Managing Atlantic salmon (*Salmo salar* L.) in the mixed stock environment: challenges and considerations

W. W. Crozier, P-J. Schönh, G. Chaput, E. C. E. Potter, N. O Máoiileidigh, and J. C. MacLean


Atlantic salmon, as a result of their population structure and behaviour, are potentially subject to a complex array of fisheries, ranging from those within rivers harvesting single stocks, to distant-water mixed stock fisheries that harvest fish from different countries, stock complexes, and continents. In addition, estuarine and in-river fisheries may catch fish from more than one stock or stock component, where these are present. One of the main challenges in managing salmon across this range of fisheries is to account for the differing status of stocks with respect to safe biological limits, noting that stocks of differing productivity may require different harvest strategies. Also, the existence of sequential harvest in different fisheries provides unique challenges, because decisions in an individual fishery cannot be made in isolation of the impacts of other fisheries on those stocks. We illustrate the uncertainties and complexities involved in managing mixed stocks of salmon, whether in homewaters or in distant-water fisheries, and examples are given to illustrate how science and management are, or should be, developing to face these challenges.

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Introduction

Atlantic salmon (*Salmo salar* L.) occur naturally in more than 2000 rivers from around 43°N to 70°N along the coasts bordering the North Atlantic Ocean, giving a European range from Spain to Russia, and from Maine to Labrador in North America (MacCrimmon and Gots, 1979). A large number of studies over the past two decades have contributed knowledge about the genetic population structure that has developed in Atlantic salmon following the last ice age. The species is highly genetically structured compared with most fish species (Ward et al., 1994). Enzyme variants (allozymes) show that approximately one-third of the total genetic diversity of Atlantic salmon results from differences between populations. A major genetic dichotomy exists between populations from either side of the North Atlantic and, on the European side, between populations in Baltic and Atlantic drainages (Stähli, 1987). There is also evidence for further regional sub-structuring within Europe, as well as genetic differentiation of local populations between and within rivers (Heggberget et al., 1986; Bourke et al., 1997).

The anadromous life cycle of Atlantic salmon results in juveniles spending from 1 to 6 years in freshwater, followed by one (1SW) to two or more years at sea (MSW), before returning to natal rivers to spawn (Hutchings and Jones, 1998). This migratory habit results in many opportunities for salmon to be fished, whether on the high seas feeding grounds, in coastal waters in the country of origin, or in other countries during the return migration, or...
in home rivers at and after entry to freshwater prior to spawning. Reflecting these diverse fishing opportunities, there has been a long and complex evolution of the fishing techniques applied. They range from driftnetting and long-lining in the distant-water fisheries at West Greenland and the Faeroe Islands, respectively, to use of various types of gillnetting, encircling and hand-held nets, as well as traps operated in coastal and estuarine waters. While rods are frequently the main method employed in freshwater fisheries, in some larger rivers a variety of gear is employed, including weirs, gillnets, driftnets, and seines (Erkinaro et al., 1999).

One of the main challenges in managing salmon across this range of fisheries is to take account of the differing status of stocks with respect to safe biological limits, noting that stocks of differing productivity may require different harvest strategies. Although the management of these river stocks, and the fisheries that exploit them, might ideally be based upon the status of each individual genetic population, this is not generally practical. Managers therefore have had to consider how populations or river stocks should be grouped. Such groups fall within the meaning of a stock as to consider how populations or river stocks should be grouped. This is not generally practical. Managers therefore have had to consider how populations or river stocks should be grouped. Such groups fall within the meaning of a stock as “an exploited or managed unit” (Royce, 1984) and are consistent with the ICES definition of salmon “stocks” as “units of a size (encompassing one or more populations) which provide a practical basis for the fishery manager” (ICES, 1996). Where this has involved grouping a larger number of river stocks, there has been a tendency to refer to them as stock complexes or groupings, to avoid confusion.

The degree of mixed stock composition of fisheries varies greatly; from the distant waters, where from dozens to several hundreds of river stocks can be present in the fishery at any time, through homewater coastal fisheries, where salmon from local rivers may be taken, along with some fish returning to neighbouring countries. In addition, estuarine and in-river fisheries may take fish from more than one river stock or stock component, where these are present. The existence of sequential harvest in various fisheries provides unique challenges, because decisions in an individual fishery cannot be made in isolation of the impacts of other fishing on those stocks. For example, when all North American fisheries were operating, salmon migrating from many Canadian and USA rivers were potentially taken as non-maturing 1SW fish in the West Greenland fishery and in the marine coastal fisheries of eastern Canada, as they returned as maturing two-sea-winter (2SW) salmon, and finally by rods in the natal river. In many cases, maturing 1SW components of these stocks would also have been taken in Canadian coastal fisheries and in home rivers.

The present paper summarizes recent progress in management of fisheries for Atlantic salmon in the North Atlantic. Some of the issues raised and examples given formed part of the work of the SALMODEL project initiated as a European Commission 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 Organization (NASCO) and within the requirement of sustainability”. We illustrate the uncertainties and complexities involved in managing mixed stocks of Atlantic salmon, whether in homewaters or in distant-water fisheries, and provide examples to illustrate how science and management are, or should be, developing to face these challenges.

### Evolution of Atlantic salmon fisheries and management

Catches of salmon in the North Atlantic reflect variously the evolution of fishery types, the abundance of salmon, and also the impact of management measures. Nominal (declared) catches during the past 40+ years show an increase to a peak of around 12 000 t annually in the 1960s and 1970s (Figure 1). The increase mainly reflected the development of driftnetting in coastal waters, particularly in European countries, together with the emergence of a large-scale driftnet fishery at West Greenland, which exploited non-maturing 1SW fish from North America and mainly southern Europe. The Faeroese longline fishery also developed during the 1970s, taking mainly non-maturing 1SW fish from northern European countries. Total catches were in steep decline during the 1980s and 1990s.

It was in response to the development of the high seas fisheries in the 1970s and the decline in abundance of salmon in homewaters that NASCO was set up in 1984 by international convention (the Convention for the Conservation of Salmon in the North Atlantic Ocean). The primary management objective of NASCO is: (i) to contribute through consultation and cooperation to the conservation, restoration, enhancement, and rational management of salmon stocks, taking into account the best scientific advice available (NASCO CNL31.210).

NASCO fulfils its responsibility for management of distant-water fisheries for wild salmon at West Greenland and the Faeroe Islands through management measures derived from catch advice commissioned from ICES. While sovereign states retained their role in the regulation of salmon fisheries in national homewaters, distant-water salmon fisheries, such as those at Greenland and the Faeroe Islands, which take salmon originating from rivers of another Party, were regulated by NASCO under the terms of the Convention. NASCO now has seven Parties that are signatories to the Convention, including the European Union, which represents its Member States.

In the 1980s, reducing stock abundance began to impact catches seriously, and more recently catches declined further as a result of management measures introduced to conserve stocks (O’Connell et al., 1992). The latter have
included various compensatory non-fishing schemes in the distant-water fisheries, progressive moratoria, buy-outs and closures of commercial homewater salmon fisheries in some countries, together with restrictions on rod fisheries in many rivers (ICES, 2003). Since the adoption of the Convention for the Conservation of Salmon in the North Atlantic Ocean, the distant-water fisheries at West Greenland and the Faeroes have been regulated by internationally negotiated quotas, which have been greatly reduced and in some recent years have not been fished, because of locally negotiated arrangements with interested parties. Current arrangements for the West Greenland fishery allow for a local subsistence fishery of ca. 20 t (NASCO, 2003).

In Europe, as stock status declined, most countries took measures to close or restrict coastal fisheries, including closure of the Norwegian drift net fishery in 1989 (Jensen et al., 1999), and progressive restrictions (mainly effort) on coastal netting in most countries of the European Union. Buy-out schemes have been used to reduce coastal net fisheries in several European countries, including the UK (both England and Wales, and Northern Ireland). In North America, almost all coastal netting has now ceased, save for aboriginal/resident’s food fisheries in some areas of Canada, and recreational fishing is restricted in many rivers where conservation requirements are not being met (CSAS, 2002; DFO, 2003). In the USA, there are currently no fisheries for sea-run Atlantic salmon, as a result of angling closures in 1999. Two population segments in North America have been listed as Endangered by their respective national legislation; one listing consists of 8 rivers in Maine, USA (Maine Distinct Population Segment), and the other consists of 33 rivers in the inner Bay of Fundy, Canada. In rod fisheries for Atlantic salmon, the practice of catch and release (hook and release) has become increasingly common as a conservation measure in the light of decreasing stock abundance, though there is debate as to its effectiveness as a conservation measure (Aas et al., 2002; Dempson et al., 2002). While there are large differences between and within countries on implementation of catch and release, and some cases are not recorded, information available suggests that in 2003, almost 127 000 salmon caught in rod fisheries were released alive (ICES, 2004).

The overall provisional nominal catch of salmon in the North Atlantic in 2003 was 2461 t, with a further 847 t estimated to be unreported (ICES, 2004). Although many fisheries for Atlantic salmon have been restricted or closed, substantial commercial and recreational fisheries still operate in several European countries (Table 1), and

<table>
<thead>
<tr>
<th>Country</th>
<th>Coastal catch (t)</th>
<th>Estuarine catch (t)</th>
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</thead>
<tbody>
<tr>
<td>France</td>
<td>0.5</td>
<td>4</td>
</tr>
<tr>
<td>Ireland</td>
<td>468</td>
<td>90</td>
</tr>
<tr>
<td>Norway</td>
<td>598</td>
<td>0</td>
</tr>
<tr>
<td>Russia</td>
<td>60</td>
<td>3</td>
</tr>
<tr>
<td>Sweden</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>UK (England and Wales)</td>
<td>107</td>
<td>25</td>
</tr>
<tr>
<td>UK (N. Ireland)</td>
<td>45</td>
<td>14</td>
</tr>
<tr>
<td>UK (Scotland)</td>
<td>65</td>
<td>22</td>
</tr>
</tbody>
</table>

Table 1. Average nominal catches, 1999–2003, for coastal and estuarine salmon fisheries in European countries (after ICES, 2004). In-river catches are excluded.
current management of those fisheries is increasingly reflecting attempts to match exploitation to stock status at local, regional, and international scales (ICES, 2004).

Development of catch advice in a precautionary framework

In accordance with the growing trend worldwide to develop conservation-orientated policies that seek to implement a precautionary approach to fisheries management, NASCO adopted the Agreement on the Adoption of the Precautionary Approach for Atlantic salmon conservation, management, and exploitation (NASCO, 1998). NASCO has set up the Standing Committee on the Precautionary Approach (SCPA; NASCO, 2000), consisting of managers and scientists tasked with incorporating the precautionary approach into salmon management within its jurisdiction. The SCPA is working across all possible areas in which the precautionary approach will have an impact on management of salmon stocks, including habitat conservation and restoration (NASCO, 2001) and socio-economic aspects of salmon fisheries (NASCO, 2002). It is also facilitating dialogue between managers and scientists about how much risk managers are prepared to accept in the management of salmon stocks.

While there is no single accepted definition or set of guidelines for the implementation of the precautionary principle (CEC, 2000) it generally implies that (i) management decisions corresponding to critical states of the system must be pre-agreed, (ii) key indicators must be identified to monitor the state of the fishery in terms of spawning stock size, fishing pressure, and critical habitats, and (iii) biological reference points (BRPs), related to these indicators, must be determined (Garcia, 2000).

Consideration of uncertainty in stock size and productivity is intimately linked to precautionary management and risk (Kirkwood and Smith, 1996; Gabriel and Mace, 1999), i.e. more uncertain situations require more biologically conservative measures in setting management regulations (Rosenberg and Restrepo, 1996). There is increased pressure on scientists to utilize all the information available, regardless of imperfections, to develop BRPs, to evaluate management options, and to account explicitly for the sources of uncertainty (Potter, 2001). Kirkwood and Smith (1996) suggest that a management strategy should be evaluated, both in terms of meeting the management objectives and the degrees of precaution, by identifying performance criteria. A key step in identifying such criteria, and in order to develop fishery control policies, is to establish both target and limit BRPs (Kirkwood and Smith, 1996).

Development of BRPs

A number of possible BRPs may be derived from a stock-recruitment (SR) relationship, and these can be used to identify safe biological limits for exploitation of salmon stocks (Potter, 2001). The definition of safe biological limits originally developed by ICES with respect to Atlantic salmon and adopted by NASCO, is the level of stock that will achieve long-term maximum sustainable yield (MSY) to fisheries ($S_{MSY}$ or $S_{opt}$; ICES, 1993). Accordingly, the spawning stock at the MSY point on an adult-to-adult Atlantic salmon SR relationship was adopted as the conservation limit (CL).

Although the setting of age-specific conservation limits for individual river stocks is the central theme of the developing approach to international salmon management, a CL only represents the number of fish actually required to spawn in order to achieve long-term average MSY for a stock. ICES (2002) has recently stressed that a CL should be used as a limit reference point, rather than a target reference point, making it clear that a CL is a point below which stocks ideally should not fall, rather than a target to aim at. Accordingly, ICES have begun to refer to $S_{lim}$, which (in the form $B_{lim}$) is used widely for stock assessments in marine species, but in the case of salmon, the limit (which is still at $S_{MSY}$) refers to numbers of spawning fish rather than biomass, because conservation limits for salmon are usually stated in terms of numbers of fish (or eggs).

In accordance with the precautionary approach, the uncertainty in the estimates of limit reference points should be taken into account. In management of marine fish stocks, ICES attempts this by setting a precautionary reference point ($B_{pa}$), which is higher than $B_{lim}$, so forming a “precautionary buffer”. The precautionary reference point acts as a threshold to ensure sustainability by maintaining a low risk of recruitment decline or collapse. The setting of such specific risk levels in terms of reference points is not present in Atlantic salmon management, and it is currently up to managers to decide on an acceptable level of risk for stocks falling below $S_{lim}$. However, Atlantic salmon conservation limits are more conservative than the limit reference points proposed by NAFO (1997) and ICES (1999) for marine fish species, thereby accounting for some degree of uncertainty.

NASCO states that stocks should be maintained above the conservation limits by the use of management targets. These should be set relative to the conservation limits, on the basis of the risks of not achieving the management objectives. The management target must therefore take account of uncertainties in the data used to set conservation limits and the ability to manage fisheries to achieve the required number of spawning fish in each stock. Whereas conservation limits are usually derived from biological (stock dynamic) data, management targets can encompass socio-economic as well as purely biological considerations (such as the need to protect a genetically valuable, or a numerically vulnerable, stock). A management target can be regarded as a target reference point (i.e. a stock level to aim for, in order to achieve the management objectives). To
date, no detailed methods for setting management targets for Atlantic salmon have been proposed, and no target reference points have been identified for Atlantic salmon (with the possible exception of one river in Canada).

While NASCO’s remit in distant-water fisheries clearly requires an international approach, the use of conservation limits at national, regional, and local levels is also highly important. At these levels, data on compliance with conservation limits for individual rivers or groups of rivers provides important information on the status of stocks. These data are in some cases already being used to manage fisheries at regional and local levels, and this is likely to increase, as more river-specific conservation limits are set. The use of conservation limits is now generally accepted as providing the most viable and objective means of providing management advice for salmon at all levels, from river stocks through to stock complexes.

### Management procedures currently applied to Atlantic salmon fisheries: limitations and progress

Biological Reference Points are performance standards of the management regime that serve as triggers for management actions or are parameters in harvest control rules (Gabriel and Mace, 1999). In a precautionary context, the choice of a limit reference point is arguably of secondary importance to the choice of the associated harvest strategy (Gabriel and Mace, 1999). However, harvest strategies are framed in terms of the BRPs, and the choice of strategy will thus depend in part on the selected BRPs (Caddy and Mahon, 1995).

A harvest strategy is a pre-agreed plan stating how the catch taken from the stock will be adjusted depending on the size of the stock, the economic or social conditions of the fishery, and the uncertainty regarding biological knowledge (Hilborn and Walters, 1992). Harvest strategies may include fixed catch, fixed harvest rate, fixed escapement, or floor strategies (for a review, see Potter et al., 2003). The actual choice of the harvest strategy should be agreed by the managers and resource users, while the scientist should perform a technical role in evaluating the risks or likely outcomes of alternative harvest strategies. Fisheries management objectives may be achieved by measures of input controls (restrictions on the amount of fishing effort) or output controls (limitation on catches), framed within a particular harvest strategy.

The choice of harvesting strategy generally involves trade-offs between average yield and variability of yield (Hilborn and Walters, 1992). Lande et al. (1997) suggest that the risks of stock depletion must also be considered and, with this consideration, threshold harvesting strategies (floor strategies) are optimal especially under conditions of uncertainty in stock dynamics and fisheries behaviour. There may be practical difficulties in managing fisheries to respect the threshold when returns are expected to be just above the threshold escapement level.

Management of salmon exploitation ideally should take account of the different requirements of commercial and recreational fisheries. Many fisheries operate to provide all or part of the livelihood of the operators, the profit being derived entirely from the catch. For such fisheries, it may be preferable to limit catches by allowing fishers to operate efficiently (e.g. with sufficient nets), but only for short periods. This may not be ideal biologically, because it can result in selection for particular stock components. Maintaining rod fisheries, however, may not depend upon killing fish, because the value of the fishery is related more to the provision of good catches as part of an overall angling experience. Therefore, there may be a greater need to allow fishers the opportunity to fish, even if the number of salmon they can kill is greatly limited. For example, it might be appropriate to permit rod-fishing to continue when stocks are close to or below CL as long as they employ compulsory catch and release, because post-release mortality is believed to be minimal. Therefore, a range of alternative strategies must be considered for different types of fisheries.

However, given the overriding need to protect spawning escapement for the many hundreds of individual salmon stocks across the North Atlantic range, ICES and NASCO have therefore tended to favour a fixed escapement strategy.

In practice, the fixed escapement strategy chosen as the underlying strategy for Atlantic salmon is being implemented in a variety of ways, with, in some cases, approaches similar to floor policies or proportional threshold harvesting being used. For example, in the West Greenland fishery, variable annual quotas have been set, based upon an exploitable quantity of fish above the conservation requirement, but allocated proportionally to West Greenland and North America (NASCO, 1993). In homewater fisheries, several approaches are evident, ranging from variable annual quotas to effort control. Examples are given below, together with comments on whether the strategies being employed and the advice provided are compatible with the precautionary approach, and where further developments are needed or are under way.

### Distant-water mixed stock fisheries

#### West Greenland fishery

This fishery mainly exploits non-maturing 1SW salmon from the North American and southern European areas. As a result of regulatory measures, responding to declines in stock status, catches in this fishery have fallen considerably from >1000 t in the early 1980s to a subsistence level of around 20 t in the most recent two years (ICES, 2004). Although it is a small fishery, compared with historical levels, many of the stocks potentially exploited are of poor

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**References:**

status, while in overall terms both stock complexes contributing to the fishery are outside safe biological limits, as defined by ICES (ICES, 2004). Annual regulatory measures for this fishery are required under the NASCO Convention. Of central interest, given the theme of the present paper, is that catch advice for the West Greenland fishery is provided in a risk analysis framework, which incorporates the uncertainty in all the factors used to develop the catch options based on a fixed escapement strategy (Figure 2). The development of the catch advice considers the consequences to the objective of meeting conservation limits in the rivers of North America of catching different quantities of fish at West Greenland.

The pre-fishery abundance (PFA) for both North American and Northeast Atlantic (NEAC) origin salmon is derived using catch-based backward reconstruction using observations (returns, harvests) of the age group of interest at different times, adjusted for natural mortality (Potter and Dunkley, 1993; Rago et al., 1993). Models for forecasting the PFA of North American origin salmon in the year of the fishery have been based on an index of thermal habitat in the northwest Atlantic, and spawning stock indices. The thermal habitat variable was developed from studies implying that salmon stocks over wide geographic areas may have synchronous survival rates, and that the winter period may be the critical stage for post-smolt survival and maturation (Friedland et al., 1993). A recent analysis of the sequence of PFA and lagged spawner levels for North America suggested two states of Atlantic salmon production, with a transition period from 1988 to 1990 (ICES, 2003). This dynamic indicates that mortality of salmon between the spawner and PFA recruit stage changed in the last 15 years, and that the previously used thermal habitat variable has become non-informative. This reformulated model, which includes the phase change and spawner indices, has been used subsequently to derive PFA forecasts for the North American stock complex at West Greenland (ICES, 2004).

For a level of fishery under consideration, the weight of the catch is converted to fish of each continent’s origin, and subtracted from one of the simulated forecast values of PFA. The number of fish of North American or European origin in a given catch (t) is conditioned by the continent of origin of the fish (propNa, propE), by the average weight of fish in the fishery (Wt1SWNA, Wt1SWE), and a correction factor by weight for the other age groups in the fishery (ACF), based upon historic sampling (Figure 2). After the fishery, fish returning to homewaters are discounted for natural mortality from the time they leave West Greenland to the time they return to rivers, a total of 11 months at a rate of M = 0.03 (equating to 28.1% mortality). The fish that survive to homewaters are then distributed among the regions, and estimates of the total fish escaping to each region are compared with the region’s 2SW spawning requirements.

North America is divided into six stock areas that correspond to the areas used to estimate returns and

Figure 2. Flowchart of risk analysis of catch options at West Greenland using the PFA<sub>NA</sub> and the PFA<sub>NEAC</sub> predictions for the year of the fishery. Inputs with solid borders are considered known without error. Inputs with dashed borders are estimated, and contain observation error that is incorporated in the analysis. Solid arrows are functions that introduce or transfer without error, and dashed arrows transfer errors through the analysis. For definitions of the parameters used, see text.
spawning escapements, and which reflect phenotypic characteristics of the stocks in North America. Under an assumption of recruitment in direct proportion to the spawner requirement from all stock areas, just over 172,000 fish would need to escape to North America as 2SW spawners to achieve the spawner requirement simultaneously in all six stock areas at a 50% probability level. This value is higher than the point estimate for the North American stock complex, because it includes the annual variation in proportion female, and the objective to have sufficient escapement in six stock areas simultaneously.

The spawning requirement used for North America is for the continent as a whole, and does not reflect differences in the expected returns to the six regions. Hence, even if 172,000 2SW salmon reached the coast of North America, there would likely be severe under-escapement in some regions, because recruitment varies considerably in relation to spawner requirements.

The final step in the risk analysis involves comparing the conservation requirement or management objectives with the probability distribution of the returns to North America for different catch options. Estimated returns to each region were compared with the conservation objectives of the four northern regions of North American (Labrador, Newfoundland, Quebec, and Gulf) and to an alternative objective of achieving a 10% or a 25% increase relative to average land, Quebec, and Gulf) and to an alternative objective of achieving a 10% or a 25% increase relative to average land, Quebec, and Gulf) and to an alternative objective of achieving a 10% or a 25% increase relative to average land.

The spawning requirement from all stock areas, just over 172,000, was incorporated into a risk framework in a manner similar to that for West Greenland. While a sharing agreement for any surplus identified has not yet been negotiated, the historical breakdown of catches in earlier years suggests that it has been around 40:60, Faeroes:Europe (ICES, 2003).

Homewater marine fisheries

While the development of catch advice for the distant-water mixed stock fisheries, particularly at West Greenland, has tended to proceed along the lines of integrated assessment incorporating a risk analysis framework, the same is generally not the case in many homewater fisheries around the North Atlantic. In practice, several approaches have evolved continuously over the past decade or so, until recently, quantitative catch advice for this fishery was based on North American stocks alone, because no prediction of the PFA was available for European stocks present at West Greenland. However, a model to predict the PFA of southern NEAC stocks at West Greenland has recently been developed arising from the SALMODEL project (Crozier et al., 2003), and this prediction was incorporated into the catch advice process for the first time in 2003 (ICES, 2003), via a similar risk framework (Figure 2).

Further developments to enhance catch advice for this fishery are being considered, including refining genetic analysis of continent of origin, to investigate finer scale resolution, including region or population levels. Further, development of PFA prediction models to reflect changes in status of production and survival is also needed. For example, the incorporation of a phase change into the model to predict the PFA for the southern European stock complex may be considered, because there is evidence that such changes in production are not restricted to North America.

Faeroese mixed stock fishery

Development of predictions of PFA of southern European stocks contributing fish to the West Greenland fishery has been paralleled by studies to predict the PFA of the northern European stock complex, as required if quantitative catch advice is to be given for the Faeroes fishery (Crozier et al., 2003; Potter et al., 2003). A similar modelling approach, using differing marine habitat variables and estimates of stock based on maturing 1SW fish from each cohort, is testing the potential to provide these predictions. If successful, this and other outputs will be incorporated into a risk framework in a manner similar to that for West Greenland. While a sharing agreement for any surplus identified has not yet been negotiated, the historical breakdown of catches in earlier years suggests that it has been around 40:60, Faeroes:Europe (ICES, 2003).

UK (England and Wales)

The use of conservation limits in England and Wales has developed in line with the requirements of ICES and NASCO, to set criteria against which to give advice on stock status and the need for management action. Conservation limits are set for all principal salmon rivers, and these then provide the basis for the application of
a harvest strategy akin to a floor policy; fishing is permitted if the spawning escapement has remained above its CL and is controlled by effort restrictions, thus imposing a roughly constant exploitation rate. However, when stocks fall below the CL, this does not usually result in immediate closure of the fishery; rather, further controls on fishing effort are introduced to permit the stock to return to a more satisfactory level. Differences in the status of stocks or stock components (e.g. sea age groups) are catered for on a qualitative basis, by applying management controls, which provide greater protection to the more depleted stocks or stock components. In recent years, mixed stock fisheries in many areas have been subject to progressive phase-out schemes. For example, in the mixed stock fisheries on the northeast coast of England, only 16 driftnet licences were issued in 2003, down by 77% from the 69 in 2002.

The management objective in England and Wales is to ensure that spawning stocks remain above their conservation limits for at least four years out of five. Compliance with this objective is assessed in three-year blocks (i.e. average over three years), based upon rules relating to “episodes” (periods of years) when the escapement falls below the CL (Environment Agency, 1998). Compliance fails if an episode lasts longer than two years, or if the gap between episodes does not exceed two years. A river would remain a “compliance failure” until a reassessment, for a subsequent three-year period, showed a pass. Compliance failure cannot distinguish between real deterioration in egg deposition and a chance (1 year in 20) false alarm, so the circumstances have to be investigated to determine which was the more likely explanation, so that corrective action can be taken if necessary. This compliance assessment is currently being reviewed to permit comparable annual assessments for all stocks. Furthermore, management targets are now being developed for each river stock, in order to assist managers in introducing new controls on fisheries.

Ireland

The Irish salmon fishery accounts for approximately 20% of the total declared landings of North Atlantic salmon (ICES, 2003). In 2002, management of Ireland’s commercial salmon fishery switched from effort limitation only (i.e. regulations covering season length, gear type, licence numbers, etc.) to a fixed escapement strategy applied by means of effort limitation and additional catch controls. The “fixed-escapement” advised by scientists is the aggregated district spawning stock providing Maximum Sustainable Yield (MSY), referred to as the District CL ($S_{\text{lim}}$). From 2001 to 2003, these District conservation limits were derived from a model currently used to estimate national conservation limits ($S_{\text{lim}}$) for each of the Northeast Atlantic salmon-producing countries (Potter et al., 1998; ICES, 2003).

A new methodology, using Bayesian Hierarchical Stock and Recruitment analyses (BHSRA, Prévost et al., 2003) was introduced for 2004, where SR parameters from 15 well-studied European monitored rivers were “transported” to rivers where long-term SR data sets were not available. Riverine wetted area accessible to salmon and latitude for all salmon rivers in Ireland (McGinnity et al., 2003) were introduced as covariates explaining variations in the SR-derived parameters between rivers. The predicted individual river conservation limits were then aggregated at district level to provide District conservation limits, or $S_{\text{lim}}$.

For each of Ireland’s 17 salmon-fishing districts, data are available on reported catch, unreported catch, and exploitation rates. These data allow the application of a model used by ICES to estimate the PFA for each of the Northeast Atlantic salmon-producing countries (Potter et al. 1998; ICES, 2003). The main output from this model for use in Irish fisheries management (Ó Maoléidigh et al., 2001a, b) is an estimate of the PFA for each district since 1971. The average PFA for a baseline period starting from 1997 is adjusted to take account of survival from the high seas to homewater return, so providing a measure of the total number of fish available prior to the fishery taking place. In order to provide precautionary catch advice for each district, the exploitable surplus is estimated by subtracting the District $S_{\text{lim}}$ (spawning requirement) from the total number of fish available. The management plans are premised on the following conditions (or harvest rules) for the fisheries: (i) Where an exploitable surplus exists and is more than equal to the average catch for the baseline period, the catch should be maintained at the average catch for the baseline period. In following a precautionary approach, increases over the 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. (ii) Where the exploitable surplus is less than the average catch for the baseline period, the catch should not exceed the exploitable surplus. (iii) Where there is no exploitable surplus or where the total returns are less than the $S_{\text{lim}}$, there should be no catch or the fishery should be severely restricted while stock rebuilding takes place.

The final commercial TACs for each district are then decided following consultation with the state and semi-state agencies involved with salmon management, the National Salmon Commission (representing the interests of the state and fishing industry), and fishers and fishing organizations. These negotiations take account of the socio-economic as well as the biological concerns of the fisheries. Management and enforcement of district TACs has been greatly facilitated by the instigation of a salmon carcass tagging and logbook scheme for all fishing methods. Commercial fishers are allocated commercial fishing tags based on their recent catch history, whereas anglers are restricted to a set number of tags for the season. The sum of the carcass tags allocated should not exceed the TAC allocated in that district. The fishers are obliged to record details of their catch in an official logbook, which is returned at the end of the season. These data are entered on a national database.
and a full report of the fishery is provided at the end of each season.

UK (Northern Ireland)
In Northern Ireland, management measures in coastal fisheries have consisted of mainly effort controls achieved through specified close seasons, weekly close periods and number and type of licences issued. Recently, additional effort restrictions have been introduced in the Fishery Conservancy Board (FCB) area, in response to scientific advice on the status of local salmon stocks. In all, 32 coastal salmon nets were licensed to fish in the FCB area, comprising driftnets, and tidal and fixed bag nets. Managers reached agreement with the licence-holders for voluntary restrictions on fishing in 2001, with 23 licences being issued, though not all of these were fished. This preceded a private: public sponsored buy-out of this fishery, starting in 2002, when only 14 licences were issued, the remainder having being bought out.

Data on exploitation of returning wild River Bush salmon in fisheries in the FCB area and elsewhere around Ireland (ICES, 2003) indicate that overall exploitation of this mainly ISW stock in Irish/Northern Irish coastal and estuarine fisheries averages around 60%. Using the methods of apportioning coastal exploitation given in Crozier and Kennedy (1994), the proportion of this exploitation occurring in the FCB area averages 0.72, whereas that in coastal fisheries outside the FCB area averages 0.28. The coastal fisheries in adjacent fishery districts thus effectively act as interceptory fisheries for salmon returning to the FCB area rivers, and in some cases act sequentially, fish having to pass through these districts before reaching the FCB district. This pattern of exploitation clearly will restrict the impact of any management measures taken solely in the FCB area.

Preliminary evaluation of the impact of these actions taken in 2000/2001 indicates that declared catches in the FCB area fell from around 11,000 fish to <4000 fish in the two-year period. However, data from the River Bush tagging programme show that, although catch has fallen substantially in the local FCB area, overall exploitation of the monitored River Bush stock in Irish coastal waters remained close to the long-term average in 2002. Analysis of catch returns from fishery districts outside the FCB area provides an explanation, catches in the immediately adjacent Foyle area increasing considerably in 2002 (40,768) compared with 2001 (22,976). In this case, the increase was particularly evident in driftnet catches, which would be expected to have the greatest impact on fish moving through coastal waters to other districts. Therefore, in the case of homewater fisheries around Ireland, management decisions taken to protect stock status in one area can be impacted by events in fisheries in other areas. The number, location, and method of operation of these coastal fisheries make it difficult to regulate fisheries in one district to ensure conservation in stocks in that district, especially when variability of catches within and between seasons is considered. This task would become more manageable if fishing were to become restricted to inshore locations only, with stocks ideally being managed on a river-by-river basis.

Accounting for population structure in mixed stock fisheries
Within a mixed stock fishery, the identification of the origin and composition of the exploited resource is important for responsible management of the shared resource, especially where some stocks are at low status or even listed as endangered. Fitness and productivity may be compromised, if important genetic units of Atlantic salmon are not recognized. Genetic consequences of harvesting need to be assessed both at the level of local (sub) populations and at the level of the total population (Tufto and Hindar, 2003).

In the case of continent of origin of fish caught at West Greenland, biological analysis of scale structures verified by DNA analysis has been used to distinguish North American from European stocks in the catches, but only at a continental level to date. Recent analyses have indicated the potential for identifying stock complexes at a finer level of resolution than continent (Spidle et al., 2003). In one particular example (ICES, 2003), this technique was used to identify fish from the Maine Distinct Population Segment (DPS) occurring in the fishery, and hence to determine how many fish from this DPS were being harvested in the fishery. Use of hypervariable DNA markers can in theory be used to distinguish any population group from another, provided that there is a positive correlation between genetic and geographic distance and that a sufficient number of unlinked loci are studied. However, it remains to be seen how well these techniques can distinguish between the many populations contributing to the distant-water mixed stock fisheries. The composition of the reference data sets greatly affects the accuracy of assignment, and current reference data sets are deficient in this regard.

The identification of stocks and stock complexes contributing to the Faeroese fishery presents additional difficulties, because there are many more stocks represented there, with most if not all NEAC countries contributing to the fishery. Recent preliminary studies indicate some degree of detectable genetic structuring within and between northern and southern European stock complexes that may allow assignment at finer levels (Crozier et al., 2003).

While identifying stock composition of the distant-water mixed stock fisheries presents particular challenges, application of similar stock identification techniques to coastal mixed stock fisheries in homewaters, where many fewer stocks are taken, may be more feasible. For example, in the UK (Northern Ireland), analysis of genetic variation at microsatellite loci in baseline samples from river populations and a mixed stock fishery in the Foyle area is used to identify river populations contributing to the fishery
(Crozier and Booth, 2003). Analysis of the stock composition of the mixed stock fishery in the estuary and coastal waters from a test year, using both traditional conditional maximum likelihood estimation (CMLE) techniques (Milner et al., 1985), and a new Bayesian approach (Pella and Masuda, 2001), have indicated that the fishery mainly exploits populations from several areas of the Foyle system of rivers, while other areas are under-represented in catches (Figure 3). Results of this analysis may enable managers to regulate the fishery to achieve conservation in all stocks and to identify where specific action is needed to restore production in vulnerable or under-producing stocks.

Recent insights into the structure of river stocks indicates that in-river fisheries might also be considered as mixed stock fisheries because they are likely to be exploiting salmon from different populations. Much of the evidence for in-river stock structure comes from radio-tracking studies (Laughton and Smith, 1992; Walker and Walker, 1992; Webb, 1992, 1998; Smith and Johnstone, 1996; Smith et al., 1998), in which it has been demonstrated that salmon returning to freshwater at different times of the year generally home to spatially discrete spawning locations. The run-timing characteristic is a heritable attribute (Stewart et al., 2002). Furthermore, field observations have indicated that population units can exist over spatial scales of ca. 10 km (Youngson et al., 1994). Therefore, it is possible that many Atlantic salmon rivers will consist of more than one salmon population, each of which might ideally be treated as a discrete management unit. However, this is clearly impractical, and population units need to be grouped in some convenient way for management purposes. Straying of salmon will potentially complicate assignment of groups of fish to management units (Jonsson et al., 2003). One potential criterion for grouping populations is to consider those showing similar abundance trends as a single management unit (Youngson et al., 2002). Progress has been made with this approach, and it has been demonstrated that different run-timing groups exhibit different abundance trends that ultimately contribute to the overall variability in abundance observed in many salmon stocks.

For example, in the UK (Scotland), a two-stage process is being developed (Potter et al., 2003). First, rod catches, or abundance indices derived from catches, at sub-catchment scales will be compared with reference catch levels, established from periods when stocks were judged to be at satisfactory status. Where current catch falls below the reference point, juvenile electro-fishing surveys will be undertaken to identify the severity of the reduced spawner abundance. Depending on the outcome and the possible reasons identified for the reductions, management policies can be targeted at the local level, within the sub-catchment itself (say habitat), or on the fishery that exploits that population component.

**Conservation and rebuilding considerations for mixed stock fisheries**

The mixed stock nature of many North Atlantic salmon fisheries poses significant problems because there are more than 1500 European rivers and more than 600 North American rivers with highly variable stock status, most of which are unknown. Individual rivers are considered to contain discrete stocks in magnitudes of 100s or 1000s of fish per stock, rather than millions. The aim of management is to regulate catches while achieving overall spawning...
escapement reflecting the spawner limits in the large number of generally small North American and European rivers (ICES, 2003). In addition, stocks differ in biological characteristics (especially size and fecundity), in status, and in productivity (Prévost et al., 2003). Low-productivity stocks are particularly vulnerable in mixed stock fishery situations (Hilborn, 1985; Chaput, 2003).

Acknowledging that conservation can only be achieved when production takes place in all the available habitat (or by all the spawning components in the river), the formulation of fisheries management advice should take account of the complexity of the mixed stock fishery being managed, and the number of distinct production areas that must be seeded. As the number of these areas increases, the required number of fish that should be released from the fisheries must also increase (Chaput, 2003). Increasing the regional spawner requirement (implying smaller permitted catches) 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 low-productivity stocks. These considerations clearly become critical when considering mixed stock fisheries that exploit stocks already well below CL, especially if those stocks are of low productivity.

With many salmon stocks around the North Atlantic currently below CL, and in some cases threatened or endangered, managers are beginning to place emphasis on seeking catch advice in terms of rebuilding objectives for particular stocks or groups of stocks. In 2003, ICES considered the provision of long-term projections for stock rebuilding, focusing on trajectories for restoring stocks to target levels above CL (ICES, 2003). Trajectories for stock rebuilding depend on many parameters that are not known with certainty, or that may change over time. Stock—recruitment curves representing highly productive stocks through low-productivity stocks were applied to a forward-projecting stochastic framework that could produce recovery trajectories for a variety of states and exploitations. The purpose of this exercise was to estimate recovery times and the frequency of achieving conservation over a 50-year time frame under a range of exploitation rates for stocks of differing productivity.

As outlined in ICES (2003), parameters for Ricker stock and recruitment functions were obtained from Crozier et al. (2003), for the rivers Bush, North Esk, and Nivelle, and exploitation rate and recruitment at optimum spawning stock were used to obtain the parameters alpha (α—productivity) and beta (β) for the Ricker stock—recruitment relationship. Starting spawning stock sizes were 10% and 50% of S\text{lim}. Projections were run with exploitation rates of 0% (no exploitation), 50% of the current exploitation, current exploitation rate, and an exploitation rate at optimum spawning stock. Forward simulations were run 10,000 times in an @Risk framework in Excel, and the aggregated output was collected to produce a trajectory with mean and variance for each year. The number of years required to rebuild to S\text{lim}, as well as the number of years during the 50-year projection below the S\text{lim}, were recorded for each simulation.

One of the key findings from this analysis was that the number of years to recovery was unobtainable in 50-year projections in a low-productivity river, and possibly unobtainable in a moderate productivity river, because the recovery time in years was more dependent on the productivity than the start point. The time to recovery, and the proportion of annual recruitment less than the S\text{lim}, increased with lower productivity and the starting point (Figure 4). Recovery was particularly sensitive to increasing exploitation at lower alpha. In order to incorporate these approaches into catch advice on specific stocks, more complex approaches will be needed, because many factors additional to stock productivity and exploitation will influence rates of recovery.

![Figure 4](https://example.com/figure4.png)
ICES concluded that there was an increased probability of not achieving $S_{\text{lim}}$ with increased exploitation and lower alpha, and suggested that increased caution is needed when considering exploitation of low-productivity stocks. It also suggested that current management strategies for mixed stock fisheries are likely to fail to protect “the weakest link”, i.e. those stocks that are far below their $S_{\text{lim}}$ and which are of low productivity.

The alternative, restocking programmes, may also be confounded by poor marine survival, and high or variable exploitation rates, and even negative interactions between hatchery-reared fish and their wild counterparts (McGinnity et al., 1997) affect different stocks to different degrees. Rebuilding from low productivity or restoring extinct stocks appear to pose similar difficulties in both the Atlantic and Baltic areas, and in this regard the results from the theoretical approach outlined above are consistent with the actual outcome from ongoing stock-rebuilding programmes worldwide. This difficulty in rebuilding salmon stocks when stock levels fall below $S_{\text{lim}}$ is now recognized as one of the greatest challenges to salmon management, and lends considerable support to the adoption of the $S_{\text{lim}}$ (MSY) point as the most appropriate limit reference in the provision of advice for Atlantic salmon populations.

Discussion and conclusions

Although Atlantic salmon management is moving steadily towards almost universal application of reference points within the interpretation of the precautionary approach, there is a considerable debate on the validity of reference points for fishery management (e.g. Hilborn, 2002; Koeller, 2003). Hilborn (2002) highlights some of the perceived problems involved in application of reference points, including: (i) uncertainties in stock biomass, with changes in input data leading to sometimes manifold change in stock size assessments (reference points need measures of absolute abundance), (ii) inappropriateness of the reference points used in species from which they were not derived, (iii) inadequate treatment of uncertainty, (iv) use of reference points leads scientists to ignore other potential management policies, (v) trajectories for returning stocks to equilibrium are rarely considered, and (vi) obsession with reference points leads to displacement activity, precluding the investigation of more fundamental problems associated with management.

Some of these criticisms certainly apply also to Atlantic salmon, although stringent efforts are being made to address them. We have shown above that risk is taken into account in framing catch advice for mainly the distant-water mixed stock fisheries, increasingly so in homewater fisheries, where management targets are being developed and are addressing risks of not achieving conservation requirements. In contrast to most marine species, stock abundance is relatively well known in salmon, especially in monitored rivers. In addition, run-reconstruction techniques are used to estimate total stock size at critical points in the life cycle. This is based on catches and counts that, in many cases, form a large component of the abundance of the stocks to be assessed (e.g. up to 30%). In some cases, however, these estimates have relatively great uncertainty, especially when aggregated at stock-complex level, given that many of the stocks are not monitored.

Rosenberg (2002) notes that uncertainty is not generally well considered in management. However, this is demonstrably becoming a larger aspect of salmon science with, for example, treatment of uncertainty ranging from simple qualitative descriptions of uncertain areas, through Monte Carlo and Bayesian methods applied across various problems. The identification of appropriate limit reference points and associated emphasis on use of high probabilities of exceeding them (75% in some cases), are providing a conservative framework for management that is increasingly accepted by managers.

While reference points have come to the fore in Atlantic salmon management in the past few years, they have not prevented alternative methods of management being implemented. An example of data-based management, as favoured by Hilborn (2002), is the ad hoc management system implemented in 2002 at West Greenland, whereby in-season quotas were amended within a pre-agreed management framework, depending on in-season assessment of abundance, which was based on relationships between vessel catch rate and the PFA (ICES, 2002). This indicates that data-based systems can complement the use of reference points to derive management advice. Similarly, there are several examples from North America (e.g. Chaput et al., 2000), and one from Europe (R. Foyle, UK [Northern Ireland]) of management systems that use in-season abundance estimates to regulate fisheries in relation to reference-point-based management objectives for a river stock.

Finally, although SR data are only available for a small number of salmon populations relative to the total (e.g. 23 out of 1533 NEAC populations; Crozier et al., 2003), they do at least cover much of the range in productivity in the species, and are sufficient to have allowed salmon-specific reference points to be developed. In contrast to Hilborn’s view, salmon scientists would contend that application of reference points has in fact encouraged managers to look for reasons underlying salmon declines, because they have served to highlight just how far below safe biological limits many stocks are. The stock-rebuilding scenarios outlined in this paper also serve to reinforce the need for managers to adhere to limit reference points.

Rosenberg (2002) charts the progress of fishery management towards implementing the precautionary approach, and when compared against the points in his review, Atlantic salmon comes out demonstrably well. Interestingly, both Hilborn (2002) and Rosenberg (2002) agree that
management structures and process have a large role to play in implementing the precautionary approach. This is particularly relevant for Atlantic salmon, given the range of fisheries and jurisdictions across which we must manage stocks. Significant progress has been made, particularly through NASCO, in interpreting and implementing the precautionary approach to Atlantic salmon, not just in reference points, but in seeking to apply the precautionary approach to areas outside catch regulation, notably habitat issues, introductions, and transfers, and now consideration of socio-economic issues in the management process. The development of a decision structure by NASCO and contracting parties is not to be underestimated (NASCO, 2002), because this will drive scientists and managers to ask and to answer the right questions, and is designed to lead to pre-agreed management actions, or at least to explicitly justify management decisions.

We believe that we have demonstrated above that management of mixed stock salmon fisheries on the high seas and in homewater in Europe is developing along the lines of the precautionary approach, and that further developments are underway that should enhance ability to manage these fisheries. However, the mixed stock scenario cannot be regarded as ideal, because it often compromises the principle that individual river stocks should be maintained, with high probability, above their reference levels (Potter, 2001), and is usually only justifiable on socio-economic grounds. The impact of mixed stock fisheries can be greatest on the small stocks, especially if these are of low relative productivity. A particular challenge exists in the case of the West Greenland fishery, where so many stocks are potentially exploited, ranging from those that are endangered to those that are meeting their conservation requirements. In respect of this, ICES notes when giving guidance to those that are meeting their conservation requirements. In respect of this, ICES notes when giving guidance to those that are meeting their conservation requirements.

In contrast, the home water mixed stock fisheries that still operate in some European countries take rather fewer stocks, and it is more likely that stocks of similar productivity are being taken from these more localized areas. However, these fisheries still may take stocks of differing status with respect to conservation requirements. Additionally, the problems of sequential or simultaneous fishing still remain, and as shown here, the outcome of management decisions made in one fishery can be influenced by what happens in other fisheries. Ideally, most fisheries would be managed in a river-by-river basis, but there remains the issue in some or many river systems of taking into account the different stock components or populations that may be present, and that may have differing conservation requirements. With the advent of decision structures, modelling of trajectories for recovery of below-conservation stocks, and identification of the stocks contributing to fisheries, it may at least be possible to place management of many of the fisheries on a more precautionary basis than before.

As a final point, although we must continue to strive for improvements to catch advice and management systems for Atlantic salmon fisheries, and noting that mixed stock fisheries present particular challenges, there must be equal effort directed at understanding the reasons behind the causes of stock declines. These may include habitat loss and degradation, pollution, predation, climate change effects, and a myriad of other potential factors. It is doubtful if overexploitation has been the sole or even the main cause of driving stocks downwards, and although exploitation control is obviously part of the solution, we must continue to look elsewhere as well.

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