$_{reg}$ equals CL$_{reg}$, there is a 50% chance that fewer than six stocks will simultaneously exceed CLfem$_i$ (Figure 8). For a 50% probability of meeting or exceeding CLfem$_i$ simultaneously in 14 of the 15 stocks, Sp$_{reg}$ must equal 160% of CL$_{reg}$ (Figure 8). Even when Sp$_{reg}$ is twice CL$_{reg}$, the small and low productivity River Oir would only have a 25% chance of meeting its stock-specific requirement (Figures 8, 9). The most productive river (the Faughan) meets or exceeds its CLfem$_i$ when Sp$_{reg}$ equals 50% of CL$_{reg}$, with minimal annual variation in Spfem$_i$ (Figure 9).

The variation in realized spawners (Spfem$_i$) to the river is determined by the size of the stock, whereas the probability of meeting individual river requirements is determined by the relative productivity of the river. This is illustrated by comparing the performance of the River Oir and Girnock Burn (Figure 9). Both are small stocks and have large annual variation in the proportion of CLfem$_i$ achieved. The relative productivity of the Girnock Burn was estimated at 2.13, that for the River Oir at 1.26 (Table 2). Consequently, there is a 50% chance of exceeding CLfem$_i$ for the Girnock Burn when Sp$_{reg}$ equals 120% of CL$_{reg}$, whereas for the River Oir, there is a $<$25% chance of exceeding CLfem$_i$ when Sp$_{reg}$ equals 200% of CL$_{reg}$ (Figure 9). The response is similar for the medium-sized rivers of contrasting relative productivities (Figure 9).

Discussion

The use of reference points to manage single- and mixed-stock fisheries must include consideration of the uncertainties of achieving the objective. The factors that contribute to the uncertainties include variation in catch levels, variation in biological characteristics of the fish (sex ratio, size, fecundity), and inherent uncertainty around the reference point itself. There is additional uncertainty associated with managing small discrete units (fish). For Atlantic salmon specifically, this can be important, because individual river runs (considered to be stocks or populations) generally number in the hundreds or thousands of fish, rather than millions (Chaput, 1998; Chaput and Prévost, 1999). In such circumstances, managers must consider the uncertainty (probability) of achieving the spawning objective for small stocks, even under conditions of ideal fisheries management.

The present analyses considered the uncertainties in achieving the reference points defined in currencies of female fish. Fisheries harvest fish, not eggs, so if reference levels are set in terms of eggs, they must be translated into

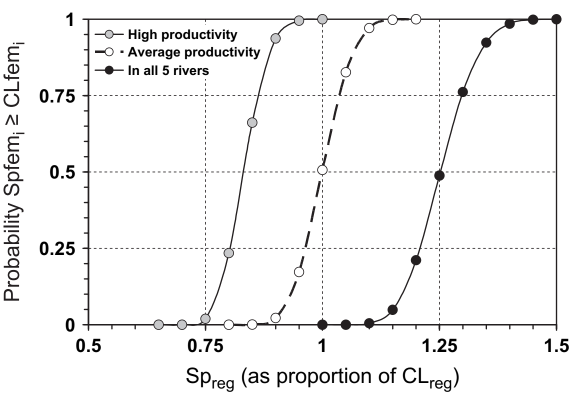

Figure 5. Monte-Carlo-derived probability profiles of simultaneously exceeding CLfem$_i$ in a complex of five rivers with similar CL$_i$ (1000 fish), but differing relative productivities.

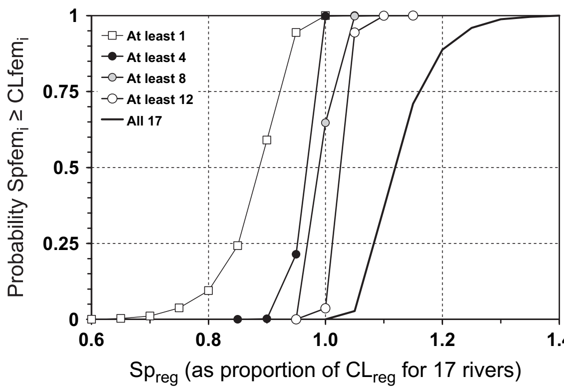

Figure 6. Monte-Carlo-derived probability profiles of meeting or exceeding CLfem$_i$ in at least one river, and simultaneously in increasing numbers of rivers for the 17 Welsh rivers, relative to Sp$_{reg}$. The spawning requirement (CL$_{reg}$) for the 17 rivers is 31 061 fish.

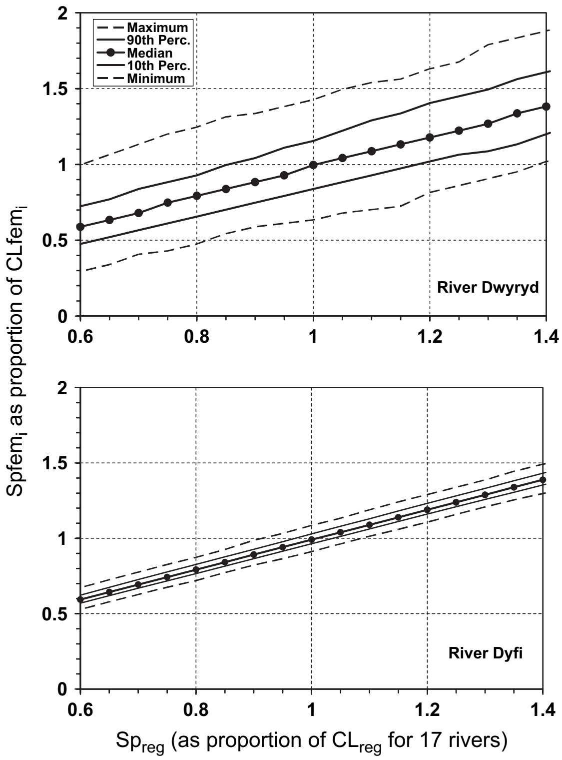

Figure 7. Individual river performance expressed as the proportion of CLfem$_i$ achieved for the smallest stock (upper) and a medium-sized stock (lower), within the 17 rivers of Wales, relative to Sp$_{reg}$.

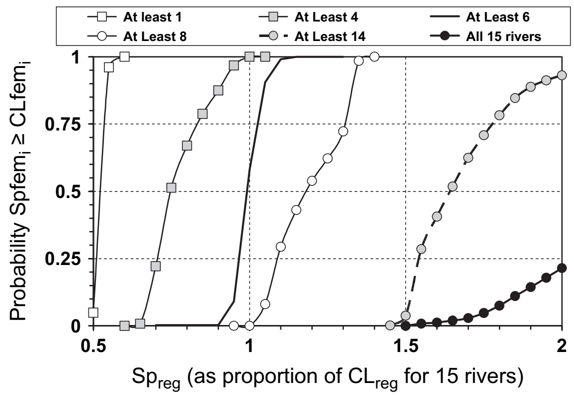

Figure 8. Monte-Carlo-derived probability profiles of meeting or exceeding CLfem$_i$ in at least one river, and simultaneously in increasing numbers of rivers for the 15 monitored rivers in the Northeast Atlantic, relative to Sp$_{reg}$. The sum of the spawner requirements for the 15 rivers (CL$_{reg}$) is 30 464 fish.

fish equivalents. As only females contribute eggs, the fish equivalents are further converted to female equivalents. These currency exchanges require information on the average or recent biological characteristics of the stock. As the characteristics of the fish that will be harvested or return to spawn are unknown prior to a fishery, they must be assumed from previous years. Such assumptions introduce more uncertainty into the probability of attaining spawner objectives.

For the most part, the probability profile for achieving the spawning requirement objective in a specific year, relative to the number of fish surviving the fishery, is determined by the size of the river stock, the proportion female in the stock, and annual variation in the biological characteristics (such as proportion female). In managing mixed-stock fisheries, the aggregation of individual river requirements into a regional or continental objective introduces additional uncertainty to the achievement of individual stock objectives. Factors that can affect the probability profiles in aggregated complexes include the number of stocks that are aggregated, the relative size of the stocks in the aggregate, and disproportionate productivity rates among the stocks. For illustrative purposes, natural mortality between the time of the fishery and spawning was considered to be negligible, but its magnitude and variability would add further uncertainty to managing the fisheries.

There is greater uncertainty in managing small stocks or populations than in managing large ones. In the single-stock scenario, the properties of the binomial distribution are relevant. Relative variability is an inverse function of stock size. For any fixed number of fish surviving the fishery, the variation in the number of female fish in a given year relative to the river requirement will be much greater in small rivers than in large ones. Relative variability is also a function of the proportion female in a stock. The probability profiles of achieving the required number of females for a given return of fish to the river are shallower (more uncertain) for a stock with a proportion female close to 0.5 than for stocks where the sex ratio is biased towards females. This is consistent with the property of a binomial distribution for which the variance is proportional to $p \times (1 - p)$ – see Hilborn and Mangel (1997). As the annual variation around the mean proportion female increases, the uncertainty in attaining the female objective also increases.

Clearly therefore, application of reference points to the management of fisheries under a fixed escapement strategy should take account of the additional uncertainty associated with managing small and discrete units. Regardless of the size of the stock being managed, the proportion female in the stock, or the variability in the biological characteristics, managing a fishery for survivals of fish equal to the reference level results in a 50% chance of meeting or exceeding the spawner objective, and conversely, a 50% chance of not meeting it. The probability profiles of meeting the spawner objective relative to the number of fish surviving a fishery are determined by all three above factors.

The operation of mixed-stock fisheries compromises the principle that individual river spawning stocks will be

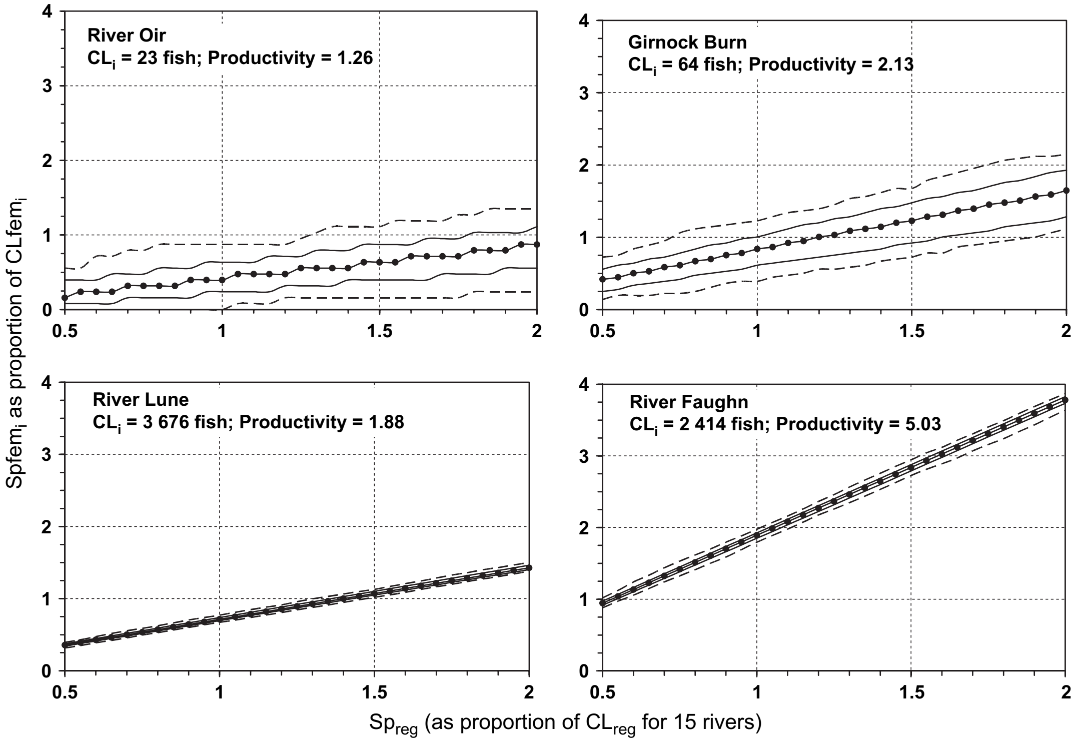

Figure 9. Annual variation in proportion of $CLfem_i$ achieved relative to Sp_{reg} for four of the 15 NEAC rivers. The upper panels show the variation for small stocks of different productivities, the lower panels medium-sized stocks with different productivities. Lines and symbols are interpreted as in Figure 7.

maintained, with high probability, above their reference levels (Potter, 2001). Specifically, managing mixed-stock fisheries on the basis of a requirement calculated as the sum of individual stock spawner requirements, or as the most likely value of a sum of reference points, as advocated by Prévost *et al.* (2003), provides a lower probability of simultaneously attaining the spawning requirement in the individual rivers. The spawner requirement for a stock complex must be increased as the number of stocks in the complex increases. Moreover, if rivers of differing productivity rates are aggregated into a complex, failure to account for these differences in the derivation of the requirement of the complex will result in under-escapement to the less productive areas, and over-escapement in the productive stocks. As previously indicated by Hilborn (1985), stocks of low productivity are particularly vulnerable in mixed-stock fisheries. Increasing the regional spawner requirement in an attempt to compensate for lower productivity may alleviate the problem somewhat, but it is not a guaranteed solution to the challenge of protecting such stocks. There is an inherent contradiction in the prosecution of mixed-stock fisheries, and the objective of preserving all stock components. Protection of the stocks of low productivity is only possible when the fisheries are managed to the lowest common denominator, i.e. managed to the lowest productivity rates of the river in the complex.

A series of other factors could potentially affect the probability of meeting spawner objectives when managing fisheries. Variations in other biological characteristics, including size and fecundity (Hutchings and Jones, 1998), and variations in natural mortality between the fishery and spawning, could be considered. Straying of fish among neighbouring rivers affects the optimal yield and fishing strategy (Crozier *et al.*, 2003). In some cases, small stocks may receive a net benefit if there are large neighbouring stocks exchanging fish. The effects on the probability of meeting spawning objectives would be similar to the effect associated with different productivities. All these factors could be incorporated in a higher dimensional model of the type presented here. Single- or mixed-stock fishery situations can and should be evaluated on a case-by-case basis, and any scenario can be evaluated by the Monte Carlo technique.

Acknowledging that sustainability of fish resources can only be achieved when production covers all the available habitat (or by all the spawning components in the river), consideration could also be given to the complexity of the river system, and the number of distinct production areas that must be seeded when formulating fisheries advice. As the number of these areas increases, the required number of fish that should be released from the fisheries must also increase, but there is a limit to the number of units that can be considered within an aggregate. When the aggregate is too large, the simultaneous achievement of spawner requirements in each individual unit at high probabilities may be unattainable.

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