Managing Atlantic salmon in the mixed stock environment: Challenges and considerations.

W.W. Crozier, P-J. Schon, G. Chaput, E.C.E. Potter, N. Ó Maoiléidigh, J. MacLean

Atlantic salmon, as a result of their population structure and behavior, are potentially subject to a complex array of fisheries, ranging from coastal fisheries harvesting few to several stocks, to distant water mixed stock fisheries that harvest fish from different continents, stock complexes and countries. In addition, estuarine and in-river fisheries may take fish from more than one sub-population or stock component, where these are present. One of the main challenges therefore 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. Also the existence of sequential harvest in different fisheries provides unique challenges, as decisions in an individual fishery cannot be made in isolation of the impacts of other fishing 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.

Keywords: salmon, fisheries, stocks, harvest strategies, management.

W.W. Crozier: DARDNI, Agricultural and Environmental Sciences Division, Newforge Lane, Belfast BT9 5PX, United Kingdom [Tel +44 28 20731435, Fax +44 29 207 32130, e-mail: walter.crozier@dardni.gov.uk]; P-J Schon, Queen’s University of Belfast, School of Agriculture and Food Science, Newforge Lane, Belfast BT9 5PX, United Kingdom; G. Chaput, Department of Fisheries & Oceans, PO Box5030, Moncton, NB E1C 9B6, Canada; E.C.E. Potter, CEFAS Laboratory, Pakefield Road, Lowestoft, Suffolk, United Kingdom, NR33 OHT; N. Ó Maoiléidigh, Marine Institute, Abbotstown, Castleknock, Dublin 15, Ireland; J. C. MacLean, FRS Field Station, 16 River Street, Montrose, Angus, DD10 8DL, United Kingdom.
Introduction

Atlantic salmon, as a result of their population structure and behaviour, are potentially subject to a complex array of fisheries, ranging from coastal fisheries harvesting few to several stocks, to distant water mixed stock fisheries that harvest fish from many stocks in different countries or even continents. In addition, estuarine and in-river fisheries that exploit principally a single river stock may still take fish from more than one population or stock component, where these are present.

The present paper summarises the management arrangements and fisheries for salmon in the North Atlantic, the application of the precautionary approach to salmon management and reviews harvest strategies that may potentially be employed. We then illustrate the uncertainties and complexities involved in managing mixed stocks of Atlantic 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.

Some of the issues raised and examples given in this and other Atlantic salmon papers presented at this theme session formed part of the work of the SALMODEL project (Crozier, et al. 2003). SALMODEL was initiated as a European Commission funded Concerted Action, in 2000, for a three-year period, with the overall aim 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 NASCO and within the requirement of sustainability (the core theme of Key Action V of the WU Fifth Framework)”.

Specific objectives were to:

- improve our ability to set salmon conservation limits (CLs); addressing transportability and dynamic change issues, also taking into account underlying stock structure, and;
- to examine methods of estimating pre-fishery abundance (PFA) for north-east Atlantic (NEAC) salmon stocks and to determine whether and how PFA estimates can be used to give catch advice.

Management arrangements for salmon in the North Atlantic

The North Atlantic Salmon Conservation Organisation (NASCO) was set up in 1984 by international convention (the Convention for the Conservation of Salmon in the North Atlantic Ocean), with a responsibility for the conservation, restoration, enhancement and rational management of wild salmon in the North Atlantic. While sovereign states retain their role in the regulation of salmon fisheries in national homewaters, distant water salmon fisheries, such as those at Greenland and Faroes, which take salmon originating from rivers of another Party are regulated by NASCO under the terms of the Convention. NASCO now has seven Parties that are signatories to the Convention, including the EU which represents its Member States.

NASCO discharges these responsibilities via three Commission areas shown in Fig. 1. NASCO (NASCO CNL31.210) has identified the primary management objective of that organisation as:
“To contribute through consultation and co-operation to the conservation, restoration, enhancement and rational management of salmon stocks taking into account the best scientific advice available”.

NASCO further stated that “the Agreement on the Adoption of a Precautionary Approach states that an objective for the management of salmon fisheries is to provide the diversity and abundance of salmon stocks” and NASCO’s Standing Committee on the Precautionary Approach interpreted this as being “to maintain both the productive capacity and diversity of salmon stocks”

NASCO commissions scientific advice on fisheries within its jurisdiction from the International Council for the Exploration of the Sea (ICES), annually, via a series of questions which provide terms of reference to the ICES Working Group on North Atlantic Salmon (WGNAS).

Atlantic salmon stocks and fisheries

Atlantic salmon occur naturally in over 2000 rivers from around latitude 43°N to latitude 70°N along the coasts bordering the N. Atlantic Ocean, giving a European range from Spain to Russia, and from Maine to Labrador in N. America. The anadromous life cycle of this species results in juveniles spending from one to six years in fresh water, followed by one (1SW) to two or more years at sea (MSW), before returning to natal rivers to spawn. This migratory habit results in many opportunities to fish for salmon, whether as fish overwintering on the high seas feeding grounds, on their return to coastal waters in the country of origin or in other countries during the return migration and 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 fishing techniques applied to Atlantic salmon. They range from drift netting and long lining in the distant water fisheries at West Greenland and Faroes, respectively, to use of various types of gilling, encircling and hand-held nets as well as traps operated in coastal and estuarine waters and also rods in freshwater fisheries.

The overall provisional nominal catch of Atlantic salmon in 2002 was 2,625t, with a further 1,039t estimated to be unreported (ICES, 2003).

Catch trends for salmon in the N. Atlantic reflect variously the evolution of fishery types, the abundance of salmon and also the impact of management measures. Data on nominal (declared) catches during the past 40+ years (Fig. 2), shows an increase to a peak of around 12,000t in the 1960’s –1970’s, mainly reflecting the development of drift netting in coastal waters in European countries in particular, together with the emergence of a large scale drift net fishery at West Greenland, which exploits non-maturing 1SW fish from N. America and (mainly southern) Europe, and where catches peaked at over 2,000t. Subsequently, the Faroes long line fishery developed, taking mainly non-maturing 1SW fish from northern European countries. Catches have been in steep decline during the 1980s and 1990s, initially as reducing stock abundance began to seriously impact catches and more recently reflecting management measures introduced to conserve stocks. The latter have included various compensated non-fishing schemes in the distant water fisheries, progressive moratoria, buyouts and
closures of commercial homewaters salmon fisheries in some countries, together with restrictions on rod fisheries in many rivers.

In North America, almost all coastal netting has now ceased, save for aboriginal/resident’s food fisheries in some areas of Canada, while rod fishing is restricted in many rivers where conservation requirements are currently not being met. In the USA, there are currently no fisheries for sea-running Atlantic salmon, as a result of angling closures in 1999, indeed, salmon in a group of rivers in Maine (Maine Distinct Population Segment) are collectively listed as Endangered. In Europe, as stock status has declined, most countries have take measures to close or restrict coastal fisheries, including closure of the Norwegian drift net fishery in 1989 and progressively (mainly effort) restrictions on coastal netting in most countries of the European Union. Buyout schemes for coastal net fisheries are active in several European countries, including UK (England & Wales) and UK (N. Ireland). Since the adoption of the Convention for the Conservation of Salmon in the North Atlantic Ocean, the distant waters fisheries at West Greenland and Faroes have been regulated by internationally negotiated quotas, which in some recent years have not been fished, due to locally negotiated arrangements with interested parties. Current arrangements for the West Greenland fishery allow for a local subsistence fishery of circa 20t (NASCO, 2003)

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. While there are large differences between and within countries on implementation of catch and release, and some cases are not recorded, information available to ICES suggests that in 2002 over 100,000 salmon were caught and released in rod fisheries.

Although many fisheries for Atlantic salmon have been restricted or closed, there are still substantial commercial and recreational fisheries operating in several countries, and current management of those fisheries is increasingly reflecting attempts to match exploitation to stock status at local regional and intentional scales (ICES, 2003). Although various conservation arrangements have been operating in the major distant water mixed stock fisheries, there remains a need to provide scientific stock status assessments and to recommend safe catch levels, against the possible ending of non-fishing agreements and/or increased pressure to resume fishing if stocks improve again.

One of the major challenges for management of Atlantic salmon is to take account of stock structure in management. As noted above, the life cycle of salmon results in migration of stocks to distant water feeding grounds and return to homewaters and then natal rivers to spawn, meaning that many of the fisheries take fish from more than one river stock. A large number of genetic studies over the past two decades have contributed to knowledge about the genetic population structure that has developed in Atlantic salmon following the last ice age. Atlantic salmon is highly genetically structured compared to 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 genetic differences between populations. A major genetic dichotomy exists between populations from either side of the North Atlantic Ocean and on the European side, between populations in Baltic and Atlantic drainages (Ståhl 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).
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, particularly where decisions relate to the distant water fisheries. Managers therefore have had to consider how populations or river stocks should be grouped, in particular in relation to the presentation of pre-fishery abundance (PFA) estimates and forecasts to managers. Such groups fall within the meaning of a stock as ‘an exploited or managed unit’ (Royce 1984) and are consistent with the ICES (1996) definition of salmon ‘stocks’ as ‘units of a size (encompassing one or more populations) which provide a practical basis for the fishery manager’. Thus, 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 hundred 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 neighboring countries. In addition, estuarine and in-river fisheries may take fish from more than one population or stock component, where these are present. One of the main challenges therefore 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. Also the existence of sequential harvest in various fisheries provides unique challenges, as 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 Labrador fishery, and subsequently in Canadian homewaters as they returned as maturing 2SW salmon and finally by rods in the natal river. In many cases, maturing 1SW components of these stocks would have also been taken in Canadian coastal fisheries and in home rivers.

The Precautionary Approach and biological reference points as applied to Atlantic salmon

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).

While there is no single accepted definition or set of guidelines for the implementation of the precautionary principle it generally implies that:

- management decisions corresponding to critical states of the system must be pre-agreed,
- key indicators must be identified to monitor the state of the fishery in terms of spawning stock size, fishing pressure and critical habitats, and
- 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). Kirkwood and Smith
sug gest 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).

A number of possible BRPs may be derived from a stock and recruitment (SR) relationship and these can be used to identify safe biological limits for exploitation of salmon stocks. The operating 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 ($S_{\text{MSY}}$ or $S_{\text{opt}}$) (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 CLs 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 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 $S_{\text{lim}}$, which (in the form $B_{\text{lim}}$) is used widely for stock assessments in marine species, but in the case of salmon, the limit (which is still at $S_{\text{MSY}}$) refers to numbers of spawning fish rather than biomass (ICES 2002), as conservation requirements for salmon are usually stated in terms of numbers of fish.

NASCO states that stocks should be maintained above the CLs by the use of management targets. These should be set relative to the CLs, 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 CLs and ability to manage fisheries to achieve the required number of spawning fish in each stock. While CLs 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).

As noted above, NASCO fulfils its responsibility for management of distant water fisheries for wild salmon at West Greenland and Faroes through management measures derived from catch advice commissioned from ICES. In order to provide catch advice, it is necessary to have information on the stocks contributing to these fisheries, together with indications of abundance in relation to CLs. In simple terms, the difference between numbers assessed to be present at sea prior to fishing (pre-fishery abundance (PFA)) and numbers to fulfil spawning requirements in home rivers (the CL) is potentially an exploitable surplus.

While NASCO’s remit in distant water fisheries clearly requires an international approach, the use of CLs at national, regional and local levels is also highly important. At these levels, data on compliance with CLs for individual rivers or groups of rivers provides important data on 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 CLs are set. The use of CLs is now generally accepted as providing
the most viable and objective means of providing management advice for salmon at all levels, from river through to stock-complexes.

NASCO has set up the Standing Committee on the Precautionary Approach (SCPA) (NASCO 2000), comprising 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 the all important dialogue between managers and scientists about how much risk managers are prepared to accept in the management of salmon stocks.

A review of potential harvest strategies for Atlantic salmon

Biological Reference Points are not equivalent to a fishery management regime or management objective, but should be viewed as 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 LRP is of secondary importance to the choice of the associated harvest strategy (set of pre-agreed rules) (Gabriel and Mace 1999). However, harvest strategies are framed in terms of the BRPs and the choice of strategy will thus depend largely on the selected BRPs (Caddy and Mahon 1995).

Management of fish populations consists of trade-offs between maintaining catch levels and maintaining stock abundance. This is accomplished by considering harvesting strategies relative to stock status. 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). The harvest strategy should be robust to the unpredictable and uncontrollable fluctuations that are expected of the stock. As well, it should be explicit and quantitative indicating how much catch can be taken and under what circumstance (Hilborn and Walters 1992). The actual choice of the harvest strategy should be agreed by the managers and resource users, while the biologist should perform a technical role in evaluating the risks or likely outcomes of alternative harvest strategies. Harvest tactics are the regulatory tools for implementing harvest strategies (Hilborn and Walters 1992; Anon. 1998). Fisheries management objectives may be achieved by measures of input controls (restrictions on the amount of fishing effort) or output controls (limitation on catches). These management measures are framed within a particular harvest strategy.

Harvest strategies include (Fig. 3):

1. fixed catches: a constant catch is taken annually regardless of stock status,
2. fixed harvest rates: removals represent a fixed proportion of the recruitment,
3. fixed escapement: all recruitment in excess of a fixed spawning requirement is harvested, and
4. floor strategy: a fixed proportion of the recruitment is removed when recruitment exceeds the minimum spawning requirement. Lande et al. (1997) proposed a variation of this strategy, called proportional threshold harvesting.

Harvest strategies, which are a linear function of stock size, can be generalized with the following equation:

\[
\text{Catch} = \text{intercept} + \text{slope} \times \text{stock size} \quad \text{(Hilborn and Walters 1992)}
\]

where

- intercept = fixed escapement objective (spawner reserve)
- slope = fixed harvest rate

With the exception of the fixed catch strategy, these harvest strategies are known as stock-dependent strategies. Stock-dependent harvest strategies do not have to be linearly dependent on stock size. Other forms such as curves, lines with breakpoints are legitimate harvest strategies. Hilborn and Walters (1992) describe a situation where a smooth sigmoid curve relating harvest rate to stock size was agreed upon by the sockeye salmon fishery because it helped prevent arguments about which side of the thresholds the stock was each year. Non-linear harvest strategies between the biomass limit \(B_{\text{lim}}\) and the biomass target \(B_{\text{targ}}\) have been promoted as stock rebuilding strategies, i.e. as the stock abundance declines towards the limit, the harvest rate is decreased more quickly in order to slow down / prevent further decline and to promote rebuilding towards the target.

**Fixed catch strategies**

The harvest strategies have consequences on yield and on spawning stock (Fig. 3). Marine fisheries management to date has been largely based on fixed catch strategies. Crucial to the implementation of such a management strategy is the need for accurate catch, age composition and fishing effort data. Many fixed catch management systems have, however, failed due to the high degree of unreported catches and discarding leading to unreliable advice on desirable catch levels (FAO 1992). Although ‘fixed’, in most cases an adaptive policy is followed and the catch quotas are generally set on an annual basis. This enhances the problem in that the actual catch taken tends to be higher than the total allowable catch (TAC) advised by fishery scientists (Angel et al. 1994). Fixed catch strategies are also sensitive to environmental perturbations causing wide fluctuations in stock size (Beddington and May 1977). The strategy is insensitive to fish abundance, resulting in a tendency to overfish when stocks decline and also results in poor utilisation of the resource under conditions of higher stock abundance. Allocating a low fixed quota could be appropriate in situations where maintaining a moderately high stock size is imperative, as for stocks that are also important to other user groups, e.g. recreational fishermen (Caddy and Mahon 1995), but in the management of Atlantic salmon it is difficult to equate this approach with the operation of distant water and homewater net fisheries (Potter et al. 2003).

Fixed catch (pre-set catch ceilings) strategies have fallen out of favour in the management of Pacific salmon fisheries (DFO 2000b), but are still being applied in the management of some Atlantic salmon recreational fisheries. For example, in most parts of eastern Canada, a pre-set number of tags are issued with every recreational fishery license although the overall potential catch is never achieved. In Brittany (France), current fisheries management is based on a pre-season quota by individual river after setting aside an allowance for a fixed spawning escapement (Porcher and Prévost...
1996). The fixed catches (or TACs) are in fact estimated as the maximum gain (on average) which can be taken from the stock, but in-season monitoring of catches and returns are intended to preclude excessive exploitation.

**Fixed exploitation rate strategies**

Fixed exploitation rate strategies, where management aims to take the same proportion of the stock each year, have the benefit of providing simple rules for adjusting harvest in response to changes in stock size (Walters and Pearse 1996). Such strategies may also have advantages because they do not depend upon a full understanding of the SR relationship nor do they require a real-time enumeration of all catches (Caddy and Mahon 1995). Other desirable properties of fixed exploitation strategies include: they are robust to causes of fluctuations, avoid unnecessarily high inter-temporal variation in catches, are practical and relatively inexpensive to implement (Hilborn and Walters 1992; Walters and Parma 1996), and they are less sensitive to changes in density-independent parameters (Walters and Parma 1996) allowing population size to adjust to changes in marine and freshwater carrying capacity, even if such changes are not explicitly measured or detected (Walters and Korman 1999). Furthermore, obligatory to adaptive management policies, fixed exploitation rate strategies provide for a broad range of spawning stocks and thus generate more learning about underlying biological relationships (Hilborn 2001). Walters and Parma (1996) indicated that the constant harvest rate strategy was the optimal strategy for maximizing the long-term catch under variable environmental conditions, and suggested that it may be more cost-effective to focus research efforts on the implementation of such strategies rather than trying to explain and predict the effects of environmental change. This could be particularly pertinent to the management of salmon fisheries in view of current concerns about the effects of marine environmental conditions and climate change upon the survival of salmon in the sea (Friedland et al. 1993; Potter and Crozier 1999; ICES 2000).

The main criticism of a fixed harvest strategy relates to concerns about implementation using inaccurate stock assessment data (Eggers 1993). Fixed harvesting is also not applicable to stock rebuilding programmes in that continued fixed catch harvesting instigates delayed recovery of depleted stocks. Catchability increases in most fisheries due to the learning of skippers and with modernisation of fishing technology, which makes the use of a fixed harvest strategy alone impractical to achieve stable exploitation rates (Walters and Parma 1996). Although a fixed harvest rate strategy is optimal with the objective function to maximise the logarithm of the catches (risk averse utility function for catch), some authors suggest that the justification for a constant harvest rate strategy is extremely weak since the conclusion is sensitive to the optimisation criterion used (e.g., Hilborn 1985; Hilborn and Walters 1992; Lande et al. 1997). However, Caddy and Mahon (1995) advocated the reassessment of the objections to a fixed harvest management strategy considering the failures of fixed catch strategies.

**Fixed escapement strategies**

Fixed escapement strategies involve setting a threshold population size above which excess individuals may be harvested and below which no harvesting is allowed. Fixed escapement policies are often reported to be optimal in harvest policy studies, although Hilborn and Walters (1992) observed that these analyses frequently assume that: the objective is to maximise the average discounted catch; the stock is a single homogenous unit; and the model parameters are perfectly known. Clearly, all three of these
assumptions may be invalid for salmonid fisheries (Potter et al. 2003). In general, such strategies tend to maximise mean annual yield, reduce the risk of low stock, promote stock rebuilding (Caddy and Mahon 1995; Kirkwood and Smith 1996), and are optimal when environmental effects are stationary (Parma 1990). Management of fisheries for fixed escapement results in high interannual oscillating catches (Kirkwood and Smith 1996; Lande et al. 1997). This may be economically destructive in some fisheries, although it may be less important to recreational fisheries which will be most affected where such strategies are applied to migratory salmonids (Potter et al. 2003). The implementation of fixed escapement strategies is logistically difficult, due to salmon fisheries mostly taking place before the escapement target can be assessed on the spawning ground (Eggers 1993), and requires a high level of information input. Such policies are also more sensitive to change in density-dependent parameters than to changes in density-independent parameters and require knowledge of the recruitment carrying capacity parameter for each year (Walters and Parma 1996).

In terms of adaptive policy management, fixed escapement strategies perform poorly in that they provide little contrast in spawning stock size and thus little new information about the stock-recruit relationship. Walters (1986) and Walters and Pearse (1996) also argued that a major weakness of fixed escapement strategies has been their dependence on stock assessments, which are often dangerously unreliable. Coefficients of variation for most relevant variables even in well-documented fisheries are frequently in the range 10-30% or greater (Caddy and Mahon 1995), although the increasing use of electronic and acoustic fish counters may provide a means of addressing this problem for salmon fisheries (Potter et al. 2003). Although fixed escapement policies are rarely applied in contemporary fisheries, they have become the norm for managing salmon populations (Potter 2001).

**Floor strategies**

When the optimisation criterion was to maximize the mean annual catch and to minimize the risk of stock depletion, the optimal strategy always involved a threshold population size below which no individuals are harvested (Lande et al. 1997). Floor strategies permit a fixed exploitation rate on the stock, unless it falls below a threshold, in which case no harvest is allowed. Lande et al. (1997) proposed a variation on the floor strategy called proportional threshold harvesting, in which harvest is limited to a fixed proportion of the surplus stock over the threshold. With high uncertainty in population estimates, this strategy can be superior to fixed escapement strategies. A difference between a floor strategy and a proportional threshold harvesting strategy is that with the former (Fig. 3e) there is an abrupt drop off in catch at the threshold, whereas with the latter (Fig. 3f) catch declines gradually to zero as the threshold is reached. A floor strategy with the harvest rate increasing to the target rate between $B_{lim}$ and $B_{targ}$ is a strategy intended to promote stock rebuilding and reduces the risk of over-exploiting the stock in years when the actual population size is over-estimated. Floor strategies combine some of the advantages of fixed escapement and fixed exploitation policies and have been adopted in the management of some Pacific salmon.

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 that 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.

Other strategies
Other strategies discussed by Hilborn and Walters (1992) include periodic harvest strategies (where all or part of the stock is not fished every year) and size-limit strategies (such as those currently in effect in the recreational salmon fisheries of eastern Canada). Both of these are supplementary strategies to the four described above.

Conclusions on harvest strategies
Alternative harvest strategies should be compared and the one adopted by managers and users should be robust to the unpredictable and uncontrollable fluctuations in stock abundance, and it should be clearly articulated and defined by an objective function. The objective function should be understood and agreed by all stakeholders of the resource. Stock size dependent strategies are favoured over fixed catch strategies. Of these, threshold harvesting strategies reduce the risk of stock depletion and when combined with harvest rate strategies (floor strategies) can promote stock rebuilding opportunities when abundance declines.

No formal assessment of the relative merits of these various strategies has ever been made for Atlantic salmon by ICES or NASCO. However, the complex nature of these fisheries, where different sea age groups from many stocks are harvested often in several fisheries from high seas to homewaters to terminal riverine fisheries, makes setting overall levels of exploitation very difficult. For example, a stock from a southern European country can potentially be exploited at West Greenland, at Faroes, in homewaters of its own and neighbouring countries and then in terminal rod fisheries in its home river.

Management of salmon exploitation ideally should take account of the different requirements of commercial and recreational fisheries. Commercial fisheries operate to provide all or part of the livelihood of the operators, the profit being derived entirely from the catch; it may therefore been seen as unreasonable to restrict exploitation by simply making the fishery economically inefficient; indeed in some jurisdictions this may be regarded as an unreasonable legislative control. For such fisheries, it may be preferable to limit catches by allowing the fishermen 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 recreational fisheries, however, may not depend upon killing fish, since the value of the fishery is related more to the provision of fishing opportunities (i.e. actual yield is often not as important as the overall angling “experience”). Thus, there may be a greater need to allow fishermen the opportunity to fish, even if the number of salmon they can kill is greatly limited. For example, it might be appropriate to permit recreational fishing to continue when stocks are close to or below CL as long as they employ compulsory catch and release. Thus, 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.
Management strategies currently applied to Atlantic salmon: limitations and progress

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 agreed allocation of a proportion of the estimated surplus above the total spawner requirement of all North American rivers (NASCO 1993), whereas in homewater fisheries a variety of approaches is evident ranging from variable annual quotas to effort control. These and other examples are given below, together with comments on whether strategies being employed are compatible with the precautionary approach and where further developments are needed or are under way.

Distant water mixed stock fisheries

West Greenland fishery

The provision of catch advice for the West Greenland fishery uses a risk analysis framework, which incorporates the uncertainty in all the factors used to develop the catch options. As Atlantic salmon are managed with the objective of achieving spawning conservation limits, the undesirable event to be assessed is that the spawning escapement after fisheries will be below the conservation limit. Fisheries are managed for harvests of fish, not for escapes of fish. As such the development of catch advice in a risk analysis framework 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 risk analysis of catch options for Atlantic salmon from North America incorporates the following input parameter uncertainties:

1) the uncertainty in attaining the conservation requirements simultaneously in different regions,
2) the uncertainty of the pre-fishery abundance forecast, and
3) the uncertainty in the biological parameters used to translate catches (weight) into numbers of North American origin salmon.

The risk analysis proceeds as illustrated in the flowchart of Figure 4. The three primary inputs are the \( PFA_{NA} \) (prefishery abundance for North America) forecast for the year of the fishery, the harvest level being considered (t of salmon), and the spawner requirements in the rivers of North America.

Gill net fisheries in West Greenland harvest one-sea-winter (1SW) salmon about one year before they mature and return to spawn in North American and European rivers. The abundance of fish prior to the fishery (PFA) was estimated using run-reconstruction models as described by Rago et al. (1993) and Potter and Dunkley (1993). These models are essentially catch-based and reconstruct backwards in time the abundance of fish using observations (returns, harvests) of the age group at different times, adjusted for natural mortality.

Models for forecasting PFA in the year of the fishery have been based on an index of thermal habitat in the northwest Atlantic and spawning stock indices. The spawning
stock variable is an index of the 2SW age group parental stock. The thermal habitat variable was based on studies showing that salmon stocks over wide geographic areas tend to 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 revealed structure within the data set. Two states of Atlantic salmon production become evident with a transition period from 1988 to 1990 (ICES 2003). This dynamic indicates that mortality of salmon between the spawner and PFA recruit stage had changed in the last 15 years. This model was subsequently used to derive a PFA estimate for the 2003 fishery at West Greenland.

For a level of fishery under consideration, the weight of the catch is converted to fish of each continent’s origin (based upon historic sampling) and subtracted from one of the simulated forecast values of PFA_{NA}. A proportion of the exploitable surplus is then allocated to Greenland as a quota, based on a historical sharing fraction of 40%:60% West Greenland:North America.

After the fishery, fish returning to home waters 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 (equates to 28.1% mortality). The fish that survive to homewaters are then distributed among the regions and the total fish escaping to each region is compared to the region’s 2SW spawning requirements.

North America is divided into six stock areas that correspond to the areas used to estimate returns and spawning escapements, and which reflect phenotypic characteristics of the stocks in North America. Under the assumption of equal production from all stock areas (i.e., recruitment in direct proportion to the spawner requirement) just over 172,000 fish would need to escape to North America as 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 the expected returns to the six regions, i.e. even if 172,000 2SW salmon reached the coast of North America, there would likely be severe under-escapement in some regions.

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 to 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% increase or a 25% increase relative to average returns of the previous five years for the southern regions (Scotia-Fundy and USA). The alternative objective for the southern areas was developed in order to provide stock rebuilding opportunities in the southern regions in which the status of the stocks was poor and there was zero chance of meeting the conservation objectives even in the absence of fisheries (ICES 2003). Attempting to achieve increases in returns relative to previous years would lead to rebuilding of stocks. Catch advice is given to NASCO in terms of ensuring a high probability (75%) of meeting the stated management objectives and is thus viewed as risk averse.

While the West Greenland catch advice process has evolved continuously over the last decade or so, until recently, quantitative catch advice for this fishery was based on North
American stocks alone, as no prediction of PFA was available for European stocks present at West Greenland. However, a model to predict PFA of southern NEAC stocks at West Greenland has recently been developed (arising from the SALMODEL project) and this prediction was incorporated into the catch advice process for the first time in 2003 (ICES, 2003), via a similar risk framework. (Fig. 4).

Further developments to enhance the catch advice process 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 PFA for the southern European stock complex may be considered, as there is evidence that such changes in production are not restricted to N. America.

Faroes 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 PFA of the northern European stock complex, as required if quantitative catch advice is to be given for the Faroese fishery (Crozer et al 2003; Paper V21, this session). A similar modeling 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 similar manner to that for West Greenland. While a sharing agreement for any surplus identified has not yet been negotiated, historical data on breakdown of catches in former years suggests it might be around 40:60, Faroes:Europe (ICES, 2003).

Homewater fisheries

While the development of catch advice for the large distant water mixed stock fisheries particularly at West Greenland has tended to proceed along the lines of integrated assessment incorporating a risk framework and giving catch options based on explicit risks of not achieving conservation requirements, the same is generally not the case in many homewater fisheries around the N. Atlantic. In practice, a variety of approaches has been developed over the years, reflecting both the differing types of fisheries, availability of data and the ability of managers to regulate fisheries within various differing legislative frameworks. However, the fact that many stocks are exploited in both the West Greenland and Faroes fisheries is likely to complicate these decisions.

In many NEAC countries fisheries have traditionally been controlled by effort restrictions (exploitation rates being difficult to manage directly in these fisheries) and these are increasingly being applied as declining stocks approach CLs.

For example, the use of conservation limits in UK (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 being 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 conservation limit and is controlled by effort restrictions, thus imposing a roughly constant exploitation rate. However, when stocks fall below the conservation limit, 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.

The management objective in UK (England and Wales) is to ensure that spawning stocks remain above their CLs for at least four years out of five. This has been achieved by assessing compliance in three-year blocks (i.e. average over 3 years), based upon rules relating to ‘episodes’ (periods of years) when the escapement falls below the CL (Environment Agency, 1998). Compliance failure occurs if an episode lasts longer than two years, and if the gap between episodes does not exceed two years. A river classed as failing would remain classified as such until a reassessment, for a subsequent three-year period, showed a pass. Compliance failure cannot distinguish between a real deterioration in the egg deposition and a chance (1-in-20 year) false alarm, and 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 set for each river stock in England and Wales in order to assist managers in introducing new controls on fisheries.

In 2002, management of Ireland’s commercial salmon fishery was switched from effort limitation only (i.e. regulations covering season length, gear types, licence numbers etc) to a fixed escapement strategy applied by means of effort limitation and additional catch controls. For each of Ireland’s seventeen Salmon Fishing Districts, data are available on reported catch, unreported catch and exploitation rates. These data allow the application of two models currently used to estimate prefishery abundance (PFA) and national conservation limits (S\text{lim}) for each of the North East Atlantic salmon producing countries (Potter et al, 1998, ICES 2003). The two main outputs from these models for use in Irish fisheries management (Ó Maoiléidigh et al, 2001a and Ó Maoiléidigh et al, 2001b) are an estimate of PFA (the number of salmon available before the fisheries take place) for each district and the Conservation Limit or S\text{lim} (i.e. the maximum sustainable yield (MSY) which has been adopted widely as the S\text{lim} or Conservation Limit (CL) for North Atlantic Salmon (ICES, 2003). The average PFA for a baseline period starting from 1997 is adjusted to take account of survival from the high seas to homewater return. This provides a measure of the total number of fish available. In order to set a TAC for each district, the exploitable surplus is estimated by subtracting the S\text{lim} (spawning requirement) from the total number of fish available. Precautionary catch advice is provided by the scientists on the following basis:

- Where an exploitable surplus exists and is more than or 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.
- Where the exploitable surplus is less than the average catch for the baseline period, the catch should not exceed the exploitable surplus.
- 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.

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 with fishermen and fishing organisations. These negotiations take account of the socio-economic as well as the biological concerns of the fisheries. Management and
enforcement of the District TACs has been greatly facilitated by the instigation of a salmon carcass tagging and logbook scheme for all fishing methods. Commercial fishermen are allocated commercial fishing tags based on their recent catch history while 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 fishermen are obliged to record details of their catch in an official logbook which is returned at the end of the season and the data entered on a national database.

In the absence of specific stock and recruitment data for approximately 173 Irish rivers (McGinnity et al, 2003) believed to support salmon stocks, these district $S_{lim}$ values represent the lowest stock resolution for conservation limits at present. However, it is recognised that the mixed stock nature of the district fisheries (i.e. where salmon caught in any given district may be destined for an adjacent or even more distant district) will confound the estimate of conservation limit and pre-fishery abundance. In this regard the Irish scientists are moving to the establishment of conservation limits on a river by river basis using well studied stock and recruitment parameters from monitored rivers and applying the estimated requirement for eggs per m$^2$ of these rivers to the wetted areas of each river in Ireland. These individual river estimates will in turn be summed to provide new District $S_{lim}$ values for use in setting District TACs in future.

In UK (N. Ireland), management measures in coastal fisheries have comprised 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 status of local salmon stocks. A total of 32 coastal salmon nets were licensed to fish in the FCB area, comprising drift nets, and tidal and fixed bag nets. Managers reached agreement with the license holders for voluntary restrictions on fishing in 2001, with 23 licenses being issued while not all of these were fished. This preceded a private:public sponsored buyout of this fishery, starting in 2002, when only 14 licensees were issued, the remainder having being bought out.

Data on exploitation of returning wild R. Bush grilse in fisheries in the FCB area and elsewhere around N. Irish and Irish coasts (ICES, 2003) indicates that overall exploitation of this stock in Irish/N. Irish homewaters averages around 60%. Using methods of apportioning coastal exploitation given in Crozier and Kennedy (1994) the proportion of this exploitation occurring in the FCB area averages 0.72, while 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 2000/01 indicates that declared catches in the FCB area fell from around 11000 fish to less than 4000 fish in the two year period. However, data from the R. Bush tagging programme shows that although catch has fallen substantially in the local FCB area, overall exploitation of the monitored R. 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, with catches in the immediately adjacent Foyle area increasing considerably in 2002 (40768) compared to 2001 (22976). In this case, the increase was particularly evident in drift net catches, which would be expected to have the greatest
impact on fish moving through coastal waters to other districts. Thus, 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 ideally stocks being managed on a river by river basis.

The current emphasis in the North American homewater fisheries management is to direct exploitation within individual rivers. This eliminates the problems associated with mixed stock fisheries and allows harvesting to occur where conservation limits are exceeded. In Canada, the majority of the fishing gears used to exploit Atlantic salmon allow for the selective harvesting of fish by size. Many in-river gill net fisheries have been replaced with trapnets. Catch and release fishing is extensively practiced in many recreational fisheries, facilitated by regulations that restrict angling to artificial fly. In Canada, the definition of conservation also includes setting out the order in which users have rights of access to any surplus above conservation requirements, which results in access to salmon for food and ceremonial purposes being afforded first to aboriginal and first peoples groups.

River fisheries

Mixed stock fisheries are generally regarded as those which intercept returning salmon at some point in the ocean or on the coast prior to river entry on their homeward migration. However, recent insights into the structure of river stocks indicates that in-river fisheries might also be considered as mixed stock fisheries as they are likely to be exploiting salmon from different populations. Much of the evidence for in-river stock structure comes from radio tracking studies (e.g. Laughton and Smith (1992), Walker and Walker, (1992), Webb, (1992), Smith and Johnstone (1996), Webb (1998) and Smith et al., (1998)) where it has been demonstrated that salmon returning to freshwater at different times of the year home to spatially discrete spawning locations. The run-timing characteristic has been shown to be a heritable attribute (Stewart et al., 2000). Furthermore, field observations have indicated that population units can exist over spatial scales of ca. 10km (Youngson et al., 1994). Thus, 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. 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. In UK (Scotland) a two stage process is being developed (Potter et al., 2003). Firstly, rod catches, or abundance indices derived from catches, at sub-catchment scales will be compared to reference catch levels. Where current catch falls below the reference point, juvenile electrofishing 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.
While the scientific assessments and the management systems operating at all the levels outlined above are evolving and should facilitate improved management of Atlantic salmon, there are an number of areas where future developments are of critical importance for management of mixed stock fisheries:

**Pre agreed management actions and decision frameworks**

To assist in applying the Precautionary Approach to the management of North Atlantic salmon fisheries, the Council of NASCO has developed a Decision Structure, which was adopted in 2002 (NASCO, 2002; Rosenbeg, 2002). The Decision Structure provides a basis for more consistent approaches to the management of exploitation throughout the North Atlantic range of the species. It proposes the use of reference points such as conservation limits (i.e. the number of spawning salmon below which the stock would decline markedly) and management targets, or other indicators of stock status, to trigger management actions to address any failure in abundance or diversity. It is intended that the Decision Structure be widely applied by managers with stakeholders on salmon rivers. In applying the Decision Structure, management decisions should be taken in accordance with an assessment of risk, such that, in the face of uncertainty, there is a low risk to abundance and diversity of the stock(s). The probability of achieving the management goals should be high. The results of using the Decision Structure should be monitored and evaluated to ensure that the actions taken in managing salmon fisheries are consistent with the Precautionary Approach. The Contracting Parties have agreed to report annually to NASCO on their experiences in applying the Decision Structure and on the extent of its implementation.

In reporting to NASCO, contracting parties must initially identify whether the fishery exploits single or multiple stocks. If the fishery operates on multiple stocks, NASCO requests the following information:

- *The reference points used in the management of the stocks (Conservation Limits and/or Management Targets) or alternative measures used to define adequate abundance of the exploited stocks.*
- The status of all stocks relative to the reference points
- Whether all the stocks are meeting other diversity criteria (e.g. age structure, run-timing, fecundity)?
- Whether the fishery is selective for certain stock components (e.g. age groups, size, populations, river stocks)?
- Whether there are any of the stocks threatened by factors other than fisheries (e.g. habitat degradation, disease/parasites, predators)?
- The management actions that will be employed to control harvest, including measures that will be used to address any failure or trend in abundance or diversity, taking account of pre-agreed procedures (taking account all of the above, socio-economic factors and if other fisheries exploiting the stock);
- Information on programmes (including in-season programmes) that will be used to monitor the effects of the management measures, and identify information deficiencies and the timeframe for their resolution.

In this way, NASCO is developing its role in moving managers towards pre agreed and standardised management actions, linked to attainment of limits and targets for stock
escapement. The overall structure takes into account the consequences both of single and mixed stock fisheries composition in reaching rational management decisions.

Stock structure

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. For these reasons, the NASCO decision structure explicitly requires that stock composition of mixed stock fisheries should be considered when developing management actions.

In the case of continent of origin of fish caught at West Greenland, biological analysis of scale structures, supported/verified by DNA analysis has been used to determine representation of N. American and European stocks, but at continental level only to date. Recent analyses have indicated the potential for identifying stock complexes at finer level of resolution than continent, (Spidle et al. 2003) with assignment testing recently reported as being able to separate Canadian and USA stocks in samples from this fishery. 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 determine how many were being taken from these endangered populations. In theory, these and other regional assignments could be used to estimate the increase in returns that would be achieved with various harvest restrictions in the mixed stock 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 datasets greatly affects the accuracy of assignment and current reference datasets are deficient in this regard.

The identification of stocks and stock complexes contributing the Faroes fishery, presents additional difficulties, as there are many more stocks represented here, with most if not all NEAC countries contributing to this fishery, however 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 homewater mixed stock fisheries, where many fewer stocks are being taken, is providing encouraging results. For example, in UK (N. Ireland) analysis of genetic variation at microsatellite loci in baseline samples from river populations and a mixed stock fishery in the Foyle area is being used to identify river populations contributing to the fishery (Crozier and Booth, 2003). Analysis of stock composition of the mixed stock fishery in the estuary and coastal waters from a test year, using both traditional 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 underrepresented in catches (Fig. 5). 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.
A further application of this approach might be to apply it to identify origin of salmon stocks represented in the Irish fishery districts, where the setting of quotas requires that estimates are made of which districts are taking fish from other districts. Given suitable genetic baseline data, screening of these fisheries at district level may allow quantitative allocation of quotas to districts based on where the fish returning to each district are in fact caught.

**Mixed stock fisheries and stock rebuilding**

One of the biggest problems inherent in managing mixed stock fisheries, is accounting for the differing biological characteristics (especially productivity) and status of the constituent stocks being exploited, to ensure that low productivity or low abundance stocks are not threatened.

With the fixed escapement management objective, the use of spawner reference points to set catch quotas based on forecasts should incorporate the uncertainty associated with managing discrete units (fish) organized in fairly small packages (100s or 1,000s of fish per stock rather than millions). Based on work carried out in the EU SALMODEL project (and fully explored in paper V18 in this session), there are some general conclusions which can be made regarding the effects of these uncertainties on the probabilities of achieving the spawning requirements in the individual rivers.

- the smaller the stock under consideration, the more uncertain the outcome
- when annual variation in the biological characteristics is high, so is the uncertainty in the objective of achieving the spawner requirement
- the management of mixed stock fisheries involves additional risk to individual river stocks, even under perfect management, particularly for small and low productivity stocks
- if rivers of differing productivity rates are aggregated into a complex, failure to account for these differences in the aggregate spawner requirement will result in under-escapement to the less productive areas and over-escapement in the productive stocks

Acknowledging that conservation can only be achieved when production is occurring 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 which 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.

The impact of mixed stock fisheries can be most significant on the small stocks and especially if these are of low relative productivity. The impact of mixed stock fisheries on low productivity stocks is, however, more important and was earlier identified as a particularly important consideration in Pacific salmon fisheries. Increasing the regional spawner requirement in an attempt to compensate for lower productivity may alleviate the problem somewhat, but is not a guaranteed solution to the challenge of protecting low productivity stocks.

These considerations clearly becomes critical when considering mixed stock fisheries that exploit stocks that are already well below conservation limit and especially if those stocks are of low productivity. With many salmon stocks around the N. Atlantic now well
below CL, and in some cases threatened or endangered, managers are beginning to place emphasis on seeking catch advice in terms of rebuilding targets for particular stocks or groups of stocks.

In 2003, ICES considered the provision of long-term projections for stock re-building, focusing on trajectories for restoring stocks to target levels above conservation limits (ICES 2003). Trajectories for stock rebuilding depend on many parameters which are not known with certainty or which may change over time. Stock and recruitment curves representing highly productive stocks through low productive 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 frequency of achieving conservation over a 50 year time frame under a range of exploitation. The number of years required to rebuild to $S_{lim}$ as well as the number of years during the 50 year projection below the $S_{lim}$ were recorded for each simulation.

One of the key findings from this analysis was that the number of years to recovery was unobtainable in fifty-year projections in a low productivity river and possibly unobtainable in a moderate productivity river as the recovery time in years was more dependent on the value of alpha (productivity) than the start point. The time to recovery and the proportion of annual recruitment less than the $S_{lim}$ increased with lower productivity and the starting point (Fig. 6). Recovery was particularly sensitive to increasing exploitation at lower alpha.

ICES concluded that there was an increased probability of not achieving $S_{lim}$ with increased exploitation and lower alpha, and suggested that increased caution needs to be taken when assigning exploitation to low productivity stocks. It also suggests 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 $S_{lim}$ and which are of low productivity.

The mixed stock nature of the North Atlantic salmon fishery poses significant problems in this regard as there are over 1,500 European rivers and over 600 North American rivers with highly variable stock status. The aim of management is to regulate catches while achieving overall spawning escapement reflecting the spawner limits in individual North American and European rivers (ICES 2003). However, ICES had previously expressed concerns that the spawning requirement (172,000 salmon) used for North America is for the continent as a whole and does not reflect the expected returns to the six regions, i.e. even if the required 172,000 2SW salmon reach the coast of North America, there will likely be severe under-escapement in some regions. Although NASCO establishes TACs for the mixed stock high seas fisheries, benefits to particular stocks are often difficult to demonstrate, in the same way that damage to individual stocks are also difficult to identify. This is because there is no reason to expect the abundance of salmon in the North Atlantic to be proportional to the spawner requirements in each river. For example, there is a zero chance that the returns to USA rivers will meet or exceed the conservation limit (about 29,000 2SW salmon), in 2004. There is little chance of returns in 2004 being sufficient to meet the Scotia-Fundy requirement even in the absence of high seas fisheries. In 2002 an alternative management strategy was advised which would allow attainment of conservation limits simultaneously in the four northern regions of North America: Labrador, Newfoundland,
Quebec, and Gulf. For the two southern regions, Scotia-Fundy and USA, an alternate objective to that of achieving the conservation requirement would be to achieve increases in returns relative to previous years with the intention that this will lead to the rebuilding of stocks, i.e. assess fisheries relative to the objective of achieving a minimally pre-agreed increase in returns relative to the realized returns of a previous time (ICES 2003).

However, rebuilding stocks with restocking programmes may also be confounded by the mixed stock nature of the North Atlantic salmon fishery as previously noted. Low levels of marine survival, high or variable exploitation rates and even negative interactions between hatchery reared fish and their wild counterparts (McGinnity et al, 1998, Ferguson et al, 2002) affect different stocks in different degrees. Rebuilding from low productivity or even restoring extinct stocks appears 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_{lim} is now recognised as one of the greatest challenges to salmon management and lends considerable support to the adoption of the S_{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:

- Uncertainties in stock biomass, with changes in input data leading to sometimes many-fold change in stock size assessments (ref points need measures of absolute abundance),
- Inappropriateness of reference points being used in species from which they were not derived,
- Inadequate treatment of uncertainty,
- Reference point use leads scientists to ignore other potential management policies,
- Trajectories for returning stocks to equilibrium are rarely considered,
- Obsession with reference points leads to displacement activity, that keep us from investigating the 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 being taken account in framing catch advice for mainly the distant water mixed stock fisheries, and increasingly so in homewater fisheries, where management targets are being developed and these are addressing risks of not achieving conservation requirements. In contrast to most marine species, stock abundance is very well known in salmon, with run-reconstruction techniques being used to estimate total stock size at critical points in the life cycle. This is based on catches and counts which, in many cases, form a large component of the abundance of the stock(s) to be assessed (e.g. up to 30%).
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 all being applied across various problems. In addition, explicit management targets that incorporate uncertainty are being developed in many fisheries. The identification of appropriate limit reference points and associated emphasis on using high probabilities of exceedance (75% in some cases), are providing a conservative framework for management that has been generally accepted by managers.

While reference points have come to the fore in Atlantic salmon management in the past few years, these have not prevented alternative methods of management being implemented. An example of data based management as favored 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 cpue and PFA (ICES, 2002). This indicates that data-based systems can complement the use of reference points derive management advice. Finally, while stock and recruitment 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 the application of reference points had in fact encouraged managers to look for reasons underlying salmon declines, as they have served to highlight just how far below safe biological limits many stocks are.

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 in this regard. Interestingly, both Hilborn (2002) and Rosenberg (2003) are agreed 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 that we must manage stocks across. Significant progress has been made, particularly through NASCO, in interpreting and implementing the PA as applied to Atlantic salmon, not just in reference points, but seeking to apply the PA 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, as this will drive scientists and managers to ask and answer the right questions and is designed to lead to pre-agreed management actions, or at least to explicitly justify management decisions.

We have demonstrated above that management of mixed stock fisheries in the high seas and in homewaters in Europe is developing along the lines of the precautionary approach, and that further developments are underway that should enhance our ability to manage these fisheries, however, the mixed stock scenario cannot however be regarded as ideal. The impact of mixed stock fisheries can be greatest on the small stocks and especially if these are of low relative productivity. As noted by Chaput (paper V18), increasing the regional spawner requirement in an attempt to compensate for lower productivity may alleviate the problem somewhat, but is not a guaranteed solution
to the challenge of protecting low productivity stocks. A particular challenge exists in the case of the West Greenland fishery, where the stocks being potentially exploited ranges from endangered to those that are meeting their conservation requirements. In respect of this, ICES notes when giving catch advice for this fishery that “mixed stock fisheries present particular threats to conservation” (ICES, 2003).

In contrast, the homewater mixed stock fisheries that still operate in some European countries take rather fewer stocks and it is probable that stocks of similar productivity are being taken from these more localised areas. However, the problems of sequential or simultaneous fishing still remain and as shown here the outcome of management decisions made in one fishery can be affected by what happens in other fisheries. Ideally most fisheries would be managed on a river by river basis, however 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 which 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 these 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 other potential factors. It is doubtful if overexploitation has been the sole or even the main cause of driving stocks downwards, and while exploitation control is obviously part of the solution, we must continue to look elsewhere as well.

References


Figure 1. Map of the North Atlantic area, showing the NASCO Commission areas.
Figure 2. Nominal catches of salmon in four North Atlantic regions, 1960-2002.
Figure 3  Possible harvest strategies based upon straight line relationships between stock and catch, showing the effects on catch and spawning escapement at different stock levels: A. Fixed catch strategy; B. Fixed catch strategy with a threshold; C. Fixed exploitation strategy; D. Fixed escapement strategy; E. Floor policies; F. Proportional threshold harvesting. (From Potter et al. 2003)
Fig. 4. Flowchart of risk analysis of catch options at West Greenland using the PFA_{NA} and the PFA_{NEAC} predictions for the year of the fishery. Inputs with solid borders are considered known without error. Inputs with dashed borders are estimated, contain observation error which is incorporated in the analysis. Solid arrows are functions which introduce or transfer without error whereas dashed arrows transfer errors through the analysis.

\[ \text{Risk analysis summary} \]

\[ S = e^{-Mt} \quad S = e^{-Mt} \]

\[ \text{Sharing arrangement} \]

\[ \text{Returns to regions in NA} \]

\[ \text{Returns to regions in NEAC} \]

\[ \text{PropNa, PropE, Wt1SWNa, Wt1SWE, ACF} \]

\[ \text{West Greenland Harvest (t), } t = 0, 5, \ldots \]

\[ \text{Harvest1SW}_{\text{NA}} \]

\[ \text{PFA}_{\text{NA}} \]

\[ \text{Returns to regions in NA} \]

\[ \text{PFA}_{\text{NEAC}} \]

\[ \text{Returns to regions in NEAC} \]
Figure 5. Estimated stock composition of the Foyle commercial salmon fishery, using two genetic stock identification techniques.
Figure 6. Number of years for an Atlantic salmon population to attain $S_{lim}$ in 50 years for High (14.93), Medium (2.13) and Low (1.85) alpha values in a Ricker stock and recruitment function over 10,000 simulations with uncertain parameters (ICES, 2003).