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Application of pre-fishery abundance modelling and Bayesian hierarchical stock and recruitment analysis to the provision of precautionary catch advice for Irish salmon (*Salmo salar* L.) fisheries

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Ireland has one of the last remaining commercial salmon driftnet fisheries in the North Atlantic, with recent catches averaging 162 000 salmon (1997–2003), approximately 20% of the total landings of salmon in the entire North Atlantic. Since 2001, the Irish commercial salmon fishery has been managed on the basis of Total Allowable Catch (TAC) in each of 17 salmon fishing districts. This has been made possible by applying a number of new and innovative techniques to the estimation of conservation limits (CLs) and pre-fishery abundance (PFA) for combined stocks in each district. Stock and recruitment parameters from well-monitored European rivers were "transported" to all Irish rivers using a Bayesian hierarchical stock and recruitment (BHSRA) model. This provided the posterior probability distributions of the model parameters and related reference points, including individual river CLs. District PFA and the number of spawners were estimated for a baseline period of 1997–2003, using district catch data, estimates of unreported catch, and exploitation rate. Harvest guidelines were established on the basis of surplus of spawning fish over the CL for the baseline period. In line with scientific advice, the commercial fishery has been reduced from 212 000 fish in 2002 to 182 000 in 2003. In 2004, a total catch (including the rod catch) of approximately 160 000 wild salmon was advised.

Keywords: Bayesian, conservation limit, salmon, stock and recruitment.

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Introduction

Until 2002, the Irish fishery for salmon (*Salmo salar*) was managed by a combination of effort limitation and the application of technical conservation measures relating to size and type of fishing gear. While these measures regulate the efficiency of the fishery, they are not sensitive to the stock available, and allow the same level of fishing even when stocks are low. A Salmon Management Task Force established in Ireland in 1996 (Anon., 1996) recommended a new rationale for management of salmon stocks. It was based on achieving "spawning escapement targets" for each specific stock, and maintaining stocks above conservation limits (CLs). The Task Force proposed the application of a Total Allowable Catch (TAC) to allow sufficient fish to spawn to meet the CL.

In 1998, the North Atlantic Salmon Conservation Organisation (NASCO, 1998) adopted the precautionary approach to fisheries management (as outlined in FAO, 1995, 1996). Central to this was agreement that management measures should be aimed at maintaining all salmon stocks in the NASCO Convention Area above pre-agreed conservation limits.

The 17 salmon fishing districts in Ireland represent the smallest administrative entities for the management of commercial and recreational fishing, and for the provision of catch statistics. Their boundaries are statutorily defined and consist of the rivers, lakes, and estuaries, and an area of sea extending out from the land. In 1997, new legislation reduced the sea limit from 12 to 6 miles, and the fishing week from 5 days per week to 4 (daylight only). Salmon are taken mainly by surface driftnets in each of the district sea areas, although in some districts, draft nets are locally important (i.e. an estuarine or river seine-net held at one end on the shore, while the net is paid out by boat, the circle being completed by the boat returning to shore, entrapping any fish within the closing circle of net).

The homewater fisheries harvest two main components of the stock on their return to their natal rivers from their high-seas feeding grounds, i.e. 1 Sea Winter (1SW) salmon, generally referred to as "grilse", which return during summer, and 2 Sea Winter (2SW) salmon or "spring" salmon, which return during spring. In common with most other North Atlantic salmon stocks, the non-maturing component of the stock remains in the high seas, and is not exploited by the homewater fishery. The incidence of 2SW "summer salmon", and higher sea age groups is extremely low in Ireland. Similarly, the incidence of repeat spawners, from returns to monitored rivers and broodstock programmes, is low.

TACs can be set relative to stock abundance if a number of key values can be estimated, i.e. the number of fish available prior to the fishery taking place (i.e. the pre-fishery abundance, PFA), an estimate of the number of fish returning to spawn, and finally the number of fish required to spawn (the conservation limit). These values have been estimated for each of the 17 salmon fishing districts in Ireland, using PFA and pseudo stock and recruitment (PSR) models (Potter *et al.*, 1998; Ó Maoiléidigh *et al.*, 2001b, c; ICES, 2003).

More recently, the development of Bayesian hierarchical stock and recruitment analyses (BHSRA) for transporting stock and recruitment parameters from monitored rivers to rivers without stock and recruitment data (Crozier *et al.*, 2003; Prévost *et al.*, 2003) has allowed CLs to be established for individual rivers independently of catch data. The BHSRA relies on a measure of the production units available in each river. In the absence of a more refined and commonly available habitat variable, an intermediate, such as wetted area, can be used to quantify salmon production for widespread transport of stock and recruitment parameters from well-studied monitored rivers, provided the quantity of "non-productive" riverine habitat is in similar proportion from one river to the next. Accordingly, a Geographical Information System (GIS) has been developed for the salmon rivers of Ireland (McGinnity *et al.*, 2003), to provide an estimate of the size of the wetted area of each river in any given jurisdiction.

Here, we summarize the progress in management arrangements and fisheries for Irish salmon stocks, an important component of the overall North Atlantic salmon population. Several of the techniques used formed part of the work of the SALMODEL project initiated as an EC-funded Concerted Action (Crozier *et al.*, 2003). The overall aim of SALMODEL was to "Advance the scientific basis upon which advice is given to managers of local, national, and international salmon fisheries, compatible with the precautionary approach, as adopted by the North Atlantic Salmon Conservation Organisation (NASCO) and within the requirement of sustainability". The application of these new and innovative techniques to the national management of a highly prized, but vulnerable, wild salmon resource is presented. New aggregated District and National CLs, generated from the BHSRA/wetted area approach, are compared with CLs generated from the previously applied PFA and PSR approach updated with 2003 catch, unreported catch, and data on the rate of exploitation. The status of Ireland's salmon stocks is illustrated relative to the attainment of this new CL, and the catch advice for each district is illustrated.

Material and methods

Estimation of pre-fishery abundance (PFA)

Catch records from commercial salmon dealers' registers are available for the period 1971–2000. Following implementation of a salmon carcass tagging and logbook scheme in 2001 (Ó Maoiléidigh *et al.*, 2001a; Anon., 2004), the catch data derive from the logbook returns of commercial and recreational fishers.

The ICES model used to estimate the pre-fishery abundance of salmon from countries in the NEAC area employs a simple run-reconstruction approach similar to that described by Potter and Dunkley (1993) and Rago *et al.* (1993). Following Potter *et al.* (1998), the model takes the catch in numbers of 1SW salmon in each district, then raises it to account for estimates of non-reported catches and exploitation rates. The last two parameters are generated from a comprehensive national coded wire tagging and tag recovery programme (Browne, 1982; Ó Maoiléidigh *et al.*, 1996). As unreported catch cannot be estimated precisely, minimum and maximum values likely to encompass the true values are provided, based on local information or inspection. Similarly, exploitation rate data for individual districts are based on the estimated range of values for the monitored rivers in those districts or the next nearest districts. These ranges are used to delimit uniform distributions for the parameters in a Monte Carlo simulation. An example of the input data required for the national CL is shown in Table 1; a similar table is required for each of the 17 salmon fishing districts. The simulation, which uses the software package "Crystal Ball" (Risk assessment software add-in for Microsoft Excel™, from Decisioneering Inc, Decisioneering UK, Ltd, 1996) is run in Microsoft Excel™ to generate estimated distributions of the PFA values by simulating 1000 runs of the model. The PFA values are raised to take account of the natural mortality between 1 January in the first sea winter (which is the date they recruit to the first fishery, i.e. Faroes) to provide an estimate of pre-fishery abundance (PFA) or recruitment (Potter *et al.*, 1998). Subsequently, the PFA is discounted to account for natural mortality (0.03% monthly instantaneous rate of natural mortality), to estimate the total returns back to homewaters. The spawning population is then estimated by subtracting the catch from the returns.

Table 1. Input data for Irish pre-fishery abundance (PFA) analysis using Monte Carlo simulation. Estimated catch (1SW salmon only) derives from licenced salmon dealers' registers up to and including 2000, and from mandatory commercial fishing logbooks to 2003. Unreported catch and exploitation rate derive from the National Coded Wire Tagging and Tag Recovery programme.

	Catch (numbers)	Percentage unreported		Exploitation rate 1SW (%)	
Year	1SW	Minimum	Maximum	Minimum	Maximum
1971	417 428	30	45	56	74
1972	449 160	30	45	56	74
1973	460 665	30	45	56	74
1974	561 323	30	45	56	74
1975	616 249	30	45	56	74
1976	420 508	30	45	56	74
1977	368 579	30	45	56	74
1978	324 350	30	45	56	74
1979	289 539	30	45	56	74
1980	237 561	30	45	56	74
1981	157 713	30	45	51	68
1982	277 527	30	45	60	79
1983	463 602	30	45	56	75
1984	243 152	30	45	54	72
1985	456 437	30	45	63	84
1986	509 992	30	45	59	79
1987	344 066	20	40	61	82
1988	416 652	20	40	56	75
1989	316 536	20	40	60	80
1990	183 589	20	40	57	76
1991	116 923	20	40	47	62
1992	180 868	20	40	60	80
1993	152 577	15	35	51	68
1994	235 935	15	35	55	74
1995	233 313	15	35	62	83
1996	202 582	15	35	53	71
1997	152 808	10	20	54	71
1998	162 054	10	20	53	70
1999	145 336	10	20	52	70
2000	180 823	10	20	49	65
2001	234 682	5	10	58	77
2002	198 633	5	10	48	64
2003	166 151	5	10	48	64

Estimation of conservation limits (CLs)

Pseudo stock–recruitment (PSR) model

Following Potter *et al.* (1998), estimates of spawning stocks are derived as model outputs from the information on catches, unreported catch, and exploitation rate. However, stock–recruitment relationships cannot be derived directly from these data, because the spawners in year "n" contribute to the 1SW recruitment in year "n + 3" to year "n + 5", depending on the relative proportions of 1–3-year-old smolts that can be produced. Thus, spawners in year "n" may produce: 1-year-old smolts in year "n + 2", which generate 1SW recruits in year "n + 3"; 2-year-old smolts in year "n + 3", which produce 1SW recruits in year "n + 4"; and so forth.

The egg deposition in year "n" is assumed to contribute to the recruitment in year "n + 3" to "n + 5" in proportion to the numbers of smolts produced of ages 1–3. Therefore, the number of "lagged eggs" that contribute to the recruitment of maturing 1SW fish in each year can be estimated. The lagged egg estimates provide a measure of the relative spawning level that gave rise to the recruitment figures expressed above as PFA. These data can then be plotted to provide a "pseudo" stock–recruitment relationship, and a number of reference points can be derived. It is not possible to estimate stock size at maximum sustainable yield (S_{MSY}) from this relationship without making further assumptions about marine survival. As a result, a method for setting biological reference points from noisy stock–recruitment relationships was developed by Potter and Nicholson (2001). The model assumes that there is a critical stock level below which recruitment decreases linearly towards zero stock and recruitment, and above which recruitment is constant. The position of the critical stock level is determined by searching for the value that minimizes the residual sum of squares. Potter and Nicholson (2001) applied this approach to similar pseudo stock–recruitment relationships. An example of the output for the national stock based on the input data in Table 1 is shown in Figure 1.

Bayesian hierarchal stock and recruitment analysis (BHSRA)/wetted area

The analysis of stock and recruitment (SR) data is the most widely used approach for deriving biological reference points (BRPs) for salmon populations (Prévost *et al.*, 2001). While the conservation limits generated from the PSR model use stock and recruitment data for each district, they are "pseudo" because they relate to geographic entities (i.e. the number of fish returning to that district) rather than true biological stocks. They are further complicated by the

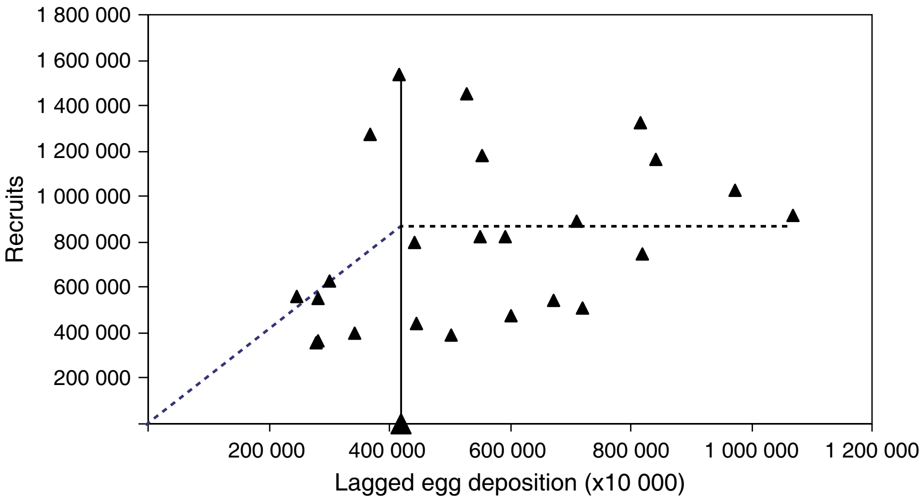

Figure 1. Example of a pseudo stock and recruitment curve for the total Irish stock. Recruits are expressed in numbers of fish available prior to the first fishery, i.e. Faroes. This date is taken as 1 January in the first sea winter. Spawning stock is expressed in number of eggs. The position of the critical stock level is determined by searching for the value that minimizes the residual sum of squares (approximately 4 billion eggs, equivalent to 171 600 1SW spawners).

mixed stock nature of these district fisheries. Browne *et al.* (1994) and Ó Maoiléidigh *et al.* (1994) showed that a significant number of tagged fish from specific rivers are caught in districts other than the district of origin.

Prévost *et al.* (2003) applied Bayesian hierarchical modelling of stock−recruitment (SR) relationships to estimate BRPs for European Atlantic salmon stocks. The structure of the hierarchical SR model developed distinguishes two nested levels of randomness, within-river and between-rivers. This is an extension of the classical Ricker modelling approach, where the parameters of the Ricker function are assumed to be different between rivers, but drawn from a common probability distribution depending on two primary covariates, river size, and river latitude. The Bayesian analysis of this hierarchical model has been developed with a set of 13 stock and recruitment data series from monitored salmon rivers located in the Northeast Atlantic. The model yields a set of predicted SR parameters for new rivers with no SR data, provided information is available on the size of the river (in this case wetted area is used), and its latitude. Posterior distributions are estimated by means of MCMC sampling (Gibbs algorithm), as implemented by the Winbugs software (Spiegelhalter *et al.*, 2000). Details of the model specification and its Bayesian treatment are given in Prévost *et al.* (2003).

The latitude value used in the analysis is the river catchment area midpoint, and the size is quantified as the riverine wetted area accessible to salmon. The wetted area is computed from statistically combined parameters, the length of upstream river, upstream catchment area, stream order, and local channel gradient, captured by aerial photography and extracted within the GIS platform (McGinnity *et al.*, 2003).

Given this latitude and wetted area information, the approach described in Prévost *et al.* (2003) was used to estimate new district CLs, defined as the sum of river-specific CLs for each fishery district.

Derivation of precautionary catch advice

The catch data used in the models is modified to account for 2SW and older salmon, and hatchery-reared fish released as smolts. There is little overlap between the run timing of the main two components of the Irish stock, i.e. the main 1SW salmon run is from June to August, whereas 2SW (spring) salmon enter rivers during spring. As the commercial fishery operates in a restricted time period (June and July), it exploits predominantly 1SW salmon. The exploitation rate on larger Multi-Sea Winter salmon (MSW) or "spring" fish is low, approximately 7.5% on average for the period 1980−1988, and declining (ICES, 2003), and legislation introduced in 1997 has eliminated commercial fishing until 12 May. As no further scale analyses have been carried out since 1988, a value of 7% has been used as the proportion of 2SW salmon in the commercial catches annually since that time. Although there may be some small contribution to subsequent 1SW stocks from the progeny of older salmon, for the purposes of providing catch advice, 2SW and older fish (including repeat spawners) are excluded from the catch data used in the models, principally because such stocks are not exposed to a significant commercial fishery, and represent only a relatively small proportion of the total population. Similarly, hatchery-reared fish released as smolts are not considered to make a contribution to spawning populations, and potential catches of these fish have been estimated and removed from the catch data. The output from the models provides the average (1997–2003) number of spawners and the total catch of adult wild 1SW salmon.

The next step is to convert the conservation limits in eggs m^{-2} from the BHSRA/wetted area analysis to total egg requirement for each river in Ireland by multiplying by the total wetted area accessible to salmon. Subsequently, the values for egg deposition are converted to adults, and then corrected for 1SW fish only in the manner outlined below.

If the total number of adults to meet CL is X, then the number of eggs will be

$$(\text{Prop}_{1SW} \times \text{Prop}_{1SW\ \text{Female}} \times \text{Eggs}_{1SW} \times X) + (\text{Prop}_{2SW} \times \text{Prop}_{2SW\ \text{Female}} \times \text{Eggs}_{2SW} \times X)$$

where Prop_{1SW} and Prop_{2SW} are the proportions of 1SW and 2SW fish (0.93 and 0.07, respectively, based on age distribution analyses from 1980 to 1988), and $\text{Prop}_{1SW\ \text{Female}}$ and $\text{Prop}_{2SW\ \text{Female}}$ are the proportions of 1SW female and 1SW male fish (0.6 and 0.4, respectively), and the proportions of 2SW female and 2SW male fish (0.85 and 0.15, respectively). These proportions are broadly based on observations of returning wild salmon in several rivers monitored in Ireland (e.g. River Burrishoole percentage 1SW females 1997–2002 = 59.9%, percentage 2SW females for the same period = 83%). Eggs_{1SW} and Eggs_{2SW} are the average fecundities of 1SW and 2SW fish (3400 and 8000 eggs, respectively). Again, these values are based broadly on monitored river data where broodstock are stripped, and eggs (including residual eggs) are counted.

The total number of adults, X = CL/2373, and therefore the CL consists of (0.93 × X) 1SW and (0.07 × X) 2SW salmon.

Once estimates of average spawners, average catch, and district CL are produced, precautionary catch advice is formulated by applying harvest guidelines, as follows. Where the average number of spawners is higher than the CL, an exploitable surplus exists. If this surplus is more than or equal to the average catch for the baseline period, this average catch can be taken in the next season. In following a precautionary approach, increases over this average are not permitted even if the surplus is higher, because of the mixed stock nature of the fishery, and the desire to protect more vulnerable stocks in other areas. Where the average number of spawners is less than the CL, the average catch must be reduced by this number of fish in the next season. Where there is no exploitable surplus or where the total returns before exploitation are less than the CL, there should be no catch, or the fishery should be severely restricted while stock rebuilding takes place.

Results

The results showed 173 salmon rivers in Ireland located between 51.6 and 55.3°N. They vary in size from 3727 to 8 795 447 m^2 of riverine wetted area accessible to salmon (median 182 949 m^2). There is wide overlap in the size of the Irish rivers and the size range of the monitored rivers used as a learning sample by Prévost *et al.* (2003), i.e. 10% of the Irish rivers are smaller than the smallest monitored river, but none are bigger than the largest one. The Irish rivers are grouped into 17 salmon fishing districts, plus that part of the River Foyle within the Republic of Ireland. The number of rivers in each fishery district varies from 1 to 30.

Owing to the lognormal structure of the hierarchical SR model used, the posterior predictive distributions of the CLs are best examined on a log-scale (Figure 2). The distribution location (e.g. the median) of the egg deposition rates of the fishery district CLs vary little around that of the national CL, because of the narrow latitudinal range within Ireland. Indeed, Prévost *et al.* (2003) show that it is the latitude covariate that governs the variations in the location of the CL posterior predictive distributions. There are large variations in the precision of the individual district posterior predictive CLs. For instance, in the Drogheda district, which consists of just one river, the posterior predictive distribution ranges from approximately 0.5 to 16 eggs m^{-2}. In districts where several rivers are aggregated, the CL predictions are more precise, e.g. the Kerry district (30 rivers) ranges from approximately 1.5 to 7 eggs m^{-2}. The variance reduction effect gained from the aggregation of several rivers under a regional entity is more pronounced when the number of rivers increases. This explains why the CL rate of egg deposition at the national level is more precisely estimated than that of any individual fishery district. The relative size of the rivers within a fishery region also has an effect on the precision of the estimates. The CL of the Lismore fishery district, which has 7 rivers with a single large one accounting for more than 75% of the wetted area accessible to salmon in the district, is estimated with a similar level of precision as the Drogheda fishery district.

The 90% probability interval of the posterior predictive distributions of CLs generally encompass the point estimate CLs derived from the PFA/PSR approach previously used for providing catch advice in Ireland (Figure 2). However the PFA/PSR CLs are overdispersed compared with their corresponding posterior predictions using the BHSRA/wetted area approach: only 5 of 17 (29%) are located in the inter-quartile interval, and 12 of 17 (71%) within the 80% probability interval. There is also a tendency of the PFA/PSR estimates to be greater than the estimates derived from the BHSRA/wetted area values approach. Indeed, 10 of 17 (59%) of the catch-based CL estimates are located in the upper half of their corresponding posterior distribution, and 6 of 17 (35%) are in the upper quartile. The noticeable exception is the Dublin fishery district, where the previous estimate based on the PFS/PSR model was significantly underestimated. The national CL derived from the PFA/PSR model results in a mean value of approximately 7 eggs m^{-2}, and is located in the upper part of the posterior predictive distribution close to the 90th percentile. This

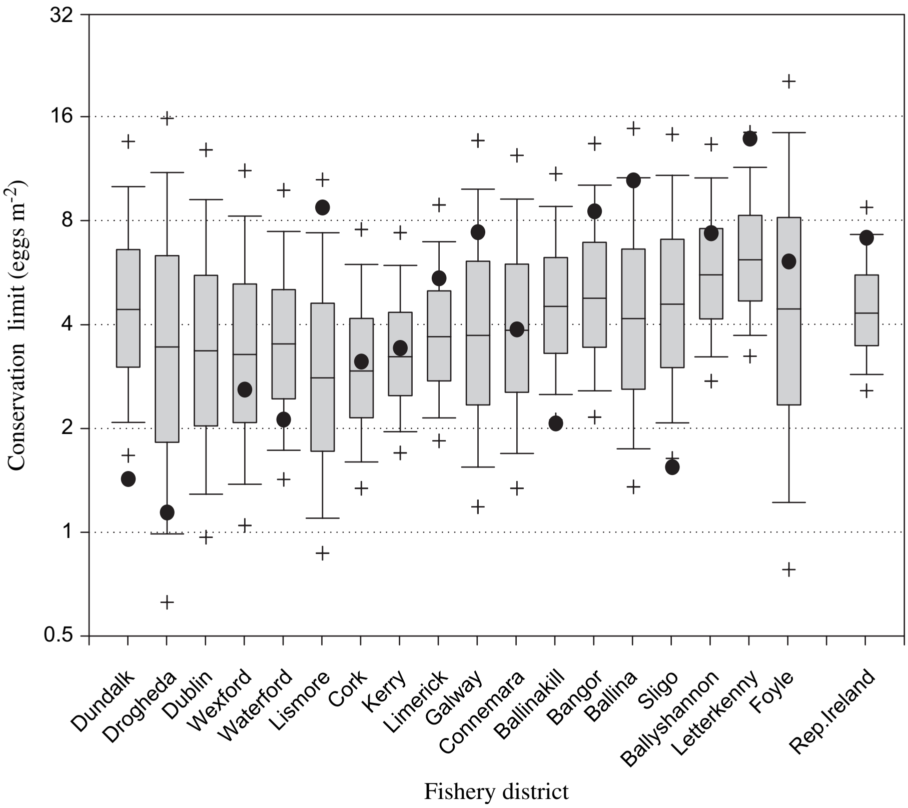

Figure 2. Posterior predictive distributions of the egg deposition rate per m^2 of riverine wetted area accessible to salmon, corresponding to the conservation limits of the fishery districts, and of Ireland as a whole. Each box plot displays on a log-scale the 5th, 10th, 25th, 50th, 75th, 90th, and 95th percentiles. Black dots represent the currently used conservation limits for management advice in Ireland for the fisheries district, and at ICES for the whole country. The Dublin fishery district conservation limit does not appear on the graph because it is lower than the lower bound of the y-axis.

compares with the BHSRA/wetted area median value of approximately 4 eggs m^{-2}.

The status of the district stocks relative to their attainment of mean post-predicted BHSRA/wetted area CLs in 2003 is shown in Figure 3. Of the 17 fisheries districts in Ireland, 6 meet their conservation limits, 6 are $>50\%$ of their CL, and the remaining districts fall as low as 15% of their CL. Nationally, the attainment of CL for 1SW salmon is just over 80%.

The precautionary catch advice is given in Table 2. This advice is predicated on wild fish only (i.e. estimated returns from hatchery-released smolts have been removed). It also relates to the total removal of fish by all means, and is not restricted to commercial fisheries. There are five districts, mainly located on the east and south coasts, where the conservation limit would not have been met even in the absence of a commercial fishery. Therefore, there is no catch indicated in the precautionary catch column. In seven of the districts, reductions in the average catch in 2004 are indicated, because these districts were below their conservation limits on average for the period prior to this. The remaining districts are meeting or exceeding their conservation limits. In this instance, the average catch is advised for 2004, recognizing the fact that the fishery is a mixed stock one, taking fish from districts that are below their conservation limit. The status of these districts will be assessed on an ongoing basis, and the advice will change in line with any significant and consistent improvement in stock size.

Discussion

Ideally, river-specific stock and recruitment analysis would be the most accurate way to determine river-specific conservation limits. However, given that river-specific stock and recruitment studies are resource-intensive and take a long time to cover several generations and a wide range of stock levels, the BHSRA/wetted area method represents the most feasible method of deriving individual river CLs for the foreseeable future (Prévost *et al.*, 2001).

The two methods of estimating conservation limits are fundamentally different in approach and independent of each other. The approach described by Prévost *et al.* (2003)

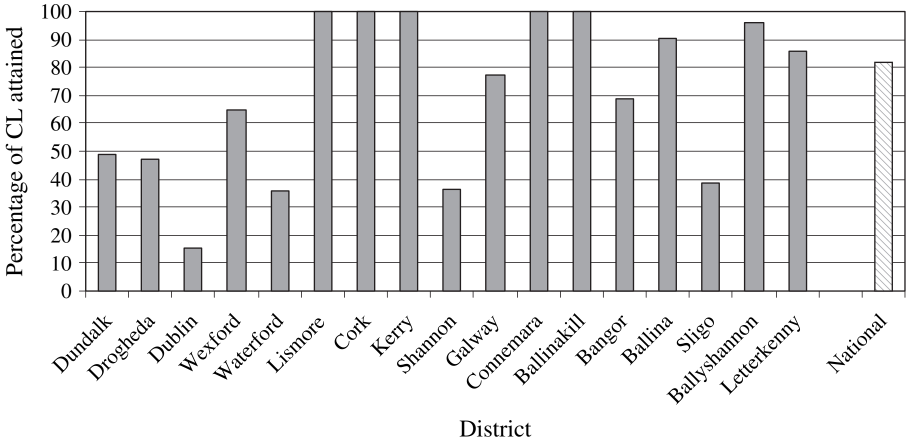

Figure 3. Average attainment of the mean posterior predicted BHSRA/wetted area conservation limit (CL) from 1997 to 2003, for each Irish salmon fishing district.

uses a training set of 13 rivers, with annual fish population size data to estimate the stock and recruitment parameters. The method provides probability distributions of the number of eggs that can be accommodated, based on the limitations imposed by the physical attributes of each river. In contrast, the PFA/PSR models use catch data to derive an aggregated stock—recruitment relationship, without explicit reference to the physical limitation of the size of the rivers comprising the aggregate (district) being considered, and assuming that the fish belong to spawning populations originating in that district. Despite the two different approaches used, the national CL based on the PFA/PSR approach (171 604 1SW salmon) is not greatly different from the equivalent value using the mean of the post-predicted BHSRA/wetted area output (197 576 1SW salmon). This tends to support the contention that the PFA/PSR models are robust means of estimating a national conservation limit, because all spawning stocks are included.

There was a variable degree of correspondence between the comparable estimates for each individual district. However, in just one case (the Dublin district) was the

Table 2. Precautionary catch advice for 2004 based on average attainment of conservation limits in each Irish salmon fishing district from 1997 to 2003.

Region	District	BHSRA/wetted area conservation limit	Average number of spawners	Estimated average wild catch (including rod catch)	Precautionary catch of wild 1SW salmon in 2004
East	Dundalk	5 037	2 468	1 478	No catch
East	Drogheda	13 204	6 254	3 743	No catch
East	Dublin	4 828	730	162	No catch
East	Wexford	8 455	5 460	2 566	No catch
South	Waterford	39 164	13 997	13 587	No catch
South	Lismore	13 420	16 666	16 074	16 074
Southwest	Cork	6 228	16 897	25 506	25 506
Southwest	Kerry	11 812	22 249	33 054	33 054
Shannon	Shannon	22 831	8 342	15 467	978
West	Galway	10 107	7 804	5 529	3 225
West	Connemara	1 534	3 447	2 395	2 395
West	Ballinakill	3 815	11 599	8 104	8 104
Northwest	Bangor	7 097	4 887	9 359	7 148
Northwest	Ballina	18 773	16 953	31 200	29 380
Northwest	Sligo	8 786	3 405	6 455	1 073
North	Ballyshannc	8 062	7 734	13 146	12 819
North	Letterkenny	14 424	12 362	21 236	19 174
National		197 576	161 253	209 060	159 929

estimate generated by the PFA/PSR model far outside the posterior predicted 90% probability range of the BHSRA/ wetted area output.

Even using best available information, the wide range of posterior predicted distributions of CLs associated with individual districts illustrates the uncertainty that managers are faced with, given that it is the mean CL that has been adopted to date. In applying precautionary catch advice, it is therefore recognized that this may not always afford adequate protection to stocks, and that fisheries that could possibly exploit at a higher rate are being restricted. However, the process itself is seen as more appropriate to the present fishery and stock levels. Development of the catch advice in a risk framework is also anticipated in the near future, and it will be possible to address some of the uncertainty issues as stocks and fisheries are monitored.

Other differences between comparative estimates at the district level could be accounted for by the following: (i) the mixed stock nature of district fisheries, and the problems this poses to the PFA/PSR models that use catch as the primary data input, i.e. the CL egg deposition rate requirement is overestimated if the district catches many fish from other districts without significant loss of its own fish to other district fisheries (possibly in Lismore, Ballina, and Letterkenny), and underestimated if the district loses a lot of fish to other districts without gaining fish from other districts (possibly in Dundalk, Drogheda, Ballinakill, and Sligo); (ii) the accuracy of the wetted area estimate, which is based on a regression model with its associated uncertainty; (iii) the degree to which water quality (or any other factor influencing the productive capacity of rivers) is compromised relative to other Irish rivers, and the 13 rivers in the training set. This will lead to over- or underestimates by the BHSRA/wetted area approach, if water quality is more or less (respectively) compromised than the training set rivers. Deterioration in water quality is a serious issue in a number of districts in east and southeast Ireland (i.e. Dundalk, Dublin, Wexford, and Waterford). The differences in outputs between the models may be an indication or measure of the reduction in carrying capacity or productive potential of the rivers in these districts, as a result of water quality problems; (iv) the PFA/PSR models used for district catch advice do not include the 2SW and MSW (or repeat spawner) fish in the CL (i.e. no input data for this component is entered in the model), because the main fisheries under quota are grilse fisheries, and information on the relative catch of MSW stocks at a district level is poor. This could affect some of the individual districts where 2SW or MSW fish constitute a larger proportion of the catch (notably Wexford and Lismore), and corrections may apply to these areas in future; (v) similarly, the index rivers used to provide exploitation rate data for the PFA/PSR model may not be representative of all districts; (vi) the PFA/PSR ICES model is based on a 30-year catch series, and has not been corrected for non-stationarity. Crozier *et al.* (2003) reported a consistent drop in productivity for 6 rivers in the Northeast Atlantic around the mid-1980s. Similarly, ICES (2003) identified a potential "phase-shift" in salmon production that occurs around 1990 (for adults) for rivers and stocks in both the Northeast Atlantic and in North America. The BHSRA/wetted area approach presented here only takes account of stock and recruitment parameters from the mid-1980s.

These factors could act discretely or cumulatively, depending on the circumstances and the dynamics of individual river populations. However, the derivation of CL probability distributions by the BHSRA/wetted area approach is an improvement on the point estimates of district CLs obtained from the PFA/PSR catch-based models, because it removes the uncertainty associated with the mixed stock nature of district fisheries. It also allows for a more in-depth appraisal of the underlying biology of individual stocks in relation to the productive capacity of the river producing them. Moreover, these river CLs can potentially be refined with more information on the physical characteristics of the catchments (compromised water quality, gradient, etc) to a higher level of precision.

While district BHSRA/wetted area CLs are preferred over the estimates derived from PFA/PSR models, it is likely that, for the foreseeable future, the PFA model will continue to be used to generate a retrospective estimate of exploitable surplus, and to assess the attainment of these new district CLs. This situation may improve with information from automatic fish counters, which could be used as indices of performance for all other rivers in each district, and to derive forward-running predictive models for pre-fishery abundance. Fish counters would also provide additional information on stock structure and run timing, which will refine many of the parameters currently used in models and in the provision of catch advice to managers.

Improvements in the collection of salmon catch statistics (mandatory carcass tagging, logbooks), and advances in analytical techniques have permitted the derivation of precautionary catch advice which is now being used to establish TACs for each district, and to apportion the surplus over spawning requirements to the various fishing engines (driftnets, draft nets, other nets, rods). In the short period of implementation from 2002 to 2004, district TACs have been applied as far as possible with reference to those districts requiring the most significant reductions in catch. However, reductions in catch alone will not in many instances result in an instant response in spawning stocks. Clearly, significant rebuilding will be required in some areas, while surpluses in spawning requirement in other districts will need to be examined in relation to the extent of mixing of stocks originating from other districts in each district's catch. Most importantly, the combined techniques have allowed the implementation of a new national management plan that provides the basis for maintaining Irish salmon stocks above conservation limits, or to rebuild deficient stocks.

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