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A Stock Assessment of Atlantic salmon in Large Riverine Catchments

A thesis submitted to The National University of Ireland in fulfilment of the requirements for the Degree of Doctor of Philosophy

By

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April 2013.

Volume I of II.

PhD. 2013
Declaration

I confirm that the work submitted in this dissertation is entirely my own work. Any work of others has been cited and acknowledged within the text of the dissertation.

Signed: ____________________________________

Louise Brennan (April 2013)
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Abstract

Large river systems can be challenging in relation to stock assessment and catchment management, especially those large rivers with numerous or important tributaries that may contain sub-populations or stocks. Initial testing of existing counter technology (resistivity, infra-red and split-beam hydroacoustics) in such a system - the River Moy, Co. Mayo - highlighted the difficulties in their use and operation. In this study, an alternative hydroacoustic system, DIDSON (Dual-frequency Identification Sonar), was deployed and assessed for the first time in Ireland. The DIDSON’s near video quality imagery allowed for observations of fish migrations and it was easy to install and operate. Methodologies for the operation and data processing using DIDSON in Irish rivers for counting Atlantic salmon have been established, including software development of DIDSON SMC Software (SoundMetrics) (e.g. CSOT Analysis), allowing for the acquisition of real time data and quality fish length measurements.

As an alternative to adult counts, mark-recapture estimates were successfully carried out on Atlantic salmon smolts on the River Deel (a tributary of the River Moy) using a screw trap. Both classic and Bayesian models were successfully applied. These stock assessment data were also used to determine the main environmental influences on Atlantic salmon migration in the River Deel. While air and water temperature were shown to be significant to adult migration, no direct correlations were determined with smolt migration.

The combined use of DIDSON and Genetic Stock Identification was developed for salmon stock assessment. The genetically determined proportion of River Deel fish were used, along with the DIDSON count, to provide the first estimate of a large river system, the River Moy, using this unique methodology. This advance in stock assessment methodology allowed for a stock assessment of all discrete populations within a large river system.
Acknowledgements

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### Glossary of Terms

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<td>Accuracy</td>
<td>The degree of closeness of measurements of a quantity to that quantity’s actual (true) value.</td>
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<td>ADFG</td>
<td>Alaskan Department of Fish and Game.</td>
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| Bimodal Distribution | Is a continuous probability distribution with two different modes.  
These appear as distinct peaks in the probability density function. |
| BS         | Background Subtraction.                                                                                                                      |
| BT         | Brown Trout.                                                                                                                               |
| CBAYES     | The software package CBAYES implements Bayesian methods of analysing microsatellite and SNP data to provide accurate estimates of stock composition as well as individual assignment to stock-of-origin. |
| CI         | Confidence Interval.                                                                                                                        |
| CL         | Conservation Limits.                                                                                                                        |
| CSOT       | Convolved Sample Over Threshold.                                                                                                             |
| DCERN      | Department of Communications Energy and Natural Resources.                                                                                   |
| .ddf file  | Name given to DIDSON files.                                                                                                                  |
| DIDSON     | Dual Frequency Identification Sonar.                                                                                                          |
| DIDSON+HRL | DIDSON operated with High Resolution Lens.                                                                                                    |
| DIDSON-LR  | DIDSON Long Range Lens.                                                                                                                       |
| DIDSON-S   | Standard DIDSON.                                                                                                                             |
| Discriminant Function Analysis | Is a statistical analysis to predict a categorical dependant variable (called a grouping variable) by one or more continuous or binary independant variables (called predictor variables). |
| DL         | DIDSON Length.                                                                                                                              |
| Down time  | Time where the DIDSON counter was not operational.                                                                                           |
| EA         | Environment Agency.                                                                                                                         |
| EPA        | Environmental Protection Agency.                                                                                                             |
| FC File    | Name given to files of data saved from the DIDSON.                                                                                           |
| GSI        | Genetic Stock Identification.                                                                                                                |
HRL
High Resolution Lens.

Hyperparameters
Is a parameter of a prior distribution, the term is used to distinguish them from parameters of the model for the underlying system under analysis.

IA
Individual Assignment.

ICES
International Council for the Exploration of the Sea.

IFI
Inland Fisheries Ireland.

IM
Image Mode.

Kernel Density Function
Estimates the proportion of a set of ‘components’ distributions which best summate to a single ‘target distribution’ composed from an unknown mixture of components.

MSA
Mixed Stock Analysis.

MSF
Mixed Stock Fishery.

MSY
Maximum Sustainable Yield.

MVA
Multivariate Analysis.

NASCO
National Atlantic Salmon Conservation Organisation.

NGSI
National Genetic Stock Identification.

NSOT
N Sample Over Threshold.

Omitted Variable Bias OVB in statistics occurs when a model is created which incorrectly leaves out one or more important causal factors. The 'bias' is created when the model compensates for the missing factor by over or underestimating the effect of one of the other factors.

ONCOR
Is a computer program that is used for genetic mixture analysis and assignment tests.

OPW
Office of Public Works.

PDF
Probability Density Function is a function that describes the relative likelihood for a random variable to take on a given value. The probability for the random variable to fall within a particular region is given by the integral of the variable’s density over the region.

Point Data
Daily data collected from a fixed location.
Precision
In this study it refers to the repeatability of a count between different methods or different individuals for the same event.

Prior Probability Distribution
The prior probability distribution is the probability that would express uncertainty before the data is taken into account and it attributes uncertainty rather than randomness to the uncertain quantity.

Rating Curve
In hydrology a rating curve is a graph of discharge versus stage for a given point on a stream, usually at a gauging station, where the stream discharge is measured across the stream channel with a flow meter.

SALSEA
Salmon at Sea: is an international program of co-operative research, adopted in 2005, designed to improve understanding of the migration and distribution of salmon at sea in relation to feeding opportunities and predation.

SALSEA-Merge
This is a follow on project from SALSEA to investigate the migration and distribution of salmon in the North-East Atlantic.

SNP
Single Nucleotide Polymorphism.

SPAM
Statistics Program for Genetic Analysis of Mixtures.

SPSS
Is a software package used for statistical analysis.

SSC
Standing Scientific Committee.

TAM
Tourist Angling Measure.

Theta
The angle of a target when a measurement is taken during processing using DIDSON processing software.

TL
True Length.

TOP
Tourist Operational Programme.

WFD

‘Work Rate’ of fish
Exertion required by a fish to swim in heavy flood conditions.
CHAPTER 1

1.0 Introduction

The principal goals of salmon fisheries management are to ensure the natural reproduction of the stocks, to maximise the catch within those limits of natural reproduction, and to ensure the genetic diversity of stocks (Mäntyniemi, 2001). Good baseline stock data is needed to achieve these goals; fisheries managers require suitable technology and established methodologies to obtain information on the current status of the stock on a river or catchment basis. Historically, management goals for escapement in populations of salmon have been estimated using stock-recruitment analyses, habitat-based models, or both (Bodtker & Peterman, 2007). However, the anadromous nature of the life cycle makes it an extremely difficult species to enumerate.

In Ireland, the primary objective of salmon fisheries management is to maintain a self-sustaining fishery for future generations. Atlantic salmon in Irish waters are of huge importance to the Irish economy but stock numbers have been decreasing steadily since the 1980s in line with global patterns (Mills, 1989). Irish salmon stocks are assessed on a yearly basis by the Standing Scientific Committee (SSC) which was established in 1999 under the Fisheries (Amendment) Act, 1999, to provide, where possible, age specific Conservation Limits (CL) on an individual river stock basis. This catch advice is in line with a move towards single stock fisheries on stocks meeting CL, and with a move to end mixed stock fishing at sea (Anon., 2008b). Conservation limits have already been established for all Irish salmon rivers but the size of migrating populations needs to be quantified to evaluate the status of these stocks relative to their conservation limits; this quantification is particularly challenging in large rivers. Given the decline in stocks over the last two decades better and more rigorous management of salmon in Ireland is of increasing importance. However, these management goals can only be achieved if the stock has been quantified, which requires that the methodologies for assessment be reliable and robust. Both direct and indirect assessment methods have been used to date, but the use of rod catch data alone for the assessment of salmon stocks and individual river conservation limits is not sufficient. Increasing closures of rivers that fail to meet their conservation limits could reduce the economic importance of
recreational fishing of salmon, thus making it more difficult to assess the status of Atlantic salmon stocks where no counter data are available.

The objective of this study was to determine the best methodology for the monitoring of Atlantic salmon in large rivers by testing existing and new counter technologies. The testing and development of reporting procedures for existing and new hydroacoustic methodologies for Irish river systems was critical to the assessment of the adult stock. The testing of hydroacoustic counters was part of an initiative to overcome the problem of counting salmon in large rivers where conventional resistivity and infra-red counters were not feasible options. The operation of counters on large rivers is very difficult due to the magnitude of the discharges, debris loadings and the greater number of both target and non-target species for counting and identification. To overcome these problems a novel hydroacoustic technology, i.e. Dual-frequency Identification Sonar (DIDSON) was acquired by the Marine Institute and was strenuously tested on the River Deel, a tributary of the River Moy, Co Mayo (Figure 2.3). In addition, alternatives to counter stock assessment methods were assessed, included a juvenile mark-recapture programme using a screw trap (smolt wheel) on the River Deel and Genetic Stock Identification (GSI).

For the River Deel, two separate stock assessment strategies were devised based on (1) a count of the adult run, and (2) a count of juvenile salmon smolt populations. The DIDSON stock assessment data were used, in combination with GSI, to obtain a count for the River Moy and for each of its discrete populations, based on the River Deel adult count. The use of the CL approach for the assessment of Atlantic salmon for a whole catchment does not provide an assessment of the adult population structure. DIDSON count data were used to estimate the raw grilse run for the 2008 cohort and from June to December 2008, these data were further broken down using length frequencies, to remove non-target species such as Brown trout (Salmon trutta) using a Bimodal Model. The aim of the DIDSON operation was to provide a methodology to obtain an estimate of the grilse run for the River Deel system. DIDSON exceeded expectations providing reliable count data and allowed for the assessment of the different components of the adult run, i.e. grilse or 1SW (One-Sea Winter) and MSW fish (Multi-Sea Winter).
The data from both the DIDSON and screw trap provided the basis for assessing the influences of environmental factors on the *upstream* migration of adults into the River Deel and the *outward* migration of smolts (via Lough Conn) to sea. Climatic factors, including the impacts of natural or anthropogenic climate change, have the potential to not only affect Atlantic salmon migrations but also the operation of equipment for the assessment of stocks.

Conservation limits in Ireland are currently calculated at the level of the whole river system but frequently this whole river approach does not allow for the protection of discrete populations within individual tributaries of large systems. The novel technique of using GSI in combination with the DIDSON counter allowed individual conservation limits to be derived and applied to each biologically significant unit or stock where discrete populations have been identified. The operation of equipment and the counting of salmon on smaller tributaries proved easier than doing so at the mouth of large rivers. DIDSON provided quality count and length data, and the near video quality images allowed inferences to be made with respect to fish behaviour and river specific run components.

1.1 The Atlantic salmon (*Salmo salar*)

The Atlantic salmon is a protected species under the 1992 EU Habitats Directive\(^1\). The freshwater phase of their anadromous life cycle can be between one and five years, depending on the river of origin. The age at migration correlates to water temperature and the newly hatched alevin remain in the spawning grounds during the development stage. Once alevin have developed gills they enter the fry stage of the life cycle and leave the breeding grounds. In Ireland, the fry develop into parr, and they feed and prepare to leave the freshwater phase of the life cycle after approximately two years (Crozier & Kennedy, 1997). Smoltification occurs at between three and six years, and is river dependant. These young fish adapt physiologically to salt water and typically begin their outward migration to sea from their natal streams and rivers between March and June each year. In the marine phase of the life cycle the smolts are known as post-smolts and undergo a rapid growth phase. Irish salmon migrate to the waters around West Greenland or the Faroe Islands where they can live for up to 3 years. While little is known about post-smolt feeding grounds the SALSEA merge (Salmon at Sea) project was set up to locate post-smolt feeding grounds. Adults

returning to their natal rivers after one year at sea are known as grilse or one sea winter fish (1 SW) and do not feed prior to spawning. The Atlantic salmon is iteroparous (it does not automatically die after spawning) and may be reconditioned to return to the sea and migrate to spawning grounds several times. These salmon are known as multi-sea winter fish (MSW) (Mills, 1991; Verspoor et al., 2007).

1.2 Declining Stocks

There is limited understanding of the decline in marine survival of Atlantic salmon stocks but these effects are likely to be complex and multi-factored (Davidson & Hazelwood, 2005). Numerous factors have led to the decline in salmon populations including over fishing, predation, destruction and pollution of their natural habitat and feeding at sea. The historical evidence of declining Atlantic salmon stocks resulting from predation, include the effects of fish farming and increases in sea lice occurrence (*Lepeophtheirus salmonis*) and farmed fish escapes is well documented (Gargan et al., 2003; Penstan & Davies, 2009; Whelan, 2010; McGinnity et al., 2003a). A combination of poor marine survival and unfavorable freshwater conditions such as reduction in water quality and increased abstractions of water have compounded problems of overexploitation and habitat degradation. Current knowledge of the distribution and migration of salmon at sea has been derived from commercial fisheries. A close relationship between marine survival rates and marine growth, particularly during the post-smolt year (Friedland et al., 2009), has been identified for Atlantic salmon (Peyronnet et al., 2007). However, changes in the marine environment may be a factor in controlling stock-complex productivity, and freshwater conditions may be a more important factor in controlling species distribution and viability (Friedland et al., 2009). The international SALSEA effort investigating the migration and distribution of salmon in the North-East Atlantic was undertaken to improve understanding of the migration and distribution of salmon at sea in relation to feeding opportunities and predation, and it involved the completion of marine surveys in both 2008 and 2009 (NASCO, (CNL(08)36) ).
1.2.1 Exploitation and Conservation – International and National Obligations

An extensive drift net fishery was established in west Greenland following the discovery of salmon feeding grounds in the 1950s. World catches of Atlantic salmon increased dramatically during the 1960s and peaked in 1973 (NASCO). This increase was associated with the expansion of marine salmon fisheries and the development of more efficient fishing technology and gears (including mono-filament nets). The stock complex of Atlantic salmon in Europe has experienced this multidecadal decline in recruitment, resulting in the lowest stock abundances observed since 1970 (Friedland et al., 2009). Also between 1979 and 1990 catches fell from 4,000,000 to 700,000 (NASCO), due to the mortality rates of Atlantic salmon at sea which more than doubled in the 1990s and the numbers of Atlantic salmon had dropped to critically low levels by 2000. Atlantic

The North Atlantic Salmon Conservation Organisation (NASCO) Atlantic) was established in 1983 to coordinate the management and conservation of Greenland and Faroes fisheries. The success of the organisation resulted in its expansion to help protect the Atlantic salmon stocks of Canada, Denmark, the European Union, Iceland, Norway, the Russian Federation, and the United States. In 1998, NASCO agreed to adopt and apply a Precautionary Approach to the conservation, management and exploitation of salmon in order to protect the resource and preserve the environments in which it lives (NASCO, CNL(98)46). The International Council for the Exploration of the Sea (ICES) compiles annual scientific reports to estimate the status of Atlantic salmon populations and provide advice to NASCO for the management of fisheries in the North Atlantic (Anon., 2008b; ICES 2008). ICES advised that management for all fisheries should be based on the assessment of the status of individual stocks (Anon., 2008b).

1.2.2 National Policy

The EU Habitats Directive (92/43/EEC) requires that Atlantic salmon must be maintained and restored to its conservation status in their natural range (Anon., 2008c). Ireland, under its ICES and NASCO obligations, must provide reliable data for stock assessments. The Irish Standing Scientific Committee (SSC) provides information to the Department of Communications Energy and Natural Resources (DCENR) on Irish salmon stocks annually.
The current status of these stocks relative to the objective of meeting biological referenced CLs and catch advice are provided on a yearly basis for the protection of future salmon stocks (Anon, 2008b). The CL used by the SSC to establish the status of individual stocks is the maximum sustainable yield (MSY) or the stock level that maximises the long-term average surplus, as defined and used by the ICES and NASCO (Anon, 2008b).

The most accurate method to determine river specific CL is stock and recruitment analysis but this approach requires 20 to 30 years of stock and recruitment data (Crozier et al., 2004). CLs from data-rich rivers have to be used for data poor rivers (Prévost et al., 2003). A Bayesian hierarchical modelling framework was developed to transport stock and recruitment information between rivers and to set CLs for each fishery district (Crozier et al., 2004; O’Maoiléidigh et al., 2004). The total return of salmon for each river is compared to the predetermined CLs on an annual basis, and those rivers not meeting the limits are closed to angling. In some instances rivers are only open to catch and release. The Mixed Stock Fishery (MSF) for salmon was eliminated in 2007 (Collins et al., 2006). The implication of this decision was that only limited data would be available from the Coded Wire Tag Programme for 2007 and rod catch data would only be available for rivers that meet their conservation limits (Anon., 2008b). This had significant implications for the calculation of individual salmon stocks on Irish rivers, if the only available data for rivers closed to angling was rod catch data. It was vital that alternative stock assessment methodologies be employed.

1.3 Atlantic salmon Stock Declines in Ireland and Irish Conservation Measures

The formal monitoring of Atlantic salmon in Ireland has been on-going since the 1980s and stocks have been decreasing steadily over that period (by 75 percent in recent years) (Anon., 2010). Until 2001, the Irish fishery for Atlantic salmon was managed by a combination of effort limitation and the application of technical conservation measures relating to size and type of fishing gears (Anon., 2008b). A number of fish counting systems were purchased and installed by the Marine Institute in Irish rivers during the late 1990s, through funding supported by the Tourist Angling Measure (TAM) of the Tourist Operational Programme (TOP). Counter trials were initiated on the Waterville (Co. Kerry) and Casla (Co. Galway) rivers to allow the production of yearly stock estimates based on a district basis. Given the continued decline in salmon stocks and the findings of the National Salmon Commission
(Collins et al., 2006), it was decided to shift to river specific, rather than district specific, catch advice (Anon., 2008b). Data from 18 counters on Irish river systems are currently used for catch advice, with the remaining rivers being assessed based on an average rod catch and a range of exploitation rates derived from the rivers with fish counters and published data (Anon., 2008b). Alternative salmon stock assessment methods are required to provide accurate river specific count data to allow for the continued assessment of stocks for the determination of yearly CLs and this work is on-going.

There was an increase in the number of counters deployed on Irish rivers from 2006, in response to the drop in salmon stocks and the pending closures of rivers not meeting their conservation limits. The closure of such rivers for rod catch fishery means that there is an absence of catch data to provide a direct assessment of the status of these stocks (Anon., 2008b). Individual stock information is required to ensure that each river is meeting its conservation limit and that those rivers with a harvestable surplus are sustainably exploited. Counters are now seen as a necessity for fisheries management where no rod catch data is available for rivers closed to angling. Using fish counters on large rivers is complex, so new technologies are required to ensure accurate estimates can be made to obtain conservation limits.

1.3.1 The Importance of Conservation Limits and Accurate Atlantic salmon Stock Assessment Data

National policy in Ireland is to maintain a wild, self-sustaining population of Atlantic salmon in each of the 148 designated salmon rivers but the SSC indicated that the number of Irish rivers meeting their CLs for the 2010 fishery was 57 (Anon., 2010). While conservation limits have been established for these rivers the size of migrating populations relative to the limits needs to be quantified to evaluate the status of these stocks. This is particularly challenging in large rivers with numerous and important tributaries that possibly contain sub-populations or stocks.

The Salmon Management Task Force (Anon., 1996) recommended that salmon management should be based on the premise that there is a definable number of spawners for a given river; thus sustainable exploitation can only take place if there is a surplus of fish over spawning
requirements (Anon., 2008b). This can only be carried out effectively where individual river stock assessment data exists and where a river has been shown to meet its conservation limits. This study was initiated to assess salmonid stock size and assessment methods on large rivers in Ireland. The River Moy, Co. Mayo, which is one of the most prolific salmon producing rivers in Europe, was chosen as a suitable experimental river due to its large catchment size, prolific salmon run (rod catch approximately 10,000 - 15,000 salmon annually) and well established fisheries management infrastructure (Inland Fisheries Ireland).

1.4 Stock Assessment Methodology

Knowledge of the life history of salmon have been studied for population estimates using a variety of direct and indirect stock assessment methodologies and these are discussed and compared below.

1.4.1 Direct Stock Assessment Techniques

Traditionally, weirs were used for direct counting; netting weirs, wooden lath weirs on permanent platforms, wire mesh weirs and fyke nets have all been used in British Columbia and Newfoundland (Anderson & McDonald, 1978). Anderson & McDonald (1978) described a portable weir that was adaptable for a wide range of river conditions that was used in Newfoundland, Canada, to monitor migrating smolt and adults. Labour intensive visual counting from towers have also been used in the US and Canada (Enzenhofer et al., 1998; Holmes et al., 2006; Maxwell & Gove, 2007). Fish fences have also been extensively used in the U.S. and Canada but have not been used in Ireland due to the perception that they require greater man-power and maintenance.

Automated fish counters have been in use since the 1940s (Eatherley et al., 2005). There are three principle types in current use: (1) resistivity, (2) optical, and (3) hydroacoustic. Resistivity and optical fish counters require the construction of in-river structures such as weirs for their deployment with the crump weir being most popular. Trapping mechanisms installed in fish ladders and Borland Lift fish passes have also been used (Eatherley et al., 2005).
1.4.1.a Resistivity and Optical Counters

The main type of resistivity counter used in Ireland today is the Logie counter, named after the location on the North Esk where trials were first conducted (Simpson et al., 1998; Eatherley et al., 2005). The movement of the fish over three electrodes is recorded. The electrodes are installed either on a crump weir or in a closed cylindrical configuration in a tube (Eatherley et al., 2005). Optical counters work on the basis that the fish interrupt a number of vertically arranged beams of light. The pattern created from the breaking of the beam by the fish generates a silhouette of the fish which can be used to determine its size and direction of motion. The Vaki counter is the only optical counter used in Ireland and is installed mainly in weirs and fish ladders.

These methods involve the restricted passage of fish either over a weir or through a restricted area, using resistivity counters or the Vaki counter. The restriction of fish movement can have implications for fish migration patterns. The installation of weir mounted counters can lead to changing morphology and hydrology of the river where they are installed. Resistivity counters can only detect fish swimming close to the sensors; under flood conditions fish tend to swim too high in the water column for detection when passing over a weir. The number of downstream moving fish is often underestimated due to the fish migrating passively downstream with the current and can go undetected by the resistivity counter (Smith et al., 1996; Johnstone et al., 1998). Missed counts in fish ladders are less likely than in weirs as fish are forced through a narrow gap and multiple fish exits are unusual because the size of the gap discourages simultaneous passage of fish (Struthers, 1998). Underwater cameras have been used to validate resistivity counters (Dunkley & Shearer, 1982; Fewings, 1998; Forbes et al., 1999a; Forbes et al., 2000). However, visual validation methods are themselves subject to error, especially when the water is turbid, with low light intensity and glare (Struthers, 1998). In an Irish context, the operation of resistivity counters on weirs in high flows is problematic as counters cannot be validated by visual methods (N. Bond, pers. comm.). However, traps can be used for counter validation by placing them upstream and downstream of a fish counter, and they can be used in turbid waters (Reddin et al., 1992).
While there is abundant evidence for the successful use of resistivity and Vaki counters (Hellawell, 1973; Dunkley & Shearer, 1982; Dunkley & Shelton, 1991; Fewings, 1998; Thorley et al., 2005; Reddin et al., 1992; Fewings, 1994; Eatherley et al., 2005; Shardlow & Hyatt, 2004; Anderson et al., 2007) other studies have shown that these counters have numerous limitations due to limited detection of fish by the sensors during flood conditions, missed downstream counts, poor performance in high turbidity and the restriction of fish movement (Dunkley & Shearer, 1982; Smith et al., 1996, Johnstone et al., 1998, Struthers, 1998; Shardlow & Hyatt, 2004; Baumgartner et al., 2010). In assessing the Vaki, Baumgartner et al. (2010) showed that when operated in conjunction with sonar technology, fish behaviour differed around the counter and trap. Fish approached the units but failed to move through them. This behaviour was not seen when using sonar technology. The study also showed the negative effects of turbidity on the Vaki counter performance (Baumgartner et al., 2010).

Lethlean counters and electromagnetic counter developed by Jackson were installed on Electrical Supply Board (ESB) weirs and passes from the early 1950s in Ireland (McGrath, 1975; Holden, 1988), prior to the use of resistivity and infra-red counters. McGrath (1975) described modifications made to the design of electronic counting tubes which significantly improved the speed of counting and general operations. The operation of these counters in Ireland greatly enhanced the development of Logie counter operations for Irish and European rivers (McGrath, 1975; N. Bond, pers. comm.). As discussed above a number of fish counting systems were purchased and installed in Irish rivers during the late 1990s (Bond, 2005). These counters have been used mainly on small rivers or on weirs installed on large rivers (to provide partial counts). Since 1995, fish counting systems have been installed in twenty two Irish salmon and sea trout rivers using resistivity, infrared and hydroacoustic equipment for establishing CLs (Anon., 2003). There are no Irish publications that deal directly with the operational and performance aspects of resistivity and Vaki fish counters in Ireland. However, fish counter data have been used in studies for the comparison with rod catch data (Crozier & Kennedy, 2001) to analyse long term declines in fish size (Quinn et al., 2006) and in comparison to redd count data for the development of a Bayesian modelling approach to estimate salmonid spawner abundances (Dauphine et al., 2010).
As described earlier, data are available to the SSC for establishing CLs from eighteen of the twenty two counters in Ireland (Anon., 2010). Fish counter data are provided by Inland Fisheries Ireland (IFI) and some private fisheries, except for one site in the Eastern Region, where an experimental counter is operated by the Marine Institute on the River Liffey. Under the terms of the Water Framework Directive (WFD) an emphasis has been put on maintaining the natural river morphology (European Parliament, 2000). Weir mounted counters can interfere with river hydrology and morphology. Because they require a weir or narrow channels for installation, resistivity and infra-red counters can be difficult and costly to install on large rivers. Vaki counters can also interfere with fish migration, as it requires the fish to pass through a narrow channel (Vaki Aqua System Manual, 2009). Turbid water restricts the penetration of the infra-red beam making the system ineffective for counts. The acquisition of accurate length measurements can be difficult to obtain using Vaki and Logie counters (N. Bond, pers. comm.); however, Vaki and Logie counter length data have been used to analyse long term declines in fish size (Quinn et al., 2006). Vaki and Logie counters were tested as part of this study and their effectiveness varied depending on the site of deployment, quality of the installation and the hydrology of the river catchment (Appendix I: Chapter 3a). Split-beam hydroacoustic methods previously operated in Ireland had limited success (Good, 1999) but the DIDSON was highlighted as a viable method based on accuracy (Holmes et al., 2006) and ability to size fish (Burwen et al., 2007; ICES, 2009; Burwen et al., 2010). The DIDSON has been shown to provide accurate estimates of the salmon stocks in the River Deel (ICES, 2009).

1.4.1.b Hydroacoustic Counters

Hydroacoustic counters operate using the principles of sound transmission through water or sonar. A fish is ensonified by a beam of sound and the reflections from the fish are detected by an underwater transducer (Simmonds & MacLennan, 2005). The reflection occurs because of the sudden change in impedance to sound waves within the fish, particularly at the swimbladder (90 percent of the reflection) (Simmonds & MacLennan, 2005). Hydroacoustic counters do not require in-river structures such as weirs. However, the operation of a hydroacoustic counter requires greater technical skills and knowledge for installation and operation than other non-acoustic counters. The lack of a requirement for any in-river
structure makes these counters an attractive proposition for fish stock assessments, particularly for large rivers.

**Hydroacoustic Counter for Salmon Stock Assessments**

Hydroacoustic methods have been used worldwide for the enumeration of fish populations for both marine and freshwater applications. Burgos and Horne (2008) study used split-beam for biomass estimates of walleye pollock (*Theragra chalcogramma*) in the eastern Bering Sea. Other fish species enumeration by acoustics include skipjack tuna, round scad, horse mackerel anchovy and larval fish (Lu & Lee, 1995).

Hydroacoustic counters have been used in a number of North American rivers since the 1960s to estimate adult river escapement (Johnston & Steig, 1995). The Alaskan Department of Fish and Game (ADFG) have been using various hydroacoustic counters since the 1970s. Single and split-beam acoustic techniques have been used since 1977 at Mission, British Columbia for gross estimation of sockeye salmon escapement (*Oncorhynchus nerka*) on the Fraser River (Woodey, 1984; Banneheka et al., 1995; Xie et al., 2002). Only two types of hydroacoustics have been used in the UK to date: the HTI Split-beam, and SoundMetrics’ DIDSON (Dual-Frequency Identification Sonar). The HTI Split-beam was operated on numerous UK rivers such as the Rivers Dovey and Wye and the DIDSON was tested on the Rivers Frome, Tywi, Wye, Dee and Tyne. The performance of hydroacoustic counters vary depending on the site (Maxwell & Gove, 2007). Recent advances in processing software have made the interpretation and analysis of hydroacoustic data more manageable.

Since 1992, spilt-beam hydroacoustic techniques have been used to monitor adult salmonid escapement (*Oncorhynchus* spp. and *Salmo* spp.) in 14 rivers in North America and Europe (Ranson et al., 1998). Hydroacoustic counters are a less intrusive method of quantifying salmon stocks in large rivers but deployment of equipment can be difficult due to flow rates, changing water levels and debris making monitoring in rivers one of the most challenging applications for fisheries acoustics (Ransom et al., 1998). Ransom et al. (1998) reported that rivers typically have a high reverberation level, uneven bottom bathymetry and nonlaminar hydraulics, requiring sophisticated equipment and careful deployment, calibration and testing.
Split-beam hydroacoustics has been found to be more advantageous for in-river deployment particularly for large rivers (Ehrenberg & Torkelson, 1996; Ranson et al., 1995a; Ranson et al., 1995b; Ransom et al., 1998). The development of split-beam techniques (Ehrenberg, 1983) offered several advantages over single-beam and dual-beam techniques (Ehrenberg & Torkelson, 1996; Ranson et al., 1995a; Ranson et al., 1995b, Ransom et al., 1998).

Originally, the application of the split-beam technique for fisheries was developed for providing *in situ* Target Strength (TS) estimates in order to scale echo integrator output for marine mobile surveys (Ransom et al., 1998). In the early 1990s, the split-beam acoustic technique was applied to riverine monitoring (Ehrenberg & Torkelson, 1996). Some assessments of fixed location in-river deployments of single and dual-beam hydroacoustics were tested by Johnston and Steig (1995) and Mesiar et al. (1990). The split-beam technique showed better performance where background noise was an issue, producing target strength estimates that were more accurate and less variable than dual-beam estimates (Traynor & Ehrenberg, 1990; Burwen et al., 1995).

Studies using hydroacoustic counters such as split-beam HTI in the UK have indicated fish detection rates of 50 to 80 percent, though one study found detection rates as low as three percent (Eatherley et al., 2005). Mobile survey evaluations using split-beam for fish enumeration are not recommended and are rarely used for adult salmon assessments in rivers (Cheng et al., 1991). While the method is very good for enumeration, there are significant problems discriminating fish species. This can be overcome by using a standard Target Strength to Length formula (Love, 1971). While the formula is for fish in dorsal aspect, the majority of fish being detected using split-beam acoustics are ensonified in side aspect. This results in a slightly higher signal (approximately 2-3 dB higher) even when good quality data is collected. Kubecká (1998) demonstrated the importance of body aspect for describing relations between acoustic size and real size in freshwater fish species. However, very little research has been carried out in the UK and Ireland relating target strength data to fish species.

A number of companies produce hydroacoustic systems that can be used to monitor fish passage. The system used on the River Moy was produced by Seattle-based Hydroacoustic Technology Inc. (HTI). Prior to this study, initial testing of four split-beam HTI counters for
salmon stock assessments on large rivers was carried out in 1999 with limited success (Rivers Moy, Suir, Laune and Munster Blackwater). Operations on the River Moy began in May 1999 and ran until July 1999 (Good, 1999). The objective of this trial was to collect and examine data from and make recommendations on system operation on the River Moy (Good, 1999). None of the trials on the four test rivers assessed the target strengths of salmonids or carried out validation of the count data obtained. No specific methodology was documented for the operation, making continued operations difficult for the Inland Fisheries Ireland (IFI). The system was assessed as part of this study (Vol. II Appendix Section I, Chapter 3a). The Simrad (EK60) has been successfully tested in various European settings (Knudsen et al., 2004; Knudsen & Gjelland, 2004) and it was tested in an Irish setting for the first time in this study (Vol. II Appendix Section I, Chapter 3a).

1.4.1.b.i DIDSON – (Dual Frequency Identification Sonar)

Advances have been made in acoustic technology and a new system on the market, DIDSON, was taken on board for fish stock assessments. The standard DIDSON is a multi-beam, high frequency sonar operating at two frequencies, 1.8 and 1.1 MHz with an acoustic lens that focuses sound energy to create near-video like images where fish can be observed moving across the static background of the river bed when deployed at a fixed location (Belcher et al., 2002; Maxwell & Gove, 2007). Sites previously unsuitable for split-beam systems are suitable for the DIDSON system because of design and operating characteristics that are more flexible with respect to physical site characteristics (Holmes et al., 2005). The DIDSON imaging system was developed for the United States Navy by the Applied Physics Laboratory at the University of Washington as a tool for harbour surveillance and underwater mine detection (Belcher et al., 2001). Because the DIDSON system uses near-video quality imagery fish can be ‘seen’ moving through the beam allowing fish to be counted and fish behaviour documented. DIDSON was deployed to monitor salmon behaviour near dams (Moursund et al., 2003) but the first DIDSON purchased for use in salmon stock enumeration was by the Alaskan Department of Fish and Game and was tested over a two year period from 2002 to 2003 (Burwen et al., 2004). The first attempt to integrate the DIDSON system operationally for sockeye salmon assessment programmes in British Columbia was on the Horsefly River in 2005 (Cronkite et al., 2006). Not only was the DIDSON data much easier
to interpret but it provided images of fish behaviour never seen before including milling and backsliding during migration and also salmon behaviour near dams (Moursund et al., 2003), fish behaviour around traps and entrances to fish-ways (Baumgartner et al., 2006). The DIDSON count data interpreted by different users produced high precision (Holmes et al., 2006). DIDSON is not known to deter salmonoid migration.

Baumgartner et al. (2005) reported that the DIDSON allowed fish to be observed on-screen even in turbid waters and in heavy flood conditions and Mueller et al. (2006) showed that the system was better at detecting fish than underwater video camera in these conditions. DIDSON has been found to easily detect fish and their direction of travel (Moursund et al., 2003; Burwen et al., 2004; Burwen, et al., 2007; Maxwell & Gove, 2007). To date, DIDSON has been used for a variety of experiments for both stock estimates and behavioural studies of several species. The DIDSON system has even been used for the enumeration of autumn Chinook salmon (*O. tshawytscha*) redds by Tiffan et al. (2004).

DIDSON has been successfully proven as a useful tool for fisheries conservation worldwide (Moursund et al., 2003; Burwen et al., 2004; Galbreath & Barber, 2005; Holmes et al., 2005; Baumgartner et al., 2006; Cronkite et al., 2006; Holmes et al., 2006; Mueller et al., 2006; Maxwell & Gove, 2007). DIDSON has been shown to be easier to install and operate, and is better at collecting data than other hydroacoustic counters (Hately & Gregory, 2006; ICES, 2008) and can be deployed for marine, estuarine and freshwater applications (ICES, 2008). Downstream moving fish were easily distinguished from downstream moving targets such as debris using the DIDSON (Xie et al., 2005; Burwen et al., 2006; Maxwell & Gove, 2007; ICES, 2008). The DIDSON beam can be partially aimed into the substrate because its bottom-subtraction feature can remove stationary structures from the image and the wider vertical beam offers greater coverage of the water column (Burwen et al., 2006). This is a huge advantage over split-beam hydroacoustics for in-river monitoring. In terms of mobile acoustic surveys, the operation of DIDSON showed the reaction of fish to vessels, where DIDSON confirmed changes in behaviour regarding normal upstream swimming directions in sockeye salmon (Xie et al., 2005). DIDSON was highlighted as a viable method of counting salmon based on the accuracy of count data (Holmes et al., 2006; Maxwell & Gove, 2007) and its ability to size fish (Galbreath & Barber, 2005; Baumgartner et al., 2006;
Mueller et al., 2006; Burwen et al., 2007; Maxwell & Gove, 2007; Burwen et al., 2010). Since then DIDSON has been successfully proven as a useful tool for fisheries studies on many different species including chinook salmon (*Oncorhynchus tsawytscha*) (Moursund et al., 2003; Burwen et al., 2007), sockeye salmon (*Oncorhynchus nerka*) (Xie et al., 2002; Burwen et al., 2004; Holmes et al., 2006; Cronkite et al., 2006; Burwen et al., 2007; Maxwell & Gove, 2007), dolly varden (*Salvelinus malma* Walbaum) (Burwen et al., 2007), rainbow trout (*Oncorhynchus mykiss*) and Pacific lamprey (*Lampetra tridentate*) (Moursund et al., 2003). The most significant advantage in an Irish context is that it provides a full fish image rather than an acoustic signal, allowing greater ease for the processing of data.

1.4.2 Indirect Stock Assessment Techniques for Adult and Juvenile Assessments

Indirect stock assessment for adult salmon and juvenile fish stocks can involve the use of traps and mark-recapture (Dempson & Stansbury, 1991; Whelan et al., 1993; Matthews et al., 1997; Poole et al., 1996; Byrne et al., 2003; Byrne et al., 2004; RESCALE, 2010), redd counts (Taggart et al., 2001; Dauphine et al., 2010), rod catch data (Milner et al., 2001; Gargan et al., 2001; Whelan et al., 2001; Thorley et al., 2007), tagging (Dempson & Stansbury, 1991; Jokikokko et al., 2006; Hedger et al., 2008), and electrofishing (Crozier & Kennedy, 1995a; Crozier & Kennedy, 1995b; Niemelä et al., 1999). There is a large variation in data quality with the use of these methods. In Ireland, acoustic tagging and tracking of fish has been carried out nationally by IFI. In 1992, a research programme using the external acoustic tagging and tracking of adult salmon was initiated to investigate the River Moy’s potential for producing salmon, and to develop a management plan for the river (O’Maoileidigh & Bond, 1994). Although used with credible results, redd counts can be unreliable due to flooding which renders them invisible, redds overlapping and by females spawning multiple times (Taggart et al., 2001; Dauphine et al., 2010). The IFI collate annual redd count data nationally, but this data is not used in stock assessments.

In Ireland, estimates of spawning adults are typically made from commercial data (draft net, traps/bags, snapnets and driftnets), rod catch data and fish counter data. National catch statistics have been collated since 1970 by the IFI and from 2001 has included the gill tagging of all commercial and recreational caught salmon and sea trout. The National Microtagging Programme was initiated in 1980 and was designed to estimate the exploitation
rate of salmon stocks in high seas fisheries and home water commercial fisheries. However, with the closure of the majority of commercial fisheries in 2007 and with the closure of many rivers to angling, the need to develop alternate enumeration technologies was critical (Anon., 2010).

The National Microtagging Programme, initiated in 1980 was designed to estimate the exploitation of salmon stocks in high seas fisheries and home water commercial fisheries. The data collected are used to provide detailed profiles of catch, stock origins and survival off the Irish Coast, and are used nationally and internationally (Anon., 2008b). Since the ban on drift netting in 2007, these data sets have been limited. National catch statistics have been collated since 1970 by the IFI and since 2001 has included gill tagging of all commercial and recreational caught salmon and sea trout. These data provide greater detailed information for scientific advice. Since 2007, information on catch statistics on a river by river basis has become limited due to the prohibition of fishing on rivers not meeting their conservation limits. Since 2007 information on juvenile stocks derived from IFI electrofishing surveys have been used in conjunction with other indicators as a surrogate of stock abundance to provide the SSC with information on which to base stock advice (Anon., 2008b).

Alternative salmon stock assessment methods are required to provide accurate river specific count data where counters cannot be installed, particularly in sensitive areas where in-river works are not permitted, e.g. Freshwater Pearl Mussel (*Margaratifera margaratifera*) habitats and where resources and funding are limited. A measure of the number of outward migrating smolts is one of the most valuable pieces of information at early life stage of salmon populations. A smolt count is a critical fisheries reference point as it represents the outcome of freshwater production (Cowx, 2003). A smolt stock assessment using a screw trap (smolt wheel) as recommended by Cowx (2003) so that juvenile stock assessments could be assessed as an alternative method to adult stock assessments.

As recommended by Cowx (2003), the juvenile assessment technique selected for this study was a smolt count using a screw trap (smolt wheel). Although widely used in the US (Thedinga et al., 1994) and Canada (Chaput & Jones, 2004; Flanagan et al., 2006; Rayton & Wagner, 2006) screw traps had not previously been operated successfully in Ireland and
standard protocols for their use in Irish waters have not been established. Given that there was no adult count baseline data for the River Deel, the screw trap data could also be used to verify adult stock estimates for the river obtained using DIDSON.

1.4.2.1 Trapping Methods for Smolt Mark-recapture Studies

Screw traps facilitate the estimation of fish populations by trapping a proportion of fish migration in a river system applying a mark and at some distant point/time assessing for marked and unmarked animals. Thus, some form of mark-recapture model is required to estimate the total run from the proportion of the run sampled. Mark-recapture methods have been widely used for the biological stock assessments of many species (Cormack, 1964; Ricker, 1967; Otis et al., 1978; Seber, 1982; Schwarz & Seber, 1999; Miyakoshi & Kudo, 1999; Newcomb & Coon, 2001; Schwarz & Taylor, 2009). Mark-recapture data is modeled to estimate trap efficiency and to estimate the salmon population for an individual river (within the model limits (Chapman, 1951; Seber, 1982; Pollock, 2000; Ogle, 2010)).

Various trapping methods have been used for the assessment of smolts. Screw traps were developed for the sampling of rivers on the west coast of North America in the 1980s (McLemore et al., 1989) and have been widely used internationally (Harvey et al., 1997; Thedinga et al., 1994; Chaput & Jones, 2004; Bradford et al., 2007; Scace et al., 2007; Guo Xi-geng et al., 2010; Music et al., 2010). Screw traps allow for the passive sampling of fish species with little impact on the riverine environment; they take advantage of water flow to capture and retain downstream migrating fish and are non-size and non-species selective (Chaput & Jones, 2004). Many studies have been carried out using fences with traps or traps alone, across rivers to intercept fish migrations (Dempson & Stansbury, 1991; Whelan et al., 1993; Matthews et al., 1997; Poole et al., 1996; Byrne et al., 2003; Byrne et al., 2004; RESCALE, 2010) but such trapping can become impossible during flood conditions, particularly for the sampling of juvenile fish (Chaput & Jones, 2004). Traps have been used for the estimation of smolt production in the Burrishoole system, Co. Mayo since 1970 (Whelan et al., 1993; Poole et al., 1996; Matthews et al., 1997; Byrne et al., 2003; Byrne et al., 2004), the River Corrib, Co. Galway (Browne, 1988) and on the River Bush, Northern
Ireland (Kennedy & Crozier, 2010). To date, however, there are no publications of the use of a screw trap for the estimate of smolt output from an Irish river system.

The rate of fish mortality using screw traps must be considered (Thedinga et al., 2008; McLemore et al., 1989) as mortality rates will have an impact on the population estimate. Music et al. (2010) show that the most frequent cause of mortality to fish in screw traps resulted from physical injury associated with debris loading and over-crowding in the live trap; under typical conditions, however, minimal injury could be expected. Mortality due to the fish marking process can occur (Cross, 1972a; Hansen, 1987; O’Grady et al., 2001). However, Riley et al. (2007) showed that there was only a short-term delay in the resumption of smolt migration after tagging rather than a long-term disruption of their behaviour. An earlier study by Cross (1972a) showed that where the tail fin was clipped, regeneration of tissue does occur. Cross (1972a) also found that regeneration of the adipose fin does not occur and that such clipping did not affect smolt behaviour.

1.4.2.1 Data Analysis of Mark-Recapture Data

One of the simplest mark-recapture models for estimating population size is the Lincoln-Petersen (Petersen, 1896, Lincoln, 1930; Ogle, 2010). This model assumes that the population is closed, meaning there is no immigration or emigration and so, the proportion of marked fish in a random sample can provide an estimate of the proportion marked in the total population. This model has undergone several modifications (Schumacher and Eschmeyer 1943; Chapman, 1951; Bailey, 1952; Seber, 1982) but was used by others before and after Petersen (Eberhardt et al., 1979). In 1938, Schnabel developed an extension of the Lincoln-Petersen estimator using multiple sampling surveys to estimate the population size. The assumptions for the Schnabel method were similar to those for the Peterson method; however, the Schnabel method deals with the violation of the assumptions in a more robust way. Modifications were made to the Schnabel method by Schumacher and Eschmeyer (1943). The assumptions made for the modified Schumacher and Eschmeyer method were the same as for the Petersen method and the Schnabel method. Chao (1988) found that the Schnabel estimates were considerably lower than the true population size for estimating
small mammal populations. The method assumed that the population size remained constant throughout the period of mark and recapture, meaning that there was no recruitment, mortality or migration of fish (Schnabel, 1938). However, the advantage for Irish river studies is that the Schnabel modification does not require a large catch at any one time. Catch size is an important factor for consideration when determining which model to apply to mark-recapture data, with newer Bayesian models performing better when catch sizes are small (Gazey & Staley, 1986, Su et al., 2001; Rivot & Prévost, 2002).

**Advances in Mark-recapture Data Analysis Modelling**

Advances have been made in the analysis of mark-recapture data in recent years with the focus now on estimating population *survival* rather than *size* (Lebreton et al., 1992). The advantage of these methods is that the survival estimators are more robust to the partial failure of the assumptions than are estimators of population size where bias can be large (Seber, 1982; Lebreton et al., 1992). Bayesian estimators have been found to perform better than classical estimators in data-poor situations (Gazey & Staley, 1986). Gazey and Staley (1986) found that the Bayesian approach yielded larger mean abundance estimates than traditional methods and that there was little difference in the estimates for larger sampling effort (for relatively small sample sizes). These models have been used widely in fishery research (Gazey & Staley, 1986; McAllister & Kirkwood, 1998; Meyer & Millar, 1999; Su et al., 2001; Rivot & Prévost, 2002; and, Mäntyniemi & Romakkaniemi, 2002).

McAllister and Kirkwood (1998) and Meyer and Millar (1999) cautioned that if priors (prior probability distribution) were not carefully constructed that results may be very biased. Hierarchical modelling has been used to account for differences in run timing between years for Atlantic and Pink salmon (*Oncorhynchus gorbuscha*) and this method significantly improves escapement estimates where limited data are available (Su et al., 2001; Rivot & Prévost, 2002). An advantage of this method is that the ‘between day’ or ‘between year’ analysis of the data by the hierarchical model organises the transfer of information between days or year. This allows the use of the whole experimental data over the course of the run to create modified priors to improve daily inference (Rivot & Prévost, 2002). Mäntyniemi and Romakkaniemi (2002) investigated the implications of schooling behaviour and the effect on
trap efficiency of environmental variables. They presented a probability distribution of the population size from stratified mark-recapture data using Bayesian modelling and Schwarz and Dempson’s (1994) detailed statistical models.

1.4.2.2 Geographical Information Systems (GIS) Supported Estimates

The size of a salmon stock is constrained by its river of origin which controls salmon productivity (Prévost et al., 2001). Geographical Information System is a valuable tool used to transport conservation limits between rivers where no stock assessment data exists. An intermediate habitat variable, the wetted area, has been identified as the only viable approach in the short to medium term for quantifying production areas for transport between rivers (Potter et al., 1998; Crozier et al., 2003). The wetted surface area accessible to salmon appears to be the ‘smallest common denominator’ which can be used across the North East Atlantic area for the calculation of CLs (Anon., 2008b). Stock assessment data for Atlantic salmon are not available for all rivers and the majority of CLs are set using catchment area data as the basis of transport between rivers (Crozier et al., 2003). This approach has been successfully used for Irish rivers were no stock assessment data are available (McGinnity et al., 2003b; Anon., 2008).

Smolt production depends on the amount and quality of freshwater habitat available and there is considerable variation between different rivers even in the same region. McGinnity et al. (1999) used a GIS supported approach to determine an estimate of the potential smolt output of 1st order rivers and sub-catchments in the Northwest Mayo region. This project examined the relationship between salmon smolt productivity and the carrying capacity of the catchment. A modelling approach was used to identify the principal causative factors of such variations (e.g. stream gradient, width, surface area and water chemistry) and that estimates of likely smolt numbers could be predicted (McGinnity et al., 1999). The largest smolt production region in Northwest Mayo was found to be the River Moy (approximately 654,000 smolts or 53 percent of the smolt output for the region). The River Deel sub-catchment was estimated to produce some 72,000 smolts while a sub-catchment of the River Deel, the Shanvolahan River, was estimated to produce 2,147 smolts (McGinnity et al.,
1999). These data provided a broad baseline for the potential smolt production for both the River Moy and River Deel.

1.5 Genetic Stock Identification (GSI)

Genetic studies have shown that Atlantic salmon from both North American and European continents are highly divergent and, within continents, estimates of gene flow between rivers suggest that salmon populations are sufficiently isolated to allow the development of local adaptations through natural selection (Crozier et al., 2003). In Ireland, variations in genetic structure between Atlantic salmon populations belonging to different large river systems (Dillane et al., 2007) and between tributaries of large river systems (Dillane et al., 2008) have been shown.

Genetic Stock Identification has become a widely used tool in fisheries management (Galvin et al., 1995; Ruzzante et al., 2000; Beacham et al., 2004). The National Genetic Stock Identification (NGSI) project (2010) established the baseline of genetic stocks for Irish rivers and it represents a new and valuable resource for the management of Irish salmon stocks. The migratory behaviour of Atlantic salmon makes them susceptible to capture in Mixed Stock Fisheries (MSF) that operate outside estuary limits (Potter & Ó’Maoiléidigh, 2006). Sampling of drift net fisheries identified the Mixed Stock Fishery as taking salmon from more than one river stock when harvested fish were genetically identified to river of origin (Crozier et al., 2004). These data confirmed that fisheries in estuaries and in rivers were more likely to fulfill the requirements of targeting individual stocks that have been shown to be above CLs (Potter & Ó’Maoiléidigh, 2006). In light of these findings, the Irish MSF was closed in 2007 (for drift nets and some coastal draft nets) and the decision was made to move to a single stock fishing on stocks meeting and exceeding CLs (Anon., 2008b).

1.5.1 The Importance of Genetic Stock Identification for Fisheries Management

The National Atlantic Salmon Genetic Stock Identification Project recommended the use of genetic stock identification to support stock size assessments in large Irish rivers, and a baseline was developed from 145 rivers sampled as part of the programme (Anon., 2010a). Accurate count data for large river systems are required for effective management of Atlantic salmon stocks in Ireland. One of the biggest challenges for Atlantic salmon stock assessment
is the acquisition of resources and manpower for the operation of counter technology on large rivers, as previously discussed. This increased the need for new counter technology that could operate under a range of environmental conditions and that could be used for further development of alternative assessment techniques. Closed rivers that were not meeting their conservation limits in 2007 could not be re-opened until salmon stock assessments could be made of such systems. Under the EU Habitats Directive, even small rivers where there are insignificant fisheries hold important stocks of spawning populations and must be maintained for biodiversity (Anon., 2008c).

Large rivers with Atlantic salmon have been shown to be difficult to count due to the expense of the installation of weirs or traps, the technical difficulty of the operation of some counters and demands regarding their operation (Vol. II Appendix Section I: Chapter 3a). Fish stock assessments on smaller tributaries of large rivers are more manageable where the assessment gear require less maintenance and personnel (ICES, 2009).

Genetic Stock Identification (GSI) has been used to identify populations of salmon specific to individual Irish river systems (Dillane et al., 2007). Dillane et al. (2008) described five separate population units within the River Moy system (the River Deel is one of these discrete populations). The Deel was selected for my study because of the genetic distinctiveness of the population and because of the river’s suitability for the deployment of the DIDSON (Vol. II Appendix Section I: Chapter 3a). An accurate estimate of the 2008 cohort for one discrete population within the river was completed using the DIDSON (ICES, 2009). This allowed for the development and use of genetic traits for the purpose of stock assessments. The technique envisaged the use of a counting method that takes population structure into account during data analysis.

1.6 Environmental Variables Affecting Atlantic salmon Migrations

Although there is considerable genetic control over the timing of upstream migration and spawning, environmental factors also play an important role (Quinn et al., 1997). River and catchment specific data can be used to determine key migration triggers for adult and juvenile migration. Studies looking at the influences of environmental factors on Atlantic salmon migration have been undertaken both at the river entry stage (Karppinen et al., 2004;
Thorstad & Heggberget, 1998; Lilja & Romakkaniemi, 2003) and during in-river migration (Smith, 1997; Orell et al., 2007).

1.6.1 Rainfall Patterns

The average annual rainfall in Ireland varies between 700 and 2,000 mm (Met Éireann) with the wettest areas along the western seaboard and mountainous regions (Vol. II Appendix Section VI). Intense rainfall of short duration can happen almost anywhere on a year-round basis causing localised flash flooding. Given the intimate relationship between rainfall and runoff, fish migration can be influenced by the level of rainfall particularly where low summer rainfall events occur (Quinn et al., 1997). Catchment specific information is required to establish the nature of rainfall and discharge relationships, especially where rivers are heavily influenced by groundwater.

A great deal of hydrometric information has been assembled in Ireland which shows that both flood and low flow events occur (MacCarthaigh, 2002; Cawley et al., 2005). Low flows measured towards the end of the 1976 drought have been a standard for the comparison of the severity of droughts in Ireland (MacCarthaigh, 2002). Two-day decreases of over 100 mm were recorded in parts of the west and southwest on the 18th and 19th of November 2009, with some 2-day totals in the Galway region having return periods in excess of 100 years (Walsh, 2010). In 1989, more than 100 mm of rain fell in a 24 hour period over North West Mayo causing major flooding on the River Deel at Crossmalina, Co. Mayo, on the 27th and 28th October (Cawley et al., 2005). The increased intensity of these rainfall events compared to average annual rainfall are significant as they show the possible future difficulty for the operation of existing fish counters and the future installation of fish counter technology in general. Intensive rainfall recorded in the Burrishoole catchment peaked on the 2nd July 2009, where approximately 50 mm of rain fell in two hours on the east side of the catchment (RESCALE, 2010). Current predictions suggest that the magnitude of rainfall events is likely to increase but not their frequency (RESCALE (2010).

1.6.2 Changes in Air and Water Temperatures

Riverine ecosystems are highly susceptible to changes in air and water temperature. Fifteen of the warmest years on record have all occurred since 1990 (RESCALE, 2010). Global
average temperatures have increased by approximately 0.8 °C since 1880 (GISS, 2010). Variations in the annual temperatures recorded at Malin Head, Ireland from 1961 to 1990 (Vol. II Appendix Section VI: Fig. 1.2) show a steady increase in temperature from 1984 onwards by comparison with the 30-year mean (1960 - 1991).

Temperature influences the rates of nearly all chemical and biological processes in water, and thus water temperature impacts directly on habitats in rivers and streams (Elliott, 1984; Eaton & Scheller, 1996). Very few long-term data sets exist for river temperatures but there are notable examples. More than 50 years of temperature data has been collated for the Columbia River (USA) (Petersen & Kitchell, 2001; Webb & Nobilis, 2007). Hind-casting has been undertaken on the River Loire to infer increases in the average annual and summer values of approximately 0.8 °C over the last 120 years due to rising air temperatures and declining discharges (Moatar & Gailhard, 2006; Webb & Nobilis, 2007). Long-term data from Austrian rivers have shown significant rises in river temperatures during the 20th century broadly driven by rising air temperatures (Webb & Nobilis, 2007). Long-term trends suggest river water temperatures respond to climate shifts and climatic influences such as the North Atlantic Oscillation (Elliott et al., 2000; Webb & Nobilis, 2007) and the El Niño Southern Oscillation (Kiffney et al., 2002; Webb & Nobilis, 2007). Changes in river water temperatures are likely to be exacerbated by alterations in rainfall patterns, which, in the case of prolonged droughts, may exacerbate extreme river water temperatures (Graham & Harrod, 2009). The timing of fluctuations in river water temperature is important since the occurrence of extreme temperature events during critical stages in fish development can have negative impacts on fish populations (McGinnity et al., 2009).

1.6.3 Climate Change

The future temperature rise for mid-to-high latitude land areas, such as Europe, is projected to be greater than the increase expected for the planet as a whole (RESCALE, 2010). European temperatures have risen by an average of 0.95 °C in the last 100 years and are projected to increase by a further 2.0 – 6.3 °C this century (compared to 0.74 °C and 1.8 – 4.0 °C globally respectively) (EEA, 2010). Rises in air temperature are matched by warming of freshwater systems (Winder & Schindler, 2004; Hari et al., 2006; Arvola et al., 2010; RESCALE, 2010). Ireland’s temperate climate is principally influenced by the North Atlantic
Ocean and particularly the Gulf Stream circulation (Sweeney et al., 2002). Sweeney et al. (2002) suggest that there is evidence that anthropogenically-induced climate change has influenced Ireland’s climate and ecosystems. This is in line with the latest findings which stated that human activities have contributed significantly to global warming since pre-industrial times and that there is a 90% probability that greenhouse gases produced by human activities have caused most of the observed global warming since the mid-20th century.

Projected changes in rainfall and temperature are likely to have significant impacts on the ecology of fresh and transitional waters in Ireland (RESCALE, 2010). Ocean climate changes are already known to have an impact on growth rates and survival of salmon at sea (Peyronnet et al., 2007). The impacts of climate change on aquatic ecosystems are complex and difficult to predict (Graham & Harrod, 2009; RESCALE, 2010). However, the potential impacts on outward migration of smolts and returning adults has been described by Walsh and Kilsby (2007). The RESCALE report (2010) describes how previous studies have shown that the warming of freshwater and the resulting changes in water quality have had an impact on fish physiology (Fry, 1971; Stefansson et al., 2003); fish phenology (Zydlewski et al., 2005; McGinnity et al., 2009); species distributions (Friedland et al., 2003; Davidson & Hazelwood, 2005); and survival (King et al., 2007; McGinnity et al., 2009).

Although a number of climate change models have predicted increased summer and autumn temperatures and increased winter precipitation, Fowler and Kilsby (2003) highlight that the uncertainty in climate change projections may result from many different factors such as future emissions, model parameterisation and natural climate variability. Reductions in high flows during the bulk of upstream migration during the autumn and winter months would seriously affect rivers where salmon require such high flows to reach spawning grounds. This is particularly important to salmon migration during the summer months as low summer flows can delay salmon migration (Solomon et al., 1999). Increased flood conditions can cause exhaustion in fish migrating upstream (Healey, 2001).

Projected changes to rainfall patterns will impact on water flow regimes in rivers, which will affect the timing of migrations into and out of freshwater and may reduce the survival of
various life history stages of salmonids (RESCALE, 2010). In the Burrishoole system, monthly mean projected river water temperatures remained within the ideal range for salmonid fish habitats (7°C to 20°C) (RESCALE, 2010). However, the number of days when river water temperature exceeded 22°C (the threshold when salmon parr cease feeding and seek refuge) increased in all four time periods for both modeled scenarios (RESCALE, 2010).

With the onset of climate change, the use of index rivers and fish stock assessment sites could prove to be even more valuable (Chadwick, 1985c). The collation of environmental data at Atlantic salmon stock assessment sites has become increasingly more significant in light of the reduction in the number of returning fish to Irish waters and the possible predicted changes due to natural or climate-induced change. The majority of studies in relation to Atlantic salmon have looked at the effects of climate change on the survival and growth of Atlantic salmon in the marine environment (Crozier & Kennedy, 1993; Friedland & Haas, 1996; Friedland et al., 1996; Crozier & Kennedy, 1999; Friedland et al., 2000). In the context of this study, it was important to determine the influence of environmental factors on in-river Atlantic salmon migrations. Predicted climate change may impact not only on these in-river migrations in the future but also on the ability of managers to enumerate these stocks.

In this study fish, migrations past the DIDSON and into the screw trap were assessed in relation to rainfall, water level, flow and air and water temperatures. This is the first study in Ireland to look at the effects of these factors on the migration of both adults and smolts in the same river system.

1.7 Study Rationale - the Stock Assessment of Atlantic salmon on Large River Systems

1.7.1 Aims and Objectives

The aim of this project is to establish a basic salmonid stock assessment approach for large riverine catchments in Ireland. As part of the project, as recommended by the SSC, new counters (adult), existing trapping facilities (adult), juvenile assessments, redd counts and rod catch data were all examined to determine the best technology to provide river by river
spawning status. The methodology developed in this study allows for the possibility of several methods being combined to produce more accurate estimates.

This thesis is presented in two volumes: Volume I covers the literature review, the data collection and presentation and the discussion and conclusions of the study (see below); in the first year of the study existing technologies were assessed and the technical details are presented in Volume II. Volume II also contains additional papers, photographs, maps and a CD of DIDSON images and presentations.

Study Objectives:

- New methods are required to tackle the problems associated with counting Atlantic salmon in large Irish rivers. Hydroacoustics are a non-invasive way of counting salmon and DIDSON (Dual-frequency Identification Sonar) is the hydroacoustic counter of choice for this purpose.

- Juvenile stock assessments can be carried out effectively on smaller rivers to provide good quality smolt stock estimates and in-turn estimates for the returning grilse stocks.

- Environmental factors can be used to determine the timing of stock migration in and out of the system, the influences on the timing of the main migration, and how river discharge can affect the operation of in-river stock assessment technology.

- When used in conjunction with Genetic Stock Identification where discrete genetic populations exit within a river system, the DIDSON counter can provide an estimate of Atlantic salmon from one individual tributary for the Atlantic salmon stocks for the whole catchment,

This thesis describes the testing of existing and new methodologies to determine the best method and/or methods incorporating the effects of the riverine catchment on fish migration behaviour. The results are reported in five chapters and the significance of their findings discussed in detail in the final concluding chapters:
• Chapter 2 provides a detailed description of the selected test catchment, the River Moy and its tributary, the River Deel. All methodology is provided in Chapter 2,

• In Chapter 3 new technologies were examined and methods developed in an Irish context to quantify salmon populations using DIDSON. (Existing technologies tested on the River Moy are described in Appendix Section I Chapter 3a),

• In Chapter 4 stock estimates for the River Deel using the DIDSON counter are examined. Details of fish migrations over a 14-month period are provided for grilse and multi-sea winter (MSW) salmon using new modelling techniques are presented.

• Chapter 5 examines the use of a screw trap and mark-recapture estimates for juvenile salmon stocks on the River Deel,

• Chapter 6 establishes relationships with salmon migration and environmental variables. The effect of environmental variables on in-river stock assessment equipment in the River Deel is detailed,

• Chapter 7 investigates the use of the DIDSON counter in combination with Genetic Stock Identification as a tool for salmon stock assessments,

• Chapter 8 discusses the above methodologies and results,

• Chapter 9 provides conclusions and recommendations regarding the optimum techniques for assessing salmon stocks on large rivers.
CHAPTER 2

2.0 Materials and Methods

2.1 Site Descriptions
To test both methods of direct and indirect counting methodologies the River Moy was chosen as a test catchment. The River Moy is one of nine rivers that has consistently achieved and exceeded its Conservation Limits (O’Maoileidigh et al., 2006). The CLs for 2010 was 16,974 (Anon., 2010). Over the last four years the average salmon run was 43,216 (grilse & MSW). Hydrometric data for the River Moy has been collated by the Office of Public Works (OPW) and the Environmental Protection Agency (EPA) where long-standing gauges have been in place in some parts of the catchment since the 1950s (OPW). These catchment characteristics determined from existing resources were used to examine where the various methodologies could be tested within the catchment. As previously described, the River Deel holds one of five discrete populations of salmon in the River Moy (Dillane et al., 2008), and was chosen as a suitable site at which to assess the utility of a combination of DIDSON fish counting technique and Genetic Stock Identification. The River Deel provided suitability site locations for the deployment of both the DIDSON and screw trap. This made it an ideal catchment for the testing of both direct and indirect counting methodologies.

2.1.1 The River Moy
The River Moy is the fourth largest catchment in Ireland and has an area of 2,108 km² (Fig. 2.1). The source of the River Moy is on the eastern side of the Ox Mountains, Knocknashea, Co. Sligo. It flows in a south-westerly direction to Swinford and Foxford and then flows in a northerly direction through Ballina town, into Killala Bay, where it enters the Atlantic. The catchment includes the Nephin Beg range to the west in Co. Mayo and part of North Co. Roscommon (Fig. 2.1). The main channel of the River Moy is 90 km in length with a smaller catchment than for example other major salmon rivers the Rivers Suir (3,611 km²), Boyne (2,694 km²) and the Nore (2,531 km²). The River Moy although smaller in size than the other three catchments is a more productive catchment for salmon (Anon., 1992). The river is fed by 25 tributaries and streams with approximately 278 lakes in the catchment. Lough Conn
(57 km²) and Lough Cullin (10 km²) are the two largest lakes in the catchment with many smaller lakes and ponds of only a few km². Lough Cullin is linked to the main Moy channel south of Foxford by a small river known locally as the Cross River and Lough Cullin is joined to Lough Conn at Pontoon. The main tributary of Lough Conn is the River Deel, draining a catchment of 227 km² and is a major sub-catchment of the Moy (Anon., 1992) (Fig. 2.2). Other important rivers on the west side of Lough Conn include the Castlehill, Addergoole, Clydagh and Manulla and on the east side the Glenree, Yellow, Strade, Gweestion, Trimogue, Sonnagh, Mullaghanoe, Owengarve, Eighnagh and Owenaher. Earlier genetic work had determined the relative abundance of the five discrete stocks of salmon in the River Moy catchment: Cloonacool, Manulla, Clydagh, Deel and the Main Moy genetic management units (Dillane et al., 2008).

2.1.1.1 Fish movement in the River Moy

Adult salmon migrate into the River Moy every month of the year with multi-sea winter (MSW) fish and grilse (1SW) present. The peak of the spring MSW run is thought to be in April, with grilse running from early May. In addition to Atlantic salmon and brown trout (Salmo trutta), the Moy system contains five species listed under Annex II of the EU Habitats Directive (Habitats Directive 92/43/EEC): the Atlantic salmon (Salmo salar), sea lamprey (Petromyzon marinus), otter (Lutra lutra), white-clawed crayfish (Austropotamobius pallipes), and the freshwater pearl mussel (Margaritifera margaritifera). The sea lamprey is regularly encountered in the lower stretches of the river around Ballina while otter and crayfish are widespread throughout the system (NPWS). The River Deel is an important site for the freshwater pearl mussel, indicative of the pristine nature of this part of the Moy catchment.
The River Moy, one of 26 Irish salmon rivers currently listed as Scientific Areas of Conservation (SAC 002298) under the EU Habitats Directive that annually meets its Conservation Limits (CL), was selected as the ideal location for the assessment of salmon stock assessment methodology. Although accurate figures are not available, it was suggested based on best available information that the salmon population in the River Moy has the potential to produce approximately 700,000 smolts (McGinnity et al., 1999). Recent historic
levels of adult fish were estimated at 150,000 (K. Whelan pers comm.). Historically the River Moy has produced up to 10,000 salmon to the rod alone. The River Moy has a wetted area of 7 km\(^2\) with the highest total CL of 16,974 adult salmon in Ireland (Anon., 2010). The commercial fishery (draft net and trap) which operated until 1998 took up to 15,000 fish in a given year (IFI). Also, the River Moy consistently produces the largest salmon run in the country (Ó’Maoiléidigh et al., 1994; Anon., 2009b).

2.1.1.2 Catchment Characteristics

The main underlying geology of the catchment is carboniferous limestone and carboniferous sandstone present to the extreme west with dalradian quartzites and schists at the south west. Numerous tributaries to the east and south of Lough Conn and all tributaries of Lough Cullin are underlain by granite and while surface flow dominates there is a significant groundwater component. The main landuse in the Moy Catchment is agriculture, mainly pastures and silage. Forestry is present along some major tributaries of the Moy, including the River Deel, Clydagh and Manulla (Vol. II Appendix Section III). No harvesting of the watershed’s forestry has taken place in recent years (Coillte) and there has yet to be any development of hydroelectric power on the system which could potentially interfere with salmon migration patterns. The River Moy maintains good water quality of both surface and groundwater (EPA, 2010).

Very disruptive drainage works were undertaken in the River Moy in the 1960s creating a canal-like river bed profile especially along the main River Moy channel. This is maintained by on-going dredging by the Office of Public Works (OPW). The immediate impact of arterial drainage schemes on Irish rivers was shown to have a negative impact from a fisheries perspective (McCarthy, 1977; McCarthy, 1983). The long-term effects on a number of Irish salmonid catchments have been shown to be very variable, from negative to neutral to positive (O’Grady, 1991; O’Grady, 1992; O’Grady et al., 1992). Toner et al. (1965) found a partial recovery of salmonid stocks on the Bunree system one year after drainage works were carried out. A review of the conditions at the same site in 1990 by O’Grady and King (1992) indicated a complete recovery for both general ecology and fish stocks.
2.1.2 The River Deel - Test Tributary
The River Deel is the largest tributary of the Moy Catchment, with an area of 227 km$^2$. The river rises in the Nephin Beg range and flows for 28 km through a series of peat and agricultural land, to the town of Crossmolina, entering Lough Conn at the northern end of the lake. The River Deel underwent arterial drainage works in the reach immediately downstream of Crossmolina town to its outfall at Lough Conn (Cawley et al., 2005). There are no precise estimates of the productivity of this tributary but estimates based on a GIS simulation to determine the potential smolt output, indicated that the River Deel is the most productive tributary of the west portion of the Moy Catchment (McGinnity et al., 1999). The River Deel was chosen to test the DIDSON as it is a major sub-catchment of the Moy River and has a genetically distinct population of salmon (Dillane et al., 2008). It is an ideal experimental river within the Moy catchment due to the ease of access, its proximity to resources for operation of equipment and existing monitoring sites of the EPA and OPW for the collation of environmental data.

2.2 Direct Counting Methods
Resistivity (Logie), infra-red (Vaki) and three types of hydroacoustic counters were tested during the course of the study: (1) HTI (split-beam); (2) Simrad (split-beam); and (3) DIDSON (Dual-Frequency Identification Sonar). As described below, the existing IFI Logie and Vaki counters on the River Moy were initially tested and an assessment made of the HTI hydroacoustic equipment (Vol. II Appendix Section I: Chapter 3a) (previously operated by Good, 1999). Additional hydroacoustic technology used successfully in other countries, i.e. Simrad split-beam (Vol. II Appendix Section I: Chapter 3a), and newer DIDSON sonar were also assessed. Three exploratory trips were undertaken to obtain training and operational functionality of alternative hydroacoustic counters in Wales, UK (HTI split-beam); Norway (Simrad Manufacturers), and Alaska (ADFG) where DIDSON has been in use since 2003.

2.2.1 Existing Stock Assessment Methodology Tested, River Moy
As part of this study, an assessment of the existing counter technology was part of determining the best methodology for direct stock assessment prior to the testing of the newer hydroacoustic technology. The existing stock assessment technology to be tested was described in Vol. II Appendix Section I: Chapter 3a. An assessment was made of the IFI’s
existing fish counters on the River Moy at the traps, Ballina, Co. Mayo in August 2006. This was to facilitate the testing of counter technology in existence on the River Moy prior to the purchase and operation of new equipment. Three Vaki infra-red counters and a Logie (Resistivity) counter (installed by the IFI in trap 7 on the September 2006) were assessed. The performance of these counters up to the summer of 2007 was limited and validation of the Logie counter on trap 7 at that time was not undertaken as cameras had not yet been installed for validation purposes. The operational needs of the counters increased during flood conditions where a large number of ‘no images’ were recorded on the Vaki counters and the number of ‘error’ reading on the resistivity counter increased due to water turbulence. Flooding also caused large amount of debris to become trapped in the traps where the counters were installed, interfering with fish migration and preventing the affective operation of these counters.

Split-Beam Hydroacoustic System – River Moy

Previous problems encountered running HTI split-beam hydroacoustic counter in 1999 on the Moy main channel included site profile, resources, and adequately trained staff to operate the equipment were taken into account during the counter trials. The system trialed at Hollister’s, Ballina, Co. Mayo, on the River Moy was a HTI Model 241 Split-Beam Hydroacoustic system. The initial structure constructed in 1999 at the site was re-developed and used again for the trials of the HTI split-beam counter in 2006 (Vol. II Appendix Section I: Chapter 3a). Due to the problems encountered operating split-beam in the main River Moy channel at the Hollister’s site, alternative sites and split-beam equipment were assessed. The HTI split-beam sonar was transported to Mount Falcon, River Moy (Fig. 2.4 below) to determine if a better beam fit for the river bed could be achieved at this site. The continuous excessive downtime of the HTI system, particularly at the Hollister’s site, made it impossible to obtain good quality data for processing. As part of the training schedule for the PhD, a site visit was undertaken in June 2006 to the Environment Agency (EA), Wales. Four sites with HTI hydroacoustic counters were visited. The purpose of the visit was to see HTI counters operational in other catchments and discuss parameter settings, calibration and beam mapping methodologies. The counters visited were not functioning during the visit due to high water levels but site logistics were noted and problems regarding site operations in flood conditions, data processing and downtime were observed. This was vital as part of the initial
assessment of the HTI equipment for use in large river catchments for Ireland. This also emphasised the need for the testing of alternative split-beam systems and the new DIDSON hydroacoustic technology.

Due to the cost of DIDSON and from the above findings, a decision was made to firstly trial alternative split-beam hydroacoustic equipment, the Simrad EK60 (on loan from Simrad, Norway). This allowed for the testing of the most up-to-date split-beam sonar on the market. Trials using the Simrad EK60 were carried out at Mount Falcon, River Moy and on the River Deel in December 2007 (Vol. II Appendix Section I: Chapter 3a) (Fig. 2.3 below). Simrad was easier to operate, more intuitive and did not suffer from the same tedium of operation due to system downtime like HTI. Bottom profiling was also carried out using the Simrad EK60, on four tributaries of the River Moy for the purpose of locating suitable sites based on their profiles for a new site to deploy the Simrad EK60 split-beam hydroacoustic (Vol. II Appendix Section I: Chapter 3a) (Fig. 2.4). These tributaries were selected due to their discrete genetic salmon stocks (Dillane et al., 2008). However, data analysis was still an issue in terms of the identification of individual fish targets from the echo data received. Simrad EK60 was very effective for use for bottom profiling and these bottom profiles were also used to determine if a better bottom profile could be located for the testing of DIDSON. The River Deel was found to provide the best bottom profile for acoustic surveys and flooding of the river banks was not a frequent occurrence on this river as with the other tributaries profiled.

It was clear from the above trials and data analysis, that split-beam systems were inadequate for salmon stock assessments in Irish rivers similar to the situation in the US, Canada and UK (Vol. II Appendix Section I: Chapter 3a). The DIDSON’s near-video quality imagery and an easier counting methodology allowed for easy testing of the most up to date hydroacoustic technology. The UK Environment Agency (EA) reported that the DIDSON counter was easier to install, operate and the near-video quality imagery made fish counting easier and more reliable (Hateley & Gregory, 2006). Thus, from the above findings, DIDSON was the technology of choice for the purchase and testing of new technology for this study. The DIDSON counter and a partial fish fence to block the passage behind the sonar were installed as part of the study on the River Deel to determine its suitability for
Atlantic salmon stock assessment. The counting of one discrete salmon population on a tributary of a large river was determined as easier and more effective method of obtaining salmon count data. As described above, previous trials of existing counter technology, particularly split-beam hydroacoustics, proved very problematic on the main channel due to debris loading in large rivers and difficulties in finding a suitable site due to the post drainage bed profile of the River Moy. (Vol. II Appendix Section I: Chapter 3a). The operation of equipment on smaller rivers was less onerous, with a reduction in maintenance and interference with the count due to debris loadings. In smaller tributaries, non-target species should be less of an issue for species apportionment and counting as they could potentially be less numerous. Thus, the new DIDSON was tested and operated on the largest tributary of the River Moy, the River Deel for the purpose of assessing it for Atlantic salmon stock assessment.
Figure 2.3: Counter site locations in the River Moy catchment (Map data sourced from EPA).

Figure 2.4: Bottom profiling locations in the River Moy catchment for the location of a hydroacoustic counter (Map data sourced from EPA).
2.2.2 DIDSON – Dual Frequency Identification Sonar

The standard DIDSON is a multi-beam, high frequency sonar operating at two frequencies, namely 1.8 and 1.1MHz, with an acoustic lens that focuses sound energy to create near-video like images where fish can be observed moving across the static background of the river bed when deployed at a fixed location (Vol. II Appendix Section III) (Belcher et al., 2002; Maxwell & Gove, 2007).

The DIDSON system used in this study was a standard model consisting of a transducer, top side box, 200 ft transducer cable and connection, compass software, and was operated from a computer. The system operates by way of a lens that forms an acoustic image on the transducer array at the rear of the sonar and then software converts the acoustic image into a digital image on a computer screen. The standard operating frequency in identification mode is 1.8 MHz (High Frequency (HF)), with a beam width (two-way) of 0.3 degree horizontal by 14 degree vertical. With a total of 96 beams the DIDSON ranges from 1 m to 15 m at this frequency. The unit dimensions are 30 cm by 20 cm by 17 cm (Sound Metrics). The cross-range resolution is (Fig. 2.5): (range/2) / number of beams and the down-range resolution: window-length / 512. Example: Range 5 m using a 10 m window Standard HF.

- Cross-range resolution = 250 / 96 = 2.6 cm
- Down-range resolution = 1000 / 512 = 1.95 cm
When using the DIDSON to image objects, 96 pulses (12 at a time x 8) send back sonar beams as a function of range and beam number and the display maps the reflected sonar beams. Objects ensonified from the side appear to be seen from above and generally have an acoustic shadow (Sound Metrics) (Fig. 2.6: (a) and (b)).

2.2.3 DIDSON Installation and Operation

The DIDSON counter was brought to the River Boyne, Blackcastle, Navan, Co. Meath on the 25th September 2007 for field testing, to ensure that all equipment was working and allow for the construction of a support or ‘H’– frame for mounting the DIDSON (as per design taken from training with the Alaskan Department of Fish and Game (ADFG), August 2007). The
The pan and tilt mechanism was tested and was fully operational. The DIDSON was deployed in the River Boyne for trials from the 8th – 10th October 2007 (Plate 2.1). These data were used to familiarise the operator with the software and workings of the DIDSON. Initial problems with Sound Metrics SMC software was rectified by the company with new software. Training received in Alaska in August 2007, from the Alaskan Department of Fish & Game was essential to the immediate deployment and ability to operate the DIDSON for initial trials, operation and data collection.


2.2.3.1 DIDSON Site Selection and Beam Mapping

To ensure that the best site was selected for the installation of the DIDSON on the River Deel, river bed profiling was carried out on the 20th September 2007, with the assistance of the IFI (Vol. II Appendix Section III). Further profiling was carried out in November 2007. An optimum site for deployment of a DIDSON requires a gently sloping river bed on the sonar side with a sharp increase in the bed profile towards the opposite bank (E-type channel as described by O’Grady (2006). The DIDSON can be used to carry out river bed profiling (Maxwell & Smith, 2007) but at the Deel this work was carried out prior to the arrival of the DIDSON to select potential sites for testing and deployment. As part of a desk study, a visual aid was used in Excel to help predict beam position in relation to the river bed once profiling...
was completed (Fig. 2.7) (Maxwell & Smith, 2007). This allowed the beam to be moved in relation to the bed to determine beam best fit and was carried out for each site prior to installation; thus allowing for the rapid selection of trial sites and for the deployment of DIDSON. Maxwell and Smith (2007) method also highlighted the need for in-river work during installation to maximise beam coverage to obtain a 10 m counting zone using HF. From these data, Sites 1, 7 and 8 above Knockadangan Bridge (Fig. 2.8), were selected for field trials. Site 7 was selected as the best fit regarding the river bed in terms of river hydrology and suspected fish migration patterns. Fig. 2.7 shows the potential beam position for Site 7, in relation to the river bed and where bed modification works and the installation of a fish fence were required to create a 10 m counting zone.

Figure 2.7: Bottom profile showing water levels, river bed and DIDSON beam potential location, Site 7, River Deel, 2007 (Note: Blue = water level, light blue = changes to water level, red = DIDSON beam and purple = river bed).
To determine the location of the beam in terms of the river bed, two targets of known target strength were used to test which target would be most suitable for the DIDSON trials, namely a tungsten carbide sphere (-38.5 dB) and an experimental target (-30 dB - as developed and used in HTI experiments (Vol. II: Section I: Chapter 3a) ). The H-frame mount for the DIDSON which was constructed for initial trials on the River Boyne was used to mount the DIDSON for deployment on the River Deel Trial Sites 7 and 8. These sites ranged from Knockadangan Bridge to approximately 200 m upstream. During the trials on the River Deel, which commenced on the 18th October 2007, the counter position was moved and the standard tungsten target (-38.5 dB) and a second experimental target (-30 dB) were used to map the beam and ensure that the beam was covering the entire river bed. The beam location was also determined in relation to the water surface at different water levels. The tungsten sphere was an easier target to move in the water on the rod and line on the River Deel for beam mapping during DIDSON operations (Plate 2.2).
Bed modification work was carried out once the site profile was established to remove any large boulders that blocked the beam on the river bed. Hard packed ‘dauby’ clay at 1-3 m in front of the beam was removed to improve beam coverage and reduce reflective backscatter. During beam mapping, calibration of the pan and tilt mechanism with Sound Metrics compass software was undertaken. The angle from the pan and tilt and that of the compass software were recorded when the transducer was level. The pan and tilt mechanism operated successfully to move the transducer from right to left and the H-frame was constructed so that the frame did not restrict the movement of the transducer. Records were made of the water depth at the transducer, water depth from the river bed to the surface of the transducer and the distance from the river bank to the transducer, each time the transducer was moved or beam mapping was undertaken. A minimum of one metre (1 m) water depth was maintained above the transducer at all times.

2.2.3.2 Fish Fence Construction and Installation

Installation of the fish fence and deployment of the counter was only possible in October and November of 2007, due to low water levels and lower than average monthly rainfall during that period (Vol. II Appendix Section VI: A). The fish fence was constructed to create a counting zone to test the DIDSON at its best frequency i.e. High Frequency (HF) at a 10 m
range using a standard DIDSON. The fence also acted both as a secure deployment structure for the DIDSON and as a walkway out to where the transducer was deployed (11 m from the left bank). The fence ensured that fish passed in front of the DIDSON beam within the counting zone and prevented fish from swimming behind it. Fence construction commenced on the 24th October 2007 and was completed to the point where fish could only pass upstream in front of the transducer on the 7th November 2007 and walkway construction continued until the 17th December 2007 when repairs were carried out due to flood damage in early December 2007 (Plate 2.3 and Vol. II Appendix Section III). Another fence was installed at an angle from the end of the walkway to the rivers left bank to ensure that debris did not gather on the fish fence and walkway (water level was not affected by the installation of this fence) (Vol. II Appendix Section III). A deflector fence was installed on the 27th November 2007 to guide fish moving upstream further out from the transducer and into the wider part of the beam. This deflector fence was approximately 2 m long and positioned at an angle downstream from the transducer to prevent debris collecting behind the transducer and fish fence (Plates 2.4).

Plate 2.3: Bed profile adjustment and fish fence and walkway installation, Deel DIDSON site, River Deel (Nigel Bond, MI and Eddie Doherty, IFI) (Louise Brennan, 24/10/2007).
Plate 2.4: DIDSON counter site, showing downstream deflector fence at end of walkway and upstream deflector fence for debris. DIDSON was installed at the end of the walkway (Louise Brennan, 18/12/2007).

Due to bank erosion on the right hand bank after severe flooding in March 2008, another fence of approximately 3 m length was installed on the right bank at a downstream angle, to provide bank protection and to ensure that the counting zone was maintained (Vol. II Appendix Section III). The National Parks and Wildlife Service was consulted regarding the use of bank protection and NPWS carried out a snorkel survey of the site to assess the site prior to river works (Vol. II Appendix Section VIII: CD: Image 2.1 - NPWS snorkel survey, River Deel DIDSON site).

2.2.3.3 DIDSON Software Settings

Initially 10 minute files were used for data collection in continuous mode (as recommended by ADFG); the file size was then changed to 15 minute files in January 2008 so that counts could be collected every 15 minutes (water level data collected every 15 min). Continuous mode was used to collect data to test the different software processing methods and to determine potential bias in the count associated with the use of processing methods applied. Data was collected at a frame rate of 7; receiver gain was fixed at 30 dB and the settings to adjust for Transmission Loss were operated.
2.2.3.4 DIDSON Daily operational needs – Power Sources

The system was operated from a generator using two 12 V batteries. The generator required refueling every 24 hours when running the equipment with a PC and every 48 hours with a laptop. The power drain using the PC meant that once the generator stopped running the batteries lost power within approximately one hour. The installation of an electricity supply on the 17th December 2007 allowed the DIDSON to be operated on a 24-hour basis with a much reduced man power requirement and downtime.

2.2.3.5 Maintenance of DIDSON Counter, Interior Lenses and the Fish Fence

The fish fence was cleaned as necessary depending on the water level for safe access. Leaf litter made up the bulk of debris caught in the fence and these were easily removed using a garden rake. The angle of the deflector fence allowed larger debris to pass safely in front of the DIDSON even at flows just below the top of the fence. Continuous system checks were carried out to ensure the DIDSON was running and recording data accurately. The DIDSON unit and lenses were cleaned on a monthly basis. Where there was increased algal growth in the river with low water levels and/or flood conditions with increased siltation; the DIDSON required more frequent cleaning. A silt box installed over the DIDSON eventually much reduced the frequency for cleaning. (Vol. II Appendix Section III) (Vol. II Appendix Section VIII CD: Image 2.2 Algal movement downstream). No abrasive brushes or chemicals were used to clean the DIDSON as they could cause damage to the lenses. The intensity of this cleaning varied throughout the year prior to the installation of the silt box (Silt box standard installation procedure – Sound Metrics). The silt box almost removed the need for monthly cleaning of the DIDSON unit and lenses (Vol. II Appendix Section III). Increased turbidity and the use of the silt box were noted to reduce the range of the DIDSON at the River Deel site.

All site works were recorded in relation to the duration of downtime due to site works and/or power outages. These data were recorded on an Excel spreadsheet to allow the calculation of downtime of the DIDSON and the adjustment to fish counts where necessary.
2.2.3.6 DIDSON Data Processing and Analysis

The initial assessment of data obtained from trials on the River Deel were used to determine the best site profile, define a counting zone and to assess fish behaviour in the counting zone. Once fish behaviour was established and target work completed, the fish count became the focus of data analysis. Any abnormal fish behaviour was noted if it deviated from the initial assessment. Initially, all files analysed concentrated on obtaining the fish count, measurement and time of fish movement.

Initial testing was carried out to determine the best, most accurate method for obtaining fish counts with the smallest file size using the DIDSON SMC software. The following methods were selected:

1. Image mode analysis.
2. Tallywacking as used and recommended by Suzanne Maxwell, Alaskan Department of Fish and Game, (A.D.F.G) and EA report.
3. N Samples Over Threshold (NSOT) – (Motion Detection).

Both methods of Tallywacking and Image Mode analysis were tested and used to process data collected until a successful method using motion detection was established. Due to the laborious nature of the methods trialed, a semi-automated method was developed during the study, to establish a baseline of the run in the River Deel, to determine fish sizes and to estimate numbers of fish and to identify species in the river (where possible).

2.2.3.7 Semi-Automated Processing

Sound Metrics SMC software was used to develop a semi-automated processing technique. Continuous DIDSON .ddf files were processed using a CSOT (Convolved Sample Over Threshold) processing tool to pick-out fish of length approximately > 30 cm. CSOT only saved the frames in each file where the targets met the criteria selected. Table 2.1 below shows the settings applied for CSOT processing on the River Deel. This subsequently reduced the file size for ease of processing. These shorter CSOT files were viewed in image mode and analysed using the Mark Fish Tool in the SMC software and fish counts and
measurements were collected into an output file (Fig. 2.9 below). These data were automatically registered as upstream, downstream or unknown movement depending on the direction the measurement was taken. Fish length data from the DIDSON were used to determine the proportion of Atlantic salmon migrating past the DIDSON counter in the River Deel. Classification of the motion or type of movement was entered after each measurement was taken. The following fish movement options were taken to mean:

- **Running** = fish actively migrating upstream or downstream through the beam
- **Milling** = fish moving randomly in the beam and not actively migrating
- **Backsliding** = Fish moving backwards, downstream
- **Hanging** = Fish remaining in the same place in the beam
- **Tethered** = Fish attached to a line during validation

The Mark Fish Tool in the SMC software included an arbitrary quality system for rating the quality of measurements after each fish was measured. The analyst rated each measurement and assigned a Q of 1-5. The rating system equated to the following:

- **Q 1** = Unreliable measurement – only part of the fish in the beam.
- **Q 2** = Poor Quality Measurement – Angle too great / strong image reflection.
- **Q 3** = Either tail or head can be seen clearly.
- **Q 4** = Both tail and head seen clearly.
- **Q 5** = Perfect image for measurement.
Data Analysis and Post-processing using Semi-automated Techniques

The migration patterns of fish were counted over a 14 month period and their run timings examined. Ground truthing assessment of the auto-measuring tool in DIDSON SMC software showed that auto estimates were more variable and underestimated length more frequently than manual measurements (Baumgartner et al., 2006). Thus, the manual measuring tool was used to count and measure each fish. The FC files (files of data obtained from DIDSON which are saved in Note Pad format) generated by the SMC semi-automated processing using CSOT were exported to Excel for analysis.

Figure 2.9: Sound metrics SMC software DIDSON output, Deel DIDSON site, River Deel (Louise Brennan, 14/11/2008).
Table 2.1: Settings applied for CSOT processing using DIDSON SMC software (V. 5.18) for the identification of fish migration (> 30 cm), River Deel.

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<tr>
<td></td>
<td>Alpha (dB /m): N</td>
<td>20</td>
<td></td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>Transducer</th>
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</thead>
<tbody>
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<td>Beam Pattern</td>
<td>Threshold (dB)</td>
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<td>Set to Display Threshold</td>
</tr>
<tr>
<td></td>
<td>Maximum Correction (dB)</td>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>
2.2.3.8 Assessment of the Quality Procedure for DIDSON Data Processing

Verification was carried out using three analysts. Initial testing of the semi-automated processing method using CSOT was carried out on 73 test files. These files were assessed using data collected from October 2007 to June 2008, and included twenty-three 10 min ddf files and fifty 15 min .ddf files. Each file was processed using CSOT and both ddf and .csot files were viewed. Background Subtraction (BS) was not used during the test. Three analysts viewed the files in image mode using the manual Mark Fish tool before and after semi-automated processing using CSOT, at a maximum frame rate of 20, counting only fish > 30 cm and recording other events of importance, i.e. otter/mink, lamprey/eel and the presence of shoals of fish approximately < 16 cm. The size, total number of frames per file and processing times of each file were recorded by each analyst for data comparisons. Analyst 1 had 1 year of processing experience, while, Analyst 2 and 3 had three weeks previous DIDSON training and processing experience.

2.2.3.9 Determination of the Ability to Detect Fish in the Counting Zone and the Accuracy of DIDSON Length Data for Species Discrimination

Count validation was carried out using DIDSON for two purposes: firstly to confirm that the DIDSON was recording all fish movements in the beam and that the whole of the counting zone was being observed; and, secondly, to determine the accuracy of DIDSON for length measurements taken during the processing of DIDSON data using the SMC software. The validation was carried out on the 16th and 17th October and the 6th and 26th November 2008, using live tethered fish of known length passed through the DIDSON beam using a rod and line at the DIDSON, River Deel Site, Moy Catchment. Coho salmon (Oncorhynchus kisutch) have been used successfully as a test target from a tethered line to validate the DIDSON-LR (Long Range), (Galbreath & Barber, 2005).

Live fish were netted with the assistance of IFI using a four inch gill net located at Cloghan’s Bay, east of Lough Conn, as part of their pike removal programme. These fish were held in portable aerated tanks pre- and post-validation. A Mitchell (Delphina 420) Surf 130 high modulus carbon hi-tech casting rod was used in the test. The reel used was a B Square Surf 7000 9 ball bearing hyperbalance with a gear ratio of 4:1:1. Sixty two fish of known length
were lightly hooked to a rod and line and allowed to swim naturally through the beam to determine if the DIDSON could detect the fish and to assess the quality of measurements taken by the DIDSON. The data was collected using the 10 m range settings as per operations carried out over the 14 months of data collection, at a frame rate 7. This simulated the daily counting conditions at the site.

Details recorded on each fish included the date netted, species, fork length and total length (cm). Measuring boards were used to manually record the fork length and total length (cm), prior to the fish entering the water. The range (m) where the fish were seen passing through the beam was recorded. Fish were handled by an experienced angler from the IFI, who guided and encouraged the fish to swim near the river bed and surface to ensure the fish could be seen across the whole beam and counting zone. All data was entered into the DIDSON site logbook for processing. True fish lengths and DIDSON recorded lengths were graphed to determine the relationship between these length measurements.

The data was collected at a frame rate of 7 and a range of 10 m, settings as per operations carried out over the 14 months of data collection. This simulated the daily counting conditions at the site. The total fish length (cm) was measured prior to the fish entering the water. The total fish lengths and DIDSON recorded lengths were analysed, to determine the relationship between these length measurements. DIDSON fish lengths were taken using the manual mark fish tool in the SMC software, using the ‘zoom’ tool for ease of measurement.

2.2.3.10 Alternative Semi-Automated Processing Techniques for DIDSON data

Two alternative semi-automated processing techniques were assessed using River Deel DIDSON data from two different manufacturers:

- Sonar 5 (Dr. Balk, H., University of Oslo, Norway) (Balk & Lindem, 2004)

- Echoview (Myriax).
Five files were selected and run through both software packages to see if the same count was obtained as with SMC and to determine if the method would be faster and/or offer better processing options to SMC software. Three 15 minute .ddf files from the 20th December 2008 (16:00-16:45) and two 15 min .ddf files from the 21st December 2008 (13:45-14:15) were tested and the data compared to determine the software performance using River Deel DIDSON data.

2.2.3.11 DIDSON Count Data Analysis, River Deel

Greater than 20,000 fish length measurements were taken using the DIDSON during the 14 month period of this study. Prior to the data analysis for the estimation of Atlantic salmon population and species apportionment, the following was undertaken:

1. Establishing the Atlantic salmon run characteristics for the River Deel.

2. Justifying the use of DIDSON length frequency distribution data for species apportionment, count data adjustments and the determination of run components.

3. Accounting for downtime of the DIDSON used on the River Deel.

1. Establishing the Atlantic salmon Run Characteristics for the River Deel

Before DIDSON length data was analysed, it was important to determine the size of migrating fish present within the River Deel for comparison. Live sampling was not undertaken of adult salmon during the operation of the DIDSON on the River Deel. However, data from the operation of the Ballina traps for floy tagging (Vol. II Appendix Section V: B) on the River Moy and the collation of fish length data from the Moy Fishery, River Moy, for the salmon fishing season from 2007 and 2008 allowed the size range of adult salmon migrating in this system to be determined. Length frequency distributions of 2007 and 2008 fish on the main Moy channel are shown in Fig. 2.10 below. The IFI Ballina Fishery staff used measuring boards to manually record the salmon lengths; weights and scale samples were also provided for genetic analysis. These data were stored in and recorded on scale envelops provided. For the months of April to May 2007 and March to May 2008, screw trap data provided an insight into the fish lengths for the River Deel.
(Chapter 5). However, this sampling was for downstream migrations only, three adult salmon were trapped in 2008 during its operation (one of these fish was trapped migrating downstream on the 6th May 2008 and measured 57 cm).

**River Moy – Moy Fishery Statistics**

The IFI use a simple estimate to separate grilse from spring salmon based on rod catch data (Moy Fishery statistics) of weight to length approximations for salmon run identification. Average sized River Moy grilse are classified by the IFI as salmon ranging from a maximum of 2.5 – 2.7 Kg (approximately a 60 cm salmon). Spring salmon on the River Moy are classified as ranging 3.2 – 3.6 Kg, which they equate to an approximately 70 cm salmon. Fig. 2.10 shows the relationship between length and weight of salmon on the River Moy, re-enforcing the IFI estimations ($r^2 = 0.890$). Fig. 2.11 shows the length frequency histogram of rod caught salmon from the Moy Fishery and Ballina traps, River Moy for 2007 and 2008. The mean salmon length for the River Moy from these data was recorded as 58.7 cm (SD = 9.8) (range: 31 - 97 cm). In 2007, all River Moy salmon sampled were above 40 cm with larger salmon of greater than 70 cm running in May and early June 2007. The majority of salmon running from late June to July ranged in size from 45 – 60 cm, with an increase in salmon length from 55 – 72 cm from August to September in 2007. In 2008, smaller grilse migrated from June to July, with larger grilse and / or MSW salmon running in autumn 2008. Early running rod caught fish from May to early June 2008 were above the average length recorded in this data set, with numerous rod caught salmon above 70 cm.
These data identified the possible problem of distinguishing smaller grilse (≤ 40 cm) from larger brown trout (≥ 35 cm) in the River Deel. However, in both study years, only one salmon was ≤ 35 cm and only seven ≤ 40 cm were sampled in the River Moy (Fig. 2.10) (n = 419). Comparable size samples for trout were not obtained from this data set for the River Moy. Therefore, it was not thought that the Deel DIDSON data would be significantly affected by this cross-over of species when the length frequencies of River Moy salmon were observed. During the period sampled, these data also showed that there was potentially not a significant run of MSW fish on the River Moy (74 salmon were ≥ 70 cm (n = 419)). It was decided that in the context of this study that the Deel DIDSON count data could still provide an accurate estimate with the inclusion of both grilse and MSW salmon in the initial analysis,
prior to determining the grilse run and subsequently the MSW estimation. Thus all three estimates were included using different length cut-offs of $\geq 40$ cm, $\geq 45$ cm and the Bimodal Model developed. This method was used in the absence of age data to show the separation of grilse from MSW salmon.

**Screw Trap Operation River Deel - Species Trapped and Length Statistics**

The operation of a screw trap for smolt estimates (Section 2.3 below) on the River Deel in 2007 and 2008 trapped numerous species within the system (Vol. II, Appendix Section V: C). Brown trout are known to migrate upstream from Lough Conn into the River Deel and the discovery of a dead brown trout kelt of approximately 41 cm confirmed that larger brown trout are present in the system (Vol. II, Appendix Section V: C). This was evidence that some larger brown trout migrated past the DIDSON site. However, of the 802 brown trout trapped during the mark-recapture programme in 2007 and 2008 on the River Deel, only four brown trout were $\geq 30$ cm in length (Vol. II Appendix Section V: C). In both study years, the two largest non-target species trapped were brown trout (*Salmo trutta*) and roach (*Rutilus rutilus*) (Table 2.2). In 2008, brown trout averaged 13 cm with only three trout $> 28$ cm. These fish measured, 31.9, 32, 34.4 cm in length. Roach, in the same year, averaged 12 cm with a maximum of 27 cm but the majority were $< 20$ cm. These data show that where there is an overlap of brown trout and smaller grilse in the River Deel, the numbers were low and proportions low.

*Table 2.2 Mean and maximum length of brown trout (BT) and roach, River Deel, 2007 & 2008 (Brown trout: n = 822 & Roach: n = 385)*

<table>
<thead>
<tr>
<th>Year</th>
<th>Mean Length BT (cm)</th>
<th>Mean Length Roach (cm)</th>
<th>Maximum Length BT (cm)</th>
<th>Maximum Length Roach (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>14.2</td>
<td>14.2</td>
<td>31.9</td>
<td>22.1</td>
</tr>
<tr>
<td>2008</td>
<td>14.6</td>
<td>12.0</td>
<td>34.4</td>
<td>27.0</td>
</tr>
</tbody>
</table>
2. Justification for the use of DIDSON Length Frequency Distribution Data for Species Apportionment, Count Data Adjustments and the Determination of Run Components

During validation all fish targets were detected in the beam DIDSON from the river bed to the surface (Chapter 3). Verification of the semi-automated processing method developed using three analysts, showed that Analyst 3, processing approximately 94% of the DIDSON data, did so at an accuracy of 99% (Chapter 3). It was not therefore necessary to adjust the count data for such a low percentage error accrued during processing (Chapter 3). DIDSON length data has been shown to provide information for the discrimination of fish species (Burwen et al., 2007; Burwen et al., 2010). When comparisons were made during validation of the DIDSON, true length data and DIDSON length data showed a highly correlated linear relationship with the DIDSON estimated length ($r^2 = 0.923$) ($n = 601$) (Chapter 3). These tests provided confidence that the length data as estimated by the DIDSON was sufficiently robust to be used directly without a requirement for any error adjustment.

3. Accounting for Downtime, Deel DIDSON, River Deel

During initial analysis of DIDSON count data, downtime was quantified for a sample of data for the months of November 2007 to February 2008. There was very little difference between the raw total net upstream count and where sample count data were adjusted for downtime. In November 2007, a difference of 116 fish ($\geq 15$ cm) was counted pre- and post-downtime adjustments (this was the first month of operation from a generator; therefore, more downtime was logged than normal). For December 2007, there was a 41 fish difference between the raw net upstream count and the net upstream count adjusted for downtime. There was no downtime in January 2008 and in February 2008 there was only a 10 fish difference. On this basis, a decision was made not to adjust the count data for downtime in calculating monthly fish counts, as data lost was not during the peak migration of salmon and was therefore insignificant. Also, the use of the probability model to discriminate and determine the count for both salmon and brown trout on a monthly basis would not allow for the traditional methods of accounting for downtime i.e. adjusting the downtime hourly counts by calculation the average fish movement (three days prior and three days post downtime to coincide with water flows (N. O’Maoileidigh, pers. comm..). River Deel adult salmon
migrations were found to be triggered by air and water temperature and not by water level or flow (Chapter 6).
Species Apportionment, Establishing the 2008 Cohort and the Estimation of the
Atlantic salmon population, River Deel

DIDSON count and length frequency data were analysed to determine:

(a) the number of fish migrating past the DIDSON counter over the 14 months of
operation;

(b) if DIDSON length data could be used to apportion species, i.e. salmon and brown trout?;

(c) if DIDSON count and length data could be used to define the 2008 cohort and to
quantify the grilse run for 2008 cohort?;

(d) if DIDSON count and length data could be used to estimate the 2007 kelt run, to
estimate the MSW spring run for 2008 and the early grilse migration for 2008?; and,

(e) if DIDSON count and length data could be used to estimate the proportion of the
MSW components of the 2008 cohort?.

DIDSON is unable to directly identify fish species thus length data is used to classify species.
To resolve this issue, firstly, daily fish count data were graphed to determine peaks and
trends in migration patterns for the River Deel. These count data were then graphed on a
monthly basis to analyse monthly peaks in the total, upstream and downstream migration
patterns for the 14 months data collection. These data showed the overlap of both the 2007
and 2008 cohorts. DIDSON length data were graphed in monthly length frequency
histograms to analyse monthly changes in fish size and to apportion species. DIDSON is
unable to directly identify fish species and uses length data to apportion species (Chapter 3),
thus initially basic length cut-off techniques were used to discriminate between these two
species and secondly, a Bimodal model was developed. These methods were also used to try
to determine sea-age at detection by DIDSON (noting that date of detection may not have
been the date of initial fish migration into the River Deel system due to multiple migrations
into and out of Lough Conn). The quality of data facilitated the breakdown of monthly run
components on the River Deel. This also enabled an estimation of the MSW run component.
Two problems were encountered with determining the salmon count from the DIDSON data which were species discrimination between salmon and brown trout (as described above), and salmon sea-age.

**Species Discrimination of Atlantic salmon and Brown trout – Models Applied**

- **Use of Basic Length Cut-offs**
  The SSC apply an arbitrary length cut off of all fish ≥ 40 cm being salmon and all fish ≤ 40 cm being brown trout (Salmo trutta) or sea trout (Salmo trutta L.) for counter data (Anon., 2008b). This basic length cut-off was applied to the DIDSON data. Due to the finding of a dead brown trout of 41 cm in the River Deel as discussed above (Vol. II, Appendix Section V: C), a second length cut-off of ≥ 45 cm was applied to provide a count where it was assumed that all fish ≥ 45 cm were salmon and all fish ≤ 45 cm were brown trout.

- **The Development of the Bimodal Model for Species Apportionment, using DIDSON Length Frequency Data**
  To try to improve on the above methodology, a Bimodal Model was developed to determine the proportion of Atlantic salmon and brown trout from the River Deel using DIDSON length data. Assuming that the distributions within the bimodal distribution obtained from the length frequency data below, that only two main species were present, i.e. salmon and brown trout (noting fish size of non-target species measured in the screw trap (Vol. II Appendix Section V: C). The Bimodal model proportioned the cross-over of the monthly run to salmon or brown trout depending on the length of fish. Random numbers were generated from both distributions by estimating the mean and standard deviation of the Predicted Model 1: trout and Predicted Model 2: salmon. The model allocated the proportion of salmon and trout within the overlapping size ranges. This was the first attempt to develop a model based on Irish data that could be used to overcome the problem of species allocation using DIDSON.

  A length frequency histogram was plotted from 13,306 records of length measurements obtained from the DIDSON, using only lengths classified as greater than or equal to Q3
(Highest quality DIDSON length measurements: Q3 to Q5: See section 2.2.3.8) (Fig. 2.12).

![Graph showing length frequency distribution of observed data (salmon and brown trout) with Estimated Mean, River Deel, November 2007 to December 2008 (Yellow boxes show the estimated mean of each species).](image)

Figure 2.12: Length frequency distribution of observed data (salmon and brown trout) with Estimated Mean, River Deel, November 2007 to December 2008 (Yellow boxes show the estimated mean of each species).

These data were used to develop a model to determine the proportion of salmon in the count. Fish shoals and suspected eel movement were not included in the data used. The average mean of the raw length frequency data using DIDSON length data was estimated from the bimodal distribution, assuming that the distributions within the bimodal distribution had only two main species present (i.e. salmon and brown trout) and that the distributions were normal. Random numbers were generated from both distributions by estimating the mean and standard deviation of the Predicted Model 1: brown trout and Predicted Model 2: salmon. Numbers were generated with the estimated means 1 and 2, and these numbers fluctuated around a standard deviation for SD1 and SD2. Random numbers were generated (15,000) and the predicted data plotted against the observed data which was weighted and the data compared. To improve the model and to determine the best mean and standard deviation to select using the predicted data to best follow the observed data, these random predicted data were increased, generating random numbers for means 1 and 2 and SD 1 and 2, and weightings, to give $R^2$ and P value. A mixing factor of 50 % (with SD of 0.05) was added. The model then varied around what was
seen in the original plot (Fig. 2.12 above). These data were tested repeatedly 247 times to provide a combination of random lengths for testing. All tests were made comparable in terms of volume of length records that were used in the original. A linear regression was carried out to determine the best relationship between these data, with highest $R^2$ value. The relationship between each mean and standard deviation, with best $R^2$ was the observed (Fig. 2.13 below).

![Figure 2.13: Length frequency distribution with expected and observed data, showing the allocated proportions for salmon and trout, DIDSON length data, River Deel.](image)

To determine which mean/SD/mixing factor combinations were of the greatest importance to the model, scatter plots were drawn. The scatter plots (Vol. II Appendix Section IV: B:) showed that there was a strong relationship between mean 2 and $R^2$, thus mean 2 was very sensitive to $R^2$. The standard deviation was not critically important in this model and the scatter plots showed that a wide range of SD could be used; however, the mean was critically important to the model. Plotting a scatter plot of the predicted frequency against the observed frequency provided an $R^2 = 0.9883$ and equation of line: $y = 0.9643x + 20.628$ (Fig. 2.14) showed that the patterns were robust for the regression.
To calculate the probability of the observed being salmon or trout, the equation from the sigmoidal function for the best fit model, probabilities were used (Vol. II Appendix Section IV: B). These probabilities were then applied to the monthly data to determine the number of salmon and trout.

The Accuracy in Identifying Atlantic salmon that Constitute the 2008/2009 Spawning Cohort

Run timing analysis suggested that the 2008 spawning run extended into January and February 2009. To offset the lack of data for January and February 2009, the inclusion of upstream migrating fish from the 2007 spawning cohort that migrated in January and February 2008 was used. Thus, it was assumed that these late spawners in January and February 2008, from the 2007 cohort were 2008 cohort fish. The DIDSON was operated from November 2007 to December 2008. Further data for 2009 were not obtained due to lack of resources for staff for collecting and analysing data for DIDSON.

To account for kelts from 2007 spawning cohort migrating downstream in January and February 2008, no adjustment (subtraction) was made to the January and February upstream counts. To obtain counts for the spring run component, downstream migrating kelts were also not subtracted from upstream migrating salmon in March and April 2008 (could not determine their number using DIDSON and numbers unknown for this river system). The DIDSON observed the active migration of MSW salmon upstream and downstream over this
two month period. These migrations were not inactive kelt downstream migrations but were multiple active migrations of spring fish into and out of the River Deel to Lough Conn. DIDSON images were key to this assumption that these fish were spring fish (however, this was not confirmed using live trapping).

On analysis of the data, it was determined that the 2008 cohort commenced on the 18th March 2008, the date on which there was a clear observable division between the 2007 and 2008 cohorts and the commencement of the spring run (Chapter 4: Section 4.2.6). In this scenario, the total River Deel salmon count from the 18th March to the 31st December 2008 (the date on which the DIDSON counter ceased operation) was included. This assumed that fish from the 2008 cohort did not spawn in January and February 2009. As described above, it is known from the operation of the DIDSON in the winter of 2007/2008 and from spawning surveys carried out by IFI that fish spawn in the river in January and February. To achieve a more precise estimate of the magnitude of the cohort, and possibly a more valid adjustment for the unaccounted late spawning fish in the 2009; the numbers were raised based on the relative proportions of December counted fish in 2007 to January and February counted fish in 2008. This resulted in a correction factor of 0.5499 for the River Deel count from the 18th March to 31st December 2008.

**Estimated River Deel Atlantic salmon stock assessment using the Deel DIDSON count**

To enumerate the total number of River Deel salmon from the Deel DIDSON count, counts were firstly estimated as per the methodology of national SSC using date and length cut-offs (Anon., 2008b). However, the DIDSON allowed for specific run components to be identified using DIDSON data observations. Thus, the data was analysed secondly, to determine the grilse run, and where possible the varying run components within this system using DIDSON observations, date of detection and DIDSON length data.

- **Defining the 2007 Cohort Kelt Migration, Spring Fish Migration in 2008 and Early Grilse Migration in 2008**
  
  Using the SSC methodology, it was assumed that all of the downstream counts from the 1st January to the 31st May 2008 represented out-migrating kelts (i.e. fish
ascending the river in the previous year). However, from the DIDSON data analysis, monthly patterns showed that kelt migration could be defined on the River Deel from early January to the 28th February 2008 using DIDSON observations as described above. Thus, the SSC methodology would provide an under-estimation for this river.

DIDSON length frequency data and behavioural observations of fish migration aided the identification of the spring run (March to April 2008) and the defining of the early grilse run in May. Where the SSC methodology was used, all upstream migrating fish from January to May are assumed to be spring fish. However, as described above, the 2008 cohort did not commence until the 18th March 2008, thus the spring run on the River Deel was estimated counting all fish migrating upstream ≥ 40 cm for the months of March and April 2008.

- **Defining the 2008 Cohort Grilse Migration**

  Initially, for the purpose of obtaining a grilse population estimate for the River Deel, the main grilse run was assumed to take place from June to December 2008. To adjust for fish migrating into and out of the River Deel, the downstream daily count from June to December 2008 were subtracted from the upstream daily count for the same period. The practice of correcting for multiple fish migrations past a fish counter is standard practice (Anon., 2008b). Data analysis was carried out using River Deel DIDSON length data and length cut-offs to determine the net upstream migration of grilse for 2008.

**Determination of Sea-Age and Run Components using Deel DIDSON Data, 2008**

DIDSON length data and date of detection for each fish were used to estimate the number of grilse and MSW fish in the River Deel. Fish behaviour during migration observed using the DIDSON was also used to make inferences with respect to sea age during migration, e.g. actively migrating spring fish, swimming upstream and downstream from the end of March to April 2008. This model was further improved to determine run components from DIDSON data using seasonal, month and/or date of migration and the DIDSON length data obtained for each fish. This allowed for a more detailed estimation of grilse and MSW fish counts to
be obtained without complicated modelling. The count data estimates were tabulated and graphed to show run components.

**Grilse (1SW Fish)**

Length cut offs were used for apportioning species and the same length cut-offs were also used to determine sea age, i.e. fish ≥ 40 cm were initially assumed to be the grilse and MSW run component. To remove possible MSW fish to provide a grilse estimate, all fish ≥ 40 cm and ≤ 70 cm (minimum) and ≥ 40 cm and ≤ 80 cm (maximum) migrating from June to December 2008 were assumed to be grilse.

**Multi-Sea Winter Fish (MSW Fish)**

To estimate the MSW run, firstly, spring salmon were estimated using the SSC methodology where all upstream migrating fish ≥ 40 cm between January and the 31st May 2008 were assumed to be MSW (as described above). Secondly, all upstream migrating fish ≥ 40 cm between the 1st March and the 30th April 2008 were assumed to be MSW. Finally, to provide an estimate of the yearly migration patterns and count of larger fish, two length cut-offs were used to estimate possible MSW fish migrations where, all fish ≥ 80 cm and ≥ 70 cm were assumed to be MSW fish. The length cut-off of ≥ 70 cm was assumed the likeliest for this catchment due to the known run of smaller grilse and MSW fish in the River Moy as described earlier.

**DIDSON Biological Data Analysis of Non-Target Species Detected**

During the operation of DIDSON, all movements through the DIDSON beam were detected and recorded for analysis which included both bird and mammals. Several other fish species were detected by DIDSON including eel (*Anguilla anguilla*) and lamprey (*Petromyzon marinus*). These data consisted of data where the author/analyst logged the observation as eel/lamprey during processing. These data were plotted to observe run timings for 2007 and 2008 (Vol. II Appendix Section IV: C).
2.3 Indirect Stock Estimate of Adult and Juvenile

Mark-recapture experiments were carried out on both juvenile (smolts) and adult Atlantic salmon from the River Deel and Moy Main channel as a possible alternative methodology to fish counters. Two types of fish marking were employed: numbered Floy tagging of adults and fin clipping of smolts. Adult mark-recapture data were collected through the floy tagging of ‘catch and release’ of fish on the River Moy, i.e. The Ridge Pool, Moy Fishery, Ballina and just upstream at the Ballina traps in 2007 and 2008. Unsuitable fishing conditions made the catching, tagging and recapture of floy tagged fish more difficult and it was not possible to successfully fish the Ballina traps for initial capture in 2008 owing to increased river flow. This resulted in limited tag returns and the usefulness of the data for estimation purposes. Details of methodology and results of these data can be found in Vol. II Appendix Section V: B. The experiment did however highlight the difficulty of operating traps in large rivers, i.e. the River Moy.

Prior to Duaphine et al. (2010), redd counts have not been used in Ireland to estimate salmon numbers but they provide valuable information of key spawning sites. Redd surveys undertaken on the River Deel were used to provide an indication of spawning times and in which months spawning ceased (Vol. II Appendix Section V: A). These data were used to support the assumptions made during the defining of the 2008 cohort for population estimates from the DIDSON counter. Redd surveys also indicated that there was no spawning below the DIDSON counter, thus all spawning salmon would be counted.

There is presently no individual yearly count data available for the River Deel to determine the adult run. Rod catch data does exist for the River Deel but from observations of these data (Anon., 2006) and in discussions with the IFI, Ballina Office, rod catch data for the River Deel is highly variable as the river is not consistently fished annually. This is owing to the variability in water level and flow within the catchment. Thus, rod catch exploitations rates were not determined for the River Deel as they were too variable from year to year. This variability made it impossible to accurately estimate salmon numbers.

The smolt estimate for the River Deel was carried out using a screw trap whereby a proportion of trapped fish were marked and released for possible recapture. Mark-recapture
programmes are required to determine the trap efficiency during these studies and the data modelled to produce the best stock estimates for individual river systems. Smolts were trapped using screw traps in 2007 and 2008, and marked using fin clipping. Mark-recapture data was then analysed using both classical and Bayesian models to produce baseline smolt population estimates for the River Deel. These estimates were then used to predict the adult returns for the following year using sea survival rates.

2.3.1 The Operation of a Screw Trap as a Method for Stock Assessment of Atlantic salmon Smolt, River Deel

A screw trap was operated on the River Deel to estimate the survival rate from spawning by catching smolts migrating downstream using a capture site and a recapture site. The trap is designed to intercept a proportion of the smolts migrating downstream at a fixed point. The diameter of the drum was 1.52 m and fish moving into the drum were collected in the trap at the rear of the drum (Plate 2.5 below). The River Deel screw trap site was located approximately 130 m downstream of the Deel DIDSON site and 30 m downstream from Knockadangan bridge (Fig. 2.2 & Fig. 2.8 above), where smolts were trapped and marked. The site was physically characterised by a pool located just off the river centre to the left bank where the main flow entered, with a deeper pool of greater than 1 m near the right bank. The mouth of the drum was positioned so that the main water flow entered the drum. Where there was a change in flow, trap adjustments were made where possible to coincide with river flow. There was good access from both sides of the river at low flow and from the left bank only at high flow. Trees on both sides of the river were used to secure the trap using rope. Smolts that were trapped and marked were released approximately 100 m upstream from the trap for potential recapture.

2.3.1.1 Screw Trap Deployment, Installation and Removal

The initial deployment and installation of the smolt trap took place on the 5th April 2007, following guide assembly notes and photographs from a previous installation on the River Suir as reported by O’Maoiléidigh (2004). The trap was secured to the river banks using four ropes, one attached to each end of the two floating pontoons to alder tress on the river banks. (Plates 2.5 & 2.6) Trap installation and operation has been described by several authors.
(Murdoch et al., 2000; Chaput & Jones, 2004; Volkhardt & Seiler, 2005; Flanagan et al., 2006; Rayton & Wagner, 2006).

Plates: 2.5 & 2.6: Screw trap site, downstream of Knockadangan Bridge, River Deel, 2007 & 2008. Showing ropes securing trap, sand bags and stone weir to direct flow at low water levels.

In 2007, the start of the smolt run was not determined. Therefore in 2008, an earlier installation was undertaken in March and installation was more difficult due to severe weather conditions. Two smolt traps were initially installed on the 19th March 2008. The installation of the second trap in 2008 was to facilitate re-capture so that smolts could be marked and released at trap 1 and recaptured in trap 2. However, only trap 1 remained operational (located in the same position as 2007 experiment). Trap 2, located at a site approximately 150 m downstream of trap 1, was not fishing efficiently due inadequate flow to turn the drum. This was thought to be as a result of backwatering from Lough Conn but this was not confirmed. Thus sampling using one trap commenced at trap 1 on the 20th March 2008, using the same experimental design as 2007 (Table 2.3).

Table 2.3: Screw trap operations, River Deel, 2007 & 2008

<table>
<thead>
<tr>
<th>Year</th>
<th>Trap Operational</th>
<th>Trap Removal</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>07/04/2007</td>
<td>30/05/2007</td>
</tr>
<tr>
<td>2008</td>
<td>20/03/2008</td>
<td>13/05/2008</td>
</tr>
</tbody>
</table>

Trap removal was made easier due to lower summer flows at the site in June of both years. A tractor and winch were used to lift the screw trap, piece by piece out of the river, reducing man-power requirements. It was not possible to use the tractor and winch for installation in
early spring due to high water levels and water logging on the adjacent land (Vol. II Appendix Section VIII: see enclosed CD: PowerPoint Presentation: Photo series of Screw Trap Installation, Operation and Removal).

2.3.1.2 Screw Trap Operation and Performance

The first year of operation in 2007 was used to investigate the timing of the peak smolt migration and the development of sampling protocols. The second year of screw trap operation in 2008 was to determine the start of the smolt run and to develop a batch marking technique for multiple recaptures. Migrating smolts to sea (via Lough Conn) were trapped in the screw trap and data was gathered consistently on a daily basis over the duration of the smolt run as part of the mark-recapture experiment. The standard sampling interval was 24 hours. Sampling began at approximately 10 am and ended at 4 pm during the peak of run and 10 am to 11.30 am at the end of the run. More frequent sampling was required during increased water levels and flows where debris was entering the trap. Detailed daily records were maintained of fish captured in the trap. Daily cleaning of the trap was undertaken due to large amounts of debris and algae clogging the shaft, drum and trap (Vol. II Appendix Section VIII: PowerPoint Presentation: Photo series of Screw Trap Installation, Operation and Removal). Where low flows occurred, turning the drum manually allowed the algae to enter the trap and was thus be removed. The drum position in the water column was continually adjusted with water level and flow to obtain the optimal position for operation.

2.3.1.3 Mark-recapture of Smolts and Fish Handling

Mark-recapture Techniques

Mark-recapture studies of trapped fish have been undertaken by marking fish using ink jet, tattoo, fin clipping and by tagging (Dietrich & Cunjak, 2006; Rivot & Prévost, 2002; Dussalt & Rodriguez, N.A., 1997). Each of these methods of marking fish has their own limitations with respect to the effects on the marked fish. Salmon smolts in Irish rivers are too small for floy tagging (< 16 cm on the River Deel) and floy tags could increase bird predation of smolts. The method of marking employed by Cross (1972a) appeared to be the most appropriate method of marking fish carried out by clipping a fin with a clean cut. O’Grady et
al. (2001) have shown the negative effects of fin clipping in brown trout but fin clipping has also been shown to have the least affect on smolts with respect to mortality and fin regeneration depending on which fins were clipped (Cross, 1972a; Hansen, 1987; Riley et al., 2007). For short-term experiments such as in this study, fin clipping of the adipose fin with a blunt-nosed scissors (Ricker, 1967) was chosen for marking as the recognition of individual fish was not required (Kipling & Le Crean, 1984). Regeneration after fin clipping is more rapid and more complete with young fish as compared to adult fish, and care was taken to cut diagonally as opposed to horizontally (Ricker, 1967; Cross, 1972a). Cross (1972a) reported that the incidence of infection of the wound and mortality are low using this technique and the swimming behaviour of the fish was not affected. The main advantage of this process was that it was quick and easy to employ and did the least to affect salmon behaviour.

For the purpose of this mark-recapture study, the collected smolts were removed from the trap, anaesthetised, measured and clipped. The smolts were transferred to a bucket of freshwater for recovery prior to their release approximately 230 m upstream at the release site. The release site had a stretch of slow flowing water to allow good distribution and recovery of smolts on release. There were two riffle/pool/glide regions of water downstream, which allowed for the good distribution of smolts on release.

In 2007, daily adipose fin clipping of all smolts trapped was carried out from the 9th April to the 10th May 2007. All smolts were measured to the nearest mm in fork length and a random sample of smolts was weighed to the nearest 0.1 g. The lengths and weights of a random sample of smolts (2007 n = 93 and 2008 n = 126) were taken and adipose fin tissue retained for genetic samples. Genetic material was retained in vials with pure ethanol for genetic analysis (Vol. II Appendix Section VIII: CD: PowerPoint Presentation: Photo series of Screw Trap Installation, Operation and Removal). Random samples of smolt scales were taken throughout the duration of the smolt run in 2007 and 2008. All non-target fish species trapped were counted and length measurements taken of a sample of each species. Daily catches were examined for marked fish and records kept of the number of marked and unmarked fish. The mark-recapture programme was changed in 2008 to allow for batch marking. Batch marking was carried out from the 14th April to the 15th May 2008, with five
batches of smolts marked with different markings during the smolt run for 2008. Batches were marked where there was approximately 50 smolts or more trapped.
2.4 Statistical Analysis - Smolt Data Mark-recapture Study

The experimental design of any mark-recapture study is dependant on the type of analysis to be carried out on the data to obtain a population estimate. The objective of the mark-recapture experiment on the River Deel was to obtain the best estimate for the salmon smolt population from the proportion of migrating smolts sampled by the screw trap. In the context of this study, as described in Section 2.3.1 above, smolt marking in 2007 was treated as a single experiment and these data were analysed using classical mark-recapture models. Multiple recaptures using batch marking in 2008 were assessed to improve the accuracy of the population estimate. Analysis was undertaken treating the 2008 data as both a single experiment and using multiple recaptures from each of the batches marked (Chapter 5). Several more advanced methods of data analysis were applied to the multiple recapture data for 2008, to determine the most credible estimates for the system and to provide a range of estimates of baseline data for the River Deel smolt population.

Due to the increase in the use of Bayesian methods in applied statistical analysis and salmonid mark-recapture analysis, Bayesian statistical rules of probability were employed to make inferences about the daily population estimate and the trap efficiency. Bayesian modelling takes several sources of uncertainty into account. The models were assessed to determine how favourably the Bayesian estimates compared with the classical methods tested.

To verify this baseline data, the results for the 2007 and 2008 smolt run were compared to the indirect estimate provided by McGinnity et al. (1999). Using an upper and lower range of sea survival rates of 5 and 10 % (Section 2.4.2 below) the 2007 smolt migration estimates were used to produce an adult estimate for 2008. This was then in turn compared to the River Deel DIDSON stock estimated for grilse and MSW fish (as described above in Section 2.2.3.11).
2.4.1 Mark-recapture Data Analysis Models Tested and their Assumptions

The classical mark-recapture models used to estimate smolt production were Lincoln-Petersen, Modified Lincoln-Petersen (Chapman, 1951), Schnabel, (1938) Schmacher and Eschmeyer and Modified Schmacher and Eschmeyer, 1943 (Schnabel Regression Method). The methods were used to provide estimates for the total run and where applicable, an estimate of the run for each of the five marked batches which can then be summed to the total. Daily estimates and an estimate for the entire smolt run were established using the more advanced Bayesian models of Rivot and Prévost (2002) and Mantyniemi and Romakkanieme (2002). All model estimates were compared and assessed for their quality of estimate for the River Deel by comparing with predicted returning grilse estimates and the DIDSON grilse estimate; and the potential smolt production estimate of McGinnity et al. (1999).

2.4.1.1 Closed Population Estimates – Single and Multiple Recapture Methods

Two types of mark-recapture analyses were tested, single recapture and multiple recapture methods. In a closed population, single recapture method, it is assumed that no mortality or migration takes place and there is normally only a short period of time between marking and recapture. The individuals taken in the first capture were all marked and released into the population \( (M_1) \). A second capture \( (C) \) was then taken and the fraction of the second capture that were marked \( (M_2) \) were recorded. The population size was estimated from the fraction of captures that were marked. This method has been classed as the single mark-recapture method and it was used to obtain an estimate of both the 2007 and 2008 run size. This was carried out by treating the whole mark-recapture experiment and full data series as one period by totaling all captured, marked and recaptured smolts during the period of marking and recapture.

Lincoln-Petersen and Schumacher and Eschmeyer

Initial analysis for 2007 and 2008 using Lincoln-Petersen \( (N^* = mc/r) \) were analysed according to Ricker (1968). To reduce bias in the Lincoln-Petersen, Chapman’s Modified Petersen (1951) model was applied (Seber, 1982).
Lincoln-Petersen +1 (Chapman Modification):

\[ N = \frac{(M + 1)(C + 1)}{(R + 1)} - 1, \]

Further analysis was carried out using Schumacher and Eschmeyer: Formula: \( N = \frac{CtMt}{RtMt} \) and Schumacher and Eschmeyer +1 Formula, where:

- \( Ct \) = total number of individuals captured in sample t
- \( Rt \) = number of individuals already marked in sample t
- \( Ut \) = number of individuals newly marked and released in sample t
- \( Mt \) = total number of individuals marked in population at sample t

These models were used on the full time series data for 2007 and 2008 as a single experiment.

**Schnabel**

To improve the accuracy of the population estimate a multiple mark-recapture estimate was carried out on the 2008 data. The Schnabel method can be described as the Petersen estimate based on multiple recaptures and is a weighted average of the Petersen estimate. The method assumed that the marked individuals had time to mix into the population so that each marked individual is "equally catchable" as any unmarked individual. The population size must remain the same during the course of the sampling and it is assumed that the number of marked individuals does not change between capture periods (no loss of marking, no mortality, and no migration)

**Schumacher & Eschmeyer Method or the Schnabel Regression Method:**

Schumacher and Eschmeyer (1943) pointed out that one could use a regression with a slope of \( 1/N \) passing through the origin. This formula using the regression methodology (Schnabel Regression Method) was run twice to produce two estimates, using the full time series of the 2008 run, firstly, from the start of the smolt run and secondly, from the date of initiation of marking in 2008. This methodology was also used on each of the five batches to produce population estimates from each batch.
Formula:

\[ \hat{N} = \frac{\sum_{i=1}^{s} (C_i, M_i)}{\sum_{i=1}^{s} (R_i, M_i)} \]

**Population Estimate Based upon Binomial Distribution Mark-recapture Experiment**

A binomial distribution of the mark-recapture data for both study years was calculated (D. Reddin, DFO, pers. comm.) and used to compare with the population estimate obtained using both the Lincoln-Petersen and the Modified Lincoln-Petersen method (Chapman Modification). Population intervals were started at 23000 and were increased by 500 (n = 169). The method allowed for the probability of observing marks in a given population size. The probability of each of the population intervals tested being related to the data set obtained for both study years was tested. However, this type of analysis does not allow for possible shoaling behaviour of smolts, over dispersion during migration or enable “transfer of knowledge” across sampling instances from large to small samples or across the entire sampling period, so strengthening information of the observed population frequency distribution from the sample frequency distribution. Further analysis was carried out using Bayesian modelling to determine what inferences could be made with respect to the River Deel population estimates and to account for over dispersion, shoaling and possible affects of environmental factors.

**2.4.1.2 Bayesian Population Estimate Methodology**

Two types of Bayesian estimates were tested:


Initial runs of the Bayesian models were made with uninformative prior distributions, as the salmon smolt population on the River Deel has not been studied in detail before this study. This ensured that results were influenced by the observed data only and not conditioned by a prior belief of their status.
Rivot and Prévost (2002) model was selected as their hierarchical method was found to significantly enhance the ability to estimate escapement where limited data are available. Prior to Mäntyniemi and Romakkaniemi, (2002), the implications of schooling behaviour were not taken into account in smolt abundance analysis. Mäntyniemi and Romakkaniemi (2002) presented a Bayesian probability distribution of the population size from stratified mark-recapture data. They combined the use of Bayesian modelling and detailed statistical models of Schwarz and Dempson (1994). The Mäntyniemi and Romakkaniemi (2002) model also allowed for the option of incorporating environmental covariates, which could influence the values of population estimates.

1. **Rivot and Prévost (2002):**

Rivot and Prévost (2002) developed a Hierarchical Bayesian Model (HBM) that they applied to yearly mark-recapture data for smolt migration from the River Oir (France). It was applied to the River Deel daily mark-recapture data for smolt migration. Their HBM was designed to provide estimates of the probability of capture and the total population size in a series of years. HBM assumed a hierarchical structure on both the trapping efficiency and the total population size in a series of years and that both were sampled from a common probability with unknown parameters. Applying the River Deel daily data to the HBM, the model was used to assume independence between days as opposed to between years. The model was applied to 30 days of data from the 14\textsuperscript{th} April to the 13\textsuperscript{th} May 2008. Data were collected in the same manner (as described above) as with Rivot and Prévost (2002). As with Rivot and Prévost (2002), the Deel data set contained relatively small sample sizes. This is common for capture mark-recapture studies aimed at estimating wild populations over long time periods (Rivot & Prévost, 2002).

The trap was characterised by a trapping efficiency, denoted by $\theta_i$, which can be interpreted as the probability of each individual being caught (Rivot & Prévost, 2002). The mark-recapture data were used to make inferences on both the trap efficiency $\theta$ and the population size $N$ in a series of days $i$ (Rivot & Prévost, 2002). Daily smolts captured $c_i$, batches marked $m_i$, were released upstream from the screw trap used for recapture ($rm_i$). Four classical assumptions were described by Rivot and Prévost (2002) H1 - H4. Thus for H1: equal
catchability was assumed for released marked fish on their migration downstream. H2: the population was closed during the migration time. Thus assuming that there was no mortality induced by either the capture-marking procedure or natural mortality between the time of marking and recapture for either marked or unmarked smolts. H3: there was no tag shedding (in the case of the River Deel batch marks by fin clipping, all marks are clearly identified and do not change) and all smolts marked and released will migrate out. H4: all m_i marked and released smolts have the same probability of being recaptured at the downstream screw trap. It was assumed that capture and marking do not affect the behaviour of the smolts in a way that would change their vulnerability to the trap. Thus, the probability of recapture of previously marked and released smolts was the same as the probability of capture of unmarked smolts exposed to the trap for the first time (Rivot & Prévost, 2002).

The Markov Chain Monte Carlo (MCMC) simulations were run in WinBugs 13 (Spiegelhalter et al., 2000) and the codes for the HBM were obtained from the authors: Rivot and Prévost (2002). Three MCMC chains of the model were run in parallel, each one primed to a range of pre-set initialisation points for the trapping efficiency θ and the population size N, both having hierarchical components. The HBM was used to combine all days to derive joint inferences about the entire series (N, θ). 90,000 iterations were generated to derive posterior inferences. A “burn-in” period to allow the model sufficient time to reach convergence and stabilise was determined by observing the estimates graphically and 30,000 iterations of the run for each chain were removed where there was too wide a range in the estimates across the three chains. The purpose of using both the trapping efficiency θ and the population size N was to derive joint inferences (N, θ). This provided a mean to estimate each (N_i, θ_i) by taking advantage of the information coming from the data of the other days. This allowed for between-day variations of the θ_i resulting from unpredictable changes in environmental factors or fish behaviour (e.g. river discharge or temperature). A hierarchical structure was also imposed in the total population size N_i, the size of the population was also generated and constrained by ecological processes between days. For the joint prior distribution, independence and exchangeability were assumed between trapping efficiency and total population estimates, as described by Rivot and Prévost (2002).

Using a similar concept to Rivot & Prévost (2002), Mantyniemi and Romakkaniemi (2002) combined the advantages of Bayesian modelling with the detailed statistical model of Schwarz and Dempson (1994). A biologically more realistic model assumption was developed as they considered the possibility of schooling behaviour and introduced the option of incorporating environmental data that might influence the values of the estimated parameter values. Four variants of a set model were developed by Mantyniemi and Romakkaniemi (2002) and all were applied to the River Deel data set.

Mantyniemi and Romakkaniemi (2002) analysed two data sets of Atlantic salmon smolt migration from: the Conne River, Canada (Schwarz & Dempson, 1994) and data from the River Tornionjoki, Scandinavia. The River Deel data were collected using the same methodology. The catchability was determined by knowing the number of unmarked smolts caught and from these data an estimate of the total number of smolts that migrated past the screw trap.

The data were described as per Mantyniemi and Romakkaniemi (2002):

\[ m_i = \text{smolts marked by group-specific marks in day } i. \]

\[ j = \text{trapping day.} \]

\[ r_{i,j} = \text{the number of smolts recaptured.} \]

The number of smolts recaptured in day \( j \) and released in day \( i \) were recorded \((r_{i,j})\), as were the number of unmarked smolts captured \((c_j)\).

Daily measurements of environmental covariates were recorded (see Section 2.6), including water level \((WL_j)\) and water temperature \((WT_j)\). This allowed for the influence of environment on the catchability and travelling time between the release point and the sampling point. Data were prepared as per the Jolly-Seber method (Jolly, 1965; Seber, 1965) being summed by batch, e.g. \( r(1,1) \) to \( r(5,1) \). The Jolly-Seber forecast for the River Deel provided the data in a suitable framework for the purpose of analysis using Mantyniemi and Romakkaniemi (2002). Data were tabulated to provide the sum of returns for clipped fish per batch and covered all of the catches across the five batches. These were used to define potential maximum and minimum values. The range of estimates obtained using all the non-
Bayesian models were used to provide prior information for this model, i.e. 10.132 log minimum and 15.036 log maximum relating to a potential range of from 25,134 to 3,388,909.

The four models developed by Mantyniemi and Romakkaniemi (2002) included:

**Model $M_P$:** a Bayesian version of the traditional Petersen model. This model assumed constant catchability over time and independent behaviour of individuals.

**Model $M_{SD}$:** a Bayesian version on the mark-recapture model introduced by Schwarz and Dempson (1994). This model was improved by Mantyniemi and Romakkaniemi (2002) by constructing a hierarchical structure for the model parameters. This model assumed temporally varying catchability and independent behaviour.

**Model $M_S$:** allowed for the dependent behaviour of smolts to be analysed which accounts for over-dispersion by assuming temporally varying catchability and schooling behaviour.

**Model $M_S'$:** this model was extracted from the model $M_S$ by excluding the use of environmental covariates.

Mantyniemi and Romakkaniemi (2002) assumed that:

1. all marked and unmarked smolts migrated downstream.
2. there was no mark loss between release and recapture sites
3. there was no mortality between release and recapture sites
4. the catchability of a marked smolt did not depend on the time spent in the river after release
5. marked and unmarked smolts had equal catchability and equal aggregation patterns.
6. with the additional assumptions of Petersen model and the Schwarz and Dempson model (1994).

For the model equation specifications see Mantyniemi and Romakkaniemi (2002). The priors were adjusted as prior predictions were not available. For each model, 90,000 iterations were run in two chains. The prior distribution derived for the population size estimates from the other non-Bayesian models were used:

When running model $M_P$: to test this model, two independent chains of the model were simulated in parallel three times based on the total number of smolts captured, marked and recaptured over the duration of batch marking from the 14th April to the 13th May 2008 on the
River Deel. Variable $q$ denoted the catchability which was equivalent to the trap efficiency as already tested in the model developed by Rivot and Prévost (2002). Each chain was run on:

a) **Uninformative prior or initials** - this was the simplest model run but the least informed of Mantyniemi and Romakkaniemi (2002) four models.

b) **Uninformative prior, tuned initials**

c) **Informative prior, tuned initials** - this was the most informed of the $M_P$ models run.

### 2.4.2 Use of Atlantic salmon Smolt Migration Data for the Prediction of Returning Grilse Estimates

As the DIDSON count was the first baseline adult or juvenile counts for the River Deel, model estimates for adult counts produced in Chapter 4 (Table 4.9) were compared to the estimated smolt outward migration from the River Deel for 2007 and 2008 (Chapter 5: Tables 5.5 & 5.6). Rod catch data exploitation rates were not determined for the River Deel as they were too variable from year to year. Marine survival rates in the 1990’s were at 20% (Anon., 2010). The current sea survival estimates, which are lowest in the time series, suggests that on average < 5% of the wild smolts that go to sea from Irish rivers are surviving (Anon., 2010). Returns from hatchery releases in 2008 (returning in 2009) suggested very poor marine conditions leading to poor survival (hatchery fish survival rates are usually lower than for wild fish) (Anon., 2010). The estimated smolt output for the River Deel, based on the screw trap experiment in 2007, was used to determine an estimate of the number of returning adult grilse to the system in 2008.

**Determination of Sea Survival Rates Applied**

The SSC predicted the estimated marine survival rate for returning adults in 2008 was 10% of the wild smolts that go to sea from Irish rivers (Anon., 2008). As 10% was the estimated rate of sea survival of smolts that migrated in 2007 and that returned as adults in 2008 (Anon., 2008), this sea survival rate was thus applied the 2007 and 2008 smolt estimates obtained during the smolt mark-recapture study. The Burrishoole index system (nearby catchment to the River Deel) sea survival rates range between 7 - 8% (ICES, 2010). Thus the second sea survival rate of 8% was also applied to the River Deel data. However, recent findings predicted a reduction in smolt sea survival (ICES, 2010), thus a third sea survival rate of 5% (Anon., 2010) was used to determine the possible lower limit of the River Deel
stock returning. These survival estimates were used determine potential adult runs for the subsequent year. The sea survival rates selected allowed an upper and lower range of sea survival for the prediction of River Deel stocks for 2008 and 2009, sea survival rates of 5% and 10% were applied, using the Burrishoole index of 8% as a mid way sea survival rate. It was thus possible to calibrate the DIDSON adult predications for 2008 (Chapter 4) from the smolt output of 2007 (Chapter 5).
2.5 The Combined Use of DIDSON Hydroacoustic Technology and Genetic Stock Identification, River Deel, Moy Catchment

The spatial distribution of genetically distinct populations throughout the River Moy was established in a previous study (Dillane et al., 2008). Dillane et al. (2008) described five separate population units within the River Moy and the River Deel was one of these five discrete populations. This would allow genetic traits to be used for the purpose of stock assessments to develop a counting method that takes populations structuring into account.

The method combined the use of both new hydroacoustic counter technology DIDSON (Chapter 3) and GSI for the purpose of salmon stock assessments. The method would allow for an estimate to be obtained for a large river using only one count of a single tributary (using DIDSON) and the determination of the genetic proportions of that tributary with respect to the genetic proportions of the main river. This novel stock assessment approach was the first of its kind taking population structuring into account.

2.5.1 Populations Estimates for the River Moy based on Genetic Stock Identification and the River Deel DIDSON Stock Assessment

To determine the total adult count (grilse & MSW) for the River Moy, the River Deel DIDSON count estimates were determined (Chapter 4). Four models were applied to the River Deel DIDSON data to provide estimates for the total adult run (grilse & MSW) for the 2008 cohort and from June to December 2008 (Chapter 4). These estimates were further refined to provide individual estimates for each run component, grilse and MSW (Chapter 4). These data were in turn used to estimate the River Moy salmon stocks through genetic stock identification.

Two different scenarios were tested to determine the total count for the River Moy from the River Deel count:

**Scenario A:**

In Scenario A (1) to A (3), to overcome the issue of run timings of various components and the problem of not having year round samples of genetic material for the River Moy, fish were removed from the River Deel count prior to May 2008. Thus, the emphasis here was on the provision of a count for salmon (grilse & MSW) migrating on the River Moy from the 1st
May to December 2008. This assumed that salmon (grilse & MSW) entering the River Moy were representative of the 1st May to December 2008 migration. However, there was temporal bias in the sample of 257 fish from the River Moy due to the angling season. The accuracy in identifying Atlantic salmon that actually constituted the 2008/2009 spawning cohort was determined in Section 2.2.3.11 above. The River Moy samples provided for the mixture were collected from the beginning of May to the end of September 2008 and corresponded with the duration of recreational angling fishery in 2008. No sampling was undertaken prior to May or after September, thus early running and/or late running fish (grilse & MSW) will not have been sampled. To overcome the issue of sample representativeness, it was assumed that Scenario A provided an estimate for the May to December 2008 run component of the rivers spawning stock. To adjust for this in the River Deel count, fish (grilse & MSW) migrating from June to December 2008 only were used from the count and those fish counted that entered the river in the spring were removed. This was done by removing all fish that migrated past the DIDSON prior to the 1st May 2008 and the 1st June 2008, to provide two estimates for the run (Section 2.2.3.11 above). Thus to provide a fairly conservative estimate of the number of pre-May fish and pre-June fish, to be removed from the River Deel count (to be associated with the summer run fish sampled at the River Moy entry) were subtracted from the total count. This method assumed that they were only counted once and regardless of whether they migrated downstream again.

1. Scenario A (1): River entry sample was representative of 1st May to December and 1st June to December 2008 grilse run, River Moy.

2. Scenario A (2): The River Moy fish sample was representative of the 2008 cohort with the adjustment for late spawners by the inclusion of January and February 2008 upstream migrating fish, for each of the above three models (Section 2.2.3.11 above).

3. Scenario A (3): The River Moy (fish sample of the River Moy) was representative of the 2008 cohort with the adjustment for late spawners using the correction factor as described above in Section 2.2.3.11.
Scenario B:
Scenario B (1) to B (3) assumed that the proportions of the different populations observed in the mixed stock sample were representative of the entire 2008 salmon cohort entering the River Moy and were destined to spawn in the winter of 2008/2009. The number of fish counted by the DIDSON in spring and the number of grilse and summer salmon were used from Scenario B (1) to B (3) to provide a ratio of spring run fish to summer fish as a breakdown of the 2008 cohort estimate for the River Moy population.

1. Scenario B (1): The River Moy Ridge Pool Sample (fish sample of the main channel of the River Moy) was representative of the 2008 cohort from the 18th March to the 31st December 2008, where all fish ≥ 40 cm counted by the River Deel DIDSON were assumed to be salmon (grilse & MSW) and, the River Moy, Ridge Pool Sample (fish sample of the main channel of the River Moy) was representative of the 2008 cohort (Section 2.2.3.11 above & Chapter 4); where all fish ≥ 45 cm counted by the River Deel DIDSON were assumed to be salmon (grilse & MSW) and the River Moy sample was representative of the 2008 cohort (Section 2.2.3.11 above & Chapter 4) and where all fish counted by the River Deel DIDSON were apportioned for species using the Bimodal Model to assign salmon (grilse & MSW) (Section 2.2.3.11 above & Chapter 4).

2. Scenario B (2): The River Moy Ridge Pool Sample (fish sample of the main channel of the River Moy) was representative of the 2008 cohort with the inclusion of January and February 2008, upstream migrating fish, for each of the above three models (Section 2.2.3.11 above).

3. Scenario B (3): The River Moy Ridge Pool Sample (fish sample of the main channel of the River Moy) was representative of the 2008 cohort, with the adjustment for late spawners using the correction factor as described in above in Section 2.2.3.11.

2.5.2 Collection of Genetic Material

Collection of Genetic Material from the River Moy Fishery and Ballina Traps
Samples were collected from the River Moy from angled fish at the Moy Fishery (Ridge Pool and Cathedral beats) at the head of tide on the River Moy between May to September 2008.
As part of a mark-recapture programme operated for the assessment of adult fish in 2007 and 2008, fish were also sampled from the Ballina Commercial Traps (now used for experimental purposes only), River Moy (Section 2.2.3.11 above). Of the samples collected from the Moy Fishery in 2008, 261 of the River Moy 2008 adult scale samples were genetically analysed to determine the proportion of returning adult salmon that belonged to the River Deel population. This proportion along with count data from the DIDSON hydroacoustic station on the River Deel were then used to calculate the total stock for the River Moy.

The breakdown of the number of samples obtained monthly is shown in Table 2.4 below. In total, 257 scale samples from the Moy fishery in 2008 were analysed in the laboratory. Samples were only considered successful where they were genotyped for at least 12 of the 15 loci.

<table>
<thead>
<tr>
<th>Month</th>
<th>No. Rod Caught Atlantic salmon Sampled, Moy Fishery, River Moy (2008)</th>
</tr>
</thead>
<tbody>
<tr>
<td>May</td>
<td>36</td>
</tr>
<tr>
<td>June</td>
<td>99</td>
</tr>
<tr>
<td>July</td>
<td>79</td>
</tr>
<tr>
<td>August</td>
<td>42</td>
</tr>
<tr>
<td>September</td>
<td>1</td>
</tr>
</tbody>
</table>

**Table 2.4: Number of rod caught salmon sampled per month, Moy Fishery, River Moy, 2008.**

**Collection of Genetic Material from the Deel River Screw Trap Operation**

Samples were collected from the operation of a screw trap on the River Deel as part of the smolt mark-recapture programme for 2007 and 2008 (Section 2.2.3.11 above). River Deel smolt samples collected in 2007 as part of the mark-recapture programme from the 9th April to the 10th May 2007 (Chapter 5) were used in this study (n = 273 tissue samples (non-distinctively sampled fin clips)). Individual Assignment (IA) methodologies were used to determine if any of the smolts trapped and sampled in 2007 were caught and sampled during the collection of scale samples on the main River Moy channel during the adult mark-recapture programme in 2008. The samples were genetically screened for comparison with the 2008 adult sample.
**Genetic Analysis**

DNA was extracted from scales from the fishery using an Illustra tissue & cells genomic Prep Mini Spin Kit (GE Healthcare). Detailed laboratory protocols are provided in Appendix VII. The DNA was extracted from 2-3 scales per individual following kit instructions. Each sample was screened for variation at 13 presumed neutral microsatellite loci, and two microsatellites linked with genes of the salmonid major histocompatibility complex (MHC). Presumed neutral loci were as follows; Ssa197, Ssa171, Ssa202 (O’Reilly et al., 1996), Ssa170 (EMBL accession number: AF525205), Sssp2201, Sssp2216, Sssp2210, Sssp1605, Sssp3016 (Paterson et al., 2004), SSOSL85 (Slettan et al., 1995), Ssa157, SsaD71 & SsaD48 (King et al., 2005). MHCI and MHCII were from Grimholt et al. (2002) and Stet et al. (2002) respectively. PCR was carried out in 10 µl volumes, including 1 µl of DNA, 0.25 mM dNTPs, 0.5U Taq DNA Polymerase (Promega™), 2 µl of 5x buffer (Promega™) supplemented with 0.5 mM MgCl2 and 0.25-2 µM each of forward and reverse primers (Table 2.3), one of which was 3’-end-labelled with IRD800 or IRD700 (MWG BIOTECH™). Where possible, some reactions were multiplexed (where primers for more than 2-3 loci were included in a single PCR) to reduce costs (Table 2.5).

Amplifications were carried out on a Hybaid™ thermocycler and consisted of an initial denaturation step of 3 min at 95 °C, followed by 30 cycles of denaturation at 95 °C, annealing at 56 °C for 30 cycles and extension at 72 °C for 30 cycles. Alleles were resolved on 6 % denaturing polyacrylamide gels using a LiCOR4300™ automated DNA sequencer. PCR products of different loci were combined for loading (so that even where loci could not be combined for a multiplex PCR they could still be loaded in a single run to save time (Table 2.5). In this way, 15 loci could be screened in just 9 PCRs and 6 loads on a Licor gel. Allele sizes were determined using a combination of a molecular weight marker (LiCOR™) and allele cocktail standards to ensure consistent scoring of genotypes.
Table 2.5: Details of multiplex reactions and primer concentrations.

<table>
<thead>
<tr>
<th>Locus</th>
<th>Primer concentration</th>
<th>PCR Load</th>
<th>Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ssa202</td>
<td>0.25 μM</td>
<td>Multiplex</td>
<td>Single</td>
</tr>
<tr>
<td>SsaD170</td>
<td>0.5 μM</td>
<td>PCR</td>
<td>Single</td>
</tr>
<tr>
<td>SsaD157</td>
<td>1.0 μM</td>
<td>PCR</td>
<td>Single</td>
</tr>
<tr>
<td>SsaD71</td>
<td>2.0 μM</td>
<td>Multiplex</td>
<td>Single</td>
</tr>
<tr>
<td>Sssp2216</td>
<td>0.25 μM</td>
<td>PCR</td>
<td>Single</td>
</tr>
<tr>
<td>Ssa197</td>
<td>0.5 μM</td>
<td>Multiplex</td>
<td>Single</td>
</tr>
<tr>
<td>Ssa171</td>
<td>0.5 μM</td>
<td>PCR</td>
<td>Single</td>
</tr>
<tr>
<td>Sssp3016</td>
<td>0.5 μM</td>
<td>PCR</td>
<td>Single</td>
</tr>
<tr>
<td>SsaD48</td>
<td>1.0 μM</td>
<td>Multiplex</td>
<td>Single</td>
</tr>
<tr>
<td>Sssp1605</td>
<td>0.25 μM</td>
<td>PCR</td>
<td>Single</td>
</tr>
<tr>
<td>Sssp2210</td>
<td>0.25 μM</td>
<td>Multiplex</td>
<td>Single</td>
</tr>
<tr>
<td>Sssp2201</td>
<td>1.0 μM</td>
<td>PCR</td>
<td>Single</td>
</tr>
<tr>
<td>MHC II</td>
<td>1.0 μM</td>
<td>Multiplex</td>
<td>Single</td>
</tr>
<tr>
<td>MHC I</td>
<td>0.5 μM</td>
<td>Single</td>
<td></td>
</tr>
<tr>
<td>SSOSL85</td>
<td>1.0 μM</td>
<td>Single</td>
<td></td>
</tr>
</tbody>
</table>

All data were entered into Microsoft Excel spreadsheets in a two column format (one allele per column) for statistical analysis and raw genotypic data were checked for errors using the Excel microsatellite toolkit (Park, 2001).

2.5.3 Genetic Baseline
Genetic stock identification of the adult samples caught in the Moy fishery during 2008 was carried out in three stages. Firstly, the baseline against which the samples were to be tested was assembled (from data collated in the course of the National Genetic Stock Identification (NGSI) project). Secondly, the baseline was tested using simulated mixtures containing different proportions of River Deel fish and thirdly, the actual set of samples (n = 257) was tested against the baseline.

Baseline Assembly
The NGSI baseline has an extensive coverage of Irish salmon populations with approximately 150 sites within 80 rivers included. Temporal variation in many of these sites was also covered. For the purpose of the present study, the baseline was trimmed to 1455 individuals which included seven tributaries of the River Moy, all of which were sampled for
at least two cohorts (Table 2.6 below). It also included neighbouring catchments which could potentially contribute to the Moy fishery (Rivers Brusna, Cloonaghmore, Easkey, Ballysadare, Owenmore and Owenduff) (Fig. 2.15) and two other catchments, the Roughty River in Co. Kerry and River Boyne in Co. Meath which were intended to represent other salmon lineages within Ireland.

![Map of River Moy and its tributaries](image)

*Figure 2.15: River Moy and its tributaries, showing neighbouring river systems: 1 = River Deel, 2 = Clydagh, 3 = Manulla, 4 = Spaddagh, 5 = Owengarve, 6 = Cloonacool, 7 = Ballasadare River, 8 = Easkey, 9 = Brusna and 10 = Cloonaghmore (Map data provided by Dr. E. Dillane, UCC).*

The genetic baseline used in the current study was taken from the work of three different studies. Firstly, Dillane et al. (2008) study of population structure in the River Moy looked at twelve tributaries and reported five population groupings (Rivers Deel, Clydagh, Manulla, East Moy & Cloonacool) (Fig. 2.16). Dillane et al. (2008) study looked at 12 microsatellite loci (ten of which were common to this study).
Secondly, in the course of the Marine Institute’s National Genetic Stock Identification Program (National GSI, 2010), 15 loci were analysed (the same 15 used in this study) and the five loci missing from Dillane et al. (2008) were carried out on selected tributaries of the River Moy (namely the River Deel, Clydagh, Manulla, Trimoge, Owengarve and Cloonacool). Thirdly, a more detailed study of temporal variation in the River Moy was undertaken as part of the SALSEA-Merge project (Antoniacomi, 2009). This incorporated more temporal samples into the River Moy baseline as well as including another tributary (River Spaddagh). Samples from catchments in close proximity to the River Moy were also included in the baseline as well as some samples from more distant rivers in other districts. Table 2.6 below provides the breakdown of samples in the baseline and the projects they were screened under.
Table 2.6: Breakdown of the screening of genetic samples included in the baseline

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Tributary</th>
<th>N</th>
<th>Year</th>
<th>Class</th>
<th>Date of Collection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boyne</td>
<td>Blackwater</td>
<td>41</td>
<td>0+</td>
<td></td>
<td>Jul-06</td>
</tr>
<tr>
<td></td>
<td></td>
<td>42</td>
<td>1+</td>
<td></td>
<td>Jul-06</td>
</tr>
<tr>
<td>Roughty</td>
<td>Inshee</td>
<td>47</td>
<td>1+</td>
<td></td>
<td>Jul-06</td>
</tr>
<tr>
<td>Owenduff</td>
<td>Main channel</td>
<td>47</td>
<td>1+</td>
<td></td>
<td>Sep-05</td>
</tr>
<tr>
<td>Owenmore</td>
<td>Main channel</td>
<td>48</td>
<td>1+</td>
<td></td>
<td>Sep-05</td>
</tr>
<tr>
<td>Cloonaghmore</td>
<td></td>
<td>48</td>
<td>0+</td>
<td></td>
<td>Jul-03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>39</td>
<td>1+</td>
<td></td>
<td>Jul-03</td>
</tr>
<tr>
<td>Moy</td>
<td>Deel</td>
<td>48</td>
<td>0+</td>
<td></td>
<td>Jul-99</td>
</tr>
<tr>
<td></td>
<td></td>
<td>48</td>
<td>1+</td>
<td></td>
<td>Jul-99</td>
</tr>
<tr>
<td></td>
<td></td>
<td>39</td>
<td>0+</td>
<td></td>
<td>Jul-03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>48</td>
<td>1+</td>
<td></td>
<td>Jul-03</td>
</tr>
<tr>
<td>Clydagh</td>
<td></td>
<td>48</td>
<td>0+</td>
<td></td>
<td>Jul-03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>48</td>
<td>1+</td>
<td></td>
<td>Jul-03</td>
</tr>
<tr>
<td>Manulla lower</td>
<td></td>
<td>47</td>
<td>0+/1+</td>
<td></td>
<td>Jul-03</td>
</tr>
<tr>
<td>Manulla upper</td>
<td></td>
<td>45</td>
<td>0+/1+</td>
<td></td>
<td>Jul-03</td>
</tr>
<tr>
<td>Trimoge</td>
<td></td>
<td>48</td>
<td>0+</td>
<td></td>
<td>Jul-03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>45</td>
<td>1+</td>
<td></td>
<td>Jul-03</td>
</tr>
<tr>
<td>Spaddagh</td>
<td></td>
<td>45</td>
<td>1+</td>
<td></td>
<td>Jul-94</td>
</tr>
<tr>
<td>Spaddagh upper</td>
<td></td>
<td>38</td>
<td>0+/1+</td>
<td></td>
<td>Jul-03</td>
</tr>
<tr>
<td>Spaddagh lower</td>
<td></td>
<td>38</td>
<td>0+/1+</td>
<td></td>
<td>Jul-03</td>
</tr>
<tr>
<td>Owengarve</td>
<td></td>
<td>48</td>
<td>0+</td>
<td></td>
<td>Jul-03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>47</td>
<td>1+</td>
<td></td>
<td>Jul-03</td>
</tr>
<tr>
<td>Cloonacool</td>
<td></td>
<td>48</td>
<td>0+</td>
<td></td>
<td>Jul-99</td>
</tr>
<tr>
<td></td>
<td></td>
<td>48</td>
<td>1+</td>
<td></td>
<td>Jul-99</td>
</tr>
<tr>
<td>Cloonacool lower</td>
<td></td>
<td>46</td>
<td>0+/1+</td>
<td></td>
<td>Jul-03</td>
</tr>
<tr>
<td>Cloonacool upper</td>
<td></td>
<td>42</td>
<td>0+/1+</td>
<td></td>
<td>Jul-03</td>
</tr>
<tr>
<td>Brusna</td>
<td>Main channel lower</td>
<td>48</td>
<td>0+/1+</td>
<td></td>
<td>Jul-03</td>
</tr>
<tr>
<td></td>
<td>Main channel upper</td>
<td>48</td>
<td>0+/1+</td>
<td></td>
<td>Jul-03</td>
</tr>
<tr>
<td>Easkey</td>
<td>Main channel</td>
<td>48</td>
<td>0+</td>
<td></td>
<td>Jul-03</td>
</tr>
<tr>
<td>Ballasadare</td>
<td>Main channel</td>
<td>40</td>
<td>0+</td>
<td></td>
<td>Jul-03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>49</td>
<td>1+</td>
<td></td>
<td>Jul-03</td>
</tr>
</tbody>
</table>

2.5.4 Statistical Analysis
The ONCOR statistical package was used for estimating proportional contributions of the different samples and tributaries in the baseline to the fishery sample from the River Moy through a mixed stock analysis (MSA). This program was chosen in preference to SPAM and CBAYES as the former have previously been shown to drastically underperform and the latter is susceptible to significant variations in contributing proportions (the software works
best when fishery samples or mixtures are comprised of equal numbers from each of the contributing populations, it also has a tendency to overestimate the proportions for small contributions). ONCOR appears to be less sensitive to these issues.

As listed in Table 2.6 above, the baseline consisted of 32 samples from 15 different rivers/tributaries (Fig. 2.15). Samples from the River Boyne, Roughty, Owenduff and Owenmore were included to represent outgroup populations so that the proportion of fish from outside the River Moy area could be estimated. The Rivers Cloonaghmore, Brusna, Easkey and Ballysadare were included as population samples within the River Moy area but outside the River Moy main stem. The River Moy samples included the tributaries of the River Deel, Clydagh, and Manulla which represent the western sub-catchment, and the tributaries of the River Trimoge, Spadagh, Owengarve and Cloonacool which represent the eastern (most productive) sub-catchment.

As has previously been noted by Dillane et al. (2008), population differentiation within the eastern catchment of the River Moy, while statistically significant, is low and insufficient for reliable stock discrimination to different tributary populations in this area. However, the tributaries of the River Deel, Clydagh and Manulla show marked and substantial differentiation from each other and from the rest of the River Moy tributaries. The River Brusna, which drains into the River Moy main stem estuary, is also characterised by low differentiation from the eastern River Moy populations (suspected to be due to substantial gene flow from straying) (Dillane et al., 2008). The Rivers Easkey, Cloonaghmore and Ballysadare show distinct population differentiation from the Rivers Moy.

The aim of this study was to accurately assess the proportion of River Deel fish occurring in the River Moy fishery (as sampled in 2008) so that this proportion could be used along with real count data from the DIDSON to estimate the total number of salmon running into the River Moy. In order to test the integrity of the baseline, a simulated mixture was created using ONCOR and this tested whether different proportions of River Deel fish could be accurately measured, a number of simulated mixtures containing various proportions of River Deel fish (from 0 to 100%) were constructed using ONCOR. Each simulated mixture
comprised of 2,800 individuals and contained equal proportions of each of the 28 non-Deel samples and equal but varying proportions from the four River Deel samples. Results from the testing of the different proportions of River Deel fish using a number of simulated mixtures containing various proportions of River Deel fish (from 0 to 100%) are presented in Chapter 7, which shows the performance of ONCOR. In all, 11 simulated mixtures were constructed with River Deel sample proportions that were 0 %, 1 %, 2 %, 4 %, 6 %, 8 %, 10 %, 15 %, 25 %, 50 % & 100 % of the total mixture respectively (Chapter 7).
2.5.5 Mixed Stock Analysis of Fishery Samples

Mixed Stock Analysis (MSA) which estimates proportions in a mixture was employed using the same program ONCOR to carry out on the Moy fishery sample from 2008. This allowed for the determination of proportions of each river or tributary stock present, i.e. the proportion of River Deel salmon in the River Moy sample. In all cases, the simulations performed well, with River Deel proportions being well in line with those in the simulated mixtures. The analysis was carried out on the 32 groups outlined in Table 2.6 above, because it is generally perceived that pooling groups of individuals (such as temporal samples as we have here) can introduce a bias in the statistical process whereby larger sample sizes are more likely to have fish wrongly assigned to them (for example, if we pooled temporal samples prior to analysis, the River Roughty would still only have 47 individuals, while the River Deel would have 183). After analysis, the results were pooled into reporting groups representing each river/tributary, which was preferable because the output is more easily interpreted but the sample size bias is not an issue.

From the results of the simulated mixtures, Genetic Stock Identification was carried out on the 257 adults caught in the Moy fishery. Both MSA (as was carried out in the simulations) and Individual Assignment (IA), which took each fish individually and assigned it to its population of origin were undertaken. MSA is generally considered more reliable for estimating overall stock proportions, but IA allowed tracking of individuals and linkage with individual data such as date of capture (which equates with run time here). These data provided an estimate of the overall proportion for the River Deel in the sample from the Ridge Pool sample and thus the percentage of the total run of fish into the River Moy over the duration of the Moy Fishery from May to September 2008. This is a sub-set of the overall run into the River Moy and there was no way of knowing whether the proportion of River Deel fish might differ if the run on the River Moy was sampled evenly throughout the year. Thus, certain assumptions were made with respect to the determination of the overall run of fish for the River Deel DIDSON count and with respect to the five months of genetic sampling at the Moy Fishery, River Moy. However, further analysis was carried out to investigate the monthly breakdown of the proportions of the River Moy tributaries. Thus,
baseline samples which did not contribute were excluded from the results table and the eastern River Moy tributaries were pooled together and with the Brusna River.

2.6 Environmental Data Collection and Analysis

The following environmental parameters were collated for comparisons with fish stock assessment data from the DIDSON counts and screw trap smolt estimates, namely rainfall, water level and flow, air temperature and water temperature. A temperature data logger (StowAway Tidbit Data Logger) was installed on both the screw trap in 2007 and the fish fence, after installation in 2008. The Tidbit Data Logger has 12-bit resolution with the precision of + or – 0.2 °C. The temperature data logger was attached to the back of the screw trap at the trash screen from the 25th April 2007 to 6th June 2007. The average daily temperature was calculated from the data recorded every 15 minutes for comparisons with the smolt run. These data were recorded to the nearest 0.1 °C. To determine the temperature from the 1st April until the 25th April 2007 where temperature data was not recorded, temperature data from the neighbouring catchment of the Rough River, Burrishoole catchment, Co. Mayo, was used to predict data for these 25 days (Vol. II Appendix Section VI: B). To obtain temperature data during the operation of the DIDSON, a temperature data logger was installed on the 13th November 2007 and attached to the fish fence beside the DIDSON. The data logger was removed from the River Deel on the 27th January 2009 when flood water had receded.

Calibrated air temperature and rainfall data were obtained from MET Eireann. Calibrated water level and flow data were obtained from the Environmental Protection Agency’s (EPA) data logger at Knockadangan Bridge (Station No. 3402), approximately 100 m downstream of the DIDSON site (Gird Ref. 115834, 319196) (Vol. II Appendix Section VII). The site is a well-established monitoring site for routine hydrological monitoring by the EPA and has been in operation since April 1997. The average rainfall is 1440 mm/annum with a Dry Weather Flow (DWF) of 0.1 m³/s and 95 percentile flow of 0.3 m³/s. EPA water level data were calculated to the nearest 0.001 m and 0.001 m³/s for water flow. These data were rounded to the nearest 0.1 m and m³/s.
2.6.1 The Influence of Environmental Factors on Atlantic salmon Adult and Smolt Migrations

The point observation method was employed to monitor the upstream migration of salmonids at one point on the river (Lilja & Romakkaniemi, 2003). Adult salmon and smolts were recorded passing the DIDSON and trapped in the screw trap and environmental data compared with these point observations. The daily upstream migration of adult salmon on the River Deel was monitored using the DIDSON counter from the 13th November 2007 to the 31st December 2008. For the purpose of data analysis only the upstream movement during the operation of the DIDSON was compared to environmental parameters (Chapter 6).

Environmental data were analysed graphically to determine the effects of rainfall, changing river level and discharge, air and water temperature on the upstream movement of fish and adult salmon past the DIDSON counter. These data were regressed and seasonality taken into account. The effects of individual environmental factors on the upstream migration of fish were tested using (bivariate) correlations in SPSS. To determine the potential effects of environmental factors on the upstream migration of adult fish (fish ≥ 40 cm) past the DIDSON Counter site. The total daily downstream migration of smolts trapped in the screw trap were analysed graphically to determine the effects of rainfall, changing river level and discharge, air and water temperature on smolt migration. The run timing of both study years was analysed to determine if the peak of the run occurred at the same time and at what water temperature. Correlations (bivariate) with environmental data were carried out in SPSS.

Initial Assessments, River Moy

An assessment of the River Moy, and more specifically the River Deel was used to compare the nature of the river habitat with salmon migrations to determine any specific patterns. The River Deel is part of the Moy-Killala Bay Hydrometric area no. 34, which was classified by the OPW and includes the surface catchment drained by the River Moy and all streams entering the tidal water at Killala Bay between Bunwee Head and Landoon point, Co. Sligo. Hydrometric data were collated from existing gauges on the River Moy from the OPW, Local Authority (Mayo County Council) and the EPA. The Moy catchment is a well-gauged catchment with data dating back to the 1950s and some of these gauge sites where in place prior to drainage works undertaken on the River Moy. The instrumentation of the catchment was assessed regarding the number of rain gauges and flow meters already in existence (Vol.
II Appendix Section III: Map of Hydrometric gauges). Water levels are recorded on a continuous basis by both the OPW and EPA at the selected sites within the catchment and these data were used to analyse discharge in the River Deel and River Moy.

Initially, the whole Moy catchment was assessed with respect to available hydrometric data (Vol. II Appendix Section III). There are 44 staff gauges in total in the Moy Catchment and 21 automatic recorders, recording stage and/or discharge and are operated by the OPW, Mayo County Council and the EPA. The nearest OPW hydrometric gauge to the HTI counter site, Ballina, was the Rahans gauge. Counter data was not sufficient for effective comparisons to be made with the Rahans gauge data due to problems with the HTI counter itself and its operation (Vol. II Appendix Section I: Chapter 3a). Historical commercial catch data (1988 to 1989) were also sourced from Mr. William Thornton regarding the daily totals of salmon caught during commercial fishing of the Ballina traps. However, the upper tidal limit of the River Moy is at the Ballina trap site and water level readings were taken from the staff gauge (located in the ‘free gap’ (an un-obstructed gap between both sets of traps for the free passage of fish)). It was unclear of the origin of this gauge with respect to its installation and if it had been calibrated. For these reasons further analysis of these data was not undertaken. Also, Thorstad et al., (2008) discussed possible problems with the use of trap data for the purpose of comparisons with environmental factors.

Gauge data for the main tributaries of the River Moy was accessed to compare rod catch data with discharge. Known fisheries along the main Moy channel and the River Moy’s main tributaries were used to determine if there were correlations with the number of fish caught on the rod and discharge. The rod catch data for the River Moy lacked specific information in relation to the exact location and time of where fish were caught, particularly on the River Deel, making comparisons with river discharge very difficult. Thus, no correlations were determined using rod catch data and river discharge. Several authors including Thorstad et al. (2008) did not recommend comparisons of rod catch data and environmental factors as the susceptibility of fish to capture and the changes in catches may not correspond to changes in migration activity. The establishment of the River Deel DIDSON site and the River Deel screw trap operation provided specific fish migration data that could be used for comparisons.
with environmental factors using the Knockadangan bridge gauge (EPA) and the installation of a temperature data logger on both the smolt trap (2007) and the DIDSON (2008) as described above.
CHAPTER 3

3.0 The Application of a DIDSON (Dual-frequency Identification Sonar) for the Enumeration of Atlantic salmon for Irish River Catchments.

3.1 Hydroacoustic Counters

Hydroacoustic counters have been used in North American rivers since the 1960’s to estimate adult river escapement (Johnston & Steig, 1995). Single and split-beam acoustic techniques have been used since 1977 at Mission, British Columbia for gross escapement of sockeye salmon on the Fraser River (Woodey, 1984; Banneheka et al., 1995; Xie et al., 2002).

Hydroacoustic counter studies in Ireland were initiated in 1999 using split-beam hydroacoustics (HTI Ltd.) on four large Irish rivers, namely the Rivers Moy, Suir, Laune and Kerry Blackwater. The existing split-beam counter site established on the main channel of the River Moy was re-commissioned in 2006 as part of this study and operated to assess its viability for obtaining salmon stocks for large Irish rivers (Vol. II Appendix Section I: Chapter 3a). River environments are acoustically difficult, especially when fitting split-beam acoustic beams between a river's narrow boundaries (Maxwell & Gove, 2007). During this study, it was difficult to determine if the echoes received using the split-beam were target (salmon), non-target species or debris. Extensive testing over a six month period showed that the HTI split-beam hydroacoustics technology was difficult to operate and maintain. It failed to provide a viable salmon count for the River Moy due to excessive downtime which made it impossible to obtain good quality data for processing (Vol. II Appendix Section I: Chapter 3a). Split-beam hydroacoustics have been effective in the US but they demand a great deal of technical support and verification which was not available on the River Moy. In the UK and Ireland, problems with downstream moving debris made counting fish more difficult, as was experienced on the River Moy (Vol. II Appendix Section I: Chapter 3a). Difficulties encountered on the River Moy included continual system crashes, interference due to background noise and the inability to distinguish debris loadings and fish targets (Vol. II Appendix Section I: Chapter 3a). A range of new technologies was tested including an alternative split-beam counter, Simrads EK60. This counter performed better than the HTI split-beam during trials on both the River Moy and River Deel (Vol. II Appendix Section I: Chapter 3a). However, very little research has been carried out in the UK and Ireland relating
target strength data to fish species for split-beam hydroacoustics. Where research has been conducted in the UK, this work was carried out in relation to fish movement with variation in discharge. Target strength information is imperative for the use of split-beam for the identification of targets and the identification and discrimination of confirmed fish targets. To this end, alternative hydroacoustic technology was required to provide a counting system for large rivers that was unintrusive to fish movement but that would be easier to operate and obtain count data. DIDSON (Dual-Frequency Identification Sonar) counters are rapidly replacing split-beam HTI counters in the US, Canada and the UK. DIDSON length data has been proven as a method of discrimination between Chinook salmon (Oncorhynchus tsawytscha) and sockeye salmon (Oncorhynchus nerka) in the U.S. (Burwen et al., 2007 & Burwen et al., 2010).

3.1.1 DIDSON – Dual Frequency Identification Sonar

- The DIDSON, Dual-Frequency Identification Sonar, imaging system (Sound Metrics, 2004) was developed for the United States Navy by the Applied Physics Laboratory at the University of Washington as a tool for harbour surveillance and underwater mine detection (Belcher et al., 2001). The DIDSON system uses near-video quality imagery that allows fish to be observed on-screen, even in turbid waters and in heavy flood conditions (Baumgartner et al., 2005; Vol. II Appendix Section I: Chapter 3a) and is not known to deter salmonid migration. DIDSON was found to easily detect fish and their direction of travel (Moursund et al., 2003; Burwen et al., 2004; Burwen, et al., 2006). Maxwell and Gove (2007) and Mueller et al. (2006) showed that DIDSON was better at detecting fish than using underwater video camera even in turbid water conditions.

The enumeration of Atlantic salmon has proved difficult for Irish rivers, particularly in turbid waters and large river systems. Hydroacoustic counters have provided a useful tool for fisheries stock assessments since the 1960s (Gadet, 1990; Johnston & Steig, 1995; Enzenhofer et al., 1998). This type of counter was important for river systems that were too wide for in-river weir construction or where there was turbid water (Burwen et al., 2010). To obtain accurate, reliable fish stock assessments for the calculation of conservation
requirements, a system was needed that could be applied to all Irish salmonid rivers. Prior to
the use of DIDSON, split-beam was the acoustic counter of choice and has been used in
numerous studies for salmon stock assessment providing a non-invasive way of monitoring
fish stocks (Banneheka et al., 1995; Daum & Osborne 1998; Enzenhofer et al., 1998; Ransom
et al., 1998; Xie, 2000). An evaluation of existing split-beam hydroacoustic technology in
Ireland showed that split-beam acoustics were unsuitable for stock assessments in large Irish
rivers due to difficulties in the detection and interpretation of fish signals as a result of in-
river debris and excessive background noise (Vol. II Appendix Section I: Chapter 3a).

DIDSON has been described as bridging the gap between existing assessment sonar and
optical systems (Moursund et al., 2003). The DIDSON does not require phase measurements,
thus reducing the amount of interference from the water surface and the river bed, when
obtaining target strengths (Mulligan, 2000, Holmes et al. 2006). This allows the DIDSON to
be operated in acoustically noisy river environments (Belcher et al., 2001; Mulligan, 2000).
A similar system to DIDSON, BlueView Proviewer 900 has a lower image resolution than
the standard DIDDON. Cronkite et al. (2008) found that this system does not meet the
standards of accuracy and precision needed for use in salmon stock assessments.

Over a two year period from 2002 to 2003, the Alaskan Department of Fish and Game
evaluated DIDSON for counting fish migrations in rivers (Burwen et al., 2004; Maxwell &
Gove, 2007). DIDSON sonar was highlighted as a viable method of counting salmon based
on accuracy (Holmes et al., 2006; Maxwell & Gove, 2007) and its ability to size fish
(Galbreath & Barber, 2005; Baumgartner et al., 2006; Mueller et al., 2006; Burwen et al.,
2007; Maxwell & Smith, 2007; Burwen et al., 2010). Since then DIDSON has been
successfully proven as a useful tool for fisheries conservation worldwide (Moursund et al.,
2003; Burwen et al., 2004; Galbreath & Barber, 2005; Holmes et al., 2005; Baumgartner et
al., 2006; Cronkite et al., 2006; Holmes et al., 2006; Mueller et al., 2006; Maxwell & Gove,
2007).

The ability to provide timely and accurate estimates of fish passage in rivers is essential to
ensure that escapement goals are achieved (Enzenhofer & Crontike, 2000). DIDSONs
application in the study of fish behaviour and in some instances species recognition was quickly recognised (Maxwell & Gove, 2002). It has been shown that successful DIDSON enumeration of salmon stocks is dependant on the migratory behaviour of the fish (Holmes et al., 2006) and their angle in the beam (Burwen et al., 2007; Burwen et al., 2010). Further developments have been made to increase the use of DIDSON on larger rivers by testing both the extreme limits of detection of the DIDSON at High Frequency (HF) (Cronkite et al., 2006; Holmes et al., 2006; Burwen et al., 2007; Burwen et al., 2010) and at Low Frequency (LF) (Galbreath & Barber, 2005; Burwen et al., 2010). In 2005, the Low Frequency option in DIDSON was tested at distances up to 40 m for greater river width coverage on larger rivers (Galbreath & Barber, 2005). The limit of detection has been proved successful using the Long Range DIDSON for up to 80 m; however, fish length measurements at such ranges can be inaccurate (Burwen et al., 2010).

3.1.2 DIDSON Site Development
To optimise the performance of DIDSON, previous studies have used fish fences in conjunction with DIDSON for the enumeration of salmon stocks (Holmes et al., 2006; Maxwell & Gove, 2007). This has helped to overcome the problem of missing fish in the initial 2 m of the DIDSON beam which is too narrow to detect fish effectively and to create an optimum counting zone. Maxwell and Gove (2007) emphasise the importance of knowing beam coverage when using DIDSON for enumeration. A limitation of Holmes et al. (2006) study was that they were unable to determine the beam coverage due to high water velocities.

3.1.3 DIDSON Data Collection, Processing and Verification
DIDSON was found to easily detect fish and their direction of travel (Moursund, 2003; Burwen et al., 2004; Burwen et al., 2007; Burwen et al., 2010). Mueller et al. (2006) showed that DIDSON was better at detecting fish than underwater video cameras even in turbid water conditions. Verification of all fish counters is essential part for accurate and reproducible counts. Several authors have verified DIDSON’s accuracy for salmon stock assessments (Baumgartner et al., 2006; Cronkite et al., 2006; Holmes et al., 2006; Burwen et al., 2007; Maxwell & Gove, 2007; Burwen et al., 2010). To improve data collection using DIDSON in turbid waters, Sound Metrics developed a silt box that up to the commencement of this study
had not been significantly tested to determine its operational potential. This study included the use of the silt box to determine its effectiveness at limiting the problems related to the reduction in image quality due to siltation in the DIDSON lens.

Pacific salmon data enumeration using DIDSON involved the replaying of DIDSON images on a screen and the counting of fish by visual enumeration or ‘tallywhacking’ (Cronkite et al., 2006; Holmes et al., 2006; Maxwell & Gove, 2007). Hately and Gregory (2006) found the ‘tallywhacking’ or manual counting method laborious for stock assessments of Atlantic salmon in UK waters. This method was not applicable for Irish rivers for counting Atlantic salmon as they run twelve months of the year in much lower numbers. In Pacific salmon studies, fish were predominantly moving close to the river banks, making them easier to count than Atlantic salmon. Several types of software for automated (Higgingbottom, 2005; Baumgartner et al., 2006; Hateley & Gregory, 2006) and semi-automated (Boswell et al., 2008) processing of DIDSON data have been tested. Baumgartner et al. (2006) showed that manual fish counts were better than the automated counts generated by the SMC software. However, new developments in SMC software have improved both the semi-automated and the automated counting techniques (Bill Hanot, SoundMetrics, pers. comm.). Alternative software has been used for the processing of DIDSON data. Boswell et al. (2008) used Myriax Echoview software. Model development and trials have also been undertaken using Sonar 6 for the processing of DIDSON files (Balk & Lindem, 2004).

As described previously (Chapter 2, Section 2.2.3.8), the existing SMC software designed by Sound Metrics was refined during this study to enable the counting of Irish Atlantic salmon for 7 days a week, 24 hours a day. Changes were made by SoundMetrics to develop new processing algorithms within the SMC software to allow for better motion detection of fish which refined the accuracy as a requirement of this study. Studies have shown that user confidence plays a role in the effective target identification and the direction of movement where a target has been identified as a fish (Cronkite et al., 2006; Holmes et al., 2006). The ability to ‘see fish’ in the DIDSON display requires training to distinguish from in-river debris and the river substrate. This is much easier to achieve with DIDSON than split-beam due to the image output from DIDSON. Holmes et al. (2006) showed that high precision combined with accuracy is the most desirable combination of attributes for count data. Count
data have been shown to exhibit high precision among different observers (Holmes et al., 2006) concomitant with user experience. The use of DIDSON for salmon enumeration is vulnerable to the same tedium related errors as visual counting or viewing of video recordings (Galbreath & Barber, 2005). Galbreath and Barber (2005) recommended that DIDSON data be reviewed by two analysts, followed by a review together to confirm inconsistencies between records to improve the precision and accuracy of the data. This method would prove very time consuming in an Irish context. Based on past experience, a lack of precision and accuracy in counts will increase with greater fish density (Holmes et al., 2006). This would not be a problem for Irish rivers as the numbers encountered (at maximum thousands) are modest in comparison with equivalent runs of Pacific salmon (many millions).

A method of species discrimination is required using DIDSON as very few fish species can be identified from DIDSON images. Length data has been used to help distinguish between species (Mueller et al., 2006; Burwen et al., 2007; Burwen et al., 2010). Length measurements can be an indicator of fish species depending on the number of species in the system and their size ranges. Baumgartner et al. (2006) showed that manual length measurements taken using the SMC software were more accurate than automatic length measurements taken by the SMC software. DIDSON length measurements are easier to determine using the manual Mark Fish tool when fish are perpendicular to the beam (Baumgartner et al., 2006; Holmes et al., 2006; Mueller et al., 2006; Burwen et al., 2007; Burwen et al., 2010). Biases in fish length measurements have been experienced due to changing fish position (Galbreath & Barber, 2005; Baumgartner et al., 2006; Holmes et al., 2006; Mueller et al., 2006; Burwen et al., 2007; Maxwell & Gove, 2007; Boswell, 2008).

3.1.4 DIDSON Validation

Validation of DIDSON has been undertaken by operating DIDSON in conjunction with other counting methods such as visual counts (Galbreath & Barber, 2005; Cronkite et al., 2006; Maxwell & Gove, 2007) and for length measurements using both standard targets and tethered fish (Galbreath & Barber, 2005; Baumgartner et al., 2006; Burwen et al., 2007; Burwen et al., 2010). DIDSON has also been used to validate other hydroacoustic counters such as split-beam (Mueller et al., 2006; Maxwell & Gove, 2007). Visual counts cannot be
carried out in Irish waters due to water turbidity resulting from peat staining and for this reason underwater cameras have also been shown unsuitable for hydroacoustic validation purposes in Irish rivers (Vol. II Appendix Section I: Chapter 3a). The best validation method to date is performed by counting a known number of fish leaving a fish trap but it was not possible to simulate this method as part of this study due to a lack of man-power. Both frozen and live tethered fish have been used for validation by Galbreath and Barber (2005); however, it was found that the live fish (Coho salmon) worked best as they maintained an upright position in the water column as they were pulled perpendicular to the beam. Numerous experiments have observed 100% detection of migration of fish passage using the DIDSON (Galbreath & Barber, 2005; Cronkite et al., 2006; Holmes et al., 2006; Mueller, 2006).

### 3.1.5 DIDSON River Deel Study

A DIDSON was operated on the River Deel to obtain salmon counts by reviewing fish images on-screen using the DIDSON SMC processing software (e.g. CSOT Analysis) (as previously described in Chapter 2). The operation and installation of DIDSON on the River Deel proved very successful. In this study, behaviour was determined during initial data analysis to try to overcome problems with milling fish and to determine their movements to best develop the site and processing methods. Both successful verification and validation of the DIDSON were carried out. Using a semi-automated technique, a methodology for assessing the data in real time was developed. Sound Metrics SMC software was used with manual length measurements taken using the Mark Fish Tool option, which enabled the counting of migrating salmon over the 14 months of data collection.

In this chapter, detailed results are provided of the installation, operation (including downtime, site adjustments and additional equipment testing and improvements) and processing method developed for the use of DIDSON as a fish counter in Irish rivers. Both the operation of the DIDSON and the processing methodology developed were validated and verified.
3.2 Results

3.2.1 Installation and Operation, River Deel DIDSON Site

Trials on the River Deel in October 2007 allowed for the development of the site and determination of the best operational settings. The use of the standard tungsten target (-38.5 dB) and a second experimental target design (-30 dB) (Vol. II Appendix Section III: Chapter 3a) were successful in determining and maintaining full beam coverage of the river bed and counting zone. The tungsten sphere (as described in the Chapter 2), proved an easier target to move in the water on the rod and line for beam mapping (Chapter 2: Plate: 2.2).

Data were collected at the site for 415 days from the 13th November 2007 to the 31st December 2008 (Fig. 3.1 below; Appendix VIII: CD: Image 3.1: Video of Fish Migration). Over the 14 month period, the counter was operational for 349 days (84 % of operational time) with approximately 1,600 hours of downtime (16 % of operational time). Downtime was the result of a DIDSON system failure (over a 23 day period); electrical supply and generator failure; cleaning of the DIDSON unit and lenses; a lens rupture; system calibration and validation and the changing of hard drives. The minimum amount of downtime recorded in one day was 5 minutes (changing of hard drive) and the maximum was for a 23 day period due to a DIDSON system failure. Eleven 500 GB hard drives were used to ensure that drives were available for data collection and backup (where necessary). A total of 212 days of DIDSON data (51 % of data collected) were backed up onto magnetic tapes for verification and fish behaviour sample data.
Figure 3.1 Screen image of DIDSON, seven fish detected using CSOT processing with background subtraction (Louise Brennan, 13/11/08).

The installation of a robust fish fence created a 10 m counting zone. The deflector fence on the left bank acted both as a secure deployment structure for the DIDSON and as a walkway out to where the transducer was deployed. The fence ensured that the fish passed in front of the beam within the counting zone. The fence on the upstream side of the walkway was successful in providing protection for the DIDSON from large debris and diverted this debris downstream past the DIDSON (Vol. II Appendix Section VIII: CD: Image 3.2: debris going downstream). Leaf litter was the bulk of debris that gathered on the fish fence and walkway (Vol. II Appendix Section III). The water level remained the same across the river at the site indicative that the fish fence was not backing up water at the site. Routine and effective beam mapping highlighted the loss of beam coverage at the right bank when routine maintenance was carried out in April 2008, leading to the construction of the deflector fence on the right bank.
As a result of the left bank deflector, fish were easily observed and measured at distances of greater than 2 m from the transducer. The deflector fence on the right bank provided bank protection, preventing further erosion and guided fish away from the right bank out into the beam (Vol. II Appendix Section VIII: CD: Image 3.3: Fish Movement upstream around deflector fence). Fish were observed swimming around the right bank fence into the beam, where the beam was directed at the end of the fence. This fence maintained the 10 m counting zone following bank erosion of the right bank. Adequate man-power was essential for the completion of the fish fence and continuous beam mapping.

### 3.2.2 Operational Downtime, River Deel DIDSON Site

The installation of an electrical supply to the site hut was essential to the operation of the DIDSON on the River Deel. Greater man-hours were required while operating from a petrol generator powered battery supply. The electrical supply dramatically reduced the operational and maintenance needs of the DIDSON. The starting range was changed from 0.88 m start and 10.88 m end as the beam was too narrow in the initial 0.88 m. Reflective backscatter from ‘dauby’ clay made images in the first 1-3 m of the beam more difficult to view. Some of this clay was removed from the river bed to improve the image output. Downtime and the number of site visits were reduced due to these changes. This provided time for the development of data processing methods and increased the possibility of real-time counting using DIDSON. Downtime also occurred when routine lens cleaning detected a rupture in the main DIDSON lens which affected the image quality (Fig. 3.2 below) (Vol. II Appendix Section III). A major cause of downtime during operations was an electrical fault on a fuse/power board (Fig. 3.3). New fuses and power boards were received from the manufacturer and replaced under warranty. The DIDSON was operational again on the 2nd September 2008. A total of 23 days of data were lost due to these essential repairs.
Figure 3.2: Improved sonar image after new lens fitted on the 27th May 2008.

Figure 3.3: DIDSON image on the 21st August 2008, due to a problem with the fuse or power boards. This problem was originally thought to have been caused by siltation – note the lines in the beam.
3.2.3 Silt Box Operations at the River Deel DIDSON Site

Cleaning of the lenses and the DIDSON unit became more difficult during the summer months of 2008, when large amounts of algae gathered on the lenses (Vol. II Appendix Section VIII: PowerPoint Presentation December 2008). To improve image quality, a silt box was tested to determine its effectiveness. The silt box consists of a box specially constructed by Sound Metrics which encloses the DIDSON to reduce silt from gathering in the DIDSON lenses (Vol. II Appendix Section III). Prior to the installation of the silt box, the DIDSON lenses required cleaning at least once a month. The affect of siltation on the image was highlighted during the processing of data from November 2007 to September 2008, particularly during flood conditions.

The use of the silt box was very successful. The results showed that only minute quantities of silt entered the DIDSON unit and very little of this remained on the lenses after the silt box was installed (Vol. II Appendix Section III). Prior to the silt box installation, more frequent cleaning was necessary and the DIDSON image deteriorated between cleaning (Vol. II Appendix Section III). This improved the quality of data from the DIDSON, making images consistently clearer and easier to analyse during processing and provided better quality images for length measurements (Vol. II Appendix Section VIII: Image 3.4: Fish Migration). However, beam distance was lost as a result of using the silt box. The distance was reduced by approximately 0.5 m. This was also dependant on the level of siltation in the river at any given time.

3.3 Processing Method Development for River Deel DIDSON Data

Initially, data obtained from trials on the River Deel were used to determine the best site profile, counting zone and to assess fish behaviour in the counting zone. This allowed for optimum site selection to obtain the best count. A high degree of analyst time was required using manual counting in image mode or by ‘tally-whacking’. DIDSON generates 2,976 files per month when operational in continuous mode. To overcome this problem, processing software was necessary. Thus, a semi-automated counting technique was employed. To overcome the long wait time between fish and to reduce the quantity of files for viewing, batches of files were processed in CSOT processing in SMC software to ‘pick-out’ fish.
These shorter files were then replayed and each fish counted and measured manually using the Mark Fish Tool.

In order to determine the best processing method for the River Deel data, three types of software were tested: Sound Metrics SMC, Sonar 5 (Balk & Lindem, 2004) and Myriax Echoview. A higher degree of technical training was required using Sonar 5 and Myriax Echoview than SMC software for River Deel data. Both Sonar 5 and Myriax Echoview software were good at counting fish that were not ‘hanging’ in the beam. The difficulty with ‘hanging’ fish is that to the untrained eye they could be counted as multiple fish when viewed by Echogram or counted as multiple fish by automated counting options. The River Deel’s river bed was stable and suitable for using a constant image of the bed, saved when there was no fish movement in the beam. This aided the detection of fish using these software (Matt Wilson, Myriax, pers. comm.). However, fish movement detected in four files tested from the 21st December 2008, using the Myriax Echoview software, showed the difficulties detecting fish movement when fish were hanging in the beam. The system does allow the user to view both the DIDSON image and Echogram (generated from the DIDSON file) at the same time. Where fish were milling this increased the need for verification of echograms and thus offered no quicker processing option. Such software would be advantageous on well developed site where behaviour of fish at the site was well established and milling and hanging were not a problem. An advantage of Echoview over Sonar 5 software was that DIDSON files did not require conversion for processing. Using Sonar 5, DIDSON files must be converted prior to analysis.

3.3.1 A Semi-Automated Processing Technique - CSOT Processing combined with manual Mark Fish Tool in SMC Software

The novel semi-automated processing method developed during the course of this study, using SMC software (V.5.18), was advantageous over Sonar 5 and Echoview as less training was required for staff. SMC software was more user friendly and fish behaviour could be observed during daily processing. SMC software was selected for River Deel data analysis and several methods using the SMC software were tested, namely Number Samples/Area Over Threshold (NSOT), Tallywacking and Image Mode analysis, and Convolved Samples Over Threshold (CSOT). Software improvements were made during processing operations in
conjunction with colleagues at Sound Metrics. Algorithms were refined to improve fish
detection using motion detection and this was a key part of this study to improve the SMC
CSOT count method to allow for real-time count data processing using DIDSON.

To test the NSOT option, the N parameter must be set based on the smallest fish area that
was required to capture (> 30 cm fish length) a fish image, with some margin for variability
in the acoustic intensity. This method of running continuous files through NSOT was found
to be laborious, as a new file was created during replay and re-recording of the file. The
method was not found to be efficient or accurate when compared with Image mode analysis
of the same files. During Image Mode analysis, each continuous file was re-played and the
fish manually counted.

The method initially tested incorporating both methods of Tallywacking and Image Mode
analyses were successful but very slow in terms of processing. For example, 24 hours of data
with a high degree of fish movement required 12 hours of processing time. Processing times
of this magnitude were unmanageable and unrealistic for producing real-time counts from
DIDSON. File size reduction varied using NSOT depending on the amount of background
noise. The processing option CSOT in Sound Metrics SMC software was found to be the best
option to ‘pick out’ fish movement because continuous data collection was maintained,
collecting data on a 24 hours, 7 days a week basis on 500 GB removable hard drives. Each
drive was processed in batches using CSOT to detect in-river motion and/or fish movement.
The counting of smolts was not possible due to the small size of River Deel smolts < 16 cm
and the presence of shoals of non-target species of similar size.

Once the method of motion detection for the selection of frames with fish movement (CSOT)
was developed for processing continuous ddf files, realistic processing times were achieved.
These varied depending on fish movement, debris loadings and river flow, taking
approximately a minimum of 5 seconds where no fish movement and only debris was
detected and approximately 2 hours at high fish movement and debris loadings during flood
conditions. This method was dependant on user experience based on Analyst 1. This allowed
the establishment of a baseline count for the 14 months of data collected. Measurements were
easier to obtain after CSOT processing using the manual Mark Fish Tool with background
subtraction. File reduction with CSOT also provided the option of storing only shorter files as opposed to backing up very large continuous files (~296MB per 15 min). This reduced the time and cost of backing up these data on magnetic tapes. Each 500 GB drive storage of ddf files lasted approximately 3 weeks when data was saved in continuous mode. This was dependant on the variation in seasonal fish movement, debris loadings, water level conditions and siltation.

3.3.2 Fish Measurement and Counting, River Deel DIDSON Site

The semi-automated process using SMC software was very successful for the examination of fish motion detected in ddf files using CSOT processing. The aspect angle of the length measurements varied depending on the position of the fish in the beam. Fish were measured at angles between 8.7° and -59.7°. The greater angle of measurement was noted more frequently in downstream moving and milling fish and these were given a low quality rating (Q rating). These biases were assessed during validation. Good quality fish measurements were obtained using the manual Mark Fish Tool (Fig. 3.4).

Each measured fish was assigned a direction of movement or allocated behaviour during processing (Fig. 3.5). Of the 20,725 fish measured the majority of fish, 86 %, were running; of the other fish some 8% were backsliding, 3% hanging and 3% milling. Milling and hanging behaviours were the most difficult to interpret when allocating fish direction. In some instances, milling fish could have been classified as running prior to their continued movement up and downstream. This could have reduced the percentage of milling fish, as the occurrence of these behaviours was less than expected. Verification tests files showed greater problems due to hanging and milling in the first six months operation of the DIDSON. This situation arose prior to essential site works that reduced this behaviour at the site.
3.3.3 Quality of Fish Measurements, River Deel DIDSON Data

The quality rating system of Q 1-5 was used (as described in Chapter 2: Section 2.2.3.8) to differentiate the quality of the length data, a prerequisite for the development of an accurate salmon count model for the River Deel. A quality rating was allocated to 20,701 fish measurements taken using the SMC software manual Mark Fish Tool. Only 17.8% of the length measurements taken had ratings of Q 1-2 (Fig. 3.6). Some 8% of these Q 1-2 ratings were taken in the first 5 months of data collection, prior to the removal of a fallen tree and the installation of the right bank fish fence which helped reduce holding and milling at the right bank. The number of lower quality measurements dropped following completion of these site works and the installation of the silt box. Less than 10% of Q 1-2 measurements
were recorded over the remaining 9 months of data collection. This was indicative of the attainment of good quality measurements from the DIDSON and the effectiveness of site works to reduce erratic fish behaviour. This in turn improved fish aspect angle in the beam. These length data were used for both count and biological analysis of River Deel salmon migration. The mean fish length measurement taken over the 14 month sampling period was 56 cm (SE = 0.11, SD = 15.83). The minimum length measurement taken was 12.5 cm and the maximum was 115 cm. The results of the validation of the length measurement data obtained are detailed in section 3.6.
Figure 3.5: Percentage of different fish behaviours recorded during DIDSON operations, November 2007 to December 2008, River Deel (n = 20,725). number of fish allocated a direction of travel or movement.

Figure 3.6: Percentage quality ratings of fish manually measured using SMC software, manual Mark Fish Tool, DIDSON, River Deel (n = 20,701, the number of fish given a quality rating).
3.3.4 Fish Migration past the DIDSON Relative to Distance from the DIDSON Transducer, River Deel

During data processing with the SMC software manual Mark Fish Tool, length measurements to the nearest 0.1 cm were automatically saved during measuring. These included the range from the sonar at which each fish was measured moving through the beam. These data give an indication of fish movement in the 10 m counting zone (Fig. 3.7). The average range at which fish were measured migrating through the DIDSON beam was 5.78 m, with a maximum of 10.64 m and a minimum of 1.1 m (where some fish migrated around the fish fence swimming towards the DIDSON at a range of < 2 m). Range data were grouped into two metre bands and the percentage number of fish in each band recorded (Table 3.1). Results showed that the majority of fish migrated at ranges greater than 5 m. Fish appeared to favour the centre of the counting zone (5 m). This could be due to fish favouring the water flow along the sloping bed of the river at this point, which ranged from 2 m to approximately 8 m. It is worth noting that the deflector fences may also have played a role in encouraging fish movements (a) to migrate at greater than the first 2 m of the beam and (b) away from the right bank where the right bank fence was installed. A total of 60 % of fish were measured migrating at a range of > 5 m and 40 % at a range of ≤ 5 m from the DIDSON transducer. A detailed study of water levels and flows across the counting zone was not carried out but this would be of interest for future studies. The influence of environmental parameters on fish movement is discussed in Chapter 7.

Table 3.1: The percentage fish migration with range, where fish were measured migrating through the DIDSON beam, DIDSON site, River Deel.

<table>
<thead>
<tr>
<th>Range (m)</th>
<th>% of Fish Migrating</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 8 m</td>
<td>19%</td>
</tr>
<tr>
<td>&gt; 6 - ≤ 8m</td>
<td>25%</td>
</tr>
<tr>
<td>&gt; 4 - ≤ 6m</td>
<td>31%</td>
</tr>
<tr>
<td>&gt;2 - ≤ 4m</td>
<td>21%</td>
</tr>
<tr>
<td>0 - ≤ 2m</td>
<td>4%</td>
</tr>
</tbody>
</table>
Figure 3.7: Number of fish migrating relative to distance from the DIDSON transducer, River Deel. \(n = 21,411,\) Min. range = 0.88, Max. range = 10.88) (Ranges were measured to the nearest 0.1 m).

3.3.5 Unknown Target Movements/Unknown Fish Direction and Non-Target Species, River Deel DIDSON Site

A total of 840 (4\%) movements were registered as unknown, where the target movement could not be identified as a fish, or the fish direction could not be assigned (Fig. 3.8). This was a small number of targets and/or fish not identified, considering that more than 20,000 fish were successfully identified as fish detected and measured in the DIDSON beam. These events were highest in the first four months of operation, (prior to site works which reduced milling) and in the initial stages of developing user confidence in fish identification and the use of the software.
Figure 3.8: The monthly total number of fish that could not be allocated direction and/or unknown movements, River Deel, November 2007 to December 2008.

In relation to the removal of non-target species during processing i.e. fish migrations/movements which were not salmonid i.e. pike, or identified as non-targets were removed. This was carried out using visual observations from the DIDSON images during processing and swimming characteristics of the fish. Other non-target species were removed during processing, these included eel/lamprey (Vol. II, Appendix, Section VI: C), otter/mink, debris and where the movement of shoals of small fish was logged. The percentage of non-target species/images removed (total upstream and downstream combined) was 4%.

3.4 Assessment of the Quality Procedure for DIDSON Data Processing, River Deel

DIDSON Data

During this study, three analysts were provided with 73 files for counting. The verification protocol for the River Deel set the analysts playback speed at 20 frames per sec for review of files. Analysts were allowed to stop and replay the sections of file where necessary. All results were then compared to the ‘true reference count’. This simulated the method used in this study during live processing. Vol. II Appendix Section III: Plates 3.5 & 3.6 show the Hut Monitoring Station during validation and the River Deel site 26/09/08.

In previous tests to verify DIDSON data processing methodology, holding and milling fish were not counted (Cronkite et al., 2006; Holmes et al., 2006; Maxwell & Gove, 2007) and
problems were noted during file processing where fish numbers were high (Holmes et al., 2006). This was not a problem on the River Deel as the maximum number of fish to migrate past the DIDSON together was ten. For River Deel verification tests, holding and milling fish movements were included in the assessment. Reference data for comparisons with each of the three Analysts data was taken from the Analysts 1 count, counted in Image Mode (IM) (prior to processing using CSOT). This was the closest estimate to the ‘true count’ of fish movement in the test files. Therefore, Analyst 2 and Analyst 3 IM and CSOT counts were compared to the reference data, i.e. the true count (Analyst 1) (as described in Chapter 2, Section 2.2.3.9). The reference data were used to calculate the percentage accuracy for the upstream, downstream and net fish counts for each analyst (Table 3.2 (a) to 3.2 (c) and Figs. 3.9 (a) to 3.9 (c)). The semi-automated processing (CSOT) efficiency was 99% for the net count for the Analyst 1. The percentage accuracy for the downstream counts was much lower than that of the upstream counts and the net upstream counts. This was most evident for Analysts 2 and 3, highlighting the importance of user experience. The close proximity in the percentage accuracy of Analyst 2 and 3 may be due to the fact that both were trained together and had the same length of user experience (three weeks). This also showed that training provided was probably transferable to different users.
Table 3.2 (a): Raw fish counts from 73 files in Image Mode (IM). *Reference data (Analyst 1).

<table>
<thead>
<tr>
<th>Analyst</th>
<th>Upstream Count (IM)</th>
<th>Downstream Count (IM)</th>
<th>Unknown Movement (IM)</th>
<th>Net Count (IM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>175</td>
<td>106</td>
<td>2</td>
<td>69</td>
</tr>
<tr>
<td>2</td>
<td>148</td>
<td>104</td>
<td>13</td>
<td>44</td>
</tr>
<tr>
<td>3</td>
<td>137</td>
<td>86</td>
<td>18</td>
<td>51</td>
</tr>
</tbody>
</table>

Table 3.2 (b): Raw fish counts from 73 files after CSOT processing.

<table>
<thead>
<tr>
<th>Analyst</th>
<th>Upstream Count (CSOT)</th>
<th>Downstream Count (CSOT)</th>
<th>Unknown Movement (CSOT)</th>
<th>Net Count (CSOT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>150</td>
<td>80</td>
<td>1</td>
<td>70</td>
</tr>
<tr>
<td>2</td>
<td>113</td>
<td>53</td>
<td>12</td>
<td>60</td>
</tr>
<tr>
<td>3</td>
<td>102</td>
<td>45</td>
<td>0</td>
<td>57</td>
</tr>
</tbody>
</table>

Table 3.2 (c): Percentage accuracy of the upstream, downstream and net upstream counts using CSOT processing with the reference data.

<table>
<thead>
<tr>
<th>Analyst</th>
<th>Upstream</th>
<th>Downstream</th>
<th>Net Upstream</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>86%</td>
<td>76%</td>
<td>99%</td>
</tr>
<tr>
<td>2</td>
<td>76%</td>
<td>51%</td>
<td>87%</td>
</tr>
<tr>
<td>3</td>
<td>74%</td>
<td>52%</td>
<td>83%</td>
</tr>
</tbody>
</table>
Fig. 3.9 (a): Comparison of the gross fish movement in 73 sample files during verification, processing in Image Mode and after CSOT, DIDSON site, River Deel.

Fig. 3.9 (b): Comparison of the net upstream movement in 73 sample files during verification, processing in Image Mode and after CSOT, DIDSON site, River Deel.

Fig. 3.9 (c): Comparisons of the net fish movement for each analyst using CSOT processing with the reference data, DIDSON site, River Deel (*Image Mode here is reference data).
Only a small percentage of files required verification, showing the quality of the semi-automated processing method developed. Observations of net counts showed little variation from analyst’s net counts. This ensures accuracy of data analysed and highlights increased accuracy with user experience. Analyst 2 used an intensity of 79 and a Threshold of 0, this could have affected detection of fish movement. Analyst 3 started initially with an intensity of 80 and a Threshold of 0 for the first 12 files analysed and then switched to 90 and 2 respectively. These settings were closer to Analyst 1 with an intensity of 90 and a Threshold of 3). The intensity and Threshold settings will vary depending on the user and their eyesight but it can determine whether some fish will be detected or not. Familiarity with these settings comes with increased processing experience.

Analyst 1’s processing showed very little difference between counts when the net count was determined. Direction was easily determined when analysing CSOT files if fish were not milling. The difference in gross fish counts between analysts may have been due to the counting of milling fish, if the same fish were moving up and downstream continuously. This made very little difference to the net upstream fish count. A greater number of fish were counted using the CSOT method when compared to the total net upstream count for Image Mode.

The net upstream passage rates of fish determined by the analysts ranged from -10 to 11 fish in IM and -6 to 9 fish after CSOT for test files. Lack of attention has been described as a factor contributing to the variation in counts between analysts (Galbreath & Barber, 2005). The use of CSOT processing eliminates waiting for fish movement during file processing, as only frames with fish movement are recorded. However, for verification the entire file must be analysed in image mode and this can result in inaccuracies due to long wait times. Thus, making it difficult to verify data collected using motion detection shorter files (CSOT) with IM files that are laborious to count. Analyst 1’s net fish count was one fish greater than IM (Reference count) demonstrating the difficulty of counting full files in IM with low fish numbers (i.e. maximum run of fish was 10). Thus, tests show good reproducibility of data from the full IM files counted when compared with the shorter CSOT files. Therefore, CSOT processing algorithms and manual counting were successful at ‘picking out’ 99 % of the fish
movement when Analyst 1 was counting. Analyst 1 counted approximately 94% of the data collected.

3.4.1 CSOT Processing Time Reduction Analysis

There was a significant reduction in processing times after CSOT processing due to the reduction in file size (Fig. 3.10). A difference in count analysis time was noted between analysts depending on experience. Some analysts provided more detailed comments on individual fish movements during processing. When analysing CSOT files with numerous milling fish, it became more difficult to determine direction of movement. The results show that the site and user experience are the two most important factors for accurate processing of DIDSON data. The number of files and/or hours of verification data required are site specific (Suzanne Maxwell, ADFG, pers. comm.). Analysis to estimate the processing time using image mode and CSOT processing were also carried out during verification (Vol. II Appendix Section IV: B).

The software selected only frames that meet the set criteria to ‘pick out’ fish (Fig. 3.10 and Fig. 3.11 Below), resulting in significant frame reduction between the original 15 min files and the CSOT files. The reduction in file size after CSOT processing was a result of the processing parameters which include only fish of target size > 30 cm (refined by SoundMetrics for this study). This allowed for much faster processing times, with good detection of target fish sizes in the CSOT files, when compared with the original counting methods tested.
For this study, validation of the DIDSON was required to determine detection in the counting zone and the quality of the length measurements obtained using the DIDSON manual Mark Fish tool, in the SMC software. Prior to installation of the DIDSON on the River Deel, Moy Catchment, initial trials were undertaken on the River Boyne, Co. Meath from the 8th – 10th October 2007. The DIDSON was located at the head of a fish pass facing downstream of a Vaki counter that was installed in the fish pass. As fish moved upstream through the fish pass they were detected by both the Vaki counter and also by the DIDSON.
3.5.1 Validation of DIDSON for the Detection of fish in the Counting Zone, River Deel

A total of 62 fish of five different species were used to validate the DIDSON at the River Deel site (Table 3.3).

Table 3.3: Five species used for validation experiment, DIDSON site, River Deel.

<table>
<thead>
<tr>
<th>Species</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pike (Esox lucius)</td>
<td>54</td>
</tr>
<tr>
<td>Roach (Rutilus rutilus)</td>
<td>5</td>
</tr>
<tr>
<td>Perch (Perca fluviatus)</td>
<td>1</td>
</tr>
<tr>
<td>Salmon (Salmo salar)</td>
<td>1</td>
</tr>
<tr>
<td>Brown trout (Salmo trutta)</td>
<td>1</td>
</tr>
</tbody>
</table>

Each species was easily detected in the DIDSON beam at ranges throughout the beam, including fish near the surface and the direction of travel was easily determined. During validation, the range where fish moved and where they were measured using the DIDSON, varied at a minimum of 1.1 m, to a maximum of 10.6 m. The True Length (TL) recorded ranged from 30.8 cm to 110 cm and the DIDSON Length (DL) recorded ranged from 23.7 cm to 117.9 cm. Theta, the angle at which each fish was measured, varied between -14.1 and 13.0 for DL.

Comparisons of files for each fish target that swam through the beam tested during the validation experiments on the River Deel were 100% concurrent with that of the data recorded for the target fish. All the live fish target images were easily observed at all ranges tested. Target work using a tungsten sphere (-38.5 dB) was carried out regularly to ensure that all areas of the counting zone were observed and that bed coverage was maintained. The validation test and target work showed that there were no ‘blind spots’ in the counting zone.

Laboratory tests showed that the DIDSON has the ability to identify 100% of fish passage even in turbid waters (Mueller et al., 2006). It was assumed that once the target and tethered fish were seen in all areas of the counting zone that the DIDSON data were not biased as a result of fish moving through the DIDSON beam undetected.
3.5.2 Validation of Length Measurements taken - DIDSON manual Mark Fish Tool

Figures 3.12 and 3.13 show the length frequency distributions of test fish measured manually (TL) and using the DIDSON (DL). DIDSON fish lengths were on average 1.1 cm greater than the TL’s (n = 601). The mean DIDSON (n = 601) and True Lengths (n = 62) had means of 68.3 cm (SD = 16.5) and 71.3 cm (SD = 17.3). The results show a positive bias for DIDSON and True Length using tethered fish. Burwen et al. (2007) reported a positive bias when validating with tethered fish; however, the tethered fish in that experiment were stationary. The True Lengths had a linear relationship with DIDSON fish lengths in the River Deel (R² = 0.9232) (Fig. 3.14). To determine the relationship between TL and DL and the effects of distance from the transducer, a linear regression was performed with DIDSON estimated length as the variable of interest. The results showed that the DL was not affected by distance from the transducer (Table 3.5). Burwen et al. (2007 & 2009) found that length measurements for tethered fish were affected by distance from the transducer but, in contrast, tests carried out on free swimming fish showed no affect of DL with distance from the transducer in her study. Thus, the River Deel method provides accurate measurements of fish lengths for the purpose of stock assessments using different length cut-off points and data modelling, depending on the species being estimated (Chapter 4). In terms of methodology, this study’s use of live tethered fish simulates free swimming fish with the benefits of obtaining multiple passes of fish through the DIDSON beam at various desired ranges from the transducer. Live tethered fish are easier to manage and measure in water than dead fish, as they remain up-right (Baumgartner et al., 2006). The ability to resolve fish deteriorates with range due to a decrease in image resolution associated with the increased beam width and spacing (Belcher et al., 2001; Belcher, 2004). The maximum range at 1.8 MHz is 12 m. Increases in water turbidity and the use of the silt box were noted to reduce the range of the DIDSON operating on the River Deel site to approximately 10 m. Many authors have noted that the accuracy of length estimates is influenced by the aspect of the ensonified fish (Galbreath & Barber, 2005; Baumgartner et al., 2006; Mueller et al., 2006; Burwen et al., 2007; Maxwell & Gove, 2007; Burwen et al., 2010). Fish lengths were easily determined when fish were perpendicular in the beam. Fish in side aspect had significantly higher target strength than head or tail aspect. This was noted on the River Deel where two fish were swimming in circles, illustrating the effect of aspect angle versus target strength (the image
can be located on the following website by clicking on image and view the image of ‘Aspect angle’: Your Point of View) http://www.soundmetrics.com/image-gallery/circling-salmon.

Figure 3.12: Length frequency histogram of test fish DIDSON length measurements. DIDSON sample size (n = 601).

Figure 3.13: Length frequency histogram of test fish total true length measurements. manually measured live fish sample size (n = 62).
Figure 3.14: Linear relationship between DIDSON length (cm) and the True length (cm) of each fish, River Deel, Moy Catchment, Ireland ($R^2 = 0.9232$) ($n = 601$).

Table: 3.4 Linear regression performed on DIDSON estimated length as the variable of interest with respect to the distance from the transducer that each length was taken, River Deel ($R^2 = 0.9232$; $n = 601$).

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>Standard Error</th>
<th>t Stat</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>4.498</td>
<td>1.025</td>
<td>4.386</td>
</tr>
<tr>
<td>True Length</td>
<td>0.934</td>
<td>0.012</td>
<td>76.275</td>
</tr>
<tr>
<td>Range</td>
<td>-0.001</td>
<td>0.001</td>
<td>-1.277</td>
</tr>
</tbody>
</table>

Alternative Analysis for the Validation of DIDSON Length Data

As an alternative to the use of a linear regression for the validation of DIDSON length data, the following method was applied by Gurney et al. (Submitted):

Analysis of the TL and DL data showed that neither the distance of target fish to the DIDSON or the angle of the fish to the DIDSON affected the accuracy (either as single variables or in a multiple regression predicting true length from DIDON length, range and
angle) and produced a linear equation to correct DIDSON recorded Lengths, DL, by just 2.07 %, to yield True Lengths, TL:

\[ DL = 0.0 + 0.9797 \times TL + \varepsilon_D \]

Where \( \varepsilon_D \) represented the measurement error for the validation data set. The bias in the DIDSON measurements (*0.9797) was smaller than the measurement error on single length-estimates, \( \varepsilon_D \), which represented a coefficient of variation (CV %) of 3 % and was effectively normally distributed. Thus, both the 0.9797 correction factor and the single-measurement error coefficient (3%) were used to correct the physically measured ‘fish fork length component distribution’, so that they would properly match the overall ‘target distribution’ recorded from wild fish passing through the DIDSON counter (Gurney et al., Submitted). This equation was used to adjust the component distributions (of TL, accurate fork length measurements). The measurement error CV of 3 % indicated that the two distributions were nearly identical (For further details see: Gurney et al., Submitted).

### 3.5.3 Significance of the Quality of DIDSON data, River Deel

Several authors have effectively used the release of fish from fish traps to validate counts from DIDSON (Burwen et al., 2007; Burwen et al., 2010). Similar to Holmes et al. (2006) the method used on the River Deel showed 100 % concurrence of fish detection in the counting zone. All the live fish target images were easily observed at all ranges tested. Validation was carried out by Holmes et al. (2006) and Cronkite et al. (2006) in Canada using comparison with visual counts. This is not possible in Irish waters due to water turbidity. Underwater cameras have also been shown unsuitable for hydroacoustic validation purposes in Irish rivers (Vol. II Appendix Section I: Chapter 3a). The validation of DIDSON lengths was essential, as the length frequency data from the DIDSON were used to differentiate between fish of overlapping size ranges and for run component analysis.
CHAPTER 4

4.0 Enumeration and Assessment of Atlantic salmon Migration, using the DIDSON (Dual-frequency Identification Sonar), River Deel, Moy Catchment.

4.1 Introduction

River specific stock and recruitment analysis is the most accurate way to determine river specific Conservation Limits but these data are based on 20 to 30 years of stock and recruitment data (Crozier et al., 2004). Therefore, it is necessary to transport CLs from data-rich rivers to data-poor rivers (Prévost et al., 2004). The Standing Scientific Committee provides details on the status of individual stocks for Irish rivers. A Bayesian hierarchical modeling framework has been developed to transport stock and recruitment information between rivers and to set CLs accordingly (Crozier et al., 2004, Ó Maoiléidigh et al., 2004). There are currently 18 counters from which data are used by the SSC, with the remaining rivers being assessed based on an average rod catch and a range of exploitation rates derived from the rivers with fish counters and literature sources (Anon., 2009). Thus, alternative salmon stock assessment methods are required to provide accurate river specific count data on a yearly basis to allow for yearly population estimates to be obtained. As part of the project the new DIDSON counter technology was examined to determine the best technology and information to provide river by river spawning status (Chapter 3).

4.1.1 Collation of Stock Assessment Data

As previously described, the two types of counters mainly used in Ireland for salmon stock assessment are the resistivity and infra-red counters. Both of these type of counters when tested in the initial count assessments on the River Moy, varied greatly in their effectiveness depending on the site of deployment, quality of the installation and the hydrology of the river catchment (Vol. II Appendix Section I: Chapter 3a). These counters require a weir, limiting site location and can restrict passage for fish. Although they have been effectively used for the counting of salmonid species (Reddin et al., 1992; Fewings, 1998; Shardlow & Hyatt, 2004; Thorley et al., 2005), other studies have shown that these counters have numerous
limitations due to limited detection of fish by the sensors during flood conditions, missed downstream counts, poor performance in high turbidity and the restriction of fish movement (Dunkley & Shearer, 1982; Smith et al., 1996, Johnstone et al., 1998, Struthers, 1998; Holden & Struthers, 1998; Shardlow & Hyatt, 2004; Hendry et al., 2007). This will affect the quality of data obtained from these counters and thus their use in determining CLs of the rivers where they are operational (and those where extrapolated data are used from these counters). There are no publications with respect to fish counter operation and performance in Irish river systems. The SSC (Anon., 2008b) have reported that for weir mounted counters there is a high possibility of fish moving upstream over the weir without being counted. Where this occurs, counter data are raised by a further percentage depending on observations and information received from the IFI. The IFI has suggested that in some river systems that up to 70% more fish pass over the weir than are counted (Anon., 2008b) This may occur at a greater frequency at varying levels of discharge and calls into question the accuracy of such count data for establishing CLs. DIDSON has been successfully operated in the U.S. and Canada for Pacific salmon stock assessments (Holmes et al., 2006; Cronkite et al., 2006; Burwen et al., 2007; Maxwell & Gove, 2007). DIDSON has now been shown to operate in Irish rivers on a year round basis with very little downtime and was operated in flood conditions and turbid waters, thus providing more accurate count data for stock assessments and for the purpose of establishing CLs (Chapter 3; ICES, 2009).

4.1.2 Discrimination of Fish Species from Fish Counter Data
To distinguish between fish species of overlapping size ranges, size cut-off points have been applied in Ireland since the 1990’s to adjust counter data to obtain salmon counts. Very basic methods have been used, including crude length cut-offs to produce counts for adult salmon from resistivity and infra-red counters (where length data has been obtained). Atlantic salmon in Irish rivers are currently discriminated assuming that all fish ≥ 40 cm are salmon and all fish ≤ 40 cm are brown trout or sea trout (Anon., 2008b). This initial methodology was applied to the River Deel DIDSON data and further refined to try to provide a more detailed stock assessment. Fish species identification is not yet possible for most species using DIDSON images alone (Burwen et al., 2007; Maxwell & Gove, 2007; ICES, 2009; Burwen et al., 2010); however, DIDSON fish length data are already being used in Alaska to
discriminate between Pacific salmon species that migrate at the same time (Burwen et al., 2007; Burwen et al., 2010). The use of run timings and DIDSON fish length data was a much more realistic method to determine more accurately run components for Irish rivers (to estimate the proportion of grilse and the MSW salmon components of the run). To determine the various components of the run for the River Deel, the length frequency data obtained from the DIDSON were used to distinguish the variations in the spring and summer runs. More advanced modelling was also applied through the development of a Bimodal Model using DIDSON length frequency data to discriminate between grilse and brown trout. It was not possible to discriminate fish of the same size e.g. grilse and brown trout, without using DIDSON length data.

The DIDSON was also used to determine what other species could be observed. Vol. II Appendix Section IV: C outlines the confirmed species identified in the River Deel using DIDSON. DIDSON allowed for the run timing of eel migrations to be detected in 2007 and 2008 and this added to the knowledge of the system (Vol. II Appendix Section IV: C). This was the first in-river estimation of eel migration using DIDSON in Ireland.

### 4.1.3 Atlantic salmon Migration Patterns in the River Moy System

In Ireland and the UK, Atlantic salmon can enter their natal rivers throughout the year and many individuals can enter the system several months prior to spawning (Klemetsen et al., 2003). This can make counting more expensive. Early running grilse on the River Moy tend to be much smaller in size in comparison to other catchments, as described in Chapter 2: Section 2.2.3.11. Three components of the Atlantic salmon run are observed in the River Moy, namely early running MSW fish (spring fish), summer running MSW fish and grilse. Grilse first appear in May and continue to enter freshwater until November/December. These migration patterns make it difficult to define yearly cohorts. Both grilse and MSW fish migrate in the River Deel during the summer to winter months. The River Deel is an atypical river system and these fish may have entered the River Moy in spring and not migrated upstream to the River Deel until later in the season or could have multiple migrations into and out of the system prior to spawning. This made the River Deel a more difficult system to define specific run components. From June onwards, it is difficult to determine if migrating
salmon are summer grilse or MSW fish. The majority of spring fish are believed to be predominantly female and the smaller running grilse in early May are predominantly males (Anon., 1999). Later in the season, the ratio of grilse to MSW fish reverts to a 50:50 ratio (K. Whelan, pers. comm.). The location of the River Deel at the head of Lough Conn and the late run of salmon in January and to some extent February detected by the DIDSON, also made defining the yearly cohort challenging (Chapter 2: Section: 2.2.3.11).

**Quantifying Atlantic salmon Migrations, River Deel**

Quantitative methods were applied to the DIDSON data and these data were integrated to establish techniques for providing counts for Atlantic salmon in large Irish rivers using DIDSON. All fish count and length frequency data for 2008 were analysed to establish the upstream, downstream and net upstream monthly migration pattern of all fish. Initially, a total count of the net upstream fish migration was established for the 2008 cohort. The challenge was to use the DIDSON data to develop methodology to provide for species discrimination in order to estimate various salmon run components. From the screw trap operations, it was not thought there was a significant brown trout population of similar size to migrating grilse and that brown trout would not cause substantial error in the counts using only the two length cut offs applied (Chapter 2: Section:2.2.3.11). However, to try to improve the method for discrimination, a Bimodal model was developed using DIDSON length data. The models applied provided comparative estimates, allowing a range of grilse and MSW estimates to be achieved for the River Deel and in turn the River Moy through genetic analysis (Chapter 7). Further analysis of the data allowed for the extraction of MSW run component of the River Deel; however, these data were not verified with live trapping during 2008 to determine grilse and MSW lengths for this system. Comparisons will be made of the grilse estimates with adult count estimates obtained from sea survival rates for the smolt stock assessment (Chapter 5).

To facilitate the breakdown of run components, there was a need to analyse data on a monthly basis to determine patterns of salmon migration on the River Deel. These length data and monthly data analysis were used to firstly estimate the total grilse and MSW run using two length measurement cut-offs points, including all fish in the count ≥ 40 cm and ≥ 45 cm. Using length cut-offs the MSW stocks were assessed using an upper and lower limit
of ≥ 80 cm and ≥ 70 cm. These provided putative data for the River Deel. Length data from the DIDSON and run timing analysis were used to separate grilse and MSW fish from the combined 2008 cohort estimate, where 24 % of fish counted using DIDSON were ≥ 70 cm and 76 % of fish were < 70 cm for the 2008 cohort. The bulk of fish migrating in the River Deel were grilse and this was the target of the assessment.

DIDSON observations of fish migration during processing of data, was a key factor in determining the type of migrations e.g. 2007 kelt run, 2008 spring fish etc. In this chapter, as described earlier in Chapter 2, the results are presented to determine:

(a) the number of fish migrating past the DIDSON counter over the 14 months of operation;

(b) if DIDSON length data could be used to apportion species, i.e. salmon and brown trout;

(c) if DIDSON count and length data could be used to define the 2008 cohort, to estimate the 2007 kelt run, to estimate the MSW spring run for 2008 and the early grilse migration for 2008;

(d) if DIDSON count and length data could be used to quantify the grilse run for 2008 cohort; and,

(e) if DIDSON count and length data could be used to estimate the proportion of the MSW components of the 2008 cohort.
4.2 Results
The DIDSON exceeded expectations producing reliable count data with run component estimations. More than 20,000 fish were detected and length measurements taken using the DIDSON over the course of this study, showing the volume of fish movement detected over a 14 month period at the River Deel DIDSON site (Chapter 3). The data collected on the River Deel showed the key peaks in the run timing patterns of salmonids upstream and downstream prior to spawning and seasonal variations. DIDSON length data were successfully used to differentiate between salmon and trout to provide count estimates and a new model developed, namely the River Deel Bimodal Model for species apportionment. Sea-age determination was also estimated through the use of basic length cut-offs.

Initial analysis was carried out on the net upstream migration for the 2008 cohort for the River Deel which produced four model estimates of the total adult salmon run (grilse and MSW) ranging from of 2,633 to 4,897 spawning salmon. Depending on the level of analysis of the four models tested, discrimination and sea age were determined. The grilse and MSW run was estimated at 3,814 for the 2008 cohort where fish \( \geq 40 \) cm were included. This provided a breakdown of grilse of 2,903 and 911 MSW fish. A total of 512 spring fish were recorded by the DIDSON migrating upstream between March and April 2008. The early grilse run was estimated at 169 grilse migrating upstream in May 2008. The estimated grilse run from June to December 2008 was 2,455 (salmon \( \geq 40 \) cm & \( < 70 \) cm) and 888 MSW fish. Altogether a total of 2,368 MSW fish migrated upstream in 2008 (salmon \( > 70 \) cm). This net upstream count for MSW \( > 70 \) cm shows the amount of milling into and out of the River Deel to Lough Conn, when compared to the total upstream count for MSW \( > 70 \) cm. This emphasised the atypical nature of fish migration on the River Deel and the difficulty in estimating both run components. However, the ability to provide an estimate for MSW fish was a bonus to the determination of the grilse run on the River Deel considering the atypical nature of this system.
4.2.1 Estimated Monthly Fish Migrations, Deel DIDSON Site, River Deel

The DIDSON operation on the River Deel commenced on the 13\textsuperscript{th} November 2007 and ended on the 31\textsuperscript{st} December 2008. Fish migration data was collated on a daily basis operating DIDSON 24/7, detecting all fish migrating upstream and downstream. A total of 20,606 fish migrated past the DIDSON over the duration of its operation (Table 4.1).

\textit{Table 4.1: Breakdown of the total fish migrations past the DIDSON site, River Deel, November 2007 to December 2008.}

\begin{center}
\begin{tabular}{|c|c|c|c|c|}
\hline
Total Fish Migration & Fish Upstream & Fish Downstream & Monthly Peak Fish Migration Nov 2008 & Monthly Peak Upstream Fish Migration Nov 2008 \\
\hline
20,606 & 12,787 & 7,819 & 3,350 & 2,472 \\
\hline
\end{tabular}
\end{center}

The daily mean number of fish migrating upstream and downstream past the DIDSON counter over the fourteen months of data collection was 36 (SD = 47.13) and 22 (SD = 22.37), respectively. The number of fish counted by the DIDSON actively migrating upstream past the monitoring site over a 24 hour period was a minimum of one fish and a maximum of 375 fish. The number of fish counted by the DIDSON migrating downstream past the monitoring site over a 24 hours period was a minimum of one fish and a maximum of 152 fish. There were days when no fish migration took place, e.g. February 2008. Fig. 4.1 shows the daily upstream fish migrations and the specific time frames of each of the salmon run components determined using DIDSON on the River Deel. Each of the following results explains the determination of the run cohorts and run components.
Figure 4.1: Daily upstream fish migrations, Deel DIDSON site, River Deel, November 2007 to December 2008. Showing the different salmon runs, red = 2007 spawners; green = time gap between 2007 run cohort and 2008 run cohort (28th Feb. – 18th Mar. 2008); blue = MSW spring run 2008; purple = early running grilse and yellow = grilse/MSW 2008 run (August 2008 data consists of eight days of data due to downtime).

The graphed count data over 14 months showed that three distinct peaks in fish migration were observed in November and December 2007, June and July 2008, and November and December 2008 (Fig.4.2). The breakdown of upstream and downstream migrations in November and December 2007 and November and December 2008 showed the number of upstream migrating fish decreased near the end of the each year (Fig.4.3).
Figure 4.2: Monthly migration of all fish migrating past the Deel DIDSON site, River Deel (n = 20,606) (These data include all fish movement minus non-target species detected) (Note: Data collection started on the 13th November 2007 / August 2008 data consists of eight days of data due to downtime).

Figure 4.3: Monthly migration of all upstream migrating fish and all downstream migrating fish, past Deel DIDSON site, River Deel (n = 20,606) (These data include all fish movement minus non-target species detected) (Note: Data collection started on the 13th November 2007 / August 2008 data consists of eight days of data due to downtime).
4.2.2 The Use of Length Frequency Distributions to Define and Describe the 2008 Cohort, Run Components, DIDSON Data, River Deel

Counting Atlantic salmon on the River Deel for a 14 month period showed the crossover of yearly migration cohorts and the difficulty in defining a specific year cohort. Late spawning salmon in January 2008 were observed during redd counts (Vol. II Appendix Section V: (A): Redd Counts 2008) and these fish were part of the 2007 cohort. There was a distinct increase in the number of daily downstream migrating fish from January to February 2008 (Fig. 4.4) in comparison to daily upstream migrations and these were assumed to be 2007 kelts salmon migrating downstream (Fig. 4.5).

![Graph showing daily downstream migrating fish from January to May 2008](image)

**Figure 4.4**: Daily downstream migrating fish from 1st January to 31st May 2008, (all downstream migrating fish ≥ 28 cm), Deel DIDSON site, River Deel, (n = 1,643).
Figure 4.5: Daily upstream migrating fish from January to 31st May 2008 (all upstream migrating fish ≥ 28 cm), Deel DIDSON Site, River Deel, (n = 1,350).

Using the DIDSON, observations were made of the in-active nature of fish movement downstream to Lough Conn in January and February, where fish were ‘backsliding’ or ‘flopping’ downstream. This was the kelt run for the 2007 cohort and it commenced in the first week of January 2008 (2nd January 2008). These kelts were more than likely falling back to the lake to recover before migrating to sea. The cessation of the kelt run was at the end of February 2008 (28th February 2008). As fish were still migrating upstream in January 2008, these late spawning fish that were part of the 2007 cohort and were included in the count for the 2008 cohort to compensate for the lack of data for January and February 2009 (Chapter 2: Section 2.2.3.11). Thus the count was initially adjusted by including these 469 salmon (≥ 40) counted that migrated upstream in January and February 2008 by assuming that they are 2008 fish. However, fish from late January may have been spawned fish going back upstream, a common phenomenon in the Burrishoole catchment (K. Whelan, pers. comm.). It was assumed in the Deel catchment that spawned fish were not migrating back upstream past the DIDSON, however, it was not confirmed through live sampling.
Estimate of Kelt Migration from the 2007 Cohort and Spring Fish Migrations from the
2008 Cohort, DIDSON Data, River Deel

The SSC determine the kelt run for river systems by assuming all fish ≥ 40 cm migrating
downstream between January and the 31\textsuperscript{st} May are kelts (Anon., 2008b). Using this
assumption, the total number of kelts on the River Deel was 1,542 (Table 4.2). However, Fig.
4.4 above also shows the distinct gap in upstream and downstream fish migration from the
28\textsuperscript{th} February to the 18\textsuperscript{th} March 2008, with the commencement of the initial MSW run in
March and the main run of these spring fish in April 2008. These spring fish were observed
actively migrating upstream and downstream past the DIDSON site. Where the SSC
methodology was applied, downstream migrations in March and April are assumed as kelts;
however, DIDSON observations and fish length data showed that these downstream
migrations were predominantly MSW fish actively migrating back downstream to Lough
Conn. Thus, there was a possibility for over estimating the kelt migration through the
inclusion of downstream migrations of fish from March to May for the River Deel. These
MSW downstream migrations were not thought to be MSW kelts migrating back downstream
as they were actively swimming and they followed recent upstream migrations of similar
sizes and numbers of fish (Vol. II Appendix Section VIII: Image 4.1 & 4.2: Spring fish
migrations). Thus, the estimated number of kelts for the 2007 cohort migrating downstream
in January and February 2008 was 742 (Table 4.2).

<table>
<thead>
<tr>
<th>Method</th>
<th>Dates</th>
<th>2007 Kelt Estimates</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSC Method</td>
<td>Jan-31st May 2008</td>
<td>1,542</td>
</tr>
<tr>
<td>Deel DIDSON Method</td>
<td>Jan &amp; Feb 2008</td>
<td>742</td>
</tr>
</tbody>
</table>

Fig. 4.5 above was included to highlight the significant upstream migration of MSW fish on
the 26\textsuperscript{th} and 27\textsuperscript{th} April. The active migration of fish upstream and downstream in March and
April 2008 as observed using DIDSON, particularly evident at the end of April, allowed for
the assumption to be made that the majority of these migrating fish in were MSW fish
migrating back downstream. The peak of the spring run was on the 26\textsuperscript{th} April and 27\textsuperscript{th} April
where 125 and 111 MSW fish were actively swimming upstream. During the last five days in April 202 fish migrating downstream were actively migrating MSW fish that had earlier migrated upstream from the 26\textsuperscript{th} April.

**Analysis of Monthly Length Frequency Histograms, January to April 2008, River Deel & Confirmation of the Spring Run**

In Fig. 4.6 below, January had an almost normal distribution of fish length indicating both grilse and MSW fish migrations and this continued into February but in much lower numbers. The number of fish migrating in January and February ≥ 70 cm was 55, with 263 fish in January ranging in size from 40 – 64 cm. Only 68 fish migrated upstream in February, with 37 of these fish ≤ 60 cm.

![Length Frequency Data](image)

*Figure 4.6: Length frequency data for upstream migration of fish, Deel DIDSON site, River Deel, January & February 2008 (n = 536).*

In March and April, there was a notable increase in the size of fish. The upstream migration of spring fish commenced in March 2008 with a run of 88 salmon (≥ 40 cm) with an average length of 65 cm (Fig. 4.7). From the 19\textsuperscript{th} March, fish length continued to increase and the average in April was 68 cm, when 424 salmon migrated upstream. The peak size range in April was 68 – 70 cm, with 194 fish ≥ 70 cm migrating upstream. In the second half of April, some of these fish were thought to be early running grilse that began migration as 29 of these salmon ranged in size from 43 – 55 cm. This trend in smaller sized salmon migrating
continued into early May where there was a marked drop in size of fish and the average fish length dropped to 58 cm (n = 243); however, 58% of these fish were over 60 cm. The majority of this early run of smaller grilse was over in early May, where larger grilse began to migrate (Fig. 4.8).

![Length Frequency](image)

*Figure 4.7: Length frequency data for upstream migration of fish, Deel DIDSON site, River Deel, March & April 2008 (n = 520).*

The SSC make assumptions in their yearly counts for MSW fish by including all upstream fish migrations from January to the 31st May. Using the SSC methodology on the River Deel, Table 4.3 shows the breakdown of these counts. However, the River Deel as already described is not a river running directly into the sea but has a huge holding area in Lough Conn. Taking all of the above into account and to enable a count to be obtained for spring salmon migrating upstream in March and April 2008, the total number of spring MSW salmon estimated migrating upstream between March and April 2008 was 512 salmon (≥ 40 cm) (Table 4.3). These salmon were assumed as the base estimate for the spring salmon run on the River Deel prior to length cut-offs being applied.
Table: 4.3: Spring salmon migration estimates, Deel DIDSON site, River Deel, 2008 (includes upstream migrating fish for each assigned time frame).

<table>
<thead>
<tr>
<th>Method</th>
<th>Dates</th>
<th>2008 Spring Run Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSC Method</td>
<td>Jan- 31st May 2008</td>
<td>1,455</td>
</tr>
<tr>
<td>Deel DIDSON Method</td>
<td>March &amp; April 2008</td>
<td>512</td>
</tr>
</tbody>
</table>

The Use of Length Frequency Distributions to Describe, Early Grilse Run Component, DIDSON Data, River Deel

Fig 4.8 below shows DIDSON length frequency data for the upstream migration of fish in May 2008 ranging in size from 28 – 88 cm, with 340 fish migrating. From these data, 169 fish ranged in length from 28 - 52 cm, with 86 fish between 40 - 52 cm. These fish were assumed to be early running grilse. The River Moy’s grilse run can include salmon less than 30 cm (IFI, Ballina Office). Only 67 fish ≥ 68 cm migrated in May and these were thought to be the end of the MSW spring run and possible commencement of the summer grilse run.

![Length frequency data](image)

Figure 4.8: Length frequency data for upstream migration of fish, Deel DIDSON site, River Deel, May 2008 (n = 340).
4.2.3 Quantification of the River Deel Atlantic salmon Migration for the 2008 Cohort Using Length Cut-Off Techniques

The first methodology applied to discriminate salmon (grilse and MSW) from brown trout were the length cut-offs (Figs. 4.8 & Fig. 11). All fish above the two length cut-offs were assumed to be grilse and MSW. Details of the counts after each cut-off are provided in Table 4.4.

Table 4.4: Atlantic salmon grilse population estimates from June to December 2008, DIDSON site, River Deel (All fish above the assigned length cut-off were assumed to be salmon).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>≥ 40 cm</td>
<td>8,360</td>
<td>5,288</td>
<td>3,814</td>
<td>3,343</td>
</tr>
<tr>
<td>≥ 45 cm</td>
<td>7,497</td>
<td>4,897</td>
<td>3,304</td>
<td>2,855</td>
</tr>
</tbody>
</table>

The maximum upstream count was in November with 1,160 salmon ≥ 40 cm, the maximum downstream count 952 salmon and MSW ≥ 40 cm was in December and the maximum net upstream migration occurred in October 2008 with 1,805 salmon ≥ 40 cm (Fig. 4.9 & 4.10). The maximum upstream migration of salmon ≥ 45 cm was 1,477 in October, with the maximum downstream migration of 867 grilse ≥ 45 cm was in December and the maximum net migration of 990 salmon ≥ 45 cm was in October 2008 (Figs. 4.11 & 4.12). The exclusion of fish ≤ 45 cm reduced the net upstream migration salmon by 512 fish.
Figure 4.9: Total monthly migration of grilse and MSW salmon (assumed ≥ 40 cm), upstream and downstream migration, Deel DIDSON site, River Deel (n = 13,648) (August 2008 data consists of eight days of data due to downtime).

Figure 4.10: Net monthly upstream migration of grilse and MSW salmon (assumed ≥ 40 cm), Deel DIDSON site, River Deel) (Downstream kelts in January & February were not subtracted) (August 2008 data consists of eight days of data due to downtime).
Figure 4.11: Total monthly migration of grilse and MSW salmon (assumed ≥ 45 cm), upstream and downstream migration, Deel DIDSON site, River Deel (August 2008 data consists of eight days of data due to downtime).

Figure 4.12: Net monthly upstream migration of grilse and MSW salmon, (assumed ≥ 45 cm) Deel DIDSON site, River Deel (Downstream kelts in January & February were not subtracted) (August 2008 data consists of eight days of data due to downtime).
4.2.4 The Use of Length Frequency Distributions to Describe the 2008 Cohort combined Grilse and MSW Run Components, and the Determination of the Grilse and MSW Individual Components, DIDSON Data, River Deel

The daily upstream migration (Fig. 4.13) and the daily net upstream migration (Fig. 4.14) of grilse and MSW salmon from June to December 2008 showed four clear peaks in their migration in July, October, November and December 2008. As the early grilse run in May was estimated as described on page 146, the total number of grilse and MSW fish migrating upstream from June to December 2008 was 7,379, with a net upstream migration of 3,351. The three peaks in the net upstream migration of grilse was on the 20\textsuperscript{th} October at 212 fish, 14\textsuperscript{th} November at 319 fish and on the 15\textsuperscript{th} December with 227 fish (Fig. 4.14).
Figure 4.13: Daily upstream migration of salmon, June to December 2008, Deel DIDSON site, River Deel, 2008 (where salmon were assumed to be ≥ 40 cm) (n = 7,138).

Figure 4.14: Daily net upstream migration of salmon, May to December 2008, Deel DIDSON site, River Deel, 2008 (where salmon were assumed to be ≥ 40 cm) (n = 3,343).
To further analyse the run components, Fig. 4.15 (a) & Fig. 4.15 (f) below, provide a summary of the monthly upstream and net upstream migrations in length frequency histograms. Figs. 4.15 (a) to 4.15 (c) show the upstream migration of all grilse and MSW fish ≥ 40 cm, (a). January to May, (b) May to August and (c) August to December 2008. As discussed earlier, details of early running fish specific run components were made easier using DIDSON observations and migration dates. DIDSON observations showed that early spring salmon migrated back downstream to Lough Conn, thus these salmon would re-migrate later in the season. These salmon could be of similar size to larger grilse also running later in the season, compounding the difficulty of assessing run components.

In June, 918 fish migrated upstream (≥ 40 cm) with the peak of 150 fish at 68 cm which indicated the presence of larger grilse (Fig. 4.15 (b)). There were 438 fish ranging in size from 68 to 92 cm and 368 fish ranging in size from 40 - 60 cm. Both small and larger summer salmon were recorded in July and some of these larger salmon could also be MSW salmon. The majority of fish migrating upstream in July ranged in size from 48 to 72 cm. For the eight days of data recorded in August 264, fish migrated upstream ranging in size from 40 to 84 cm with a peak at 60 cm and showed a steady increase through September. In September, 589 fish migrated upstream. The peak range in size was between 56 and 68 cm with 290 and 196 salmon migrated at a size range of 72 cm. The peak of the late grilse run commenced in October, with 1,830 fish migrating. The peak run of fish in November migrating upstream shows a bimodal distribution with a run of fish ranging in sizes between approximately 40 to 50 cm and approximately 60 to 80 cm, which could be smaller grilse or trout, and larger grilse or MSW salmon. In December, a total of 1,602 salmon migrated upstream with 1,232 of these salmon ranging in size between 56 and 84 cm. Also in December, the smaller running grilse were still migrating with 278 fish between 40 and 52 cm.
Figure 4.15: DIDSON length frequency data for upstream migrating Atlantic salmon, River Deel (a), January to May 2008; (b) May to August 2008; and (c) August to December 2008 (Note: Kelts not subtracted from January and February) (August 2008 data consists of the first eight days of August due to downtime).

Figure 4.15 (a)

Figure 4.15 (b)

Figure 4.15 (c)

Figure 4.15 (d)

Figure 4.15 (e)

Figure 4.15 (f)

Figure 4.15: DIDSON length frequency data for the net upstream migration of Atlantic salmon (assuming all fish ≥ 40 cm were grilse and MSW) River Deel (d), January to May 2008; (e) May to August 2008; and (f) August to December 2008. (Note: Kelts not subtracted from January and February) (August 2008 data consists of the first eight days of August due to downtime)
Figs. 4.15 (d) to 4.15 (f) show the net upstream migration of salmon in the River Deel for 2008, January to May 2008 as described earlier. The length frequency histogram in Fig. 4.15 (e) for the net upstream migration in June was almost bimodal, showing both smaller running grilse and summer salmon. The summer run was consistent in July with fish between 40 to 60 cm dominating but the number of salmon migrating were much lower over the summer months when compared to autumn/winter 2008 (Fig. 4.15 (f) ). In September, the net upstream migration slowed down with the majority of fish size present; however, 47 of these fish were noted to be in the size range between 76 to 88 cm, and these fish were assumed MSW using the ≥ 70 cm length cut off. The bulk of the net upstream migration was in October and November. However, some of these smaller fish could possibly be trout as trout are known to run at least a month earlier than salmon. In October, the net run of fish was more constant in numbers for length frequency data with an average of 118 fish migrating for each of the size ranges from 40 to 76 cm. Of the total net upstream migration in November, 586 fish migrated between the size ranges of 40 to 48 cm, with 359 fish migrating between the size ranges of 68 to 80 cm. These were identified as two peaks in the size ranges for November as identified in the analysis of upstream migration data. The net upstream migration in December showed that the majority of salmon ranged in size from 64 to 76 cm.

Estimation of MSW fish Run Component for the 2008 Cohort using Simple Length Frequency Cut-Offs, Deel DIDSON, River Deel

Traditionally, the proportion of MSW salmon was determined using length frequency data, where it existed in the absence of age data (scale reading). It was only possible to estimate MSW fish between June and December 2008 during the peak of salmon migration by using length cut-offs as there were no samples taken for age reading. To further facilitate the extraction of the MSW count from the River Deel DIDSON data, all fish ≥ 80 and ≥ 70 cm, were extracted from the count for 2008 and assumed MSW for each length cut off to provide a putative maximum and minimum count (Chapter 2). Again, it must be noted that salmon holding in a lake such as Lough Conn can often make several false upstream migrations prior to spawning. However, the subtraction of downstream migrations will correct the count for this milling behaviour. These data showed that the migration patterns of MSW salmon were much broader and less confined to early runs as had been previously thought. The smallest
length frequency cut-off for the determination of MSW salmon applied was ≥ 70 cm (Table 4.5).

Table 4.5: Population estimate of the upstream and net upstream migration of Atlantic salmon, Multi-Sea Winter salmon, DIDSON Site, River Deel, 2008 Cohort (*January and February 2008 kelts not subtracted for net count).

<table>
<thead>
<tr>
<th>Size Cut-off</th>
<th>Jan-Dec 2008 Net MSW Upstream*</th>
<th>Jan to 31st May 2008 MSW Upstream</th>
<th>Spring Running Fish March &amp; April 2008 Upstream</th>
<th>MSW Fish (June-December) 2008 Net Upstream*</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥ 80 cm</td>
<td>230</td>
<td>51</td>
<td>38</td>
<td>246</td>
</tr>
<tr>
<td>≥ 70 cm</td>
<td>911</td>
<td>272</td>
<td>207</td>
<td>888</td>
</tr>
</tbody>
</table>

Using the ≥ 70 cm cut off, peaks in the upstream MSW migration were observed in April, June and October to December 2008 (Fig. 4.16). From April to June, 224 MSW salmon migrated upstream. The peak in the run of MSW ≥ 70 cm salmon was in December at 603 salmon, this could also be indicative of MSW salmon for the 2009 cohort early migration but this was not confirmed. From March until July 2008, there were negative net upstream migration for salmon ≥ 70 cm, again indicative of milling of these fish up and downstream past the DIDSON counter, migrating in and out of Lough Conn. The largest net upstream migration was 314 salmon ≥ 70 cm in November and the peak of 123 MSW salmon ≥ 70 cm occurred on the 14th November 2008. Table 4.5 above shows that there were very few salmon of ≥ 80 cm migrating in the River Deel.
4.2.5 The Use of Individual Run Component Data, using DIDSON length Frequency Data for Individual Stock Assessment, River Deel, Moy Catchment

The above sections show the detailed analysis of run timings and run components obtained from DIDSON count and length frequency data analysis. For the determination of individual stock assessment data, the above population estimates for the 2008 cohort were established for grilse and MSW salmon from January to December, the spring run for April and March, and the grilse run from June to December with variations in the length cut-offs shown in Tables 4.8 & 4.9. To produce a count for both run components, length cut offs provided estimates of 3,814 (salmon ≥ 40 cm) and 3,304 (salmon ≥ 45 cm) for the 2008 cohort including both grilse and MSW fish. These data provided a net upstream count for June to December 2008. When MSW salmon were subtracted (> 70 cm), an estimated grilse (salmon ≥ 40 cm & < 70 cm) count of 2,455 was obtained. The final summary Table 4.6 shows the estimated grilse population for the River Deel, 2008.
Table 4.6: River Deel grilse population estimates, Deel DIDSON site, River Deel, 2008 Cohort (grilse were assumed to be $\geq 40$ cm and $\leq 70$ cm).

<table>
<thead>
<tr>
<th>Length Frequency Cut-off</th>
<th>Grilse Count January to December 2008</th>
<th>Grilse Count June to December 2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\geq 40$ &amp; $&lt;70$ cm</td>
<td>2,903</td>
<td>2,455</td>
</tr>
</tbody>
</table>
4.2.6 The Use of the Bimodal Model for Discrimination of Atlantic salmon and Non-target Species such as Brown Trout, Deel DIDSON Data, River Deel

A frequency histogram over the 14 months of data collection is shown in Section 2.2.3.11 Fig. 2.10). A bimodal distribution from DIDSON length frequency data was obtained, indicating the presence of two distinct species (assumed to be salmon (grilse and MSW fish) and brown trout) which provided an estimated count for both species (Table 4.7). The cut-off size between the two species was estimated at approximately 51 cm. Fig. 2.10 (Chapter 2: Section 2.2.3.11) shows that there was a large crossover of the two species that required allocation to either salmon or brown trout categories.

Table 4.7: Breakdown of allocated species of salmon (Grilse and MSW Fish) and Trout (Brown Trout), River Deel Bimodal Model, Deel DIDSON site, River Deel, 2008.

<table>
<thead>
<tr>
<th>Bimodal Model</th>
<th>All Fish</th>
<th>Salmon</th>
<th>Trout</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Upstream</td>
<td>10,472</td>
<td>6,129</td>
<td>4,343</td>
</tr>
<tr>
<td>Total Downstream</td>
<td>6,474</td>
<td>4,088</td>
<td>2,386</td>
</tr>
<tr>
<td>Total Net Upstream</td>
<td>4,824</td>
<td>2,633</td>
<td>2,191</td>
</tr>
</tbody>
</table>

The model showed that the maximum of 1,271 salmon migrated upstream in December 2008, with a maximum net upstream migration of 771 in October 2008. Three distinct peaks in the upstream migration of salmon were observed in Fig. 4.17. This was indicative of the MSW fish migrating in April 2008, the grilse run in June and July 2008, with the main bulk of salmon migrating upstream from October to December 2008. The upstream count for salmon was 391, 672 and 333, for the months of April, June and July 2008. The bulk of the net upstream salmon count migrated in October and December 2008, with 1,958 salmon migrating over that period (Fig. 4.18).
Figure 4.17: Species discrimination using the Bimodal Model for the total monthly migration of Atlantic salmon (Grilse and MSW fish) upstream and downstream migration, Deel DIDSON site, River Deel. (n = 12,179) (These data included all fish movement minus non-target species detected). (Note: August 2008 data consists of only eight days of data collected due to downtime).

Figure 4.18: Species discrimination using the Bimodal Model for the net monthly upstream migration of Atlantic salmon (Grilse and MSW fish) migrations, Deel DIDSON site, River Deel (These data included all fish movement minus non-target species detected). (Note: August 2008 data consists of only eight days of data collected due to downtime).
The Bimodal model showed that the peak in brown trout migration commenced earlier than salmon with a net upstream migration in November 2008 of 963 trout (the trout upstream migration also in November was 1,333 brown trout). The greatest number of brown trout migrated upstream between October and November 2008, with a distinctive earlier run than salmon and this was reflected in the monthly net upstream counts (Fig. 4.19 & 4.20). There was a negative downstream brown trout count in April of – 52. However, these could be incorrectly discriminated as brown trout but could actually be smaller early running grilse. The bulk of the net upstream brown trout count migrated in October and November 2008, with 1,633 brown trout migrating during that period.
Figure 4.19: Species discrimination using the Bimodal Model for the total monthly migration of Brown trout upstream migration and downstream migration, Deel DIDSON site, River Deel (These data include all fish movement minus non-target species detected). (Note: August 2008 data consists of only eight days of data collected due to downtime).

Figure 4.20: Species discrimination using the Bimodal Model for the net monthly upstream migration of Brown Trout migration, Deel DIDSON site, River Deel, (n = 2,191) (These data include all fish movement minus non-target species detected). (Note: August 2008 data consists of only eight days of data collected due to downtime).
4.2.7 Summary of the River Deel Population Estimates from the Deel DIDSON using the Four Models for Species Apportionment and Sea-Aging, 2008

Data from the above analysis were used to compile Table 4.8, which provides details of estimated Atlantic salmon for each model for both the combined count of grilse and MSW and to estimate the individual grilse and MSW counts. Table 4.8 provides a summary of the net upstream migration for both grilse and MSW fish for 2008, where January and February 2008 upstream salmon were included as part of the 2008 cohort. These data in Table 4.8 were used for comparison with smolt migration data to provide an estimate range of the River Deel stock, to validate the DIDSON stock estimate against the juvenile estimate (Chapter 5: Section 5.4). The estimated combined count of grilse and MSW ranged from 2,633 – 3,814 fish (Table 4.8).

As described in Chapter 2: Section 2.2.3.11, to further develop the count estimates with respect to the determination of the 2008 cohort (grilse and MSW), three subsequent counts were provided of the three species discrimination models within the three defined scenarios for the 2008 cohort to provide the salmon estimate of the River Moy (Chapter 7). Table 4.9 shows the salmon estimate assuming that the run commenced on the 18th March and concluded on the 31st December 2008; and Table 4.10 shows the stock assessment with the inclusion of January and February 2008 upstream migrating fish to adjust for late spawners (as described in the initial analysis). Table 4.11 adjusted the 2008 cohort for late spawners using relative proportions between fish migrating in December of both study years. The original analysis in Table 4.8 combined both methods applied to Table 4.9 and Table 4.10. Data from Table 4.9 to 4.11 will be used in Chapter 7 for the development of a new methodology using DIDSON to count one tributary with a discrete population (River Deel) and GSI to estimate salmon populations for the whole catchment (River Moy) (Chapter 7). The estimated combined count of grilse and MSW of the three species discrimination models within each of the three run time scenarios ranged from 2,309 – 4,191 salmon (Table 4.9 - 4.11).

These data provide for the first stock assessment data using a DIDSON in an Irish river system and show that DIDSON can be used to estimate salmon stocks in Ireland. This is significant in terms of the ability to operate long term deployments of DIDSON for stock...
assessment data. DIDSON was shown to operate in all weather conditions and the DIDSON counter was not affected by flooding or turbidity during its operations (Chapter 3). The observations made using DIDSON also highlight that the migrations of specific run components can differ significantly river by river in terms of run timings as was seen in the River Deel.
Table 4.8: River Deel population estimates from Deel DIDSON data for the determination of sea-age, 2008 (*Where downstream migrating kelts in January and February 2008 were not subtracted from the count estimate for January to December 2008 count).

<table>
<thead>
<tr>
<th>Model</th>
<th>Jan to Dec 2008 Net* (Grilse &amp; MSW)</th>
<th>Jan to Dec 2008 Net* (Grilse)</th>
<th>Jan to Dec 2008 Net* (MSW)</th>
<th>1st June to Dec 2008 (Grilse &amp; MSW)*</th>
<th>1st June to Dec 2008 (Grilse)</th>
<th>1st June to Dec 2008 (MSW)</th>
<th>1st June to Dec 2008 (MSW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw DIDSON Count</td>
<td>4,897</td>
<td>3,986</td>
<td>911</td>
<td>4,725</td>
<td>4,256</td>
<td>3,368</td>
<td>888</td>
</tr>
<tr>
<td>≥ 40 cm</td>
<td>3,814</td>
<td>2,903</td>
<td>911</td>
<td>3,812</td>
<td>3,343</td>
<td>2,455</td>
<td>888</td>
</tr>
<tr>
<td>≥ 45 cm</td>
<td>3,304</td>
<td>2,393</td>
<td>911</td>
<td>3,291</td>
<td>2,855</td>
<td>1,967</td>
<td>888</td>
</tr>
<tr>
<td>Bimodal Model</td>
<td>2,633</td>
<td>N/A</td>
<td>N/A</td>
<td>2,614</td>
<td>2,290</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Table 4.9: River Deel population estimates of grilse and MSW salmon from the Deel DIDSON, using three models for species discrimination and sea-age, 2008 cohort estimated as 18\textsuperscript{th} Mach to 31\textsuperscript{st} December (Assumes no 2008 Cohort fish migrate in January & February 2008).

<table>
<thead>
<tr>
<th>Model</th>
<th>18th Mar to Dec 2008</th>
<th>18th Mar to 1st May 2008</th>
<th>1st May to Dec 2008</th>
<th>18th Mar to 1st June 2008</th>
<th>1st June to Dec 2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥ 40 cm</td>
<td>3,341</td>
<td>-10</td>
<td>3,351</td>
<td>-2</td>
<td>3,343</td>
</tr>
<tr>
<td>≥ 45 cm</td>
<td>2,867</td>
<td>5</td>
<td>2,862</td>
<td>12</td>
<td>2,855</td>
</tr>
<tr>
<td>Bimodal Model</td>
<td>2,309</td>
<td>24</td>
<td>2,285</td>
<td>19</td>
<td>2,290</td>
</tr>
</tbody>
</table>

Table 4.10: River Deel population estimates of grilse and MSW salmon from the Deel DIDSON, using three models for species discrimination and sea-age, 2008 cohort estimated (Assumes fish migrate in January & February 2008 are equivalent to late migrations in 2009).

<table>
<thead>
<tr>
<th>Model</th>
<th>Jan to Dec 2008</th>
<th>Jan to 1st May 2008</th>
<th>1st May to Dec 2008</th>
<th>Jan to 1st June 2008</th>
<th>1st June to Dec 2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥ 40 cm</td>
<td>3,814</td>
<td>477</td>
<td>3,820</td>
<td>463</td>
<td>3,812</td>
</tr>
<tr>
<td>≥ 45 cm</td>
<td>3,304</td>
<td>440</td>
<td>3,298</td>
<td>447</td>
<td>3,291</td>
</tr>
<tr>
<td>Bimodal Model</td>
<td>2,633</td>
<td>348</td>
<td>2,609</td>
<td>343</td>
<td>2,614</td>
</tr>
</tbody>
</table>

Table 4.11: River Deel population estimates of grilse and MSW salmon from the Deel DIDSON, using three models for species discrimination and sea-age, 2008 cohort estimated (Assumes an estimate for late migrating fish in January & February 2009 using relative proportion with respect to December 2007/December 2008).

<table>
<thead>
<tr>
<th>Model</th>
<th>Relative Proportion Adjustment: Jan to Dec 2008</th>
<th>Relative Proportion Adjustment: Jan to 1st May 2008</th>
<th>1st May to Dec 2008</th>
<th>Relative Proportion Adjustment: Jan to 1st June 2008</th>
<th>1st June to Dec 2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥ 40 cm</td>
<td>4,191</td>
<td>840</td>
<td>4,201</td>
<td>848</td>
<td>4,193</td>
</tr>
<tr>
<td>≥ 45 cm</td>
<td>3,717</td>
<td>855</td>
<td>3,712</td>
<td>862</td>
<td>3,705</td>
</tr>
<tr>
<td>Bimodal Model</td>
<td>3,159</td>
<td>874</td>
<td>3,135</td>
<td>869</td>
<td>3,140</td>
</tr>
</tbody>
</table>
Chapter 5

5.0 The Operation of a Screw Trap as a Method for Stock Assessment of Atlantic salmon Smolt.

5.1 Introduction

Accurate estimates of the rate of emigration of salmon are critical to estimating their rates of survival and their strengths in various age-classes (Cheng & Gallinat, 2004). A measure of the number of outward migrating smolts is the most valuable information on early life stage of salmon populations and is a critical fisheries reference point for salmon as it represents the outcome of freshwater production (Cowx, 2003). Smolts are the last stage of the life cycle that can be quantified or assessed before fishing mortality occurs (Dempson & Stansbury, 1991). As an alternative to an adult count, a juvenile assessment of the outward migration of smolts on the River Deel was undertaken. Counters require operation for longer periods to determine adult counts, requiring greater man-power. However, owing to the nature of smolt migration, counting operations are only required for the duration of the smolt run. For this reason it was important to assess their effective use for juvenile stock assessments in an Irish river system.

5.1.1 Atlantic salmon Smoltification and Run Timing

Where no baseline data exists, initial screw trap operations must first identify the timing of the smolt run to determine the run period and/or to ensure that the peak run is sampled, depending on the study requirements. The timing of smolt migration is determined by environmental factors in two ways, the initiation of smoltification and the trigger to migrate. Several studies have shown photoperiod and temperature to be the two main factors affecting the smoltification process (Hoar, 1988; Saunders & Henderson, 1970, Jonsson & Ruud-Hansen, 1985; McCormick et al., 1987, Duston & Saunders, 1990, Saunders & Harmon, 1990, Byrne et al., 2003; Byrne et al., 2004). These two factors affect physiological changes through the neuroendocrine system (McCormick et al., 1998). Water Temperature (Österdahl, 1969, Saunders & Henderson, 1970, Raymond, 1979, Orell et al., 2007; McCleave, 1978; Jonsson & Rudd-Hansen, 1985; Jonsson et al., 1991; Whalen et al., 1999)
and discharge (Byrne et al., 2003; Hesthagen & Garnas, 1986; Jonsson et al., 1991) have been shown by several authors to be possible triggers for salmonid smolt migration. Byrne et al. (2003) discussed what they termed a physiological ‘smolt window’ and an ecological ‘smolt window’ of migration. This limited period of readiness and the timing of seawater entry when environmental conditions are appropriate was initially described by McCormick et al. (1998). Other studies have shown that there is no temperature threshold triggering smolt migration but instead it is controlled by a combination of temperature increase and temperature condition in the river during spring (Jonsson & Rudd-Hansen, 1985; Orell, 2003; Byrne et al., 2004; Zydlewski et al., 2005). The increase in day-length in spring (photoperiod) acts as the synchroniser of an endogenous rhythm, the environmental factor that most influences the onset of parr-to-smolt transformation (Byrne et al., 2004, Jonsson & Jonsson, 2009). Environmental data was collated and assessed to determine possible correlations with the peak yearly run timing of smolt for the River Deel system (Chapter 6).

5.1.2 Mark-recapture Technique and Data Analysis Modelling
The objective of mark recapture of fish and other wildlife is to enable their abundance to be estimated indirectly (Ricker, 1967). A variety of mark-recapture estimation methods exist for both open (Darroch, 1961; Cormack, 1964; Jolly, 1965; Seber, 1986) and closed populations (Petersen, 1896, Lincoln, 1930; Schumacher & Eschmeyer 1943; Chapman, 1951; Bailey, 1952; Seber, 1982; Pollock, 2000; Ogle, 2010). Several authors have reported that capture probabilities varied during the sampling period (Dempson & Stansbury, 1991; Schwarz, 1994; Thedinga et al., 1994; Rivot & Prévost, 2002; Mäntyniemi & Romakkanieti, 2002). The difference in daily estimates and capture probabilities will change with respect to the run timing (determined by environmental and biological factors) and the efficiency of the screw trap which can be affected by water level and flow, i.e. location. The Mäntyniemi and Romakkanieti (2002) model allowed for the option of incorporating environmental covariates which would influence the population estimates. Examination of schooling behaviour and environmental covariates could potentially achieve a more realistic model for prediction of population size.
5.1.3 River Deel Study Design

In order to choose a site for salmon smolt mark and recapture abundance estimates, a section of the River Deel was surveyed. A proportion of migrating smolts were trapped in a screw trap and the trap was monitored consistently on a daily basis over the duration of the run as part of the mark-recapture programme to ensure that no migrating smolts were missed. The mark-recapture estimates allowed for the efficiency of the screw trap to be determined. The mark-recapture sampling was carried out by treating the whole run as a single mark-recapture experiment for both study years and as batches over the duration of the smolt run in 2008, where multiple recaptures were assessed. Trap efficiency is estimated as the number of recaptured smolts in the trap over the number released above the trap determined using classical models (Schnabel, 1938; Chapman, 1951; Schmacher & Eschmeyer, 1949) and new more sophisticated approaches using Bayesian modelling (Mäntyniemi & Romakkaniemi, 2002; Rivot & Prévost, 2002). There are no published studies in Ireland using these modelling techniques for mark-recapture estimates. Chaput & Jones (2004) study in eastern Canada used the same sampling method applied in the River Deel study. The River Deel experiment allowed for sampling on a 24 hour basis with one count per day. Atlantic Counting fences a popular method for counting smolt, are not operated on Irish river systems and to date only two screw traps have been purchased in Ireland. Screw trap operations in Ireland prior to this study were unsuccessful. The operation of a screw trap would allow for the determination of yearly trends in smolt production from the River Deel. The quantification of smolt output from the River Deel provided a direct measure of the yearly change in freshwater survival prior to their entry to sea. Smolt production data from this study for the 2007 smolt output was used to compare with the number of returning adults on the River Deel, as determined using the DIDSON (Chapter 4). However, the estimate determined from the 2007 study was believed to be an underestimation owing to flood conditions during the main smolt run which may have affected with the mark-recapture experiment. Important biological information was also determined with respect to other fish species trapped. Screw traps are not species or size selective and any species migrating downstream in the system can potentially be sampled (Chaput & Jones, 2004). A total of seven non-target species were captured during the operation of the screw trap in 2007 and
nine in 2008 (Vol. II Appendix Section V: C). The trap allowed for length, weight, scale and tissue samples to be taken from a sample of both smolts and other species trapped when required. An additional advantage of the operation of the screw trap was that it provided information on the overall health of the River Deel system. This type of sampling in not species specific allowing the possibility of all species within the system to be sampled and assessed.

5.1.4 Summary of Smolt Stock Estimates
In 2007, 7% of marked fish were recaptured and 6% in 2008. The various models applied produced stock estimates that ranged from 12,569 to 14,751 smolts in 2007 and 52,721 to 92,440 smolts in 2008. The more classical model of Lincoln Petersen (Chapman modification) with confidence intervals and the Bayesian model of Rivot and Prévost, (2002) provided the best estimate when compared to the McGinnity et al. (1999) indirect estimate of the smolt production potential of 72,000 smolts for the River Deel. The most productive year for smolt output from the two years of sampling was 2008. However, flooding during 2007 may have affected the potential for recaptures during the peak of the run. The operation of the screw trap in 2007 allowed for the development of methodology and protocols for the screw trap operation and an indication of the peak run in the River Deel. It was thought that multiple recaptures using batch marking in 2008 would provide better estimates. However, this was dependent on the rate of recaptures. Estimates treating the 2008 mark-recapture as one single experiment produced the best estimates for 2008 as the mark-recapture experiment should be treated as a whole experiment and not based on one batch of data for a particular year.
5.2 Results

5.2.1 Screw Trap Operation for Atlantic salmon Smolt Mark-recapture Programme
Two successful years of mark-recapture data were obtained for 2007 and 2008 for the River Deel. The screw trap was in operation for 55 days, from the 7th April to the 16th May in 2007 and for 72 days, from the 22nd March to the 16th May in 2008. Captured smolts were found to be generally of good health and there were no indications of smolts being stressed from capture in the screw trap or handling. Where water temperatures had notably increased in the live box, smolt handling was kept to a minimum and fresh water was continuously added to the recovery bin prior to their removal upstream. Daily sampling of the screw trap was undertaken to ensure that all fish trapped were not retained in the trap for long periods of time which could have increased mortalities. During periods of higher water temperature in the River Deel, smolts were observed swimming upstream after release. Thower (1998) noted that smolt migration upstream upon release after marking was thought to be due to ‘stress-induced straying’. Smolt migration upstream upon release was occasionally noted in the River Deel study and was observed to coincide with days of increased water temperature. MacDonald and Smith (1980) looked at a method to estimate the run of Sockeye salmon smolts released back to a lake and their assessment also raised questions of the behaviour of these marked smolts upon release after marking. When the main smolt run was underway, smolts were actively swimming into the trap during sampling. On such days, all fish were sampled until no more fish entered the trap. This resulted in the daily sampling period lasting up to 4 hours during peak migrations. Mäntyniemi and Romakkaniemi, (2002) reported that smolts schooling behaviour causes more variation in capture data (over dispersion) than there would be if smolts moved independently. This was noted from the River Deel data and also observed during experiments on the River Orkla, Norway (Hvidsten et al., 1995).

The ability of the screw trap to trap smolts changed with respect to the rate of water level and flow. The efficiency of the trap at different rates of water level and flow for the duration of the smolt run was observed. Observations of the trap efficiency showed that the optimal water level and river flow for the River Deel screw trap were approximately 0.3 m and 1.8 m³/s. At water levels and river flows greater than approximately 1.0 m and 26.0 m³/s, the rate of capture was reduced as the drum of the screw trap became blocked with debris (Vol.II
Appendix Section VIII: CD: PowerPoint Presentation December 2007). The most significant river level and flow recorded during screw trap operations was 1.1 m and 31.2 m$^3$/s which occurred on the 25$^{th}$ April 2007 and coincided with the timing of part of the main run. This flood could have had a significant effect on the rate of capture and recaptures of the main run in 2007. On days during high flows when the trap was not operational, estimates were not made of downtime owing to the lack of smolt migration data for this system. It must be noted however, that environmental factors also dictate the rate of smoltification and smolt migration itself and these will also have played a role in the timing of the run and the rate of capture and recapture in the screw trap (Chapter 6). The rate of increases in river level and flow during the screw trap operation showed the River Deel to be an extremely flashy catchment. This made the screw trap very difficult to access safely in order to lift the drum during flood conditions. The drum was lifted to prevent it fishing in flood conditions where fish mortality could occur were large debris blocked the drum and trap and could damage fish. Lifting the drum for two days in 2007 will have prevented the possible recapture of marked smolts and thus there is no estimate for those days. This was, however the only way to prevent smolt mortalities in the screw trap or damage to the screw trap through heavy debris loading in the river during spring flooding. Recent studies have used screw traps with debris deflectors (Rayton & Wagner, 2006).

5.2.2 Description of Atlantic salmon Smolt Migration and Smolt Run Sampled in 2007 and 2008

In 2007, 855 smolts were captured, 732 marked and 48 recaptured over the duration of the run (Fig. 5.1). The peak of the run occurred from the 19$^{th}$ April to the 23$^{rd}$ April, when flood water prevented screw trap operations for a 48 hours period, until the 26$^{th}$ April. In 2008 (Fig. 5.2), the total of 1,676 smolts were captured, 523 marked and 30 recaptured. A greater proportion of the run was trapped in 2008 owing to the earlier installation of the screw trap. Changes were made to the 2008 methodology whereby the number of smolts migrating ≥ 50 in number were marked in batches. This proved to be a better methodology for the marking and recapture of smolts as this allowed for multiple recaptures for each individual batch to be assessed. The number of smolts caught in the screw trap during both study years was observed to be influenced by water temperature and river discharge. The maximum number of migrating smolts was 170 and 219, captured on the 23$^{rd}$ April 2007 and the 24$^{th}$ April.
2008. The run timing of the main smolt run commenced within a two day period for both study years, on the 19th April 2007 and the 21st April 2008 (Chapter 6).

Figure 5.1: The total n of Atlantic salmon smolts trapped, marked and recaptured, River Deel, 2007.

Figure 5.2: The total number of Atlantic salmon smolts trapped, marked and recaptured, River Deel, 2008.
5.2.3 Length and Weights of Atlantic salmon Smolts Capture Mark-recapture

The majority of the smolts were of the same size class and from the scale analysis undertaken two year smolts were the majority cohort sampled (Vol. II Appendix Section V). In 2007 (Fig. 5.3), 92 % of smolts captured were measured and in 2008, 99 % of smolts captured were measured (Fig. 5.4). The mean length of smolts captured in 2007 was 11.6 cm (SE = 0.034 / SD = 0.940) with a range of 7.0 to 15.8 cm and in 2008 was 11.9 cm (SE = 0.28 / SD = 1.17) with a range of 5.8 to 16.8 cm. The mean length measurement for the combined data was 11.8 cm (SE = 0.022 / SD = 1.105) with a range of 5.8 to 16.8 cm (Fig. 5.5).

A total of 220 length and weight measurements were taken simultaneously of individual smolts, 94 in 2007 and 126 in 2008. In 2007, 8 % of smolts were weighted and 11 % in 2008. The sample number was low when compared to the total number of fish trapped in both years but weights were only taken on a sample of the smolt populations to prevent stress and possible mortality from extra handling. These data showed a linear relationship between smolt length and weight on the River Deel with an $r^2 = 0.844$ for the combined data. The mean weight of smolts for the combined data was 11.78 g (SE = 0.02 / SD = 1.11) with a range of 8.80 to 36.00 g. The mean weight in 2007 was 17.69 g (SE = 0.469 / SD = 4.522) with a range of 8.80 to 29.90 g. In 2008, a higher mean weight was recorded of 18.24 g (SE = 0.456 / SD = 4.117) and the range was 9.4 to 36.00 g (Fig. 5.6 to 5.8). Smolt condition ($P = 0.412$) and smolts size ($P = 0.236$) in 2008 was larger and were observed during sampling to be physically in better condition than smolts trapped in 2007. This corresponded to the length data, where the frequency of larger smolts was found in 2008 than 2007 (Fig. 5.3 to 5.5). This was confirmed by comparing length and weight data for both study years (Table 5.1 & 5.2):
Table 5.1: Comparison of smolt length for 2007 & 2008 (t test), River Deel

<table>
<thead>
<tr>
<th>Smolt Length</th>
<th>2007</th>
<th>2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>11.9</td>
<td>12.0</td>
</tr>
<tr>
<td>T Stat</td>
<td>-1.189</td>
<td></td>
</tr>
<tr>
<td>P(T&lt;=t) two-tail</td>
<td>0.236</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.2: Comparison of smolt weight for 2007 & 2008 (t test), River Deel

<table>
<thead>
<tr>
<th>Smolt Weight</th>
<th>2007</th>
<th>2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>17.691</td>
<td>18.239</td>
</tr>
<tr>
<td>Observations</td>
<td>93.000</td>
<td>126.000</td>
</tr>
<tr>
<td>t Stat</td>
<td>-0.821</td>
<td></td>
</tr>
<tr>
<td>P(T&lt;=t) two-tail</td>
<td>0.412</td>
<td></td>
</tr>
</tbody>
</table>
Figure 5.3: Length frequency distribution of Atlantic salmon smolts trapped on the River Deel, 2007 ($n = 783$).

Figure 5.4: Length frequency distribution of Atlantic salmon smolts trapped on the River Deel, 2008 ($n = 1,665$).

Fig 5.5: Length frequency distribution of Atlantic salmon smolts trapped on the River Deel, 2007 and 2008 ($n = 2,448$).
Figure 5.6: The relationship between length and weight of Atlantic salmon smolts trapped on the River Deel, 2007 (n = 93; $r^2 = 0.785$).

Figure 5.7: The relationship between length and weight of Atlantic salmon smolts trapped on the River Deel, 2008 (n = 126; $r^2 = 0.873$).

Figure 5.8: The relationship between length and weights of Atlantic salmon smolts trapped on the River Deel, 2007-2008 (n = 219; $r^2 = 0.844$).
5.2.4 Atlantic salmon Smolt Population Estimation, River Deel, 2007 and 2008
The study in 2007 led to the establishment of a protocol for the operation of the screw trap and the marking of smolts for a single mark-recapture experiment (Table 5.4). A more refined programme was adopted in 2008 to allow for batch marking and multiple recaptures identified from each individual batch. Table 5.3 provides details of the five batches marked and recaptured in 2008, with Table 5.3 summary of single recapture estimates. Batch estimates and daily estimates calculated differed greatly in some instances owing at least in part to increased river level and flow (Chapter 6) which affected the trap efficiency and thus the rate of recapture (Table 5.4).

Table 5.3: Batch data for the five batches marked in 2008.

<table>
<thead>
<tr>
<th>Batch Number</th>
<th>Batch Mark Type</th>
<th>Date</th>
<th>Total Batch Day Count</th>
<th>Total No. Clipped for Batch</th>
<th>Total No. Recaptures from Batch</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Adipose fin clip</td>
<td>14/04/2008</td>
<td>145</td>
<td>145</td>
<td>21</td>
</tr>
<tr>
<td>2</td>
<td>Top tail clip</td>
<td>22/04/2008</td>
<td>54</td>
<td>54</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Bottom tail clip</td>
<td>23/04/2008</td>
<td>139</td>
<td>139</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>Bottom tail punch</td>
<td>24/04/2008</td>
<td>79</td>
<td>76</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>Top tail punch</td>
<td>25/04/2008</td>
<td>219</td>
<td>74</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 5.4: Atlantic salmon smolt estimates using various models for single mark-recapture estimates, River Deel, 2007 & 2008.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Lincoln Peterson (Uncorrected)</td>
<td>12,810</td>
<td>54,435</td>
</tr>
<tr>
<td>Chapman (Lincoln Peterson +1)</td>
<td>14,751 (10,814, 18,689)</td>
<td>52,761 (34,923, 70,599)</td>
</tr>
<tr>
<td>Schumacher &amp; Eschmeyer</td>
<td>12,810</td>
<td>54,435</td>
</tr>
<tr>
<td>Schumacher &amp; Eschmeyer +1</td>
<td>12,810</td>
<td>54,432</td>
</tr>
</tbody>
</table>
The mean total population mean estimate for 2007 from classical single recapture estimates was 13,295 (estimate range by different models of 12,810 to 14,751) (Table 5.4). These estimates were much lower than that of 2008 and it was thought that the smolt estimate in 2007 was low due to heavy flooding causing migrating smolts to be missed, thus the real value for 2007 is higher. However, large variations in yearly smolt migration do occur, e.g. the nearby Burrishoole River yearly smolts estimates range from from a maximum of 16,136 in 1976 to a minimum of 3,794 in 1991 (RESCALE, 2010). The mean total population estimate for 2008 using classical single recapture estimates was 54,016 (estimate range by different models of 52,761 to 54,435) (Table 5.4). The comparative assessment of the data for the total population estimates showed that there was very little variation in the estimate across the initial four models tested and that they were in close agreement (Table 5.4). In 2008; however, the comparative daily counts for the same models varied greatly. This was as expected, as the daily smolt run will vary greatly depending on the run timing and environmental influences (Chapter 6). The average daily smolt run of 7,576 smolts was calculated for 2008 (where the count for Schumacher and Eschmeyer Corrected Method was removed owing to what was thought to be an extreme over estimation of the daily run when compared to McGinnity et al. (1999) smolt potential production estimate for the River Deel of 72,000). Daily changes in the number of smolts calculated from the 2008 data reflected the changes observed in the three peaks of migration that were experienced (Table 5.4).

In 2008, both daily estimates and total run estimates were determined using both classical and more advanced Bayesian models. These data were assessed to obtain population estimates from smolt trap data collected from both the 22/03/08 to the 13/05/08 (inclusive from the start of operation of the screw trap) and from the 14/04/08 to the 13/05/08 (inclusive from the start of batch marking of smolts).
Table 5.5: The mean daily estimate and total population estimate for the 2008 data, River Deel.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Lincoln-Petersen</td>
<td>5,500</td>
<td>54,435</td>
</tr>
<tr>
<td>Lincoln-Petersen +1 and Chapman (Lincoln-Petersen +1)</td>
<td>1,900 (for both model applications)</td>
<td>52,761 (for both model applications)</td>
</tr>
<tr>
<td>Schumacher and Eschmeyer</td>
<td>26,701</td>
<td>54,435</td>
</tr>
<tr>
<td>Schumacher and Eschmeyer +1</td>
<td>14,364,671</td>
<td>54,433</td>
</tr>
</tbody>
</table>

Lincoln-Petersen Models and Schumacher and Eschmeyer Models

The Lincoln-Petersen model was the most basic model applied. The mean daily population estimate using Lincoln-Petersen model was 5,500 ± 3,188 (95 % c.l.) smolts (SD = 8,760). This model produced very high daily mean estimates. When the modified model, Lincoln-Petersen +1 was applied, a lower daily mean was estimated for the smolt run on the River Deel of 1,900 ± 1,367 (95 % c.l.) smolts (SD = 3,755). These daily estimates showed large deviation in the mean daily population estimates for the duration of the run, as the estimates followed the three main pulses of smolts that migrated in 2008. Both Schumacher and Eschmeyer and the modified method of Schumacher and Eschmeyer +1, provided very high daily mean population estimates, where the average daily mean population was estimated at 7,120 ± 17,723 (95 % c.l.) smolts (SD = 48,695), with a maximum and a minimum daily estimate of 146,073 and 881 smolts.

Chapman (Lincoln-Petersen+1) Estimates with Confidence Intervals

The daily mean estimate using Lincoln-Petersen +1 was 1,900 smolts ± 1,367 (95 % c.l.) (SD = 3,755). This result was much lower than the daily mean estimate for Lincoln-Petersen Uncorrected which was 5,500 smolts as described above. The total mean population estimate for Lincoln-Petersen +1 was 52,761 smolts. This method was used to correct for the lack of knowledge regarding the frequency distribution of the Lincoln-Petersen Uncorrected. Chapman Corrected (Lincoln-Petersen +1) provided the same total mean population estimate of 52,761 smolts ± 70,599 (95 % c.l.) (SD = 9,101).
Multiple Mark-recapture Estimates for 2008 - Schnabel Estimator and Schnabel Regression Models

When applying Schnabel's method to obtain an overall estimate using the full time series of data for the duration of the 2008 (smolt run from the 22nd March to 13th May 2008), the total population estimate for the run was calculated at 44,820 smolts. Using the same model and the data from the commencement of batch marking on the 14th April to 13th May 2008, the total population estimate for the run was calculated at 25,134 smolts (Table 5.6 below). This showed the importance of having details of the whole smolt run prior to marking. Thus, the estimate obtained by including all experimental data provided the better estimate of 44,820 smolts when compared to the other classical models tested and to the McGinnity et al. (1999) indirect smolt potential production estimate of 72,000. Schumacher and Eschmeyer (1943) use of a regression of a slope of 1/N passing through the origin, (Schnabel Regression Method) provided good quality estimates and was run twice, as above. The two estimates using the full time series of the 2008 run were calculated at 64,931 and from the date of marking the estimated smolt run was calculated at 60,939 (Table 5.6). The data for the full time series over the duration of the smolt run starting on the 22nd March 2008, provided a more realistic count for the run and agreed with the experimental design of using the total count data for the run from the 22nd March 2008, as opposed to using count data starting from when batch marking commenced.

Overall individual batch estimations proved less successful for determining the total mean estimate of the smolt run as expected. Looking at individual batches provides details of the run components of the smolt population. Using Schnabel’s method, batch 1, 2, 3, 4 and 5, produced estimates of 36,000; 326,653; 56,366; 188,550 and 141,336 smolts. The mean batch estimate of the five batches was calculated at 149,781 ± 102,341 (95 % c.l.) (SD = 116,758). Only batches 1 and 3 showed population estimates close to that obtained from the full time series analysis of the smolt run of 44,820 smolts, using this model. Batch 3 estimate was very similar to that of the Petersen models. The use of all five batches gives a representation of the different components of the smolt population and all batches should be used to determine the yearly population.
Schumacher & Eschmeyer Regression method also produced very high individual batch estimates of 123,631; 3,388,909; 147,358; 1,073,844 and 270,407 smolts, for batches 1, 2, 3, 4, and 5. Thus producing some extremely high population estimates for the 2008 run. The Schumacher & Eschmeyer methodologies were found unsuccessful in the analysis of the 2008 River Deel batch data when compared to the McGinnity et al. (1999) indirect smolt potential production estimate of 72,000.

Table 5.6: Atlantic salmon smolts estimates for multiple mark-recapture methods, River Deel, 2008.

<table>
<thead>
<tr>
<th>Model Applied</th>
<th>Run Estimate 2008 (entire mark-recapture set)</th>
<th>Run Estimate from 14th April 2008 (Beginning of Batch Marking)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schnabel</td>
<td>44,820</td>
<td>25,134</td>
</tr>
<tr>
<td>Schumcher &amp; Eschmeyer</td>
<td>64,931</td>
<td>60,939</td>
</tr>
</tbody>
</table>

Population Estimation based on the Binomial Distribution

The population estimate for the Lincoln-Petersen and the Modified Lincoln-Petersen methods based upon the binomial distribution for the 2008 mark-recapture data estimated the probability of observing marks in a catch in a given population size. The method provided for sampling with replacement and produced an estimate very close to that obtained using the Lincoln-Petersen, Lincoln-Petersen +1 and Chapman (Lincoln-Petersen +1). The mean estimate using the binomial distribution population estimate had a mode of 54,500 and a median of 56,500 smolts (2.5th percentile 83,000, 97.5th percentile 40,000). Figure 5.9 shows the mode and the median estimates for the population with the binomial prediction with replacement. The Lincoln-Petersen method was the closest estimate to the predicted binomial distribution with an estimate of 54,435 (± 95% c.l. 77,738 and 38,126) (SE = 9,101). The Corrected Petersen estimate was 52,761 smolts (± 95% c.l. 70,599 and 34,923) (SE = 9,101). Using these data for comparisons with McGinnity et al. (1999), the upper limit of the binomial distribution was thought to be the possible upper limit of smolt production for the River Deel.
Figure 5.9: Population estimate based on binomial distribution of Atlantic salmon smolt mark-recapture, River Deel, 2008, compared with Petersen and Corrected Petersen estimates.
Bayesian Modelling Smolt Population Estimates

Two types of Bayesian models were tested following the methods of Rivot & Prévost (2002) and Mantyniemi & Romakkanieme (2002).


   The mean daily smolt run was estimated at 3,166, with a lower 2.5\textsuperscript{th} percentile of 2,195, and upper 97.5\textsuperscript{th} percentile of 4,286 (posterior credibility intervals) and the total smolt run was estimated at 94,967 smolts (95 \% c.l. of 65,858 and 128,565). This was greater than the indirect smolt potential production estimate of 72,000 smolts for the River Deel as determined by McGinnity et al. (1999). The posterior distributions for the trapping efficiencies and thus catchability, showed variability between days as would be expected in a flashy catchment like the River Deel. From the data over the 30 day marking period, the probability of capture at the screw trap had a mean of 13.9 \% with 95 \% posterior credibility intervals of 0.91\% to 20.7\%). The calculated efficiency using Rivot and Prévost (2002) is defined as the probability of each fish being caught. The catchability estimates for this model followed the three main pulses of smolts trapped in 2008 (Fig. 5.11). The screw trap operated at its peak rotation during higher flows and thus should have been more efficient according to the model. Trap efficiency was observed to be optimum up to a water level of > 1 m (Chapter 6). Daily changes in smolt migration were not seen however and daily population estimates using this model do not appear to follow the three peaks in the run as observed during sampling (Fig. 5.10). It is not certain if this is the fault of the model or the efficiency of the trap owing to increased river levels and flow. The catchability estimates increased with increasing river level and flow on the 26\textsuperscript{th} April 2008 (Day 13), as increased water levels and flows will increase the efficiency of the trap up to a certain water level (> 1 m). The changing river flow in flood conditions was to the centre of the river however, and migrating smolts could have been missed where screw trap adjustments were not made quickly enough to deal with the changing flow. Smolts are known to migrate in the main river flow. Debris loadings in the river could have reduced the rate of recaptures in the screw trap as the drum of the screw trap can become blocked, thus slowing drum rotations.
Posterior distributions for the daily smolt migration estimates were less variable showing less uncertainty around the posterior estimates for the daily population estimates. This could be a factor of the Rivot and Prévost (2002) HBM which was designed to analyse yearly data, where one would expected greater variation in the daily smolt migration as opposed to large variations between years of a total yearly smolt population. Thus the hierarchical structure had more of an effect on posterior inferences for trapping efficiency than for daily population size. This was also the findings of Rivot and Prévost (2002). The posterior distributions were robust for both the total population size and the trapping efficiency, to the choice of priors for the hyperparameters (a parameter of the prior). The hierarchical structure allowed for the between day variations of the probability of capture resulting from unpredictable changes in environmental conditions (eg. water temperature and river discharge) or fish behavior. The HBM considers hyperparameters as random with a prior that were updated by the data of all days in this experiment. The updating of the hyperparameters distribution allowed for the transferring of information between days. This model provided for a more robust estimate than the more simplistic Petersen models.
Figure 5.10: Marginal posterior distributions of the number of downstream migrating Atlantic salmon smolts from the 14\textsuperscript{th} April to the 13\textsuperscript{th} May 2008, using a Hierarchical Bayesian Model with Hyperpriors.

Figure 5.11: Marginal posterior distributions of the trap efficiency from the 14\textsuperscript{th} April to the 13\textsuperscript{th} May 2008, using a Hierarchical Bayesian Model with Hyperpriors. Note: eff[1] is the trap efficiency for sampling day 1 etc.

The River Deel mark-recapture study followed a similar procedure to that carried out on the River Tornionjoki study (Mäntyniemi & Romakkaniemi, 2002). For the purpose of testing these models using the River Deel 2008 data set, the prior distribution of $U$ (the estimate of population size) was based upon the other mark-recapture estimates of the non-Bayesian population estimates (log 10.491, 15.036). The ranges of population estimates produced by the four models are shown in Table 5.7 below. The selection of the best estimate from these four Mäntyniemi and Romakkaniemi (2002) Bayesian models was determined by direct comparison with the population estimates obtained from the non-Bayesian models, with the Rivot and Prévost (2002) model estimate of the River Deel smolt mark-recapture study and McGinnity et al. (1999) estimate of 72,000. The importance of having confidence intervals around the estimates was highlighted in the range of estimates obtained but jointly these models provided inferences that can be made about the size of the smolt population. For each of the models, estimates were made of the population $U$ and an estimate of the catchability $q$ for each of the days. The median estimates were in the lower end of the error bar and these may be the better estimates as they provide better indicator of the mid point (median) in the range of estimates over the four models in terms of their close proximity to the other non-Bayesian estimates. Interestingly, the mean smolt population estimate of the four models was 70,207 smolts, which was also very similar to McGinnity et al. (1999) estimate of 72,000.

Table 5.7: Atlantic salmon smolt population estimates for the River Deel, 2008, produced from four Bayesian models as described by Mäntyniemi and Romakkaniemi (2002).

<table>
<thead>
<tr>
<th>Bayesian Model</th>
<th>Mean</th>
<th>SD</th>
<th>2.50%</th>
<th>Median</th>
<th>97.50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_P$</td>
<td>54,470</td>
<td>10,140</td>
<td>38,060</td>
<td>53,300</td>
<td>77,700</td>
</tr>
<tr>
<td>$M_{SD}$</td>
<td>49,420</td>
<td>13,430</td>
<td>36,340</td>
<td>44,970</td>
<td>86,690</td>
</tr>
<tr>
<td>$M_S^I$</td>
<td>92,440</td>
<td>129,400</td>
<td>36,780</td>
<td>60,000</td>
<td>351,000</td>
</tr>
<tr>
<td>$M_S$</td>
<td>84,500</td>
<td>114,600</td>
<td>36,650</td>
<td>56,880</td>
<td>298,300</td>
</tr>
</tbody>
</table>

The Informative prior with tuned initials provided the best estimate of the $M_P$ models run, with a of 2.4 % catchability and had the least variation (Fig. 5.12). This model is the Bayesian equivalent of Lincoln-Petersen. The population estimate of 54,470 smolts (38,060, 77,700) (SD = 10,140) for the Informative prior with tuned initials of $M_P$ was a similar
estimate as obtained from the non-Bayesian estimate of Lincoln-Petersen Corrected (Chapman), 52,761 smolts (95 % c.i. 34,923 and 70,599) (SD = 9,101). A smolt population estimate for the Uninformed Prior or initials (this was the simplest and least informed of the models) and the Uninformed Prior with tuned initials was estimated at 54,810, with a lower 2.5th percentile of 37,960 and the upper 97.5th percentile of 79,960 (SD = 10,540) and 54,910, with a lower 2.5th percentile of 38,390 and the upper 97.5th percentile of 78,110) (SD = 10,180). Similar catchability of 2.4 % was estimated for all three $M_P$ models run.
Informative prior, tuned initials were also applied to model $M_{SD}$. Catchability varied across days and this explained the daily variation in the catch and suggested that when overdispersion of catches was not allowed, the model explained the extra variation in catches by random variation in the movement parameters and by between-day variation in the catchability as was observed in Mäntyniemi and Romakkaniemi (2002) analysis of the Conne River data set. The mean catchability for the $M_{SD}$ model was 20%. The smolt population estimate for the $M_{SD}$ model was estimated at 49,420, with a lower 2.5\textsuperscript{th} percentile of 36,340, and upper 97.5\textsuperscript{th} percentile of 86,690 (SD = 13,430).

Models $M_{S}^r$ and $M_S$ were both run with Informative priors and tuned initials. The $M_{S}^r$ model was the restricted version and more simplistic of $M_S$. Model $M_S$ included the potential influence of temperature and water level had on the population’s migration downstream and their capture. Model $M_S$, with the inclusion of the environmental data, estimated the mean smolt population at 84,500, with a lower 2.5\textsuperscript{th} percentile of 36,650, and upper 97.5\textsuperscript{th} percentile of 298,300 (SD = 114,600) smolts and the mean catchability was 20.3%. In the $M_S$ model, the analysis suggests that there were correlations between the environmental parameters of water level and temperature and the model parameters tested. The $M_S$ model smolt population estimate was less than the estimate for $M_{S}^r$ which was estimated at 92,440, with a lower 2.5\textsuperscript{th} percentile of 36,780 and upper 97.5\textsuperscript{th} percentile of 351,000 (SD = 129,400). In the model $M_{S}^r$, the environmental covariates were excluded from having an effect and the catchability changed slightly but not critically with the exclusion of the environmental covariates. The mean catchability in model $M_{S}^r$ was 20%. The upper limit of the smolt population estimate of $M_{S}^r$ was thought to be an over estimation of the run. These model estimates produced very high upper limit estimates with large standard deviations.

5.2.5 Model Assumptions
The River Deel met the assumptions with respect to it being a closed system with no tributaries between the two sites. All the assumptions of the classical models and the Bayesian models of Rivot and Prévost (2002) and Mäntyniemi and Romakkaniemi (2002) were applied to the River Deel data set for a closed population with equal catchability. Natural mortality was assumed to be minimal and mortality rates owing to trapping were assumed to be very low, known instances of mortality occurring only after extreme weather
conditions (only 1 dead smolt found in the screw trap in 2007). Mortalities were not thought to be of concern with respect to the fin clipping of smolts due to the care taken clipping the smolts and the recovery time allowed prior to their release upstream of the trap. Riffle areas between the release site and the screw trap downstream allowed for adequate mixing of the marked smolts with the general population. As smolts were fin clipped, error in the estimates owing to tag loss was not an issue. Thus, the probability of the recapture of previously marked and released smolts was assumed to be the same as the probability of capture of unmarked smolts exposed to the trap for the first time (Rivot & Prévost, 2002).

5.3 Model Comparisons and Predicted Smolt Population Estimations
In terms of the comparisons between estimates produced for the full data set and the individual batch estimates, the population estimates produced from the full data series for 2008 produced the best estimates when compared to McGinnity et al. (1999) estimate of 72,000. The large range in values provided by the batch estimates was a characteristic of the number of recaptures of each batch and this was a reflection of varying trap efficiency and smolt migration. The estimates obtained for all methods tested were dependant on the experiment and the level of statistical model applied. Multiple model assessments carried out on the data, provided a better estimate of the population in the River Deel where there was limited knowledge of the smolt run. This allowed for each model estimate to be compared and the techniques tested for implementation on rivers where limited smolt migration data is available.

The total number of smolts trapped over the duration of the both the 2007 and the 2008 runs show the substantial variation between days over the duration of the run. Ideally, marking carried out during the main run should yield greater recaptures. For mark-recapture studies, the sample size can be small. Rivot and Prévost model (2002) was shown to work well on mark-recapture studies with sparse data. To this end, as identified on the River Deel, where the peak run can be determined to occur within the same week for both 2007 and 2008, then this information could be used to only carry out mark-recaptures on the main bulk of the run to obtain estimates using Bayesian modelling. This would be very useful where staff and resources are limited, reducing the number of smolts required to be captured and marked, and thus reducing the impact of the experiment on the smolt population of the system.
Chapman Petersen corrected model, Schnabel Regression method and the Rivot and Prévost Bayesian model, proved the most robust models for the purpose of mark-recapture data analysis for the River Deel. The ball park estimate provided by McGinnity et al. (1999) indirect potential smolt production estimate fell within the range estimates of these models. Binomial distributions were used to provide confidence intervals for Petersen and the Petersen Modified estimates. The use of different analysis methodology allowed for a range of population estimates to be established and was part of the development of the overall method for this type of mark-recapture experiment for Irish rivers. The models that produced the best population estimate for the River Deel data set and the methodology employed for the 2008 mark-recapture estimates were the initial methodology tested on the full series of data (Batches 1-5 inclusive). These batch data produced reasonable estimates and estimates using Petersen, Petersen Corrected or the Schnabel Regression Model could be used in this manner and would be acceptable for the formulation of management plans. The Schnabel method was more applicable to large populations where the ratio of marked fish to the estimate of the population of smolts remained small. Thus the added advantage of the Bayesian models tested were to provide inferences on the catchability and the possible effect of environmental factors.

Smolts migrate at different densities on different days and this is determined by environmental factors which in turn will have influenced the performance of the trap in different water levels and flows (Chapter 7). For the River Deel data set, the smolt run would be expected to increase and decrease over time with each day as the smolt run migrated downstream. The data obtained using Rivot and Prévost (2002) model for the daily smolt catch showed a consistent movement of smolts migrating downstream. The trap efficiency however, varied greatly on a daily basis thus, affecting the ability to both trap and recapture smolts migrating. Catchability was shown to vary during the trapping period and this was shown in both Rivot and Prévost (2002) model and Mäntyniemi and Romakkaniemi (2002) Models. Rivot and Prévost (2002) showed that their model could be extended for use in different cases of data collection with regard to units of time, e.g. daily data was collected in this scenario as opposed to yearly. They encouraged the use of the model wherever enough spatial data exists to derive posterior inferences about the hyperparameters and suggested the
possibility of modelling the variations owing to water discharge with the trap efficiency. Models developed by Mäntyniemi and Romakkaniemi (2002) applied to the River Deel data provided much larger upper limits for population estimates where both over dispersion and environmental data were allowed for in models $M_S$ and $M'_S$. Of the Bayesian methods tested, Rivot and Prévost (2002) produced the more realistic estimate and was the easier model to run in comparison to Mäntyniemi and Romakkaniemi (2002) models.

5.3.1 Quality of Estimation and Model Performances
The Petersen estimator with confidence intervals was advantageous as a method of data analysis as it provided simpler, precise smolt migration estimate for 2008. The upper limits of population estimates for Mäntyniemi and Romakkaniemi (2002) $M_S$ and $M'_S$ estimates were very far apart from the River Deel smolt obtained using the classical models and that of Rivot and Prévost (2002) model tested. Thus they could not be a realistic estimate of the system, as the rivers habitats, length, volume would not be able to support or even physically accommodate a population of this size. From this study, it was clear that a method that provided estimates with confidence intervals should be selected as this will provide a more realistic estimate of the smolt population, particularly for the purpose of management decisions.

The Petersen models do not take into account trap efficiency. Chapman (1951) developed a modification of the Petersen model that produced estimates with less bias and these were reported to be more accurate estimates of the true population size. However, Mäntyniemi and Romakkaniemi (2002) reported the Peterson method to be too simplistic to be useful in real applications. Its provision of a basic ‘ballpark’ estimate that was not complicated and unproblematic was, however, seen as beneficial for cross checking the other estimates of population size. The small sample size from the River Deel study suggested the use of Rivot and Prévost (2002) model in this study to produce reliable estimates from smaller sampling effort and hence smaller sample size. The hierarchical method significantly enhances the ability to estimate escapement where limited data are available (Su et al., 2001; Rivot & Prévost, 2002). The advantage of this method was that the ‘between day’ analysis of the data by the hierarchical model organises the transfer of information between days. This allowed
the use of the whole experimental data over the course of the run to create modified priors to improve daily inferences (Rivot & Prévost, 2002).

5.3.2 Bayesian Smolt Population Estimates

Greater analytical knowledge was required to carrying out Bayesian estimates. The Bayesian models assumed a hierarchical structure on both the trapping efficiency and the population size (Rivot & Prévost, 2002). The Hierarchical Bayesian Models provided a good basis for an estimation of the smolt run despite the very low trap efficiency. These data show that even with sparse data that relatively good juvenile estimates of salmon stocks can be obtained due to the historical transfer of information from data rich to data poor periods (Rivot & Prévost, 2002), as the model allows for the transferring of information between days. The River Deel daily catchability obtained using Rivot and Prévost (2002) indicated the varying probability of trapping smolts, particularly in the first 16 days of marking the run in 2008. This was probably due to water discharge and smolt migration behaviour. Thus, the variation in efficiency over the study period shown by the model shows its effect, and the hierarchical structure of its calculation will have ensured that the little information on values and precisions that was available was transferred across days through the hyperparameters. Rivot and Prévost (2002) noted that inferences on population size are sensitive to minor changes in the data (Chao, 1989) and consequently may be non-robust to errors made when collecting data. The HBM limited the undesirable effects and significantly improved the inferences by taking the whole data set of daily catches. Rivot and Prévost (2002) also point out that the setting of a hierarchical structure improves the inferences or in the worst case, it remains neutral.

From Mäntyniemi and Romakkaniemi (2002) models, $M_P$ model was considered biologically the most accurate estimate of all four of their models tested on the River Deel. When looking at models $M_P$ and $M_{SD}$ there was very little difference in the inferences that can be made from these two population estimates and they conform very closely to the non-Bayesian models tested. In comparison, the posterior distributions obtained from models $M_{SR}$ and $M_S$ had greater variation in the upper limits of smolt population estimates. Mäntyniemi and Romakkaniemi (2002) discussed limitations of $M_{SD}$ with respect to the assumption that catches of smolts would be binomially distributed, however, when smolts migrate in shoals they do not behave independently. Thus, binomial distribution may be too tightly
concentrated to properly describe the behaviour of the catches, as it was more likely that when smolts migrate that higher or lower catches would be observed than predicted by a binomial distribution (Mäntyniemi & Romakkaniemi, 2002). This was a limitation of the Lincoln-Petersen estimates. Model $M_S$, the beta-binomial distribution allowed for the possibility of over dispersion of trapped smolts. The restricted version of $M_S$, model $M_{Sr}^r$ without environmental factors taken into account, produced higher posterior distributions. Models $M_{Sr}^r$ and $M_S$ would be expected to provide the more realistic smolt population estimations from a biological point of view, however, the higher limit for the smolt population size was not thought to be a true reflection on the upper limit of the run. Thus, looking at the median population estimates for these four models (Fig. 5.13), $M_P$ (53,300), $M_{SD}$ (44,970), $M_S$, (60,000) and $M_{Sr}^r$ (56,880) shows that they were all in close conformity with each other and the non-Bayesian model population estimates. Rivot and Prévost (2002) model median population estimate for River Deel was 94,022 smolts (mean = 94,967 (65,858, 128,565) ) was higher than the other Bayesian models tested, and this was more likely the upper limit of the smolt run on the River Deel.

5.3.3 Advantages of Bayesian Models for River Deel Smolt Population Estimates
Bayesian models allowed for inclusion of daily variations within the data which could be applied in future studies where gaps in data exist. Using hierarchical models removed the problem of small size data sets and the model allowed for exchange of daily information (Mäntyniemi & Romakkaniemi, 2002). As discussed earlier, Atlantic salmon smolt migration is determined by both biological and environmental factors. Uncertainty included in the posterior distribution of the population size was heavily dependent on assumptions made with respect to smolt migration behaviour (Mäntyniemi & Romakkaniemi, 2002). Mäntyniemi and Romakkaniemi (2002) allowed for the additional uncertainty of the tendency of smolts to shoal during migration and models $M_S$ and $M_{Sr}^r$ allowed for over dispersion in the recapture data. Mäntyniemi & Romakkaniemi (2002) showed in the Conne River example that over dispersion may have had an impact on the point estimation of the population size, where catchability is low and the amount of over dispersion is high. This may have been a problem in the River Deel study where catches during rapidly increasing water levels may have been low in terms of the actual population of smolts migrating. Catchability estimates were low for all Bayesian models tested using the River Deel data. If
over dispersion gets support from the observed data, the mode of the posterior distribution of
the population size will support larger population size than in the case of independent
behaviour (Mäntyniemi & Romakkaniemi, 2002). The $M_S$ model did provide very high upper
limits for the population estimate for the River Deel when compared to the other model
outputs.

5.3.4 Inferences for Parameters and Hyperparameters
When both Rivot and Prévost (2002) and Mäntyniemi and Romakkaniemi (2002) models
were compared, inferences for the parameters and hyperparameters of daily smolt population
estimates produced similar means. Rivot and Prévost (2002) model produced a mean of
94,967 smolts and Mäntyniemi and Romakkaniemi (2002) $M'_S$ model produced a mean of
92,440 smolt. Similar median values were obtained; however, for all four Mäntyniemi and
Romakkaniemi (2002) models the median of 94,022 smolts was almost double the median of
the Mäntyniemi and Romakkaniemi (2002). The mean catchability for the Rivot and Prévost
(2002) was much lower than that of Mäntyniemi and Romakkaniemi (2002) models. This
was indicative by the larger standard deviations associated with daily variation. As described
above, trap efficiency was a direct cause of imprecision of estimates. One of the significant
factors associated with the imprecision of estimates and wide confidence intervals was the
failure to mark and recapture sufficient numbers of smolts and this has also been documented
by (Dempson & Stansbury, 1991). Where individual batch estimates were used variation in
the trap efficiency/catchability showed the low trap efficiency from the 2008 mark-recapture
data. This affected the precision of the count between days and the overall estimate of the
smolt population when calculated from individual batches produced it resulted in
overestimations of the smolt run.

5.4 Use of Atlantic salmon Smolt Migration Data for the Prediction of Returning Grilse
Estimates
In chapter 4, the first baseline adult count for the River Deel, model estimates in Chapter 4,
Tables 4.8, were compared to the estimated smolt outward migration from the River Deel for
2007 and 2008 in Table 5.4 & 5.5 above. The estimated smolt outward migration from the
River Deel for 2007 was 14,751 smolts. Thus, where 14,751 smolts were estimated using the
Petersen Corrected to migrate to sea in 2007, the number of returning adult grilse to the River
Deel in 2008 was estimated using three survival rates (as described in Chapter 2: Section 2.3) as outlined below in Table 5.8:

<table>
<thead>
<tr>
<th>Smolt Sea Survival Rate</th>
<th>Adult Grilse Returns:</th>
<th>Adult Grilse Returns:</th>
<th>Adult Grilse Returns:</th>
<th>Adult Grilse Returns:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2007 Petersen Correlated 14,751 (+/- 10,814, 18,689) smolts</td>
<td>2008 Chapman Modification 52,761 (+/- 34,923, 70,599) smolts</td>
<td>2008 Schnabel Regression Method 60,939 smolts</td>
<td>2008 Rivot &amp; Prévost Model 94,969 (+/- 65,858, 128,565) smolts</td>
</tr>
<tr>
<td>5% (Lower Limit)</td>
<td>738 (± 541, 935) adults</td>
<td>2,638 (± 1,746, 3,530) adults</td>
<td>3,047 adults</td>
<td>4,749 (± 3,293, 6,428) adults</td>
</tr>
<tr>
<td>8% (Burrishoole)</td>
<td>1,180 (± 865, 1,495) adults</td>
<td>4,221 (± 2,794, 5,648) adults</td>
<td>4,875 adults</td>
<td>7,598 (± 5,269, 10,285) adults</td>
</tr>
<tr>
<td>10% (Upper Limit)</td>
<td>1,475 (± 1,081, 1,869) adults</td>
<td>5,276 (± 3,492, 7,060) adults</td>
<td>6,094 adults</td>
<td>9,497 (± 6,586, 12,857) adults</td>
</tr>
</tbody>
</table>

The actual DIDSON count estimate for adult grilse returns ranged from 2,393 to 3,986 grilse (January to December 2008 cohort) and ranged from 1,967 to 2,455 grilse (June to December 2008 cohort) (Chapter 4: Table 4.8). However, much lower return rates for adult grilse returns were obtained from the Petersen Corrected 2007 smolt estimate using all three sea survival rates. As described earlier, the lower adult grilse estimate from the 2007 smolt mark-recapture study was thought to be a direct result of trap efficiency due to flooding during the peak of the 2007 run and the possibility exists of more marked fish passing by the trap during the flood. However, the grilse estimate (≥ 45 cm) from June to December 2008, provided for a grilse run of 1,967 and this was thought to be at the lower end of grilse survival for this system.

However, a more accurate smolt count estimate obtained in 2008 provided higher adult grilse returns for 2009 and where estimates are compared with that of the DIDSON 2008 adult grilse, it is thought that where large fluctuations in yearly runs did not occur, then the smolt
estimate for 2008 using the Chapman Modification and the Schnabel Regression Method produced returning grilse runs within the range of that obtained for the River Deel using DIDSON. It was thought that a realistic estimate for the River Deel were at the lower end of this range (5% sea survival rates), as per the SSC findings for the rates of survival which has been lower in recent years (ICES, 2009; Anon., 2010). The estimated smolt run for 2008 were greater but variations in yearly smolt migrations are not unusual and the neighbouring index system, the Burrishoole system, has recorded smolt migration estimates ranging from 3,796 to 16,136 (RESCALE, 2010). The 2008 smolt migration estimates were thought to be more accurate indication of the outward smolt migration of the River Deel as both the operational methodology and mark-recapture techniques were fully developed for the 2008 assessment. However, the outward smolt migration estimate for 2008 for the River Deel was used to predict the 2009 adults grilse, thus comparison with these data may not be applicable.

The River Deel potential smolt production baseline estimate of approximately 72,000 smolts (McGinnity et al., 1999) was also compared to the smolt estimates of 2007 & 2008; however, the estimate was derived in the 1990’s, when smolt survival rates were at 20% (Anon., 2010). Thus, it was thought that this estimate was at the higher end of the range of smolt production but these were only ball park estimates. Using these data, the potential range of adult returns from McGinnity et al. (1999) was estimated at approximately 3,500 grilse (5% smolt survival) and approximately 7,200 grilse (10% smolt survival). The lower estimates of 5% smolt survival, using McGinnity et al. (1999), was within the range of estimates obtained using DIDSON (Chapter 4: Table 4.9). Both the DIDSON and smolt mark-recapture study provided more accurate range estimates for the River Deel adult run components and smolt migration estimates with confidence intervals than McGinnity et al. (1999).
Chapter 6

6.0 Environmental Influences on the within-river Migration of Juvenile and Adult Atlantic salmon during Stock Assessments, River Deel.

Although there is considerable genetic control over the timing of upstream migration and spawning, environmental factors also play an important role (Quinn et al., 1997). River and catchment specific data can be used to determine key migration triggers for adult and juvenile migration. The River Deel is an atypical system (see Chapter 4) and fish migrate through Lough Conn for inward and outward migrations. Point observation methods allow for the monitoring of migration timing and intensity for both adult and juvenile Atlantic salmon at that specific site, namely the River Deel for this study. The precise homing of Atlantic salmon to their natal river lends itself to these types of studies (Orell et al., 2007). The upstream migration of adult Atlantic salmon can occur over a number of months (Jensen et al., 1986; Niemelä et al., 2000; Lilja & Romakkaniemi, 2003; Orell et al., 2007; Thorstad et al., 2008) or throughout the entire year (Hawkins, 1989; Welton et al., 1999; Smith et al., 1997; Thorstad et al., 2008).

Studies looking at the influences of environmental factors on Atlantic salmon migration have been undertaken both at the river entry stage (Karppinen et al., 2004; Thorstad & Heggberget, 1998; Lilja & Romakkaniemi, 2003) and during in-river migration (Smith, 1997; Orell et al., 2007). Orell et al. (2007) used underwater video surveillance to record undisturbed the simultaneous migrations of ascending adults and descending smolts. To date, most point observation methods required fish to swim through traps at fish fences or through weirs which can interfere with the determination of specific correlations with environmental factors (Banks, 1969). The majority of point observation studies have been located at fish counter sites which were installed on weirs. Such studies would have to take into account the possible affects of weir mounted counters on the migration of salmon (Thorstads et al., 2008). Crump weir mounted counters can cause significant delay in Atlantic salmon migration (Banks, 1969) but other studies have also shown them to have less significant delay on their upstream migration (Smith et al., 1997). The effect of existing counters located on weirs can be difficult to assess on Atlantic salmon migration due to limited information with respect to the nature of their in-river upstream migration prior to the construction of the weir (Smith et al., 1997; Thorstad et al., 2008).
To date, no studies have been published using DIDSON count data for comparisons with environmental data for the determination of in-river migration patterns. High turbidity and smolt size make smolt observations difficult using DIDSON in Irish waters and the presence of other species of similar size, namely roach (*Rutilus rutilus*) can complicate the counts. The lacustrine system of the River Deel causes atypical behaviour of salmon during migration however, this study shows the potential use of DIDSON count data for the purpose of comparing adult counts with environmental factors. Several authors have shown that increasing water discharge stimulates Atlantic salmon to enter rivers from the sea (Smith et al., 1994; Thorstad et al., 1998) but few studies have shown the effects of water discharge on the within-river migration. Studies have looked at the effects of water temperature on migrating salmonoids with both positive and negative effects depending on their life history stage. Telemetry studies can be used to give greater detailed information on fish movement with respect to changing water flow (Thorstad & Heggberget, 1998) and migration patterns entering river system (Karppinen et al., 2004; Thorstad & Heggberget, 1998). However, the handling of fish can lead to migration delays (Thorstad et al., 2008). Comparison of angling catch statistics with environmental variables were not recommended by Thorstad et al. (2008) because the susceptibility of fish to capture and changes in catches may not correspond to changes in migratory activity (Solomon et al., 1999). Few studies, other than Lilja and Romakkaniemi (2003) have looked at river entry and environmental factors using hydroacoustic counter data (HTI). One limitation of the use of counter data is the lack of information on the number of fish that are present downstream of a counting site (Trépanier et al., 1996).
6.1 The effects of climate change in Atlantic salmon migration and Stock Assessments

The effects of climate change on plant and animal populations are widespread and documented for many species in many areas of the world (Biro et al., 2007). However, the possible impact of climate change on in-river species may be due to water temperature (McCarty & Houlihan, 1996; Jensen, 2003; Biro et al., 2007), water quality (Winfield et al., 2004), predation (Gilvear et al., 2002), and exploitation and management (Walsh & Kilsby, 2007). Climatic changes with respect to water temperature and flow has potential implication for all life stages of Atlantic salmon, both in freshwater and the marine environment (Walsh & Kilsby, 2007).

Changes in water temperature and dissolved oxygen affect fish behaviour and their response will differ between species with changing water temperature and dissolved oxygen levels (Rijnsdorp et al., 2009). Climatic factors will affect successive life history stages in different ways (Harley et al., 2006; Rijnsdorp et al., 2009). Prior to RESCALE (2010) very little published data exists with respect to the possible effects of climate change on fish species in Ireland. However, Graham and Harrod (2009) study showed that species that occur in Britain and Ireland that are at the edge of their distribution will be most affected, both negatively and positively. The majority of Irish studies have looked at the effects of climate change on adult growth at sea (Peyronnet et al., 2008) and the effects of climate change due to environmental changes at sea on the abundance of returning populations (Boylan & Adam, 2006). Walsh and Kilsby’s (2007) study on the River Eden in the UK focussed on the impact on Atlantic salmon of the current and predicted future hydrological regime. Their study showed that increases and decreases in river flow regime were detrimental to salmon trying to migrate upstream to spawning grounds.

Latest Climate Change Predictions for Ireland

Desmond et al. (2008) summarised the current state of knowledge on climate change and expected impacts for Ireland. Observed changes in Ireland’s mean annual temperature was reported to have increased by 0.7° C between 1890 and 2004, and six of the 10 warmest years have occurred since 1990, with possible increases of 3 to 4° C predicted towards the end of this century. Predicted increases in annual rainfall on the north and
west coasts could mean a recurrence in extreme flood events (McGrath & Lynch, 2008) as experienced in 2009 (Walsh, 2010). However, uncertainties lie around the extent of these impacts particularly for the second half of the century and may lead to negative impacts on fish migration in Irish river systems. McGrath and Lynch (2008) have shown that more intense storms and rainfall events increase the likelihood and magnitude of river flooding and the effect on Atlantic salmon may vary in Ireland from river to river depending on the size and location of the catchment. Part of their project included a hydrological study of nine river catchments in Ireland, namely the River Moy, Suck, Brosna, Boyne, Barrow, Suir, Feale, Blackwater (Munster), and Bandon. McGrath & Lynch (2008) used predictive modelling using existing data sets for these catchments from 1961-2000 to predict future (2021 - 2060) hydrological events associated with climate change. Their results suggested that increased winter precipitation will lead to a rise in winter stream flow, while the combination of increased temperature and decreased precipitation will cause a reduction in summer stream flow. Results from the Suir catchment modelling showed a predicted significant increase in the magnitude of extreme discharges events and a slight increase in their intensity, leading to an increase probability of flooding in the future (McGrath & Lynch, 2008). Predictions from the same study showed that the greatest increase in monthly temperature would likely occur in August e.g. from 1.4° C in the Moy catchment, the smallest increase occurs in June, with increased inter-annual variability between April and October. Generally, predicted inter-annual variability in mean daily temperature showed a decrease in November, December and February, with an increase of approximately 0.5 °C in January. Increased inter-annual variability in mean daily temperature affects potential evapotranspiration, which in turn influences summer low flows (McGrath & Lynch, 2008).

Analysis of mean annual and seasonal air temperatures at Furnace meteorological station, located in the Burrishoole catchment, indicated that significant warming, consistent with global and European temperature trends, has occurred over the period of 50 year record, from 1960 to 2009 (RESCALE, 2010). The mean annual air temperature anomalies (differences relative to the 1961 – 1990 average) were found to have increased by 1.48 °C (RESCALE, 2010). The greatest increases in seasonal mean temperatures were found to have occurred in spring and winter, of 1.8 °C and 1.7 °C respectively (RESCALE, 2010). Seasonal mean summer and autumn temperatures also increased by 1.5 °C and 1.4 °C respectively, over the 1960 – 2009 period (RESCALE, 2010). No significant trends were
found to have occurred in the observed seasonal mean precipitation; however, the frequency and intensity of extreme precipitation events in winter and annually were found to have increased (RESCALE, 2010). The predicted future trends for the River Moy (McGrath & Lynch, 2008) shows the same temperature increases as experienced in the Burrishoole catchment (RESCALE, 2010). Both studies show that these observed changes and predicted future changes could impact on both the future survival of Atlantic salmon and in–river stock assessments. Atlantic salmon are sensitive to small changes in temperature (McGinnity et al., 2009) and the effect on Atlantic salmon may vary in Ireland from river to river depending on the size and location of the catchment (McGrath & Lynch, 2008).

6.1.1 Environmental Factors Influencing the Migration of Adult Atlantic salmon & the Downstream Migration of Atlantic salmon Smolts

Multiple environmental factors can explain the timing of river entry of Atlantic salmon into rivers but the importance of any one of these factors probably changes as the fish move upstream (Lilja & Romakkaniemi, 2003; Thorstad et al., 2008). The role and importance of these external factors may vary between rivers and change as the fish migrate upstream and spawning approaches (Trépanier et al., 1996; Smith & Smith, 1997; Jensen et al., 1998; Solomon et al., 1999; Thorstad et al., 2008). Adult Atlantic salmon run timing has been associated with numerous factors such as physiological readiness of the fish to spawn, river discharge (Banks, 1969; Jonsson et al., 1991; Trépanier et al., 1996; Quinn et al., 1997), water temperatures (Jensen et al., 1986; Fleming, 1996; Trépanier et al., 1996; Klemetsen et al., 2003; Quinn et al., 1997; Lilja & Romakkaniemi, 2003; Orell et al., 2007), water discolouration or turbidity (Thorstad et al., 2008), photoperiod (day-length) (Hellawell, 1974; Potter, 1988), distance and difficulty of ascent (Fleming, 1996; Klemetsen et al., 2003; Thorstad et al., 2008) and sea age at maturity (Fleming, 1996; Klemetsen et al., 2003).

River discharge can influence salmon willingness to enter a river and their onward migration upstream (Jensen, 1986; Smith et al., 1994; Trépanier et al., 1996; Smith et al., 1997; Quinn et al., 1997; Cowx & Fraser, 2003). The relationships between discharge and water temperature on migration are not consistent (Trépanier et al., 1996; Quinn et al., 1997). Karppinen et al. (2004) showed that discharges in the River Tana were not significant to the timing of river entry. Jonsson (1990) and Jonsson et al. (1991) found
that increased discharge may be more important for the migration of large Atlantic salmon. However, a decline in water temperature was observed to enhance the upstream migration of 1SW Atlantic salmon in the River Tana (Karpinnen et al., 2004). Other studies have shown water temperature to have little effect on the migration rates of Atlantic salmon (Banks, 1969; Trépanier et al., 1996). Migration behaviour could be due to an underlying hierarchy of environmental factors initiating migration or to a local adaptation of fish populations to varying environmental factors among rivers (Jonsson et al., 1991).

Environmental factors affect Atlantic salmon smolt outward migration in two ways: the initiation of smoltification; and the trigger to migrate. Several studies have shown photoperiod and temperature to be the two main factors affecting the smoltification process (Hoar, 1988; Saunders & Henderson, 1970; Jonsson & Ruud-Hansen, 1985; McCormick et al., 1987; Duston & Saunders, 1990; Saunders & Harmon, 1990; Byrne et al., 2003 & Byrne et al., 2004). These two factors affect physiological changes through the neuroendocrine system (McCormick et al., 1998). Water temperature (Österdahl, 1969; Saunders & Henderson, 1970; McCleave, 1978; Raymond, 1979; Jonsson & Rudd-Hansen, 1985; Jonsson et al., 1991; Whalen, 1999; Orell et al., 2007) and discharge (Hesthagen & Garnas, 1986; Jonsson et al., 1991; Byrne et al., 2003) have been shown to be the trigger for downstream salmonid smolt migration. Byrne et al. (2003) discussed what they termed a physiological ‘smolt window’ and an ecological ‘smolt window’ of migration, as described in Chapter 5. A number of studies have shown that smolts do not commence migration until a threshold temperature has been reached (Fried et al., 1978; McCleave, 1978, Solomon, 1978b; Byrne et al., 2004). The increase in day-length in the spring (photoperiod) acts as the synchroniser of an endogenous rhythm, the environmental factor that most influences the onset of parr-to-smolt transformation (Byrne et al., 2004; Jonsson & Jonsson, 2009).

Significantly more smolts were found to migrate when discharge was increasing (Hesthagen & Garnas, 1986) in ‘flashy’ catchments (Solomon, 1978 a & b) and due to social interactions during migration (Hvidsten et al., 1995), which have also been identified as important in modifying and controlling the downstream migration of smolts. However, Orell et al. (2003) study showed that changes in discharge had no effect on smolt migration but their study did note that discharge peaks late in the migration season.
may have activated the migration of remaining smolts. Other authors found that low discharge was associated with the most active smolt migration (Veselov et al., 1998) and that peak floods had either no effect or a negative effect on smolt migration (Jonsson & Ruud-Hansen, 1985; Jensen et al., 1989).

There are no published studies in Ireland from screw trap data looking at smolt migration and the influence of environmental factors. Mark-recapture studies using tagging of smolts have been shown to provide limited information on the factors affecting migration, particularly of individual smolt migration (Thorstad et al., 2008). Smolts in Irish river systems generally migrate downstream between March and May and this window of migration is dependent on environmental factors, such as water temperature and water level (Byrne et al., 2003; Byrne et al., 2004). If smoltification takes place but the smolts are not able to migrate they die (RESCALE, 2010). Previous studies on salmonid smolt migration in Ireland have been carried out using trap data on the Burrishoole catchment (Whelan, 1993; Poole, 1996; Byrne et al., 2003; Byrne et al., 2004). Byrne et al. (2003) study showed reductions in the mean sea trout smolt output from the Burrishoole system from the 1970s to the 1990s; however the timing and duration of the sea trout smolt run was not found to vary significantly over the data time interval. The timing of sea entry is very important for smolt migration at sea and feeding in terms of their survival with respect to suitable oceanic climate (Elliott, 1994; Hvidsten et al., 1995; Salminen et al., 1995; Friedland et al., 1999).

6.1.2 River Deel Study

An aim of this study was to determine if there were significant correlations between the environmental factors of rainfall, water level, mean flow, air temperature and water temperature, and the migration patterns of both adult and smolt Atlantic salmon. Key environmental factors may have particular consequences for individual rivers due to the predicted future impacts of climate change in Ireland. This in turn will have implications on the type of enumeration equipment operated in Irish rivers systems and the usefulness of these data for comparisons with environmental variables. The current project is the first study in Ireland to look at the effects of such factors on the migration of both adults and smolts in the same river system. This is also the first Irish study to use DIDSON and a screw trap to obtain point observation data for comparisons with environmental factors. In this chapter, the results are presented to determine patterns within the River Deel with
respect to the environmental effects of rainfall, water level, water flow, air and water temperature. Comparisons were made with these data and the point observation data from the DIDSON counter to determine environmental affects on adult migration patterns and with the daily smolt count obtained using a screw trap.
6.2 Results
To determine the effects of environmental influences on both adult and juvenile migrations on the River Deel, point data (daily data from a fixed location) from the DIDSON counter and screw trap were assessed with respect to changes in rainfall, river flow, water level, air temperature and water temperature. Significant correlations were found with the variation in the rate of adult migration and air and water temperature but not with discharge, indicating that changing air and water temperature influenced the upstream migration of adults. As the River Deel is an atypical system, migrations were assessed in relation to adult salmon migrations into and out of the River Deel from Lough Conn and smolt migration to sea via Lough Conn. The nature of this river system means that there is a potential for fish to hold in Lough Conn prior to spawning and to make several migrations into and out of the River Deel prior to spawning. In some incidents, both smolts and adults were observed (during the operation of the DIDSON and the screw trap) to migrate during periods of increasing and decreasing discharge. However, the daily rate of smolt and adult migration did not show correlations with changes in discharge. Migration activity of adults did appear to be related to increasing discharges later in the year. It was more difficult to determine if correlations existed with adult salmon migrations and discharge due to the loss of data during the peak of the spawning run in 29th October and 11th December 2008.

No clear pattern was found between discharge and the initiation of smolt migration. Where there was a reduction in water flow, water temperature increased and higher water temperatures up to 15 °C were observed coincident to increased smolt migrations. As part of the mark-recapture study, smolts were marked and carried upstream for recapture in the screw trap. It is not thought that this affected the resulting correlations between environmental factors and smolts trapped, as the number of smolts recaptured was small. No significant correlations were found between smolt migration and the environmental factors of rainfall, river flow, water level, air temperature and water temperature during the smolt migration in 2007 and 2008. The peak in smolt migration occurred in both 2007 and 2008 at the same time in both years, with two days separating the start date of the peak of the run which commenced on the 19th April in 2007 and the 21st April in 2008. This window of migration was suspected to be influenced by water temperature and the two peaks in smolt migration commenced at temperatures of 9.7 °C and 9.1 °C during
2007 and 2008. The number of smolts trapped during migration was determined by screw trap efficiency (particularly in flood conditions where water levels were greater than 1 m) and how the smolts migrated with respect to their catchability (Chapter 5).

Seasonality played a key role in the changing migration patterns of both adults and smolts. In the author’s opinion from observations made during DIDSON count data processing, in some instances increasing discharge early and late in the season may have activated specific genetic cohorts of the adult run. Stewart et al. (2002) showed that Atlantic salmon from different parts of a river system may ascend at different times, indicating a genetic influence on run timing (Orell et al., 2007). Confirmation that the bulk of migration on the River Deel was late running was confirmed during the DIDSON stock assessment (Chapter 4). This was indicative of the distance travelled from the mouth of the River Moy through the lacustrine system and the possibility of spring and summer fish holding in Lough Conn, prior to adults entering the River Deel. When adults migrated past the DIDSON, they did so regardless of size. Differences in the size of migrating salmon were seen with changing seasons and this was assumed to be the variation of run components of grilse and 2 SW salmon.

6.2.1 Environmental Characteristics, River Deel

Prior to determining the influences of environmental factors affects on salmon migration, patterns within the River Deel catchment were assessed.

**Daily Mean Rainfall, Daily Mean Water Level and Daily Mean Flow, River Deel, Moy Catchment**

As expected, patterns in daily mean river flow reflected daily mean water level and were preceded by a range of different rainfall events. The maximum amount of rainfall fell on the 13th August 2008, highlighting the unpredictable nature of weather patterns during the operation of equipment for this study (Vol. II Appendix Section VI A: A1). The short-term rating curve for this study (Fig. 6.1) shows the linear relationship that exists between the daily mean level and daily mean flow, where an increase or decrease in water level caused an immediate increase or decrease in flow (Fig. 6.2). The lowest daily mean flow was recorded on the 11th June 2008 (0.5 m$^3$/s) and the highest daily mean flow was recorded on the 3rd February 2008 (15.9 m$^3$/s). Increases in flow coincided with increases in the total daily rainfall from November 2007 to the end of April 2008 and from the end
of June to December 2008 (Fig. 6.2). This was indicative of a flashy catchment where the maximum flow was well above the mean daily flow for short periods of time (24 to 48 hours duration), associated with short duration rainfall events. This was observed throughout the year, e.g. 08/12/07, 21/01/08, 03/02/08 (where a peak maximum level was 2.6 m and a peak maximum flow was 94.7 $\text{m}^3/\text{s}$), 25/06/08 to 01/07/08, 10/10/08 and the 13/12/08. However, during summer months of May and early June 2008, rainfall incidents during this period did not provide for an increase in flow at the DIDSON site. This could also be due to the slow recharge of groundwater, as the system is groundwater fed during low flows. It can be seen on Fig. 6.2 that the length of time between these rainfall events increased during this period and is matched by a longer and flatter recession. These lower flows were observed to reduce fish movement past the DIDSON.
Figure 6.1: The relationship between daily mean level and daily mean flow, DIDSON counter site, Deel River (Knockadangan Bridge, approximately 100 m downstream of DIDSON counter) \((R^2 = 0.9991 / n = 371)\).

Figure 6.2: Relationship between rainfall (Newport, Co. Mayo, MET Eireann data set) and mean daily flow (Knockadangan Bridge, approximately 100 m downstream of DIDSON counter) River Deel, November 2007 to December 2008.
Relationships between the Average Daily Air Temperature and the Average Daily Water Temperature, River Deel DIDSON Site

Fig. 6.3 shows the patterns of air and water temperature for the duration of the adult run. The highest average daily water temperature recorded at the DIDSON Counter site was 19.3 °C on the 14th May 2008. The average daily air temperature on the same day was 15.2 °C. This peak in the average daily water temperature was also a reflection of low flow. The highest average daily air temperature was recorded on the 24th July 2008 at 19.8 °C and the lowest on the 4th January 2008 at 2.0 °C. The lowest average daily water temperature was recorded at 3.5 °C on the 4th January 2008, the same day as the lowest recorded average daily air temperature of 2.0 °C (Fig. 6.3). These lower average daily air and water temperatures coincided with snow in early January 2008. A linear relationship was observed between the average daily air and water temperature ($R^2 = 0.8932$, $n = 415$) (Fig. 6.4) showing a direct correlation between these two parameters. Fig. 6.5 shows that peak upstream migration of 319 fish on the 14th November 2008 occurred at a water temperature of 10.4 °C.
Figure 6.3: Relationship between the average daily water temperature (Temperature data logger at DIDSON counter site) and average daily air temperature (Newport, Co. Mayo, MET Eireann data set), River Deel.

Figure 6.4: The linear relationship between the average daily air (MET Eireann Data, Newport) and water temperature, River Deel, Moy Catchment ($R^2 = 0.8932 / n = 415$).
6.2.2 Relationships between Environmental Factors on the within-river Migration of Adult Atlantic salmon, River Deel, Moy Catchment

Environmental factors discussed above were analysed to determine if correlations were present with the upstream migration of Atlantic salmon at the DIDSON Counter Site on the River Deel. Adult fish count data collected using the DIDSON counter were used to determine the total daily number of adult salmon ≥ 40 cm migrating upstream past the DIDSON counter on the River Deel (Chapter 4). This length cut off was used for the speciation between salmon and trout (Trutta trutta) and the assumption was made that all fish ≥ 40 cm were salmon (Anon., 2008). The lowest water temperature recorded in the River Deel during the operation of the DIDSON was at 3.5 °C on the 4th January 2008 and the highest at 19.3 °C on the 14th May 2008. The mean, minimum and maximum water level and flow over the fourteen months of data collection at the DIDSON site is shown in Table. 6.1.
Table 6.1: The mean, minimum and maximum daily water level and daily flow over the fourteen months of data collection at the DIDSON site, November 2007 to December 2008, River Deel.

<table>
<thead>
<tr>
<th>River Deel DIDSON Site</th>
<th>Daily Water Level (m)</th>
<th>Daily Flow (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.5</td>
<td>11.4</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.2</td>
<td>0.5</td>
</tr>
<tr>
<td>Maximum</td>
<td>2.6</td>
<td>94.7</td>
</tr>
</tbody>
</table>

The upstream migration of salmon was recorded using the DIDSON and the peak migration took place from October to November 2008 (Chapter 4). During the monitoring period salmon migrated past the DIDSON site every day for the month of November 2008. During peak migration the average daily water temperature in the river varied between 3.8 °C and 12.8 °C and the average daily air temperature varied between 2.4 °C and 14.1 °C. Observations of the data showed a tendency for salmon to migrate during periods of lower temperature from autumn 2008 onwards. Air and water temperature were correlated with the upstream migration of adults \( p = 0.002, p = 0.017 \).

Observations made during DIDSON data analysis showed that salmon migrated throughout the day and there was a marked increase in the ‘work rate’ of fish swimming in flood conditions.

Omitted variable bias was seen when the number of adult salmon migrating upstream (daily upstream movement of fish) were regressed with all individual environmental parameters (total daily rainfall, daily mean level, daily mean flow, average daily air temperature and average daily water temperature) and seasonality. The regression model showed a high degree of multi-co-linearity, high bivariate correlation between the dependant variables in the regression, particularly between total daily rainfall, daily mean level and daily mean flow. This inflated the standard errors to produce an inefficient model with inefficient estimators. Therefore, bivariate correlations were used to determine relationships. Other factors, namely seasonality, will affect the upstream migration which was also a driving force for migration (Thorstad et al., 2008). The extent of the correlations of fish migration with seasonality was estimated from visual observations of fish migration from monthly data (Chapter 4).

The data in Tables 6.2 to 6.6 show that the highest correlation was observed between the average daily mean air temperature and the total daily upstream salmon migration \( p = \)
0.002). A significant correlation was also observed between the average daily mean water temperature ($p = 0.017$). Both were significant at the 0.05 level (2-tailed). No significant correlations were determined between the upstream migration of salmon with daily mean water level, daily mean flow or daily mean rainfall ($p = 0.155$, $p = 0.155$ and $p = 0.136$).

**Table 6.2: Daily fish movement upstream with the daily mean level.**

<table>
<thead>
<tr>
<th></th>
<th>Daily Fish Up</th>
<th>Daily Mean Level (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spearman’s rho</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daily Fish Up</td>
<td>Correlation Coefficient</td>
<td>1.000</td>
</tr>
<tr>
<td></td>
<td>Sig. (2-tailed)</td>
<td>.</td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>370</td>
</tr>
<tr>
<td>Daily Mean Level (m)</td>
<td>Correlation Coefficient</td>
<td>.087</td>
</tr>
<tr>
<td></td>
<td>Sig. (2-tailed)</td>
<td>.115</td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>328</td>
</tr>
</tbody>
</table>

**Table 6.3: Daily fish movement upstream with the daily mean flow.**

<table>
<thead>
<tr>
<th></th>
<th>Daily Fish Up</th>
<th>Daily Mean Flow (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spearman’s rho</strong></td>
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<td></td>
</tr>
<tr>
<td>Daily Fish Up</td>
<td>Correlation Coefficient</td>
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</tr>
<tr>
<td></td>
<td>Sig. (2-tailed)</td>
<td>.</td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>370</td>
</tr>
<tr>
<td>Daily Mean Flow (m³/s)</td>
<td>Correlation Coefficient</td>
<td>0.087</td>
</tr>
<tr>
<td></td>
<td>Sig. (2-tailed)</td>
<td>.115</td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>328</td>
</tr>
</tbody>
</table>

**Table 6.4: Daily fish movement upstream with the total daily rainfall.**

<table>
<thead>
<tr>
<th></th>
<th>Daily Fish Up</th>
<th>Total Daily Rainfall (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spearman’s rho</strong></td>
<td></td>
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</tr>
<tr>
<td>Daily Fish Up</td>
<td>Correlation Coefficient</td>
<td>1.000</td>
</tr>
<tr>
<td></td>
<td>Sig. (2-tailed)</td>
<td>.</td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>370</td>
</tr>
<tr>
<td>Total Daily Rainfall (mm)</td>
<td>Correlation Coefficient</td>
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</tr>
<tr>
<td></td>
<td>Sig. (2-tailed)</td>
<td>.136</td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>370</td>
</tr>
</tbody>
</table>
Table 6.5: Daily fish movement upstream with average daily water temperature (*Correlation is significant at the 0.05 level (2-tailed)).

<table>
<thead>
<tr>
<th>Spearman’s rho</th>
<th>Daily Fish Up Correlation Coefficient</th>
<th>Average Daily Water Temp.(°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spearman’s rho</td>
<td>Daily Fish Up Correlation Coefficient</td>
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</tr>
<tr>
<td>Spearman’s rho</td>
<td>Spearman’s rho</td>
<td>0.124(*)</td>
</tr>
<tr>
<td>Spearman’s rho</td>
<td>Daily Fish Up Correlation Coefficient</td>
<td>0.017</td>
</tr>
<tr>
<td>Spearman’s rho</td>
<td>N</td>
<td>370</td>
</tr>
<tr>
<td>Spearman’s rho</td>
<td>Average Daily Water Temperature (°C) Correlation Coefficient</td>
<td>1.000</td>
</tr>
<tr>
<td>Spearman’s rho</td>
<td>Average Daily Water Temperature (°C) Correlation Coefficient</td>
<td>0.124(*)</td>
</tr>
<tr>
<td>Spearman’s rho</td>
<td>N</td>
<td>370</td>
</tr>
</tbody>
</table>

Table 6.6: Daily fish movement upstream with average daily air temperature (**Correlation is significant at the 0.05 level (2-tailed)).

<table>
<thead>
<tr>
<th>Spearman’s rho</th>
<th>Daily Fish Up Correlation Coefficient</th>
<th>Average Daily Air Temp. (°C)</th>
</tr>
</thead>
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<td>Spearman’s rho</td>
<td>Daily Fish Up Correlation Coefficient</td>
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</tr>
<tr>
<td>Spearman’s rho</td>
<td>Daily Fish Up Correlation Coefficient</td>
<td>0.164(**)</td>
</tr>
<tr>
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<td>Daily Fish Up Correlation Coefficient</td>
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<td>N</td>
<td>370</td>
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<td>Spearman’s rho</td>
<td>Average Daily Air Temperature (°C) Correlation Coefficient</td>
<td>1.000</td>
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<td>Spearman’s rho</td>
<td>Average Daily Air Temperature (°C) Correlation Coefficient</td>
<td>0.164(**)</td>
</tr>
<tr>
<td>Spearman’s rho</td>
<td>N</td>
<td>370</td>
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</tbody>
</table>

Influences of the Daily Mean Water Level, Daily Mean Flow and Daily Mean Rainfall on Adult Atlantic salmon Migration, River Deel DIDSON Site

Over the fourteen month data set daily mean water level, daily mean flow and daily mean rainfall were not shown to be significant factors for the upstream migration of Atlantic salmon but relationships were noted during specific migration periods. It was not possible to determine a daily mean level or a daily mean flow at which a predicted response to trigger salmon migration could be expected. Depending on the season, salmon reacted differently to the rise and fall of water level and varying river flows. Increases in the daily mean rainfall, daily mean water level and daily mean flow in the spring of 2008 did not correspond to an increase in salmon migration. The bulk of salmon are known to migrate on the River Deel during the autumn and winter months. However, on the 26th April 2008, 126 fish migrated upstream past the DIDSON counter. This migration followed increased rainfall two days prior to this run. These fish were discriminated as spring fish from observations of their length frequency distribution and run time data (Chapter 4). Over these two days, daily mean flow increased from 2.4 m³/s on the 25th April 2008 to...
7.2 m$^3$/s on the 27$^{th}$ April 2008. This was a 4.9 m$^3$/s increase in daily mean flow over a 48 hours period. Following a period of increased rainfall, on the 21$^{st}$ June 2008, the daily mean water level increased from 0.2 to 0.8 m, a 0.61 m increase over a 24 hours period. This led to three peaks of fish migration where 101 fish migrated upstream past the DIDSON counter on the 24$^{th}$ June, 95 on the 26$^{th}$ June and 142 on the 29$^{th}$ June 2008. The significance of these data show that the largest of these three peaks in migration occurred during falling water level and decreasing flow conditions from the 27$^{th}$ to 28$^{th}$ June 2008. This spate of fresh water entering the system stimulated the steady upstream migration of salmon past the DIDSON until early August 2008 (no count data exists from the 9$^{th}$ August to 1$^{st}$ September 2008, due to a system failure).

The increase and decrease of fish movement with the rise and fall of daily mean water level and the average daily water temperature was clearly seen from the end of September to the middle of October 2008 (Fig. 6.6). However, fish migration upstream on this river peaked in mid-November and mid-December 2008, and did not always follow increases and decreases in water level and flow. The interpretation of these data from the 29$^{th}$ October 2008 to 11$^{th}$ December 2008 was made difficult due to the loss of water level and flow data at the EPA data logger (due to a battery failure), and this may have masked the detection of correlations during peak salmon migration. Fig. 6.7 shows the log graph between salmon migration and the daily mean flow, providing greater resolution. These data show that a very complex relationship exists between the patterns of daily mean rainfall, daily mean water level and daily mean flow with the upstream migration of salmon on the River Deel at the DIDSON site. The difficulty in determining the relationship with salmon migration and discharge may also be a result of the river’s make-up, i.e. groundwater provides a significant proportion of the flow for the River Deel, especially during low flows.
Figure 6.6: The effects of daily mean flow (Knockadangan Bridge, EPA data set) on the upstream migration of Atlantic salmon, DIDSON counter site, River Deel (n = 415).

Figure 6.7: The effects of daily mean flow on the upstream migration of Atlantic salmon, DIDSON counter site, River Deel (Logarithmic scale) (Knockadangan Bridge, EPA data set) (n = 415).
Influences of the Average Daily Air Temperature and the Average Daily Water Temperature on Adult Atlantic salmon Migration, River Deel DIDSON Site

Trends over the duration of the fourteen month data set for the average daily water and the average daily air temperature were established with the upstream migration of salmon at the DIDSON counter site. Temperatures dropped from autumn to winter 2008 and resulted in an increase in salmon migration upstream on the River Deel (Fig. 6.8). Using the log scale, Fig. 6.9, the relationship between upstream migration and air and water temperature is more apparent. This was due to seasonal decreases in temperature from October 2008 onwards, coinciding with the upstream migration of salmon. From the 19th to the 26th April 2008, the average daily water temperature increased from 6.9 °C to 11.6 °C, a 4.7 °C change in temperature in one week. This coincided with a run of 126 salmon on the 26th April 2008 that also coincided with increased rainfall over a two day period, prior to this run of spring fish. The highest average daily water temperature when salmon migrated was 19.3 °C on the 14th May 2008. Water temperature is thought to inhibit salmon migration above approximately 18 °C and probably ceases between 22 °C and 25 °C (Thorstad et al., 2008). Thus, this was indicative of the very upper limit of salmon migration on the River Deel. Increasing average daily water temperature from 13.34 °C to 14.92 °C on the 23rd June to the 1st of July 2008 resulted in a run of 669 salmon over this nine day period. The peaks of this nine day run, (101 salmon migrating upstream on the 24th June, 95 on the 26th June and 142 fish on the 29th June 2008) occurred on the 29th June after dropping flow conditions from the 27th to 28th June 2008. Data from October to December 2008 showed that the majority of fish migrated in average daily water temperatures between 3 °C and 14.1 °C. Temperature effects were different at different times of the year. From October to December 2008, temperature changes of approximately 3 - 6 °C over a few days (3 - 5 days) triggered three of the main pulses of migration (salmon migration upstream ≥ 40 cm) for this three month period. On the 20th October 2008, 212 salmon migrated, 319 salmon migrated on the 14th November 2008 (the maximum daily migration over the fourteen months) and 227 salmon on the 16th December 2008. These data show the possible combined effects of environmental factors at certain times of the year, over changing seasons, on upstream salmon migration in the River Deel.
Figure 6.8: The effects of air and water temperature on the upstream migration of Atlantic salmon, DIDSON counter site, River Deel, Moy catchment (Air temperature data - MET Eireann) \((n = 415)\).

Figure 6.9: The effects of air and water temperature on the upstream migration of Atlantic salmon (Logarithmic scale), DIDSON counter site, River Deel, Moy Catchment (Air Temperature data - MET Eireann) \((n = 415)\).
6.2.3 Determination of Relationship between Fish Length and Daily Mean Flow, River Deel

The variation in fish lengths over the duration of DIDSON operation is seen in Fig. 6.10. There was no correlation between the daily mean flow and the average daily fish lengths of fish migrating (≥ 40 cm fish, all movements) past the DIDSON Counter on the River Deel (Fig. 6.11). Unlike Jonsson et al. (1990 & 1991), changes in flow were not shown to have an affect on the size of fish migrating on the River Deel; when fish moved all fish sizes were noted to move. However, over the fourteen month period of analyses, these data showed that the largest fish moved at the end of April 2008. This was more a characteristic of the run components of grilse and MSW fish which can vary in size and condition in this system.

![Graph showing fish length variations](image)

**Figure 6.10:** Comparisons between the average daily fish length of all fish, the average daily fish length ≥40 cm, and the average daily fish length ≥45 cm DIDSON counter, River Deel.
6.2.4 Influences of Environmental Factors on Atlantic salmon Smolt Migration, River Deel

For both study years, no significant correlation was found between smolt migration and the average daily water temperature or discharge on the River Deel. The results showed that the relationship between smolt migration and environmental factors is very complex and could not be easily determined using smolt count data from a screw trap. This was due to the variation in the trap efficiency which was in turn affected by the daily mean water level, daily mean flow and smolt migration. However, no significant correlations were found between discharge and smolt migration on the River Deel. Data was lost during high flows which may have masked possible relationships due to the difficulty in determining an estimate of smolt migration during flood conditions. General observations were made of the data to show the affects of environmental factors on smolts migration and the operation of the trap. Weather conditions caused some difficulties during trap operations (Chapter 5). Extreme increases and decreases in the daily mean water level and the daily mean flow affected both the rotation of the drum and the ability to service the trap on a daily basis. When this happened, there was a possible reduction in the trapping of smolts in the drum and live box. No smolts were trapped when water levels exceeded approximately 1 m, as the trap became loaded with debris.
Observed influences of the Daily Mean Water Level and Daily Mean Flow on Atlantic salmon Smolt Migration, River Deel, Moy Catchment

As described above, the River Deel was observed in this study to be a flashy catchment where rainfall has an almost immediate impact on the discharge as documented during the operation of the DIDSON. In 2007, the daily mean water level peaked on the 25th April at 1.1 m with a daily mean flow of 34.20 m$^3$/s (Fig. 6.12 & 6.13). The bulk of the smolt run migrated between the 19th to the 23rd April 2007 with 507 smolt migrating over five days. There were two main peaks in the smolt run where, 154 smolts migrated on the 19th April and 170 smolts on the 23rd April 2007. This did not follow any significant changes in discharge. However, the second peak coincided with a rising flood from the 22nd to the 24th April 2007 which prevented the operation of the smolt trap for 48 hours period.

In 2008, the daily mean water level and the daily mean flow during the smolt trap operation peaked on the 15th March at 1.32 m with a flow of 38.1 m$^3$/s (Fig 6.12 & 6.13). Once smolt migration commenced, the only flood waters to hamper the smolt trap operation in 2008 occurred on the 28th March at a water level of 1.02 m with a flow of 26.9 m$^3$/s. Prior to this flood only 35 smolts had migrated so the flood was not thought to have significantly interfered with the trap operation. In 2008, the two main peaks of the smolt run occurred from the 12th to 25th April 2008 when the daily mean water level dropped from 0.49 m to 0.28 m and the daily mean flow dropped from 8.97 m$^3$/s to 3.25 m$^3$/s (Fig 6.12 & 6.13). This was indicative of the smolts moving on falling water after a flood. The first significant peak in the 2008 smolt run was of 135 smolts on the 13th April which appeared to be migrating on a flood. The main peak of the smolt run of 219 smolts occurred on the 24th April, only 24 hours later than the peak run of smolts captured in 2007. The bulk of these 708 smolts migrated between the 21st and the 26th April 2008. It was noted from the daily mean water level and the daily mean flow data that only levels greater than approximately 1 m and flows of greater than 26 m$^3$/s (1.1 m/34.2 m$^3$/s in 2007 and 1.0 m/26.9 m$^3$/s in 2008) affected the operation of the smolt trap in both study years.
Figure 6.12: A comparison of the number of salmon smolts trapped with water level, River Deel, 2007 & 2008. (*Note: During a flood period from 24th to the 25th April 2007 - the drum was lifted and not fishing due to the force of the flood) (Note: During a flood period from the 28th and 29th March 2008 - the drum was lifted and not fishing due to the force of the flood).

Influences of the Average Daily Water Temperature on Atlantic salmon Smolt Migration, River Deel, Moy Catchment

The direct linear relationship between the average daily air temperature and the average daily water temperature was established during the operation of the DIDSON (Fig. 6.5). The average daily water temperature from the 1st April to 20th May in 2007 was 11.1 °C (SE = 0.336 / SD = 2.379) and from the 1st March to 15th May 2008 was 9.6 °C (SE = 0.379 / SD = 3.307) (Fig. 6.15 and 6.16). The average daily water temperature ranged from 7.4 °C to 15.7 °C in 2007 and 4.9 °C to 19.3 °C in 2008. A minimum average daily water temperature recorded in 2008 was lower than that of 2007 due to trap operations commencing approximately a month earlier than in 2007.
Comparison of the average daily water temperature and the number of smolts trapped in 2007 was difficult to determine as the start of the smolt run was missed. The average daily water temperature data from the 1st to the 24th April 2007 (inclusive) was extrapolated from a neighbouring river, the Rough River, Burrishoole catchment to insert temperature data prior to the installation of the temperature data logger on-site (Appendix VI: B). During trap operation in 2007, smolts began migrating on the 7th April, at a temperature of 8.5 °C. Smolts migrated until the temperature began to rise in early May reaching a peak of 15.7 °C on the 4th May 2007. The remainder of the run migrated with a slight drop in temperature until the temperature began to rise again on the 12th May 2007, when water temperature was at 12.0 °C. The last smolt trapped in 2007 was on the 15th May when the water temperature was at 12.9 °C (Fig. 6.14). This was ruled out as an effect on the determination of possible correlations with water temperature data and the smolt count in 2007, as no correlation was found in 2008 either.

In 2008, an increase in the number of smolts was observed migrating with an increase in temperature up to the end of the run (Fig. 6.15). The gradual increase in temperature in
the month of March was thought to have triggered the commencement of the run at a temperature of 6.86 °C on the 22\textsuperscript{nd} March 2008. However, higher water temperatures were recorded prior to the commencement of this part of the run. The three peaks in the smolt run during 2008 appeared to be triggered by increases in water temperature; however, this was not shown to be statistically significant.

The last smolt trapped in 2008 was caught on the 13\textsuperscript{th} May when the water temperature was 17.28 °C. As in 2007, the increase in water temperature in early May 2008 showed similar trends in that it provided for an end to the smolt run when the average daily water temperature increased from 10.96 °C on the 1\textsuperscript{st} May to a peak of 19.3 °C on the 14\textsuperscript{th} May 2008. This was thought to be the upper temperature limit at which smolt migration occurred on the River Deel. This corresponded to very low flow conditions in the river and was also thought to be a factor of seasonality.

The Determination of the Preferred Conditions for Atlantic salmon Smolt Migrations, River Deel

In both 2007 and 2008, the main bulk of the smolt run had migrated past the smolt trap by the time the water temperature had reached 15 °C. Sudden drops in temperature were also noted to reduce the numbers of migrating smolts. This was also noted where sudden increases in temperature occurred. On the 15\textsuperscript{th} April 2007 when the water temperature was 10.5 °C, in a 48 hour period, the water temperature increased to 18.3 °C coinciding with 70 smolts trapped on the 15\textsuperscript{th} April 2007. There were no smolts trapped on the 16\textsuperscript{th} April 2007, 1 smolt trapped on the 17\textsuperscript{th} April 2007 and no smolts trapped on the 18\textsuperscript{th} April 2007. On the 19\textsuperscript{th} April 2007, when the water temperature was to 9.68 °C, 154 smolts were trapped. This rise in temperature triggered the main peak of smolts to migrate between the 19\textsuperscript{th} April and the 26\textsuperscript{th} April 2007. As already described, flood conditions reduced the number of fish caught from the 25\textsuperscript{th} April until flood water subsided on the 26\textsuperscript{th} April 2007 (Fig. 6.14).
Figure 6.14: Comparison of the total number of salmon smolts trapped with the average daily water temperature (°C), River Deel, 2008 (n = 855). (Water temperature from the 1st to the 24th April 2007 was data used from the Rough river, Burrishoole Catchment showed similar trends to River Deel water temperature, Vol. II Appendix Section VI: B).

Figure 6.15: Comparison of the total number of salmon smolts trapped with the average daily water temperature (°C), River Deel, 2008 (n = 1,676).

The results in Fig. 6.16 & 6.17 show that migration conditions were suitable at
temperatures between 8.0 °C to 15.7 °C in 2007 and 6.9 °C to approximately 16.0 °C in 2008 (with one fish migrating at a temperature of 17.3 °C). Table 6.7 below provides details of the mean, maximum and minimum water temperatures for both study years. There was only 0.5 °C between the minimum, 1.6 °C between the maximum and 0.4 °C between the average daily water temperatures during this period for both years.

Table 6.7: The mean, maximum and minimum water temperatures (°C) during smolt migrations, River Deel, 2007 & 2008.

<table>
<thead>
<tr>
<th>Smolt Migration Year</th>
<th>Mean (°C)</th>
<th>Max (°C)</th>
<th>Min (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>10.0</td>
<td>15.7</td>
<td>7.4</td>
</tr>
<tr>
<td>2008</td>
<td>10.4</td>
<td>17.3</td>
<td>6.9</td>
</tr>
</tbody>
</table>

Peak Smolt Migrations

In both 2007 and 2008, the run timing of smolts for the main peak of the run occurred between the 19th and 27th April. Table 6.8 shows the mean, minimum and maximum daily water temperatures during peak migration for both study years. The peak run in 2007 started on the 19th April and the average daily water temperature during the peak run was 9.4 °C, with a maximum of 9.9 °C and a minimum of 9.0 °C. During the 2008 peak run, the average daily water temperature had a minimum of 9.1 °C, maximum 12.4 °C and an average water temperature of 11.0 °C. There was only 0.1 °C between the minimum, 2.5 °C between the maximum and 1.6 °C between the average daily water temperatures during this period for both years.
Figure 6.16: Relationship between the number of smolts captured and of water temperature (Logarithmic scale), 2007, River Deel, Moy Catchment (n = 27).

Figure 6.17: Relationship between the number of smolts captured and of water temperature (Logarithmic scale), 2008, River Deel, Moy Catchment (n = 46).
Table 6.8: The mean, minimum and maximum daily water temperatures during peak smolt migration, River Deel, 2007 and 2008.

<table>
<thead>
<tr>
<th>Smolt Migration Year</th>
<th>Mean (°C)</th>
<th>Max (°C)</th>
<th>Min (°C)</th>
</tr>
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<td>2007</td>
<td>9.4</td>
<td>9.9</td>
<td>9.0</td>
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<tr>
<td>2008</td>
<td>11.0</td>
<td>12.4</td>
<td>9.1</td>
</tr>
</tbody>
</table>

Observed Correlations between Water Temperature and Water Depth

Figs. 6.18 and 6.19 show the correlations between water temperature and water depth with shallow waters tending to heat more readily. Correlations with dropping flow and the increase in water temperature for both 2007 and 2008 was observed (Figs. 6.18 & 6.19). Temperature increased from the 1st April to its peak on the 4th May 2007 coinciding with low flows with the peak flood of the 25th April only causing a slight reduction in water temperature temporarily. This is a factor of the flashy nature of the River Deel and flood waters receded over a 24 hour period. This was also observed on the 28th March 2008 where flood water temporarily coincided with dropping temperatures. However, it was clearly noted in both 2007 and 2008 that low flows coincided with increased temperatures that initiated the bulk of migration for both years.

![Graph showing daily mean flow and water temperature correlation](image)

Figure 6.18: The relationship between the average daily water temperature and the daily mean flow, River Deel, 2007. (*Note: During a flood period from 24th to the 25th April 2007 - the drum was lifted and not fishing due to the force of the flood).
Figure 6.19: The relationship between the average daily water temperature and the daily mean flow, River Deel, 2008. (Note: During a flood period from the 28th and 29th March 2008 - the drum was lifted and not fishing due to the force of the flood).

Fig. 6.20 below clearly shows that as flow decreases, temperature increases.

Figure 6.20: The Relationship between the Average Daily Water Temperature and the Daily Mean Flow, River Deel, 2007.
6.2.5 Influences of Daylight on Atlantic salmon Migrations
Adult Atlantic salmon migrate year round on the River Deel. Daily migration activity with respect to diel effects on fish migration were not assessed as part of this study but should form the basis for future study. A general observation by the author from the processing of DIDSON data was that adults actively migrated throughout the day, with certain periods of the day showing greater numbers of fish movement. This was similar to findings by Orell et al. (2007). Further analysis of the DIDSON count data should be carried out to determine if there are any diel patterns in the migration of adult Atlantic salmon on the River Deel. This was beyond the scope and remit of this study. Very different results have been encountered with the comparison of fish counter data and daylight. Most UK studies have shown the majority of migration during the night. Solomon et al. (1999) showed that an increase in day time activity can occur during spate conditions and turbid water (Laughton, 1998). This was observed during the processing of DIDSON data.

It was not possible using the smolt trap to determine when fish were trapped and thus if any diel influences existed. Resources and the smaller number of migrating smolts in this river system only allowed for one morning fishing of the smolt trap. However, during the peak of the run, smolts were entering the trap during morning fishing (approximately 10:00). This would concur with the results of studies that showed that hours of sunshine explained a significant proportion of the day to day variation in numbers of migrating smolts (Davidsen et al., 2005; Orell et al., 2007). Strong sunlight will also have an effect on the air and water temperature and trigger movement. Several authors have noted that these conditions may favour smolt survival from predation of birds and other fish (Bakshtanskiy et al., 1980; Solomon, 1982; Veselov & Shustov, 1991; Davidsen et al., 2005; Orell et al., 2007).

6.2.6 Effects of Turbidity on the Migration of adult Atlantic salmon, River Deel, Moy Catchment
The River Deel source in the Nephin mountain range provided for turbid water conditions during flooding as observed during DIDSON operations, due to the river source running through peatland. This in turn led to water colouration from high loadings of suspended matter from the upper catchment. Turbidity was not measured as part of this study but images of the upstream migration of salmon were captured on the DIDSON in flood conditions. Despite previous assumptions, numerous authors have shown that fish passage
can occur in turbid waters (Banks, 1969; Hellawell et al., 1974; Potter, 1988; Lilja & Romakkanemi, 2003). The DIDSON confirmed the active migration of salmon on the River Deel even in high turbidity conditions and heavy floods. As discussed in Chapters 3 and 4 fish were observed actively migrating on rising floods.
CHAPTER 7

7.0 Estimating Atlantic salmon Runs Using a Novel Stock Assessment Methodology based on the Combined Use of DIDSON (Dual-frequency Identification Sonar) Hydroacoustic Technology and Genetic Stock Identification, River Deel.

Large river catchments can consist of discrete biological units or stocks with respect to sea age and/or from genetically determined discrete populations in particular tributaries (Primmer et al., 2006; Vaha et al., 2007; Dillane et al., 2008). Currently the application of the Conservation Limits (CL) approach for the assessment of Atlantic salmon in Irish rivers does not attempt to utilise sub-river structuring of the adult population. Individual rivers can be characterised by their distinctive run-timings, particularly rivers high up in catchments. This is of importance where specific rivers within the catchment have been designated for the diversity of stocks (Cowx, 2003). Large Irish rivers with numerous and important tributaries possibly containing sub-populations require quantitative assessment techniques that can provide accurate estimates of these discrete Atlantic salmon populations. Rod catch data can only provide information on salmon numbers during the fishing season, specific to a particular run type or life history cohort that is exploited and therefore does not take account of fish that enter the river outside the period of the angling season. Consequently, the conservation limit having been calculated on the basis of wetted area and latitude, which is assessed on the basis of a single run cohort, will be as a result a poor reflection of the actual total population. Grilse and MSW salmon have different run timings that are outside the angling season and thus go undetected. The determination of grilse and MSW salmon from length data alone has become increasingly difficult due to changes in Atlantic salmon stocks size observed in recent years. Where the river is not meeting its CLs and is closed to angling, no information will exist unless other technology is applied.

7.1 Historical use of Genetics for Atlantic salmon Stock Identification and the Application

Originally, allozyme variation was used to identify the origin of Chinook salmon in Pacific fisheries (Miller et al., 1983; Milner et al., 1985; Utter et al., 1987; Shaklee et al., 1999). Due to the variability of loci and the ease of assays using the polymerase chain reaction (PCR) process, microsatellites have become increasingly popular as genetic
markers for a range of applications in fisheries management (O'Reilly et al., 1996). Beacham et al. (2006) successfully applied microsatellites on a local basis to provide information on population structure and stock composition of Chinook salmon \((Oncorhynchus tshawytscha)\). The development of these genetic markers made it possible to investigate internal structuring in natural populations attributable to reproductive behaviour (Youngson et al., 2003).

Atlantic salmon populations have been studied at the catchment level (Garant et al., 2000; Landy et al., 2001) and at a regional level across the Atlantic and Baltic seas (King et al., 2001). O'Reilly et al. (1996) described microsatellite loci as ideal for assessing genetic variation in Atlantic salmon and showed that they offered advantages over other markers for this species. In a study of Atlantic salmon across the species range (King et al., 2001), Irish salmon were shown to have the largest number of unique alleles. Dillane et al. (2007) was the first study in Ireland to use microsatellites to assess the extent of genetic variation occurring within and between salmon populations in Irish rivers. Prior to Dillane et al. (2007) study, most genetic studies took place on individual rivers or within particular regions, none of which used microsatellites (McElligott & Cross, 1991; Galvin et al., 1996).

More recent studies of genetic structure in Atlantic salmon to date have focused on in-river comparison, the most recent by Primmer et al. (2006) and Dillane et al. (2008). Vaha et al. (2007) showed that the accuracy of homing to natal rivers extended beyond river specific homing and was accurate to at least the tributary level. The spatial genetic population structure of salmon in the River Teno (Norway) also showed that age-structure plays an important role in maintaining genetic diversity with respect to the proportion of MSW spawners (Vaha et al., 2007).

Although previous Irish studies have shown that differentiation within rivers is generally less than that among rivers (Dillane et al., 2007), data from the River Moy suggests that there is sufficient population genetic differentiation to delineate intra-river stocks within the Moy watershed (Dillane et al., 2008). The potential to use these genetic traits for the purpose of stock assessments lies in the in-river genetic structuring. Dillane et al. (2008) described five separate population units within the River Moy. The largest lakes in the Moy system, Lough Conn and Lough Cullin, effectively divide the catchment into distinct
areas: northwest, southwest and east, limiting within-river migration and are the most significant landscape features shaping populations in the system, e.g. Deel River (Dillane et al., 2008). Discrete populations of salmon are the smallest, non-divisible biological units that underpin recruitment to the fisheries and are at the core of any genetically based approach to management (Youngson et al., 2003). Youngson et al. (2003) also emphasised the use of a precautionary approach that takes population structuring into account.

7.1.1 Conservation Limits and Management of Atlantic salmon
The Salmon Management Task Force (Anon., 1996) advised regarding conservation of stocks that salmon management should be based on the premise that there is a definable number of spawners for a given river (Conservation Limit) and sustainable exploitation can only take place if there is a surplus of fish over spawning requirements (Anon., 2008b). As already described, this can only be carried out effectively where individual river stock assessment data exists and harvests can only then be made where a river has been shown to meet its conservation limits. Accurate count data is essential for the protection of individual river stocks. For effective management of Irish Atlantic salmon stocks, good quality stock assessment data is required for the purpose of setting of CLs and DIDSON can provide accurate counts of salmon where it has been deployed (Chapters 3 & 4; ICES, 2009).

As outlined previously individual river stock assessments using fish counter data commenced in Ireland in the 1990’s and this provided greater information on the run timings of Atlantic salmon. However, until the operation of the River Deel DIDSON (ICES 2008; ICES, 2009; Chapter 3), existing counters on the River Moy had difficulty operating in flood conditions when the water was turbid due to being heavily silted and due to debris loading (Vol. II Appendix Section I: Chapter 3a). This limited counter operations to the summer months, potentially missing key migrations of MSW fish. Where summer flood events occurred data was lost due to counter downtime. The closure of all mixed stock fisheries and the closure of many Irish rivers to angling in 2007 meant that there was no longer rod catch data for these closed systems. In 2008, the SSC estimated the number of returning adults to the River Moy at 42,320 salmon (grilse & 2SW). The number of returning adults (grilse & 2SW) to the River Moy as determined from the GIS smolt production of 654,000 smolts (McGinnity et al., 1999) provided for
an estimate of the River Moy adult count of approximately 33,000 (5 % sea survival) and 62,000 (10 % sea survival) (Sea survival rates applied in Chapter 5). The smolt production estimates produced by McGinnity et al. (1999), although useful to provide a rough baseline for the River Moy, was only a ball park figure and the estimate provided by the SCC for 2008 was the best stock estimate used to compare the stock estimate from the River Deel DIDSON – GSI count in this study.

7.1.2 DIDSON and Genetic Stock Identification, River Deel

In Chapter 3 and in Appendix I: Chapter 3a, efforts were made in the initial part of this study to determine a count on a large river, i.e. the River Moy. However, the quantity of staff and the economic cost of operating the existing counters on the River Moy were extremely costly. Furthermore, the frustration of operating counters in flood conditions on the River Moy would prevent the goal of this study from being achieved, i.e. the operation of a counter on a large river. Despite all efforts made only a partial count could be achieved using existing methods on a large river system. To this end, it was decided to test alternative new technology, but rather than deploy on the large main channel a smaller tributary river was chosen, namely the River Deel DIDSON (Chapter 3). Significantly, the salmon population in the Deel tributary has a distinct genetic profile compared to the salmon populations in the rest of the Moy system. The River Moy counter operation findings increased the need for new counter technology that could operate in a varied range of environmental conditions and the development of alternative assessment techniques.

The combined DIDSON-GSI method would allow for an estimate for the number of salmon to be obtained for a large river using only one count of a single tributary (using DIDSON) and the determination of the genetic proportions of that tributary with respect to the genetic proportions of the main river. DIDSON was operated 24/7 on the River Deel even in high winter flooding of water levels > 2 m and in turbid waters when other counters in Ireland could not operate under the same conditions (Chapter 3). To this end, the DIDSON allowed for the apportionment of species using DIDSON length frequency data and run components in the River Deel (Chapter 4). The River Deel system, having a resolvable discrete population (Dillane et al., 2008), was investigated to look at the possibility of using the nature of this discrete population within the River Moy catchment for the potential to use GSI to provide a count for the whole River Moy system. This
could be achieved where an accurate estimate of one discrete population was achieved, i.e. River Deel DIDSON count. This was the first application of this novel method and shows the potential of this method for future use and development.

Sampling on the River Moy was carried out from May to September 2008. The DIDSON counter was used to provide an accurate count of the Atlantic salmon stock on the River Deel for the 2008 cohort. Unlike other fish counters, DIDSON was shown to operate in flood conditions and in heavily silted waters (Chapter 3; ICES, 2009). Length data obtained for each fish counted migrating past the DIDSON was used to apportion species and to determine the timings of when fish entered the Deel River (Chapter 4). This allowed for the breakdown of the count into run time components e.g. early spring running fish, February to end of May and later summer running salmon, June up to spawning time. Genetic analysis carried out on scale samples of fish captured returning to the River Moy at the head of the tide in 2008 were used to genetically determine the contribution of the River Deel tributary. These data were then used within a basic mathematical model to provide an estimate of the total run into the River Moy and the proportions of each of the contributing stocks e.g. contributions from Cloonacool, Manulla, Clydagh, Deel and Main Moy genetic management units (Dillane et al., 2008).

**Individual Assignment (IA) and Within-River Structuring within the River Deel**

In order to supplement the existing genetic baseline for the River Deel, to assess it stability over time and to determine whether there was evidence of further population sub-structuring within the Deel, samples of migrating smolts were collected using a screw trap in 2007 and 2008 (Chapter 5). There were a total of 273 River Deel smolts analysed in 2007 and 257 scale samples analysed in 2008. There was some suggestion of minor temporal variability and there was no intra-river structuring apparent in this system from the data analysed.

This chapter provides details of the first attempt to combine new hydroacoustic counter technology DIDSON (Chapter 3) and GSI for the purpose of salmon stock assessment.
7.2 Results

7.2.1 Integration of the River Moy and River Deel Samples with that of the Selected Baseline and the Mixed Stock Analysis (MSA) for the River Moy and River Deel

Testing the Integrity of the Baseline

The aim of this study was to accurately assess the proportion of River Deel fish occurring in the River Moy fishery (as sampled in 2008) so that this proportion could be used along with real count data from the DIDSON to estimate the total number of salmon running into the River Moy. In order to test the integrity of the baseline, a simulated mixture was created using ONCOR and this tested whether different proportions of River Deel fish could be accurately measured, a number of simulated mixtures containing various proportions of River Deel fish (from 0 to 100%) were constructed using ONCOR, as described in Chapter 2. Results from the testing of the different proportions of River Deel fish using a number of simulated mixtures containing various proportions of River Deel fish (from 0 to 100%) are presented in Table 7.1 and Fig. 7.1, which shows the performance of ONCOR. In all, 11 simulated mixtures were constructed with River Deel sample proportions that were 0 %, 1 %, 2 %, 4 %, 6 %, 8 %, 10 %, 15 %, 25 %, 50 % & 100 % of the total mixture respectively. The raw output from simulations can be seen in Table 7.1 and Fig. 7.1.
Table 7.1: Actual and estimated proportions for each of the simulated mixtures.

<table>
<thead>
<tr>
<th></th>
<th>Deel 0%</th>
<th></th>
<th>Deel 1%</th>
<th></th>
<th>Deel 2%</th>
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<td>95% CI</td>
<td>actual proportion</td>
<td>estimated proportion</td>
<td>95% CI</td>
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<td>0.070 (0.053,0.075)</td>
<td>0.071</td>
<td>0.068 (0.052,0.074)</td>
<td>0.070</td>
<td>0.069 (0.055,0.074)</td>
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<td>0.036 (0.028,0.041)</td>
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<td>0.035 (0.027,0.042)</td>
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<td>0.034 (0.027,0.039)</td>
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<td>0.033 (0.023,0.037)</td>
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<td>0.071</td>
<td>0.066 (0.055,0.074)</td>
<td>0.070</td>
<td>0.069 (0.058,0.076)</td>
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<td>Clydagh</td>
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<td>0.071 (0.060,0.079)</td>
<td>0.071</td>
<td>0.066 (0.056,0.076)</td>
<td>0.070</td>
<td>0.070 (0.056,0.076)</td>
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<tr>
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<td>0.065 (0.052,0.076)</td>
<td>0.070</td>
<td>0.067 (0.056,0.077)</td>
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<tr>
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<td>0.102 (0.074,0.112)</td>
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<td>0.102 (0.072,0.111)</td>
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<td>0.071 (0.059,0.077)</td>
<td>0.071</td>
<td>0.069 (0.059,0.077)</td>
<td>0.070</td>
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<td>Deel 4% estimated proportion</td>
<td>95% CI</td>
<td>Deel 6% actual proportion</td>
<td>Deel 6% estimated proportion</td>
<td>95% CI</td>
</tr>
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<td>------------------------------</td>
<td>--------------</td>
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<td>0.064</td>
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</tr>
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<td>(0.025, 0.041)</td>
<td>0.034</td>
<td>0.033</td>
<td>(0.026, 0.038)</td>
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<td>(0.024, 0.038)</td>
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<td>0.033</td>
<td>(0.026, 0.038)</td>
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<td>95% CI</td>
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<td>Deel 100%</td>
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<td>0.000</td>
<td>(0.000,0.001)</td>
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<td>0.018</td>
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<td>0.000</td>
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<tr>
<td>Brusna</td>
<td>0.036</td>
<td>0.043</td>
<td>(0.037,0.059)</td>
<td>0.000</td>
<td>0.004</td>
<td>(0.004,0.018)</td>
</tr>
<tr>
<td>Easkey</td>
<td>0.036</td>
<td>0.036</td>
<td>(0.028,0.045)</td>
<td>0.000</td>
<td>0.001</td>
<td>(0.000,0.004)</td>
</tr>
<tr>
<td>Ballysadare</td>
<td>0.036</td>
<td>0.035</td>
<td>(0.028,0.039)</td>
<td>0.000</td>
<td>0.000</td>
<td>(0.000,0.001)</td>
</tr>
</tbody>
</table>
Mixed Stock Analysis

The results of the mixed stock analysis of the sample of fish collected at the Ridge pool at the head of tide on the River Moy are presented in Table 7.2. The sample consisted of 257 scales taken from salmon caught on rod and line between 1st May and 30th September, 2008 (Chapter 2: Section 2.5: Table 2.3: shows the breakdown of rod caught salmon sampled in 2008 from the Moy Fishery). This analysis suggests that the largest proportion of these fish originated in the tributaries of the eastern Moy (82%). A smaller proportion originated in the river tributaries of the western Moy (13.8%), with the River Deel, the principal tributary in the west contributing an estimated 7.1% of the total. Also there were a considerable number of fish from rivers outside the River Moy (Chapter 2: Section 2.5, Fig. 2.16) occurring in the mixed sample. For example, within the River Moy estuary, the Brusna River, whose river mouth is located approximately 1.2 km from the sampling site, represents 9% of the total, with much smaller contributions from the Cloonaghmore and the Easkey rivers. Outside the River Moy estuary, the neighbouring Owenmore contributes a sizeable 5% of the fish caught by anglers. The breakdown of the contributing populations by month are presented in Table 7.2.
Table 7.2: Proportions of the Mixed Stock Assessment of the River Moy fishery samples 2008 (n = 257).

<table>
<thead>
<tr>
<th>Region</th>
<th>River</th>
<th>Tributary</th>
<th>Estimated Proportion</th>
<th>5% &amp; 95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coastal</td>
<td>Boyne</td>
<td></td>
<td>0</td>
<td>(0.000, 0.031)</td>
</tr>
<tr>
<td></td>
<td>Roughty</td>
<td></td>
<td>0</td>
<td>(0.000, 0.000)</td>
</tr>
<tr>
<td></td>
<td>Owenduff</td>
<td></td>
<td>0.0025</td>
<td>(0.000, 0.014)</td>
</tr>
<tr>
<td>West</td>
<td>Owenmore</td>
<td>Deel</td>
<td>0.0448</td>
<td>(0.015, 0.090)</td>
</tr>
<tr>
<td></td>
<td>Moy</td>
<td>Clydagh</td>
<td>0.0556</td>
<td>(0.017, 0.078)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Manulla</td>
<td>0.0111</td>
<td>(0.0000, 0.035)</td>
</tr>
<tr>
<td>East</td>
<td>Trimogue</td>
<td></td>
<td>0.2855</td>
<td>(0.152, 0.306)</td>
</tr>
<tr>
<td></td>
<td>Spaddagh</td>
<td></td>
<td>0.1609</td>
<td>(0.083, 0.248)</td>
</tr>
<tr>
<td></td>
<td>Owengarve</td>
<td></td>
<td>0.1883</td>
<td>(0.117, 0.268)</td>
</tr>
<tr>
<td></td>
<td>Cloonacool</td>
<td></td>
<td>0.082</td>
<td>(0.042, 0.160)</td>
</tr>
<tr>
<td>Estuary</td>
<td>Brusna</td>
<td></td>
<td>0.0909</td>
<td>(0.049, 0.161)</td>
</tr>
<tr>
<td></td>
<td>Easkey</td>
<td></td>
<td>0.0032</td>
<td>(0.000, 0.051)</td>
</tr>
<tr>
<td></td>
<td>Ballysadare</td>
<td></td>
<td>0</td>
<td>(0.000, 0.008)</td>
</tr>
<tr>
<td></td>
<td>Cloonaghmore</td>
<td></td>
<td>0.0042</td>
<td>(0.000, 0.030)</td>
</tr>
</tbody>
</table>

Observations made of the variation within the River Moy system showed that there was a remarkable difference in the productivity between East and West regions of the River Moy (Table 7.2). The analysis also provided detailed monthly proportions of the individual River Moy tributaries (Table 7.3). The River Trimogue showed the highest productivity of the individual rivers that were discernable in the east Moy with 28.6%. The Owengarve was 18.8% and the Spaddagh 16.1%. The River Clydagh was 5.6% and the Manulla 1.1%. It was also noted from these proportions that the Manulla River had a distinctively early migration of salmon entry to the River Moy in the early summer sample (May/June) and were completely absent from the later summer sample. The proportions of River Deel fish in the Moy fishery varied on a monthly basis from 5.8% in May, to 5.9% in June, to 8.0% in July and to 4.4% August 2008 (Table 7.3). These data provided an indication that the main run of the River Deel was in July. However, this sample was too small and provided insufficient evidence to provide a conclusive insight with respect to the proportions of River Deel and the Manulla River fish and as to when their main runs were on the River Moy. Only a small proportion of fish were assigned to the Owenmore/Other catchments.
Table 7.3: Mixed Stock Assessment Monthly Breakdown, Moy Fishery, River Moy, 2008.

<table>
<thead>
<tr>
<th>Rivers</th>
<th>May (n = 36) Estimate</th>
<th>95% CI</th>
<th>June (n = 99) Estimate</th>
<th>95% CI</th>
<th>July (n = 79) Estimate</th>
<th>95% CI</th>
<th>August (n = 43) Estimate</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Owenmore/Others</td>
<td>0.021 (0.000,0.179)</td>
<td>0.046 (0.000,0.139)</td>
<td>0.038 (0.000,0.089)</td>
<td>0.065 (0.000,0.175)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deel</td>
<td>0.058 (0.000,0.224)</td>
<td>0.059 (0.020,0.150)</td>
<td>0.08 (0.023,0.191)</td>
<td>0.044 (0.000,0.125)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clydagh</td>
<td>0 (0.000,0.000)</td>
<td>0.08 (0.014,0.128)</td>
<td>0.083 (0.021,0.131)</td>
<td>0.001 (0.000,0.075)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manulla</td>
<td>0.077 (0.000,0.181)</td>
<td>0.001 (0.000,0.027)</td>
<td>0 (0.000,0.028)</td>
<td>0 (0.000,0.048)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>East</td>
<td>0.844 (0.616,0.941)</td>
<td>0.816 (0.684,0.890)</td>
<td>0.79 (0.684,0.900)</td>
<td>0.891 (0.720,0.994)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Individual assignment analysis breakdown is shown in Table 7.4. Of the 257 fish sampled, 18 of these fish were assigned to the River Deel. The individual assignments also reflect the greater productivity of the east Moy rivers in comparison to the number of samples assigning west of the Moy.

Table 7.4: Individual Assignment Analysis for the Moy Fishery, River Moy, May to September 2008 (n = 257).

<table>
<thead>
<tr>
<th>River</th>
<th>Number of Fish</th>
<th>Proportion of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Owenduff</td>
<td>1</td>
<td>0.389</td>
</tr>
<tr>
<td>Owenmore</td>
<td>13</td>
<td>5.058</td>
</tr>
<tr>
<td>Cloonaghmore</td>
<td>1</td>
<td>0.389</td>
</tr>
<tr>
<td>Deel</td>
<td>18</td>
<td>7.004</td>
</tr>
<tr>
<td>Clydagh</td>
<td>14</td>
<td>5.447</td>
</tr>
<tr>
<td>Manulla</td>
<td>3</td>
<td>1.167</td>
</tr>
<tr>
<td>Trimogue</td>
<td>75</td>
<td>29.183</td>
</tr>
<tr>
<td>Spaddagh</td>
<td>40</td>
<td>15.564</td>
</tr>
<tr>
<td>Owengarve</td>
<td>47</td>
<td>18.288</td>
</tr>
<tr>
<td>Cloonacool</td>
<td>20</td>
<td>7.782</td>
</tr>
<tr>
<td>Brusna</td>
<td>24</td>
<td>9.339</td>
</tr>
<tr>
<td>Easkey</td>
<td>1</td>
<td>0.389</td>
</tr>
</tbody>
</table>

7.2.2 Determination of the Atlantic salmon Stock for the River Moy using Genetic Stock Identification and the River Deel DIDSON Count

The River Deel DIDSON population estimates were determined as described in Tables 7.5 to 7.7 (Chapter 4: Table 4.8 to 4.12). The population origin data provided by the genetic mixed stock analysis (Table 7.8) was combined with the census data derived from the DIDSON counter in two different scenarios, on the basis of data on run time, species discrimination method (i.e. there were three different models tested as previously described), and the period in which the mixed sample was collected. The two run time Scenarios, A and B are presented below.
### Table 7.5: River Deel Population Estimates from the Deel DIDSON, using Three Models for Species Discrimination and Sea-age, 2008 Cohort Estimated as 18th March to 31st December (Assumes no 2008 Cohort fish migrate in January & February 2008).

<table>
<thead>
<tr>
<th>Model</th>
<th>18th Mar to Dec 2008</th>
<th>18th Mar to 1st May 2008</th>
<th>1st May to Dec 2008</th>
<th>18th Mar to 1st June 2008</th>
<th>1st June to Dec 2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥ 40 cm</td>
<td>3,341</td>
<td>-10</td>
<td>3,351</td>
<td>-2</td>
<td>3,343</td>
</tr>
<tr>
<td>≥ 45 cm</td>
<td>2,867</td>
<td>5</td>
<td>2,862</td>
<td>12</td>
<td>2,855</td>
</tr>
<tr>
<td>Bimodal Model</td>
<td>2,309</td>
<td>24</td>
<td>2,285</td>
<td>19</td>
<td>2,290</td>
</tr>
</tbody>
</table>

### Table 7.6: River Deel Population Estimates from the Deel DIDSON, using Three Models for Species Discrimination and Sea-age, 2008 Cohort Estimated (Assumes fish migrate in January & February 2008 are equivalent to late migrations in 2009).

<table>
<thead>
<tr>
<th>Model</th>
<th>Jan to Dec 2008</th>
<th>Jan to 1st May 2008</th>
<th>1st May to Dec 2008</th>
<th>Jan to 1st June 2008</th>
<th>1st June to Dec 2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥ 40 cm</td>
<td>3,814</td>
<td>477</td>
<td>3,820</td>
<td>463</td>
<td>3,812</td>
</tr>
<tr>
<td>≥ 45 cm</td>
<td>3,304</td>
<td>440</td>
<td>3,298</td>
<td>447</td>
<td>3,291</td>
</tr>
<tr>
<td>Bimodal Model</td>
<td>2,633</td>
<td>348</td>
<td>2,609</td>
<td>343</td>
<td>2,614</td>
</tr>
</tbody>
</table>

### Table 7.7: River Deel Population Estimates from the Deel DIDSON, using Three Models for Species Discrimination and Sea-age, 2008 Cohort Estimated (Assumes an estimate for late migrating fish in January & February 2009 using relative proportion with respect to Dec 07/Dec08).

<table>
<thead>
<tr>
<th>Model</th>
<th>Relative Proportion Adjustment: Jan to Dec 2008</th>
<th>Relative Proportion Adjustment: Jan to 1st May 2008</th>
<th>1st May to Dec 2008</th>
<th>Relative Proportion Adjustment: Jan to 1st June 2008</th>
<th>1st June to Dec 2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥ 40 cm</td>
<td>4,191</td>
<td>840</td>
<td>4,201</td>
<td>848</td>
<td>4,193</td>
</tr>
<tr>
<td>≥ 45 cm</td>
<td>3,717</td>
<td>855</td>
<td>3,712</td>
<td>862</td>
<td>3,705</td>
</tr>
<tr>
<td>Bimodal Model</td>
<td>3,159</td>
<td>874</td>
<td>3,135</td>
<td>869</td>
<td>3,140</td>
</tr>
</tbody>
</table>
Table 7.8: Mixed Stock Assessment Total and Monthly Proportions, Moy Fishery, River Moy, 2008.

<table>
<thead>
<tr>
<th>Rivers</th>
<th>Total Estimated Proportion</th>
<th>May Estimate n=36</th>
<th>5% &amp; 95% CL</th>
<th>June Estimate n=99</th>
<th>5% &amp; 95% CL</th>
<th>July Estimate n=79</th>
<th>5% &amp; 95% CL</th>
<th>August Estimate n=43</th>
<th>5% &amp; 95% CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Owenmore/ Others</td>
<td>0.0448</td>
<td>0.021</td>
<td>0.015, 0.090</td>
<td>0.046</td>
<td>0.000, 0.139</td>
<td>0.038</td>
<td>0.000, 0.089</td>
<td>0.065</td>
<td>0.000, 0.175</td>
</tr>
<tr>
<td>Deel</td>
<td>0.071</td>
<td>0.058</td>
<td>0.040, 0.132</td>
<td>0.059</td>
<td>0.020, 0.150</td>
<td>0.08</td>
<td>0.023, 0.191</td>
<td>0.044</td>
<td>0.000, 0.125</td>
</tr>
<tr>
<td>Clydagh</td>
<td>0.0556</td>
<td>0</td>
<td>0.017, 0.078</td>
<td>0.08</td>
<td>0.014, 0.128</td>
<td>0.083</td>
<td>0.021, 0.131</td>
<td>0.001</td>
<td>0.000, 0.075</td>
</tr>
<tr>
<td>Manulla</td>
<td>0.0111</td>
<td>0.077</td>
<td>0.000, 0.035</td>
<td>0.001</td>
<td>0.000, 0.027</td>
<td>0</td>
<td>0.000, 0.028</td>
<td>0</td>
<td>0.000, 0.048</td>
</tr>
<tr>
<td>East</td>
<td>0.8183</td>
<td>0.844</td>
<td>0.699, 0.859</td>
<td>0.816</td>
<td>0.684, 0.890</td>
<td>0.79</td>
<td>0.684, 0.900</td>
<td>0.891</td>
<td>0.720, 0.994</td>
</tr>
</tbody>
</table>
Run Time Scenario Estimates

Run Time Scenario A: In this scenario the sample collected between May and September 2008 at the Ridge Pool fishery represents the entire cohort of fish entering the River Moy. Here the objective of the assessment is to count grilse and summer salmon only. The Ridge pool sample in this case is assumed to represent the population of fish counted in the River Deel (1st May – 31st December 2008, assuming all River Deel fish have migrated past the Ridge Pool, River Moy prior to August and represent this time period), a proposition, that provides for a conservative grilse estimate. It is assumed based on the observations of Fishery personnel (IFI), that very few fish enter the river after the end September 2008. It is also assumed here that fish hold up in Lough Conn in spring and wait until the summer without making at least an initial attempt to migrate to enter the River Deel and thus recorded by the DIDSON. However, it is not possible to quantify the extent of this behaviour. Although it does appear from the DIDSON data and observations made during data processing that many fresh fish enter the river briefly on arrival in spring, only to retreat to the lake until their spawning migration later in the year. In this analysis, fish counted by the DIDSON in the River Deel prior to 1st May are excluded in the stock size assessment. On this basis a stock proportion estimate of 7.1% for the River Deel based on the sample collected as the fish enter the river from the sea is equivalent to 2,285 to 3,351 fish depending on Scenario A (1) and the model applied (see Table 7.9). Therefore 1% would be equal to between 324 and 475 fish and therefore based on the outputs of the three species discrimination models within Scenario A (1) to (3), suggest the number of fish (100%) entering the entire Moy river after May in 2008 was in the order of between 30,969 to 56,948 (Table 7.9). Table 7.9 also includes count data from the 1st June to December 2008, providing a more conservative estimate and in line with run timings identified on the River Deel (Chapter 4).

Table 7.9: Predicted Stock Abundances using River Deel DIDSON Count Models (Scenario A (1) to (3)), and Mixed Stock Assessment Proportions for the River Moy and its tributaries, 2008 (Scenarios A: River Entry Sample Represents Summer Atlantic salmon only: 1st May to Dec 2008 & 1st June to Dec 2008).
### Scenario A

<table>
<thead>
<tr>
<th>River</th>
<th>GSI Proportions 1%</th>
<th>5% &amp; 95% CI</th>
<th>Salmon ≥ 40cm</th>
<th>5% &amp; 95% CI</th>
<th>Salmon ≥ 45cm</th>
<th>5% &amp; 95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deel</td>
<td>0.071 (± 0.040, 0.132)</td>
<td>3351 (± 1889, 6230)</td>
<td>2638 (± 801, 3674)</td>
<td>532 (± 1693)</td>
<td>455 (± 1447)</td>
<td>363 (± 1155)</td>
</tr>
<tr>
<td>Clydagh</td>
<td>0.056 (± 0.017, 0.078)</td>
<td>2638 (± 801, 3674)</td>
<td>532 (± 1693)</td>
<td>455 (± 1447)</td>
<td>363 (± 1155)</td>
<td></td>
</tr>
<tr>
<td>Manulla</td>
<td>0.011 (± 0.0000, 0.035)</td>
<td>532 (± 1693)</td>
<td>455 (± 1447)</td>
<td>363 (± 1155)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>East Moy</td>
<td>0.818 (± 0.699, 0.859)</td>
<td>3351 (± 1889, 6230)</td>
<td>2638 (± 801, 3674)</td>
<td>532 (± 1693)</td>
<td>455 (± 1447)</td>
<td>363 (± 1155)</td>
</tr>
<tr>
<td>Other</td>
<td>0.045 (± 0.015, 0.090)</td>
<td>2638 (± 801, 3674)</td>
<td>532 (± 1693)</td>
<td>455 (± 1447)</td>
<td>363 (± 1155)</td>
<td></td>
</tr>
<tr>
<td>All Rivers</td>
<td>0.818 (± 0.699, 0.859)</td>
<td>3351 (± 1889, 6230)</td>
<td>2638 (± 801, 3674)</td>
<td>532 (± 1693)</td>
<td>455 (± 1447)</td>
<td>363 (± 1155)</td>
</tr>
<tr>
<td>Moy Only</td>
<td>0.818 (± 0.699, 0.859)</td>
<td>3351 (± 1889, 6230)</td>
<td>2638 (± 801, 3674)</td>
<td>532 (± 1693)</td>
<td>455 (± 1447)</td>
<td>363 (± 1155)</td>
</tr>
</tbody>
</table>

### Scenario A

<table>
<thead>
<tr>
<th>River</th>
<th>GSI Proportions 1%</th>
<th>5% &amp; 95% CI</th>
<th>Salmon ≥ 40cm</th>
<th>5% &amp; 95% CI</th>
<th>Salmon ≥ 45cm</th>
<th>5% &amp; 95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deel</td>
<td>0.071 (± 0.040, 0.132)</td>
<td>3351 (± 1889, 6230)</td>
<td>2638 (± 801, 3674)</td>
<td>532 (± 1693)</td>
<td>455 (± 1447)</td>
<td>363 (± 1155)</td>
</tr>
<tr>
<td>Clydagh</td>
<td>0.056 (± 0.017, 0.078)</td>
<td>2638 (± 801, 3674)</td>
<td>532 (± 1693)</td>
<td>455 (± 1447)</td>
<td>363 (± 1155)</td>
<td></td>
</tr>
<tr>
<td>Manulla</td>
<td>0.011 (± 0.0000, 0.035)</td>
<td>532 (± 1693)</td>
<td>455 (± 1447)</td>
<td>363 (± 1155)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>East Moy</td>
<td>0.818 (± 0.699, 0.859)</td>
<td>3351 (± 1889, 6230)</td>
<td>2638 (± 801, 3674)</td>
<td>532 (± 1693)</td>
<td>455 (± 1447)</td>
<td>363 (± 1155)</td>
</tr>
<tr>
<td>Other</td>
<td>0.045 (± 0.015, 0.090)</td>
<td>2638 (± 801, 3674)</td>
<td>532 (± 1693)</td>
<td>455 (± 1447)</td>
<td>363 (± 1155)</td>
<td></td>
</tr>
<tr>
<td>All Rivers</td>
<td>0.818 (± 0.699, 0.859)</td>
<td>3351 (± 1889, 6230)</td>
<td>2638 (± 801, 3674)</td>
<td>532 (± 1693)</td>
<td>455 (± 1447)</td>
<td>363 (± 1155)</td>
</tr>
<tr>
<td>Moy Only</td>
<td>0.818 (± 0.699, 0.859)</td>
<td>3351 (± 1889, 6230)</td>
<td>2638 (± 801, 3674)</td>
<td>532 (± 1693)</td>
<td>455 (± 1447)</td>
<td>363 (± 1155)</td>
</tr>
</tbody>
</table>

### Scenario A

<table>
<thead>
<tr>
<th>River</th>
<th>GSI Proportions 1%</th>
<th>5% &amp; 95% CI</th>
<th>Salmon ≥ 40cm</th>
<th>5% &amp; 95% CI</th>
<th>Salmon ≥ 45cm</th>
<th>5% &amp; 95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deel</td>
<td>0.071 (± 0.040, 0.132)</td>
<td>3351 (± 1889, 6230)</td>
<td>2638 (± 801, 3674)</td>
<td>532 (± 1693)</td>
<td>455 (± 1447)</td>
<td>363 (± 1155)</td>
</tr>
<tr>
<td>Clydagh</td>
<td>0.056 (± 0.017, 0.078)</td>
<td>2638 (± 801, 3674)</td>
<td>532 (± 1693)</td>
<td>455 (± 1447)</td>
<td>363 (± 1155)</td>
<td></td>
</tr>
<tr>
<td>Manulla</td>
<td>0.011 (± 0.0000, 0.035)</td>
<td>532 (± 1693)</td>
<td>455 (± 1447)</td>
<td>363 (± 1155)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>East Moy</td>
<td>0.818 (± 0.699, 0.859)</td>
<td>3351 (± 1889, 6230)</td>
<td>2638 (± 801, 3674)</td>
<td>532 (± 1693)</td>
<td>455 (± 1447)</td>
<td>363 (± 1155)</td>
</tr>
<tr>
<td>Other</td>
<td>0.045 (± 0.015, 0.090)</td>
<td>2638 (± 801, 3674)</td>
<td>532 (± 1693)</td>
<td>455 (± 1447)</td>
<td>363 (± 1155)</td>
<td></td>
</tr>
<tr>
<td>All Rivers</td>
<td>0.818 (± 0.699, 0.859)</td>
<td>3351 (± 1889, 6230)</td>
<td>2638 (± 801, 3674)</td>
<td>532 (± 1693)</td>
<td>455 (± 1447)</td>
<td>363 (± 1155)</td>
</tr>
<tr>
<td>Moy Only</td>
<td>0.818 (± 0.699, 0.859)</td>
<td>3351 (± 1889, 6230)</td>
<td>2638 (± 801, 3674)</td>
<td>532 (± 1693)</td>
<td>455 (± 1447)</td>
<td>363 (± 1155)</td>
</tr>
</tbody>
</table>
Table 7.9 Contd.

<table>
<thead>
<tr>
<th>Scenario A</th>
<th>Rivers</th>
<th>GSI Proportions 1%</th>
<th>5% &amp; 95% CI</th>
<th>Salmon ≥ 40cm 5% &amp; 95% CI</th>
<th>Salmon ≥ 45cm 5% &amp; 95% CI</th>
<th>Bimodal Model 5% &amp; 95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Count Estimates:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A (3) Deel</td>
<td></td>
<td>0.071</td>
<td>(± 0.040, 0.132)</td>
<td>4202 (± 2367, 7812)</td>
<td>3715 (± 2093, 6907)</td>
<td>3137 (± 1768, 5833)</td>
</tr>
<tr>
<td>1st May to Dec 2008 Clydagh</td>
<td></td>
<td>0.056</td>
<td>(± 0.017, 0.078)</td>
<td>3308 (± 1004, 4607)</td>
<td>2925 (± 888, 4074)</td>
<td>2470 (± 750, 3440)</td>
</tr>
<tr>
<td>Manulla</td>
<td></td>
<td>0.011</td>
<td>(± 0.0000, 0.035)</td>
<td>668 (± 0, 2124)</td>
<td>590 (± 0, 1878)</td>
<td>498 (± 1586, 1586)</td>
</tr>
<tr>
<td>East Moy</td>
<td></td>
<td>0.818</td>
<td>(± 0.699, 0.859)</td>
<td>48771 (± 41676, 51215)</td>
<td>43124 (± 36851, 45286)</td>
<td>36414 (± 31117, 38240)</td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td>0.045</td>
<td>(± 0.015, 0.090)</td>
<td>2658 (± 886, 5316)</td>
<td>2350 (± 783, 4701)</td>
<td>1985 (± 662, 3969)</td>
</tr>
<tr>
<td>All Rivers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manulla</td>
<td></td>
<td>0.011</td>
<td>(± 0.0000, 0.035)</td>
<td>668 (± 0, 2120)</td>
<td>590 (± 0, 1878)</td>
<td>498 (± 1586, 1586)</td>
</tr>
<tr>
<td>East Moy</td>
<td></td>
<td>0.818</td>
<td>(± 0.699, 0.859)</td>
<td>48771 (± 41676, 51215)</td>
<td>43124 (± 36851, 45286)</td>
<td>36414 (± 31117, 38240)</td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td>0.045</td>
<td>(± 0.015, 0.090)</td>
<td>2658 (± 886, 5316)</td>
<td>2350 (± 783, 4701)</td>
<td>1985 (± 662, 3969)</td>
</tr>
<tr>
<td>All Rivers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manulla</td>
<td></td>
<td>0.011</td>
<td>(± 0.0000, 0.035)</td>
<td>668 (± 0, 2120)</td>
<td>590 (± 0, 1878)</td>
<td>498 (± 1586, 1586)</td>
</tr>
<tr>
<td>East Moy</td>
<td></td>
<td>0.818</td>
<td>(± 0.699, 0.859)</td>
<td>48771 (± 41676, 51215)</td>
<td>43124 (± 36851, 45286)</td>
<td>36414 (± 31117, 38240)</td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td>0.045</td>
<td>(± 0.015, 0.090)</td>
<td>2658 (± 886, 5316)</td>
<td>2350 (± 783, 4701)</td>
<td>1985 (± 662, 3969)</td>
</tr>
<tr>
<td>All Rivers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Run Time Scenario B:** assumes that the proportions of the different populations observed in the mixed stock sample are representative of the entire 2008 salmon cohort entering the River Moy and are destined to spawn in the winter of 2008/2009 and would include the broad spectrum of run time and sea age phenotypes: early running spring fish; grilse; summer salmon; and autumn salmon. In this scenario, the total River Deel salmon count from the 18th March, the date on which there is a clearly observable division between the 2007 and 2008 cohorts and the commencement of the spring run (see Chapter 4: Section 4.2.2) to 31st December, the date on which the DIDSON counter ceased operation in 2008, was used. In this second assessment, it is assumed that fish from this cohort do not spawn in January and February 2009. On this basis, the stock proportion of 7.1 % for the River Deel derived from the mixed sample is equivalent to 2,309 to 3,341 fish depending on Scenario B (1) and the model applied (Table 7.10 below). Therefore 1 % is equal to between 328 and 474 fish and thus an estimate for the entire River Moy of 100 % is estimated to be between 31,340 and 45,291 salmon.

However, it is necessary to adjust this estimate to achieve a more precise quantification of the magnitude of the cohort, as it is known from the operation of the DIDSON in the winter of 2007/2008 and from spawning surveys carried out by Fisheries protection personnel (IFI) that substantial numbers of fish spawn in the river in January and February. In order to adjust the estimate to allow for the inclusion of late spawning fish not counted in 2009, it might be reasonable to assume that the numbers of late spawning fish in 2007/08 represent a reasonable estimate of late spawning fish in 2009. Thus to enable this assessment the same number of late fish observed in January and February 2008 were added to the 2008/2009 spawning cohort. When this adjustment is applied to Scenario B (2), the 7.1 % is now equivalent to 2,633 to 3,814 fish and consequently the estimate for the River Moy is increased to between 35,686 and 51,693. Alternately, and possibly a more valid adjustment is for the unaccounted late spawning fish in the 2009 spawning population to be raised based on the relative proportions of December counted fish in 2007 to January and February counted fish in 2008, Scenario B (3). Using this correction factor (0.5499) an estimate for the total population in the River Moy is of the order of between 42,806 and 56,757 fish is obtained, again depending on the species identification method, (Table 7.10).
In scenario A, an estimate of the magnitude of the entire run including spring and summer components is achieved by assuming that the sample collected at the Ridge Pool between May and September is representative of the fish entering the river before sampling commenced and after it ceased. Another way of considering the data is not to assume that the sample collected at the Ridge Pool is representative of the entire run as is presented in Scenario B, but instead assume that the ratio of early spring to summer run salmon observed in the River Deel is a general phenomenon throughout the River Moy and to raise the estimated number of summer grilse and salmon accordingly to provide an estimate of the total run for the River Moy. The number of fish counted by the DIDSON in spring 2008 was 512 fish. Thus if the number of grilse and summer salmon is between 2,285 and 3,351 (Scenario B (1)), and the ratio of spring run fish to summer fish is 82:18 and 86:13, then a new estimate for the total River Moy population in 2008, spawning 2008/2009 is between 31,340 and 45,291, made up of between 5,641 and 5,888 spring fish and 25,699 and 39,403 summer run fish. This provided the most conservative estimate for Scenario B. In Scenario B (2) the ratio of spring run fish to summer fish is 84:16 and 88:12, and in Scenario B (3) the ratio of spring run fish to summer fish is 86:14 and 89:11. Table 7.11 provides the new estimates for the spring and summer salmon on the River Moy based on these assumptions.

Therefore, one method estimates the total number of fish in the River Moy assuming the sample collected during the summer at the head of the tide is representative. The second method assumes that the ratio of early run fish and summer fish observed on the River Deel is representative of the entire population of salmon entering the Moy.
Table 7.10: Predicted Stock Abundances using River Deel DIDSON Count Models (Scenario B (1) to (3)), and Mixed Stock Assessment Proportions for the River Moy and its tributaries, 2008 (River Deel GSI Proportions at 1 %) (Scenarios B: River Entry Sample Represents 2008 Cohort).

<table>
<thead>
<tr>
<th>Scenario B</th>
<th>Rivers</th>
<th>GSI Proportions 1%</th>
<th>5% &amp; 95% CI</th>
<th>Salmon ≥ 40cm 5% &amp; 95% CI</th>
<th>Salmon ≥ 45cm 5% &amp; 95% CI</th>
<th>Bimodal Model 5% &amp; 95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>B (1): 18th Mar-Dec 2008</strong></td>
<td>Deel</td>
<td>0.071</td>
<td>(±0.040, 0.132)</td>
<td>3342 (± 1883, 6213)</td>
<td>2869 (± 1616, 5334)</td>
<td>2312 (± 1303, 4298)</td>
</tr>
<tr>
<td></td>
<td>Clydagh</td>
<td>0.056</td>
<td>(±0.017, 0.078)</td>
<td>2635 (± 800, 3670)</td>
<td>2263 (± 687, 3152)</td>
<td>1824 (± 553, 2541)</td>
</tr>
<tr>
<td></td>
<td>Manulla</td>
<td>0.011</td>
<td>(±0.0000, 0.035)</td>
<td>526 (± 0, 1674)</td>
<td>452 (± 0, 1438)</td>
<td>364 (± 0, 1158)</td>
</tr>
<tr>
<td></td>
<td>East Moy</td>
<td>0.818</td>
<td>(± 0.699, 0.859)</td>
<td>38787 (± 33144,40731)</td>
<td>33305 (±28460, 34974)</td>
<td>26840 (±22935, 28185)</td>
</tr>
<tr>
<td></td>
<td>Owenmore/Other</td>
<td>0.045</td>
<td>(± 0.015, 0.090)</td>
<td>2114 (± 705, 4228)</td>
<td>1815 (± 605, 3630)</td>
<td>1463 (± 488, 2926)</td>
</tr>
<tr>
<td></td>
<td>All Rivers</td>
<td></td>
<td></td>
<td>45291 (± 2148, 7786)</td>
<td>3715 (± 2148, 7786)</td>
<td>31340 (± 2148, 7786)</td>
</tr>
<tr>
<td><strong>B (2): 2008 Cohort with Inclusion of Jan-Feb 08 u/s fish</strong></td>
<td>Deel</td>
<td>0.071</td>
<td>(± 0.040, 0.132)</td>
<td>3814 (± 2148, 7786)</td>
<td>3306 (± 2148, 7786)</td>
<td>2633 (± 1483, 4895)</td>
</tr>
<tr>
<td></td>
<td>Clydagh</td>
<td>0.056</td>
<td>(± 0.017, 0.078)</td>
<td>3008 (± 913, 4190)</td>
<td>2608 (± 791, 3633)</td>
<td>2077 (± 631, 2893)</td>
</tr>
<tr>
<td></td>
<td>Manulla</td>
<td>0.011</td>
<td>(± 0.0000, 0.035)</td>
<td>601 (± 0, 1912)</td>
<td>521 (± 0, 1658)</td>
<td>415 (± 0, 1321)</td>
</tr>
<tr>
<td></td>
<td>East Moy</td>
<td>0.818</td>
<td>(± 0.699, 0.859)</td>
<td>44270 (± 37893,46489)</td>
<td>38378 (± 32795, 40302)</td>
<td>30561 (± 26115, 32093)</td>
</tr>
<tr>
<td></td>
<td>Owenmore/Other</td>
<td>0.045</td>
<td>(± 0.015, 0.090)</td>
<td>2413 (± 804, 4826)</td>
<td>2092 (± 697, 4707)</td>
<td>1666 (± 555, 3332)</td>
</tr>
<tr>
<td></td>
<td>All Rivers</td>
<td></td>
<td></td>
<td>54105 (± 2148, 7786)</td>
<td>53735 (± 2148, 7786)</td>
<td>45864 (± 2148, 7786)</td>
</tr>
<tr>
<td><strong>B (3): 2008 Cohort for Late Spawners using Relative Proportions</strong></td>
<td>Deel</td>
<td>0.071</td>
<td>(± 0.040, 0.132)</td>
<td>4188 (± 2148, 7786)</td>
<td>3715 (± 2148, 7786)</td>
<td>3158 (± 1779, 5871)</td>
</tr>
<tr>
<td></td>
<td>Clydagh</td>
<td>0.056</td>
<td>(± 0.017, 0.078)</td>
<td>3303 (± 1002, 4600)</td>
<td>2930 (± 890, 4081)</td>
<td>2491 (± 756, 3470)</td>
</tr>
<tr>
<td></td>
<td>Manulla</td>
<td>0.011</td>
<td>(± 0.0000, 0.035)</td>
<td>659 (± 0, 2098)</td>
<td>585 (± 0, 1861)</td>
<td>497 (± 0, 1581)</td>
</tr>
<tr>
<td></td>
<td>East Moy</td>
<td>0.818</td>
<td>(± 0.699, 0.859)</td>
<td>48607 (± 41535,51043)</td>
<td>43124 (± 36851,45286)</td>
<td>36660 (± 31327, 38498)</td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>0.045</td>
<td>(± 0.015, 0.090)</td>
<td>2649 (± 883, 5299)</td>
<td>2350 (± 783, 4700)</td>
<td>1998 (± 666, 3996)</td>
</tr>
<tr>
<td></td>
<td>All Rivers</td>
<td></td>
<td></td>
<td>59406 (± 2148, 7786)</td>
<td>52705 (± 2148, 7786)</td>
<td>44804 (± 2148, 7786)</td>
</tr>
<tr>
<td></td>
<td>Moy Only</td>
<td></td>
<td></td>
<td>56757 (± 2148, 7786)</td>
<td>50355 (± 2148, 7786)</td>
<td>42806 (± 2148, 7786)</td>
</tr>
</tbody>
</table>
Table 7.11: Estimated Grilse and MSW Atlantic salmon on the River Moy, using Scenario B (1) – (3), Combined DIDSON-GSI Technique.

<table>
<thead>
<tr>
<th>Scenario B</th>
<th>River Moy (Grilse &amp; MSW)</th>
<th>River Moy (Grilse)</th>
<th>River Moy (MSW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Count Estimates:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Count Estimates:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B (2): 2008 Cohort with Inclusion of Jan-Feb</td>
<td>35,686 - 51,693</td>
<td>29,976 - 45,490</td>
<td>5,710 - 6,203</td>
</tr>
<tr>
<td>2008 upstream fish</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Count Estimates:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B (3): 2008 Cohort including late spawner</td>
<td>42,806 - 56,757</td>
<td>36,813 - 50,514</td>
<td>5,993 - 6,243</td>
</tr>
<tr>
<td>estimated using Relative Proportions</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
7.2.3 Existing River Moy Stock Estimates and Comparison with New Combined DIDSON-GSI Stock Estimate

The last four years estimates by the SSC of the total returning spawners to the River Moy have increased annually since 2007. The mean return for this period of both grilse and MSW fish was 43,216 (SD = 2,241, SE = 1,121) (Table 7.12).

Table 7.12: Yearly Estimated Grilse and MSW Returning Spawners to the River Moy (Anon., 2007; Anon., 2008b; Anon., 2009; Anon., 2010).

<table>
<thead>
<tr>
<th>Year</th>
<th>Estimated Grilse &amp; MSW Returning Spawners River Moy</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>40,538</td>
</tr>
<tr>
<td>2008</td>
<td>42,320</td>
</tr>
<tr>
<td>2009</td>
<td>44,409</td>
</tr>
<tr>
<td>2010</td>
<td>45,597</td>
</tr>
</tbody>
</table>

The Standing Scientific Committee status of Irish Salmon Stocks in 2008 predicted that the status of Total River Moy Atlantic salmon stock precautionary catch advice for the 2009 CLs were grilse (adults) at 15,786 and MSW (adults) at 1,188. This provided for a total (adults) of 16,974 CL with an estimated surplus of 23,268 ISW and 2,078 MSW (25,346 total surplus) (Anon., 2008b). Similar results were obtained when the count estimate provided for the River Moy using DIDSON-GSI technique were compared with that of the estimated salmon stock for the River Moy using rod catch estimate of 42,320 (Table 7.11) provided by the SSC (Anon., 2008b). The model in Scenario A that provided the closest estimate to that of the existing estimate (42,320 (Table 7.12) ) were the length cut-off estimates using ≥ 40 cm for Scenario A (1) of 45,417 salmon and Scenario A (2) the length cut-off estimates using ≥ 45 cm, 44,717 salmon. In Scenario A (3), the Bimodal model produced the closest estimate of 42,520 salmon. It was thought that the Bimodal model overestimated the number of trout that it allocated as being trout, particularly in the 40 to 50 cm length range (Chapter 4). However the range of estimates provided using the three models within Scenarios A (1) – (3) provided upper and lower range estimates for the River Moy. Using the length cut-off models in Scenario A still provided good estimates of the River Moy run without using further modelling of the data.
The smolt estimate of 654,000 smolts for the River Moy by McGinnity et al. (1999) and assumed sea survival rates already applied in Chapter 5, were used to make comparisons with the River Moy count obtained using the DIDSON and GSI combined method. These data show that all model estimates fall close to or within the range provided using the upper and lower sea survival rates of 5% & 10% from previously reported sea survival rates for Irish rivers (ICES, 2010). The number of returning adults (grilse & MSW) to the River Moy as determined from the ball park GIS smolt production of approximately 654,000 smolts (McGinnity et al., 1999) provided for an estimate of the River Moy adult count of approximately 33,000 (5% sea survival) and 62,000 (10% sea survival).

Looking at the Standing Scientific Committee status of Irish Salmon Stocks in 2009 predicted that the status of River Moy Atlantic salmon stock at 44,409 fish and precautionary catch advice for the 2009 CLs were 1SW (adults) at 15,786 and 2SW (adults) at 1,188. This provided for a total (adults) of 16,974 CL which was the same as set for 2008, with an estimated surplus of 21,675 1SW and 5,760 MSW (27,435 total surplus) (Anon., 2009). These data show that there was little change in the salmon stock estimates for 2008 and 2009 with only 1,489 salmon in the difference. However, more than twice the number of MSW fish was estimated as part of the surplus in 2009 than in 2008. The SSC 2009 count estimate for the River Moy when compared with that of 2008 emphasizes the need for a counting technique that can estimate both run components and the requirement for the protection of the MSW fish component.

Where the DIDSON-GSI technique improved on both the SSC (2008) and McGinnity et al. (1999) is that a direct sample of the River Deel adult count was obtained for a full year providing details of the 2008 cohort without interfering with fish migration (DIDSON causes no obstruction to migration) or the handling of large numbers of fish (using some fish traps or during electrofishing). These data were significant in that they were not dependant on extrapolated data from rod catch data or predicted based on smolt productivities using carrying capacities of the system and GIS. Genetically sampled adult salmon from the River Moy were used to estimate the percentage proportions of River Deel fish migrating upstream on the River Moy. This allowed for not only an estimate of the River Moy but also the other
discrete populations within the system, namely, River Clydagh, Manulla and East Moy, all from one single count of a discrete population from the River Deel. The technique offers a new solution to counting on large rivers and exceeded the goal of this study providing an estimated adult count (grilse & MSW) for the River Moy and each of its discrete populations. This method solved the problems previously encountered with operating counters on large rivers which in the past proved intractible, allowing the count of a smaller tributary (less fish to count and easier to operate equipment on) with a discrete population to obtain a count for a large river system.

These data show that both the length cut offs and Bimodal model developed performed well within the Scenarios tested, to provide an estimate for the River Moy through the DIDSON-GSI estimate and further validates the new DIDSON counting technique when the DIDSON-GSI estimate for the River Moy was compared to that of the SSC (2008b) estimate. This indirectly validates the method developed, both operational and data processing, using DIDSON for the River Deel estimate and confirms the quality of data obtained using DIDSON on the River Deel
CHAPTER 8

8.0 General Discussion

Atlantic salmon have been shown to be difficult to count on large river systems due logistic problems related to their size, the expense of installation of weirs or traps, the technical difficulty of the operation of some types of counters and personnel demands for their operation. The methodology developed in this study tested of the most up to date hydroacoustic technology DIDSON for adult stock assessment and an alternative methodology for juvenile stock assessments. The combined use of DIDSON and Genetic Stock Identification also allowed for the development of a novel method for obtaining count data for a large river catchment using a count from one tributary’s discrete population using DIDSON.

In this study, DIDSON was operated on an Irish river system 24/7 in all weather conditions. Quality length and count data provided for both species apportionment and the determination of specific run cohorts and run components, using DIDSON length data and date of detection. DIDSONs near-video quality imagery allowed fish migration to be observed and fish behaviour studied, i.e. actively migrating, milling, backsliding and holding in front of the beam. These data allowed inferences to be made about the type of migration and run component depending on the time of year and fish size. Existing counters operated on large rivers to date have proved costly (IFI) and ineffective, particularly in flood conditions and established the need for a counter that can operate in all weather and river conditions. DIDSON was non-invasive to fish migrations unlike some weir mounted counters. DIDSON was shown in this study to be the counter of choice for salmon stock assessments.

The need for alternative methods was highlighted and as an alternative method to an adult count for the River Deel, a smolt stock assessment was undertaken using a screw trap and mark-recapture study. This allowed for baseline estimates of smolt migrations for 2007 and 2008 and these data were used to provide estimated adult grilse returns for 2008 and 2009. Juvenile stock estimates of smolts where more applicable where counter installations would
not be permitted or in the absence of a suitable site location. This methodology proved less expensive and required less man hours for operation over the smolt run. Where discrete populations exist they require protection and the combined DIDSON-GSI method developed in this study allowed for the provision of count data for a large river, namely the River Moy, from a single tributary, River Deel. This novel method provide greater accuracy than operating counters on a large river and overcomes the problem of installation and operation of counters on large rivers, where stock estimates for all discrete populations within the River Moy were now possible from one tributary count. Both the DIDSON and smolt mark-recapture study provided more accurate range estimates for the River Deel adult run components and smolt migration estimates with confidence intervals than McGinnity et al. (1999) study. The combined DIDSON-GSI method developed in this study produced a range of estimates that were very close to the average River Moy stock estimate produced by the SSC over the last four years. However, this methodology allowed the direct sampling of the River Deel run and thus is thought to be a more accurate assessment of the River Moy population.

Environmental data collated during this study allowed for adult and smolt salmon migration data to be used to determine if correlations exited with rainfall, water level, water flow and air and water temperature. Correlations were found with adult migration and changing air and water temperature. No correlations were determined with smolt migration data. However, two yearly patterns of smolt migration were determined, with the start of peak smolt migration occurring within two days of both study years at similar water temperatures.

8.1 Stock Assessment Methods Applied, River Deel

8.1.1 Effectiveness of Alternative Acoustic Technology, DIDSON (Dual-frequency Identification Sonar)
The aim of using the DIDSON in Irish waters was to develop methodologies that are easy to operate, maintain, obtain count data and are non-intrusive to fish migrations. This was the first successful operation of DIDSON in Ireland and the first successful enumeration of Atlantic salmon using DIDSON. Unlike the use of split-beam hydroacoustics in fisheries stock assessments, the interpretation of DIDSON data required less technical training and user experience. Site selection and user experience are the two most important factors for
accurate processing of DIDSON data. The testing of the DIDSON SMC software using CSOT processing allowed for the development of a method suitable for DIDSON use in Irish waters that was easy to use for both field staff and scientists. From experience gained on the River Deel, some form of semi-automated or automated processing is required and analyst experience was vital to ensure fish detection and accurate determination of direction during processing (where real time count data are required).

**DIDSON Site Selection and Data Collection**

The use of DIDSON is limited at present by the maximum window length at High Frequency of 12 m, where accurate fish length measurements are required for species apportionment. This increased the amount of in-river works required to maintain the counting zone depending on the river site conditions, such as bed profile, flow and in-river debris. A protocol was established for the River Deel, where the detection of all fish passing through the beam was achieved, with consistent beam mapping and validation of the DIDSON. Migrating fish were easily differentiated from debris; however, in-river debris (particularly algae) and increased flow and turbidity can impair counting for part of the year increasing processing times. Site development was shown to play a major part in improving the quality of data and reducing milling and hanging behaviour of fish that interfere with the software’s ability to detect fish movement.

DIDSON users in Irish waters may have unrealistic time frames for data analysis without some semi-automated or automated software processing. Pacific salmon count data using DIDSON on the Kenai River in Alaska are multiplied up from 10 min counts at the top of each hour. The nature and quantity of the Pacific salmon run allows for this type of calculation. This was not possible when counting Atlantic salmon on the River Deel where fish migrate twelve months of the year in much lower numbers, with large time differences between fish movements and peak migration in Irish rivers. Species apportionment was a problem with DIDSON where there was an overlap in size of target species with non-target species (salmon and brown trout). Knowledge of the river and the use of length cut-offs and the modeling of DIDSON length data helped reduce this problem. The upstream and downstream movements of non-migratory residents were assumed to be neutral which may
be species dependent (Cronkite et al., 2006). Live sampling would provide essential information on the river biology and/or the tagging of fish where possible. This would also provide information on run components for grilse and MSW populations and improve count estimates from DIDSON.

The use of the silt box on the River Deel was the first long-term installation and this study showed that it was very successful. When it was deployed with the DIDSON, only minute quantities of silt entered the DIDSON unit after the silt box was installed. Prior to the silt box installation, more frequent cleaning was necessary, whereas with the use of the silt box only a monthly clean was necessary. However, approximately 0.5 m of beam distance was lost as a result of using the silt box and this was also dependant on the level of siltation in the river at any given time. Recently, Lilja et al. (2010) study encountered problems with pollen covering the DIDSON lens during their operation of DIDSON on the River Tornionjoki, Sweden. The successful use of the silt box in the River Deel suggests that if used by Lilja et al. (2010), the installation of a silt box could alleviate their problems with pollen.

**DIDSON Data Processing – Accuracy and Precision**

For DIDSON data processing, it is recommended that technical training be provided and that during analysis of the first three months of processing DIDSON data, regular verification should be carried out to ensure quality control of the data being processed. The percentage of files that will require verification will be site specific, as the bed profile and fish behaviour in the counting zone will determine the effectiveness of CSOT processing. Holmes et al. (2006) noted some variability in counts of migrating salmon among analysts and that the precision of counts produced from the DIDSON system increased as the number of fish counted increased. The assessment of River Deel DIDSON data by three different analysts showed that the quality of data processing was dependant on analyst experience (ICES, 2009). It is important to have speed with accuracy when processing to enable real time counting to be achieved. The reduction in time due to a reduction in the number of frames saved and thus a reduction in file size, after processing using CSOT, was a positive development. This allowed the user to save only the shorter CSOT files for back up where a percentage of continuous files have been stored for verification. However, this was only carried out where the percentage accuracy had been calculated for using CSOT during verification tests. During
the processing of the autumn/winter 2008 data the processing method was changed and Background Subtraction (BS) was used making it easier to identify and measure fish. The use of Background Subtraction is recommended during CSOT processing for DIDSON data processing.

Comparison of test files showed that files where fish were milling and backsliding downstream at various angles that CSOT processing cannot ‘see’ fish as the motion detection was not triggered. When it was triggered where fish were milling, often an insufficient number of frames were saved to determine direction due to the aspect angle of the swimming fish. This also resulted in the possibility of greater variation in the accuracy of counts depending on how much milling behaviour was observed. It was difficult in some instances to determine actively migrating fish from milling fish, as was noted by Cronkite et al. (2006). Some of the difference could be accounted for between Analyst 1 and Analyst 2 and 3 due to their inability to determine fish direction and thus logging a fish as an unknown movement. In these instances, Analyst 1 had determined direction of movement and/or had detected fish that Analyst 2 and 3 had missed. This emphasised the importance of processing experience and to ensure a uniform set of agreed protocols for a small group of conscientious analysts. The technique developed in this study is obviously transferable but it takes time to obtain user experience in processing these data to ensure the user detects all movement and is able to allocate the direction of that movement.

Holmes et al. (2006) also showed that DIDSON processing techniques are transferable; however, it takes time to train the user’s eye to ‘see’ all movement and to allocate the direction of that movement. The maximum counting speed of 20 frames/sec may have been too high a frame rate limit for inexperienced analysts. However, other studies have applied this method to ‘smooth out’ the image making fish easier to see (Galbreath & Barber, 2005; Hateley & Gregory, 2006). Time analysis showed the important need for some form of automation to the processing of these data for counting Atlantic salmon in Ireland. This emphasises the need for the semi-automated approach developed in this study. Hateley & Gregory (2006) tested motion detection methods in the SMC software to develop methods for data collection and processing but with mixed results. These methods are not
recommended for data collection until significant baseline data has been collected and the methods fully verified. Automated counting has not yet been shown as an accurate means of stock enumeration of Atlantic salmon using DIDSON SMC software and should be tested in an Irish context. Boswell et al. (2006) have also shown an effective method of semi-automatic counting procedure for DIDSON using Echoview software. However, this software requires greater training time and technical experience.

Further research is required to determine if there is a significant difference in downstream fish measurements using the DIDSON length compared to the true length. It was noted from verification tests that less fish were observed moving downstream when compared with the reference data. This was thought due to the position of fish in the beam migrating downstream and thus may also result in greater variation between DIDSON length and True Length.

**Validation Methodology**

The method developed on the River Deel to determine of the ability of DIDSON to detect fish in the counting zone and to test the accuracy of DIDSON length data for species discrimination was the best method that could be used under the weather and hydrological conditions encountered during operations. Similar to Holmes et al. (2006) the method used on the River Deel showed 100% concurrence of fish detection in the counting zone. It was assumed in this study, that once the target and tethered fish were seen in all areas of the counting zone, that the DIDSON data were not biased as a result of fish moving through the counting zone undetected. A limitation of Holmes et al. (2006) study was that they were unable to determine the beam coverage due to high water velocities. Maxwell and Smith (2007) emphasised the importance of knowing beam coverage when using DIDSON for enumeration. The validation experiment on the River Deel showed that the counting zone was free from blind zones near the water surface and river bed where fish could possibly move undetected. A process of consistent beam mapping ensured that blind zones were eliminated, ensuring quality of the count data.
Testing the accuracy and precision of DIDSON length data was essential, as the length frequency data from the DIDSON were used to differentiate between fish species of overlapping size ranges and to estimate run components. Validation of the River Deel DIDSON showed that DIDSON length data was highly correlated with the true length ($R^2 = 0.9232$). The ability to obtain fish length estimates using DIDSON removed the need for the handling of large numbers of fish as the technique was non-intrusive. Burwen et al. (2007 & 2010), found that length measurements for tethered fish were affected by distance from the transducer but in contrast, tests carried out on free swimming fish showed no affect of DL with distance from the transducer in their study. In terms of methodology, this study’s use of live tethered fish simulated free swimming fish with the benefits of obtaining multiple passes of fish through the DIDSON beam at various desired ranges from the transducer. Thus, the River Deel method validated DIDSON length data for the purpose of stock assessments using different length cut-off points and data modelling. For Irish rivers, further scientific assessment of DIDSON is required to operate DIDSON at greater ranges and to determine the effectiveness of taking length measurements at greater ranges using the standard DIDSON at low frequency. Where possible the use of the Long Range DIDSON should also be tested in Ireland however, length data may be more difficult to obtained as fish will appear smaller using this DIDSON as image resolution is reduced (Burwen et al., 2007; Burwen et al., 2010). The use of the High Resolution Lens (HRL) can improve the accuracy and precision of fish lengths obtained (Burwen et al., 2010). The operation of DIDSON at all future DIDSON count sites should be assessed to determine its ability to detect fish in the counting zone and to determine the accuracy of DIDSON length measurements for species apportionment.

**Quality of DIDSON Data for the Purpose of Stock Assessments**

DIDSON was shown in this study to produce high quality data for both species apportionment and the determination of run components as shown during verification and validation described above. Very little operational downtime occurred using DIDSON (three weeks in August 2008 of data loss was due to a system failure and this particular problem was never recorded using DIDSON prior to its operation on the River Deel). Observations made during processing allowed for inferences to be made with respect to run timings and
run components, which would not be possible using other counting technology. The quality of DIDSON length data as described above, provided for the successful use of length cut-offs for species apportionment and the determination of run components, and the development of a new Bimodal Model for the River Deel that allowed for species apportionment. Further development of the Bimodal model is required as it was thought that the model over estimated the number of trout in the length ranges of 45 – 55 cm fish. These data showed that DIDSON can be used in an Irish context to provide quality stock data for the purpose of determining run sizes, producing a range of estimates for the River Deel. However, during DIDSON operations, the atypical nature of the River Deel system with its lacustrine system, did make the determination of run component more difficult, particularly to estimate the MSW stock which can hold up in Lough Cullin and Lough Conn prior to their migration into the River Deel.

**Defining the 2008 Cohort using Deel DIDSON Data, River Deel**

Another advantage of using DIDSON was that it was possible to observe the continued active migration of upstream migrating salmon from the 2007 cohort into January and February 2008 and to define the downstream migration of salmon in January and February. These were assumed to be kelts from 2007 spawning due to their behavioural traits in migration as observed during analysis using DIDSON. These fish were not actively migrating past the DIDSON and were observed ‘flopping’ downstream. Redd counts carried out in January 2008 also confirmed these late migrations and spawning of the 2007 cohort, with two spawning pairs identified in the Upper River Deel spawning on the 29th January 2008. The River Deel DIDSON data also showed a distinct gap in the run between the end of February and the beginning of the next run of fish observed in March 2008 (approximately 2 - 3 weeks). This was assumed to correspond to the end of spawning for 2007 in February 2008, and the beginning of the 2008 cohort spawning run in March 2008. The 2008 cohort spawning run from the 18th March to April 2008 were clearly actively migrating and there was an evident increase in the size of the fish migrating. These were assumed to be spring fish. The observation of this behavioural distinction and the quality of fish length data was only possible to obtain using DIDSON.
Further Modelling of DIDSON Data for Species Apportionment and Sea-Aging

Recent studies by Bacon et al. (2009) have shown that the average size of Atlantic salmon in Scotland vary seasonally within the year. Bacon et al. (2011) have shown that the combination of seasonal-date and body-length of fresh-run Atlantic salmon in Scotland gives a very reliable discrimination (c. 95%) between grilse and MSW salmon (see also http://www.mathstat.strath.ac.uk/outreach/salwrd for extended details). However, although this approach may be possible for application on the River Deel, the SALWRD method has not yet been calibrated with data on Atlantic salmon from Ireland and its approach relies on knowing the fish are Atlantic salmon, which is not the case with the River Deel data. However, this methodology has now been applied to the River Deel DIDSON data to determine if this is a feasible method for application for an Irish river system (Gurney et al., Submitted). This would potentially improve methodology for the determination of sea-aging using DIDSON data. Gurney et al. (Submitted) confirmed that the distance of target fish from the DIDSON did not affect the accuracy of length measurements and provided a simple linear equation to correct DIDSON length data. The equation was used to correct the small positive bias in the DIDSON length measurements prior to analysis.

8.1.2 Use of a Screw Trap for Juvenile Stock Assessment – Smolt Mark-recapture, River Deel

Alternative methodology in the form of a juvenile stock assessment was undertaken on the River Deel for smolt stock assessment. This was the first successful operation of a screw trap in Ireland. A protocol was established for the operation of the screw trap mark-recapture technique and modelling techniques for the River Deel which could be implemented on future studies for similar sized rivers throughout Ireland.

Screw Trap Operation, Performance and Mark-recapture Experiment

The screw trap operation showed that the peak smolt migration timing fell within two days of both study years on the 19th April 2007 and the 21st April 2008, with an average temperature for the two years of 10.3 °C. Where peak smolt migration can be determined to occur within the same week then this information could be used to only carry out mark-recaptures on the main peak of the run to obtain estimates using classical and Bayesian modelling (where sample size can be small, Rivot and Prévost (2002) model). This would be very useful where
limited staff and resources existed for the operation of equipment, reducing the number of smolts being captured and marked, thus reducing the impact of the experiment on the smolt population. These monitoring efforts provided valuable information during the two years of sampling, not just for the estimation of the smolt run but also providing an insight into the diversity of this river system, in particular the size of resident brown trout populations.

The challenges of operating a screw trap can introduce bias particularly at extremes of high and low flows. Once the River Deel exceeded water levels of greater than 1 m at the site, the operation of the trap became unsafe and the quantity of debris loading prevented the drum from rotating. When the trap was not operational this lead to difficulties for estimating daily migration trends as no smolts were trapped in high flood conditions. Where smolt captures and recaptures are affected by flow, estimates are likely to be biased (Seiler et al., 2001; Griffith et al., 2005). The operation of a screw trap has however, been shown in this study as a suitable method for estimating smolt output in a river system where no existing trap is in operation. Screw traps are not a constant barrier to the upstream migration of adults and are only operated for the duration of the smolt run and are less expensive to purchase and operate. The operation of the screw trap was at a much lower cost than the installation of weirs for fish counters, some of which are permanent fixtures in rivers and require operation for longer periods, thus requiring greater man-power.

The operation of the screw trap was improved using in-river works via the installation of a stone weir and sand bags which increased flow through the screw trap thus improving trap efficiency particularly at low flows. This helped to improve the estimates by potentially increasing the number of marked smolts recaptured through consistent trap rotation. McLemore et al. (1989) described the screw trap as self-cleaning, operating effectively at several ranges of river flow and able to handle floating debris without loss of efficiency. On the River Deel however, particularly during extremes of high and low flows, the screw trap became blocked with twigs and even large branches of trees in high flow and thick algal growth in low flows. Unlike permanent trapping facilities, during periods of moderate flows the screw trap was shown to be self cleaning. Traditional permanent traps on large rivers also do not operate well under such conditions, as was experienced during the operation of the Ballina Traps, River Moy. Thus in an Irish context, as a result of these findings, screw trap
operations are only recommended on smaller tributaries of large rivers due to the volume of debris loading in flood conditions. Scace et al. (2007) and Rayton and Wagner (2006) have made alterations to the traditional design of the screw trap for their operation in rivers with heavy debris loadings in high flows and their new design requires less cleaning. The new designs have increased trap efficiency (Rayton & Wagner, 2006; Scace et al., 2007) and could be investigated further for future Irish studies.

Similar to the findings of Music et al. (2010), smolt mortality was only experienced during flooding and was due to physical injuries from debris loading in the trap. Several authors have had similar experiences regarding the effect of heavy debris loading and high flow on the operation of smolt traps (Rayton & Wagner, 2006; Chaput & Jones, 2004; Scace et al., 2007; Music et al., 2010). The low mortality of smolts that was experienced on the River Deel was associated with the flood event experienced on the 25\textsuperscript{th} April 2007. Safety concerns for the sampling of the screw trap were also an issue for its access in rising floods. One advantage of the River Deel screw trap operation was that with only one trap used for both capture and recapture, the same trap efficiency existed. Thus there was the same likelihood of trapping marked smolts and fish exposed to the trap for the first time. Several studies use separate traps for capture and recapture and this can affect trap efficiency with respect to river flow at each trap site (Thedinga et al., 2008). A greater distance is advised between the capture site and in this case the upstream release site to ensure optimum mixing of marked smolts with the general smolt population. River discharge is known to affect trap efficiency and it is a recommendation of this study that the velocity of water passing into the drum of the screw trap is measured to quantify its impact on drum rotation and thus trapping efficiency. Uncertainty about the efficiency of the trap is closely related to the migration behaviour of smolts (as smolts tend to move in shoals), environmental factors and thus can cause extra variation to mark-recapture data (Mäntyniemi & Romakkaniemi, 2002).

**Atlantic salmon Smolt Migration Stock Assessment, River Deel**

The data from the Bayesian Models tested were more informative when put into context with estimates of the smolt run from other classical mark-recapture models tested. In light of this a combined method of using both classical and Bayesian models, with confidence intervals
should be employed for mark-recapture studies of this kind. McGinnity et al. (1999) estimate of the potential smolt production for the River Deel was thought to be in the upper ranges when compared to the River Deel screw trap estimates; however, no confidence intervals were provided from that study. The River Deel screw trap estimates provided greater certainty than that of McGinnity et al. (1999).

Initial analysis carried out using the classical models with confidence intervals produced good baseline information for the overall population estimate of the smolt run. The importance of having confidence intervals around the estimates was highlighted in the range of estimates obtained but jointly these models provided inferences that can be made about the size of the smolt population. The models applied to the full time series of the mark-recapture data in 2008 produced the best estimates for the smolt run in 2008 for the non-Bayesian estimates. The Bayesian models applied to the 30 days of mark-recapture data allowed for direct probability statements to be made about the parameters and these models provided information on the trapping efficiency, the effects of smolt behaviour (shoaling) and the impact of environmental factors. Rivot and Prévost (2002) pooled data estimates of the population allowed for the catchability to be taken into account but did not allow for overdispersion or the effects of environmental factors on smolt migration and catchability. The daily estimates did not however, show the variability in estimations as expected and estimated in, e.g. Petersen Corrected (Chapman). Rivot and Prévost (2002) model was applied to yearly data and thus may not be as applicable to daily data analysis. However, the advantages of Mäntyniemi and Romakkaniemi (2002) models was that they allowed for inferences to be made across four models that looked at the binomial distributions in comparison to estimates where over dispersion was taken into account and environmental factors. Posterior inferences made for each model did however, show wide variation in confidence intervals for the smolt population estimates. For the purpose of smolt population estimates the combined use of the Petersen Modified (Chapman), the Schnabel Regression model and the Rivot and Prévost (2002) model were thought to provide the best estimates for smolt populations on river systems where limited data was available.
This technique shows that these methods can be successfully used to improve and/or as additional information to provide data for stock assessments of large riverine catchments. The results provided an initial assessment of the use of Bayesian modelling for the purpose of mark-recapture data using a screw trap for Irish rivers and support for future smolt stock assessments for Irish waters. The identification of the ‘best’ models for the River Deel data were specific to the River Deel but will be an aid to the operation of mark-recapture analysis of this kind and best describes the type of methodology and analysis required for Irish river catchments. The relative performance of a range of models should continue to be evaluated when these models are applied to different data sets (He & Bence, 2007). Bayesian modelling should be further tested on future smolt mark-recapture applications of this kind.

If a mark-recapture experiment was performed according to a constant design in successive years, it would be possible to obtain prior information about the relationship between environmental factors and model parameters (Mäntyniemi & Romakkaniemi, 2002). Further yearly estimates are required on the River Deel to improve the M₃ model (Mäntyniemi & Romakkaniemi, 2002) and make better posterior inference on the effects of temperature and water level on catchability/trap efficiency and smolt migration. The Rivot and Prévost (2002) HBM assumed a specific hierarchical structure on both the trapping efficiencies and the total population size, combining all years together through a methodology of estimation that explicitly accounts for the similarities in the mark-recapture experiment and for the dependence among the population sizes. HBM limits the problems that can occur from minor changes in the data (Choa, 1989) including possible errors made when collecting data that significantly improves the inferences (Rivot & Prévost, 2002). Using this model on daily data may not however, have included the variation between days to be observed. It would be useful to further develop this model to incorporate a degree of independence between sampling instances in the hierarchical structure to make it more applicable to daily data and the potentially large variability in daily runs as seen in the two years of trapping on the River Deel.

Smolt outward migration data provide essential information on stocks prior to their migration to sea and show the productivity of a river catchment. The experimental design can only be
improved with experience of operation and data analysis. Best estimates are an essential part of stock assessments as total counts are often very difficult to obtain, particularly in Irish river systems where environmental conditions play a major role in the effectiveness of equipment. These classical models provide good baseline estimates that were not complicated and unproblematic, and this was seen as beneficial for cross checking the estimates of population size. Bayesian models provided valuable inferences on catchability and trap efficiency. Rivot and Prévost (2002) recommended the use of hierarchical modelling in any ecological study where data are collected on several sampling units that share some common features.

The quality of the estimate from smolt mark-recapture studies such as this one will have significant implications for the predicted returns of adults where it is used as a management tool. The smolt stock assessments of 2007 and 2008 were further used in this study to estimate the adult grilse returns for 2008 and 2009. Using upper and lower limits for sea survival rates allowed for baseline data for the River Deel grilse returns to be established and compared to that of the DIDSON adult stock estimates. However, the quality of the 2007 smolt estimate was reduced due to trap efficiency during flooding and thus the reduction in recaptures of marked fish. The estimated adult grilse returns for 2009, using the 2008 smolt estimate was more successful due to more consistent trap efficiency. Assuming annual smolt populations do not vary greatly on the River Deel, then the stock estimates for 2009 using the 2008 smolt estimates were comparable with that of the River Deel DIDSON grilse estimate for 2008.

8.1.3 Estimating Atlantic salmon Runs Using a Novel Stock Assessment Methodology based on the Combined Use of DIDSON (Dual-frequency Identification Sonar) Hydroacoustic Technology and Genetic Stock Identification, River Deel

For genetically sub-structured species like salmonid fish, it is important to determine which populations or other units below the species level deserve special attention in management (Hindar et al., 2004). The use of DIDSON and Genetic Stock Identification enabled the enumeration of a large river through the collation of DIDSON count data for one tributary of that system, to obtain a count for the whole river and the majority of its tributaries. The method accurately assessed the proportion of River Deel fish occurring in the River Moy
fishery (as sampled in 2008) so that this proportion could be used along with real count data from the DIDSON to estimate the total number of salmon running into the River Moy. The technique produced a range of salmon stock estimates for the River Moy and its tributaries ranging from simplified data analysis to more sophisticated modelling techniques. The method was dependant on the river system having resolvable discrete populations, i.e. the River Moy and an accurate count of the Atlantic salmon stock for one tributary with a discrete genetic population to be counted, namely the River Deel. In terms of obtaining the proportions of assignments to rivers outside of the River Moy, these proportions were small and consequently were unlikely to affect the estimates of component stock assignment. The most important aspect of the method was to ensure that all fish were correctly assigned to the outside rivers and not to those within the River Moy. Thus, the contribution to rivers outside the River Moy was removed prior to allocating the remainder on a pro-rata basis.

The DIDSON allowed for the accurate counting of Atlantic salmon stocks for this system which operated in all weather conditions to provide 14 months of count data as described above (ICES,2009). These data allowed for a yearly cohort to be examined and sea-age to be determined for 2008. This methodology also provided further support for the significance of the results with respect to the accuracy of the River Deel estimate using a DIDSON when comparisons of the DIDSON-GSI stock estimates for the River Moy were made with that of the SSC rod catch data estimated and further validates the use of DIDSON for salmon stock assessments for Irish rivers.

The advantage of using GSI and the selection of a discrete population of one tributary for counting on a large river catchment in Ireland would provide an easier method for stock enumeration due to the problems experienced nationally for the operation of counters on large rivers. The operation of counters on large rivers is extremely difficult due to inconsistent flows, including increasing incidence of summer flood conditions, large quantities of debris, turbidity, non-target species and the milling behaviour of fish near the mouth of large rivers. This technique has the potential to save the IFI, in both the capital and operational costs of fish counters nationally. It has been shown that existing counter technology (infra-red and resistivity) and HTI split-beam do not operate well on large Irish
rivers. The installation of weirs on Irish river systems both large and small is costly and these are permanent structures. DIDSON has an initial high capital cost but does not require expensive weir installation and is portable to deploy in different river catchments. As described earlier, the ability to count on a smaller system with a discrete population was found easier for the operation of equipment, man-power and less fish to count than on the main river.

**Further Applications within Ireland**

However, this methodology is dependant on the catchment having identifiable discrete stocks and rivers from the Waterford and Lismore districts show a high degree of genetic similarity (Dillane et al., 2007). Dillane et al. (2007) reported problems with distinguishing genetic samples from the south eastern region. This was noted as a limitation of the combined DIDSON-GSI methods application on a national basis. Further investigation indicated that the incorrectly assigned and apportioned samples went to neighbouring catchments in the Waterford and Lismore districts (the Rivers Nore, Suir, Blackwater and Bride). These districts have had numerous river closures to angling (e.g. River Noir) and thus require methodology for their future assessment. This situation is very unusual in the context of Irish salmon populations. Various other assignment and Mixed Stock Assessment simulations revealed that salmon could be clearly designated to their river of origin, with the exception of fish from this area, which would assign to Waterford and Lismore, but not accurately to the specific river of origin. For this reason, the results of assignments and proportions were combined for these rivers, into a group called SEPC (South Eastern Population Complex) (Dillane et al., 2007). As part of the Beaufort project, samples from that area are being screened for an additional 12 microsatellite loci, several of which are embedded in functional genes, as part of an undergraduate research project as part of the National Salmon Genetic Stock Identification Project (2010). Thus, the method may be more applicable to a greater number of large Irish rivers in the future. However, rivers in this area may represent a meta-population or a complex of populations which could constitute a single Genetic Management Unit (GMU) (Dillane et al., 2007).
It is a recommendation of the National Salmon Genetic Stock Identification Project (2010), that the use of additional genetic markers including single nucleotide polymorphic loci (SNPs) are used in future studies, especially in cases of low discrimination. Mixed Stock Analysis (MSA) should be used as a management tool in Ireland with the inclusion of larger numbers of microsatellites or single nucleotide polymorphisms (SNPs) and more extensive coverage of salmon producing rivers (Dillane et al., 2007). Moving forward, SNPs are now being used and are easier to use across laboratories as a standard protocol and for higher throughput (E. Dillane, pers. comm.). The SALSEA project has used a panel of 15 microsatellites and 360 SNPs to provide greater information for each post-smolt sampled. This is allowing for the development of this methodology within Ireland.

The Effectiveness of DIDSON and Genetic Stock Identification for Estimating Atlantic salmon Stock for a Large River Catchment

As discussed above, certain limitations to the DIDSON-GSI technique were noted but this study showed that this was an excellent demonstration of how this approach would work. The potential for this approach regarding the methodology is dependant on the river system having resolvable discrete populations, temporal stability and an accurate count of one discrete population. In order to evaluate the veracity of the estimated stock size that emerged from this counting technique an assessment of the representativeness of the sample collected of fish entering the River Moy was undertaken, the accuracy of the DIDSON count on the River Deel was assessed and what fish constituted the 2008/2009 spawning cohort were determined. Assumptions were made with respect to the methodology employed due to the sample size and the sampling period. Issues relating to the defining of the run were a direct result of the biology of the River Deel system and the behaviour of fish migration.

- Representativeness of the Sample

The River Moy samples were collected from the beginning of May to the end of September 2008 corresponded with the duration of recreational angling fishery in 2008. The number of fish trapped in each month may or may not have corresponded with the magnitude of the numbers of fish entering the river in these months. As no samples were taken of fish prior to May or after September, early running and/or late
running fish will not have been sampled. Thus it is unlikely, though not certain whether the sample collected was representative of the entire population spawning in the River Moy catchment. River flow may also have affected the availability of fish for capture by angling in the Moy Fishery.

To overcome the issue of sample representativeness, two scenarios were used to enable analysis to proceed. Firstly in Scenario A, it was assumed that the samples collected at the river mouth represented the entire population and that the proportions presented by the genetic analysis were those that prevail every month of the year. On the basis of this assumption estimated individual stock contributions and the total stock size for the River Moy were calculated and the estimates depended on which approach was used to count salmon i.e. raw data, ≥ 40 cm, ≥ 45cm, or the Binomial Model. With respect to Scenario A, there were some difficulties with this assumption as it was unlikely that the proportions of the different contributing populations did not change throughout the year e.g. greater or lesser occurrence of spring fish or autumn fish in each population. Unpublished data from a study of stock composition from 2004 which included samples collected earlier in the year (April/May), suggested that run timing can vary substantially among populations (Dillane et al., in prep.). Scenario B was used to overcome the limitations of Scenario A. The Scenario B estimate was confined to the summer run only. Therefore, Scenario B provided an estimate for only the summer run component of the Moy spawning stock and this allowed for increased confidence in the representativeness of the sample of fish entering the river to reflect the summer run. It was assumed however, that the majority of fish counted on the River Deel were available for sampling on the main River Moy channel, thus, bias due to sampling on the River Moy were minimal.

Running the ‘whole run’ estimate scenario allowed the benefit of being able to use the entire River Deel count for the 2008 cohort without having to adjust for early running fish. However, there may be a substantial loss in confidence related to the strong possibility that the sample collected on the River Moy was not representative of the entire run. Using the ‘summer run’ estimate allowed for good confidence in the
representativeness of the sample collected at river system entry (River Moy), but then this method encountered the difficulty of having to accurately adjust the River Deel count for fish that enter the River Moy prior to May. Assuming that there was a bias, then fish counted in the River Deel must be removed prior to May 2008 to produce the count. This allowed for increased confidence in the representativeness of the sample of fish entering the river to reflect the summer run. Sample size was a limitation of the method employed as only 257 fish were sampled in 2008 on the angling beats of the River Moy. It was impossible to determine if this fish sample was representative of the total population of salmon available for spawning in the River Moy. Increasing the sample size by including all months would improve the result and provide better confidence for genetic analysis as samples were only taken from May to September.

For this study, the migration patterns of River Deel salmon were found to be an issue with respect to the determination of run components, particularly MSW fish. Some spring fish will have waited in Lough Conn and migrated upstream during the summer months. However, there was a strong tendency for these early migrating fish to fall back to Lough Conn, as was suggested by the almost equal registering of counts for upstream and downstream movements provided by the DIDSON counter for March and April 2008. Where fish migrated upstream and downstream from the lake several times, there may have been a high incidence of multiple records for single fish. Fish may also have held up in Lough Conn and they may not have migrated past the DIDSON until autumn. Thus to provide a fairly conservative estimate, the number of pre-May fish were removed from the total River Deel and were associated with the summer run fish sampled at the River Moy entry. However, this method assumed that they were only counted once and regardless of whether they migrated downstream again (as ‘a rule of thumb’ in fish stock assessment downstream migrating fish are subtracted from upstream migrating fish to provide a net count). For the above reasoning, an autumn run of MSW fish could not be confirmed as numerous MSW fish will have remained in Lough Conn from early in the season and larger fish migrating in the autumn may have initially migrated in the
spring and dropped back into the Lough Conn. Downtime encountered during the last three weeks of August 2008 due to a technical fault also made their identification more difficult.

As discussed above, due to possible multiple counts of single fish, the subtraction of downstream fish from the upstream count on a daily and monthly basis was used to provide the net count. However, this is the standard method of calculating net upstream migration on river systems as the subtraction of downstream migrating fish is used to account for possible multiple migrations, milling fish and / or straying fish. Thus it was assumed that spring fish (assuming that the same fish was not counted a number of times) could be removed and that all spring fish that migrated into Lough Conn passed the DIDSON between January and April 2008.

- **Run Timings and Productivity**

  As described above, River Deel run timings were shown in different proportions migrating during the summer of 2008, with the bulk of the River Deel adult salmon migration on the River Moy detected in July, therefore, there was a bias towards July. However, the sample size was too small to provide an accurate insight and the lack of sampling prior to May does not allow for the determination of River Deel migration in these months. Recent work by Dillane et al. (in prep.) has shown that the main run of River Deel fish on the River Moy is July, thus the assumptions made with respect to the majority of River Deel fish proportion of the run being sampled during May to September 2008 on the River Moy would provide good estimates. This may not have been the case for e.g. the Manulla River which has a much earlier run. The methodology also allowed for comparisons to be made with respect to the east and west of the River Moy. East of the River Moy was shown to be the most productive, with the River Trimogue the most productive of the discernable east Moy rivers.
• The Accuracy of the Atlantic salmon Stock Assessment Count Data and Fish Length Data Collated Using a DIDSON, River Deel

The River Deel stock assessment was estimated assuming that the raw DIDSON count was correct and representative of the number of salmon migrating in this system. As described above, validation tests carried out using DIDSON on the River Deel showed 100% concurrence for the detection of a known number of fish moving through the beam and DIDSON length data showed that there was a linear relationship between DIDSON length and true fish length for the River Deel DIDSON data \( (R^2 = 0.09232) \) (ICES, 2009). DIDSON length data has effectively been shown to provide information for species apportionment (Burwen et al., 2007; Burwen et al., 2010). Data processing using DIDSON involved the use of CSOT processing technique that shortened DIDSON files through the detection of fish movement (predetermined by the analyst). Verification of the analysis technique and methodology were undertaken, showed that the CSOT processing algorithms (ICES, 2009) and manual counting were successful at ‘picking out’ 99% of the fish movement when Analyst 1 was counting (Analyst 1 counted approximately 94% of the data collected).

Genetic Variation in Large River Catchments

GSI complements the use of DIDSON in this study and the genetic differentiation observed between the River Deel and Cloonacool river samples suggests that large river systems maintain multiple genetically distinct populations (Dillane et al., 2007). This emphasised the importance of obtaining a count not just for the whole River Moy catchment but for its intra-river populations. Advancements in research to determine the level of genetic variation within-rivers has shown homing within the River Teno system to be accurate to at least the tributary level (Vaha et al., 2007). This study also emphasised the importance of MSW stocks for maintaining genetic diversity and the requirement for the monitoring of MSW populations for their protection. Vaha et al. (2007) showed the importance of MSW females in the population for maintaining allelic richness of populations. This new novel combined DIDSON-GSI method would provide a better management tool for salmon stock assessments for the protection of genetically distinct populations.
8.1.4 The Influences of Environmental Factors on Atlantic salmon Migration, River Deel

Management of discrete populations in large rivers is made more difficult by the different run timings of these stocks to their tributary of origin. The ability to determine possible environmental cues could help with stock enumeration and protection. This study was the first stock assessment of both adult salmon and smolt migration using a DIDSON and screw trap to determine the effects of environmental factors on their migration in an Irish river system. Water temperature has been shown to be a major environmental factor in triggering the migration of Atlantic salmon (McCleave, 1978). The River Deel showed adult migratory timings to be correlated with air and water temperature but no significant correlation with discharge was obtained. No correlations were found with smolts and the environmental factors recorded. The screw trap did not allow for the comparison of individuals with environmental factors due to the nature of the fishing of the trap. The use of screw trap data for the River Deel was not thought to be representative of changes in the run with changes in environmental factors as only daily fishing of the trap was required. However, these data did show that for both study years the peak in smolt migration occurred at the same time and within a specific temperature window, from the 19th to the 27th April 2008 at a mean daily water temperature of 10.5 °C (with only a 0.4 °C difference in the mean daily water temperature during peak migration for both study years).

The River Deel’s hydrology made it a challenging environment for the operation of both pieces of equipment. The DIDSON can monitor salmon migration in an unintrusive manner, without interference to salmon migration. Using point observations such as fish counter sites are not ideal for identifying the migration patterns with environmental factors (Smith & Smith, 1997), especially when their migration is not directly from sea to river, e.g. through Lough Conn. Numerous studies have shown delays to Atlantic salmon migration as a direct result of in-river structures such as weirs and fish passes. In-river structures can have possible affects on the inward and outward migrations of salmon, but this has been shown to be river dependant (Thorstad et al., 2008). However, the combined use of a fish fence and the DIDSON did not interfere with fish migration in the River Deel with the methodology employed. This reinforces this method for enumerating fish in a non-intrusive manner. Studies on river migration using telemetry have been shown to be more favourable for
detecting the influence of environmental factors on fish migration, particularly to changing water flow (Thorstad & Heggberget, 1998). However, the majority of such studies were carried out on fish movement at the mouths of river over a few months and the handling of fish can disorient fish migration and cause mortality (Thorstad et al., 2008).

Possible extreme changes in water temperature and discharge could have significant affects on fish migration in the River Deel, whether they are a natural occurrence or due to climatic changes. While the projected changes in climate and their implications are presented in the RESCALE (2010) (specific to the Burrishoole system) they are illustrative of likely changes in similar characteristic catchments along the west coast of Ireland. The studies of Taylor (1991) and Freidland et al. (2009) proposed the development of catchment specific adaptation strategies as salmon are locally adapted and individual river stocks may require management as a species. While air and water temperature had the most significant influence on salmon migration on the River Deel, McGinnity et al. (2009) suggested that over an extended time period, wild Atlantic salmon may be able to adapt to future changes in water temperature in an ideal situation.

**The Influence of Air and Water Temperature on adult Atlantic salmon Migration and Stock Assessments, River Deel**

This study is one of very few studies that have correlated water temperature with in-river salmon migration, where no migration barriers existed (Erkinaro et al., 1999; Karppinen, 2004; Thorstad et al., 2008). Water temperature was shown in this study to have a significant affect on the upstream migration of adult salmon past the DIDSON. Previous assessments of migration patterns with water temperature using weir counter data showed limited effect of water temperature on the number of fish migrating (Trépanier, 1996; Thorstad et al., 2008). Erkinaro et al. (1999) showed that a reduction in river water temperature was observed to enhance the upstream migration of grilse. However, similar results relating to water temperature and fish movement have been shown to have little effect on the migration rates of Atlantic salmon (Banks, 1969; Trépanier et al., 1996). This reinforces the theory that the effects of environmental factors are river specific. Higher summer water temperatures in the River Deel were observed to slow the upstream migration of adult salmon. Swimming
capabilities have been shown to be reduced at lower and higher water temperatures (Beamish, 1978; Booth et al., 1996; Thorstad et al., 2008). This would also explain the correlation between water temperature and salmon migration on the River Deel. Water temperature can also lead to greater mortality in Atlantic salmon where catch and release are undertaken (Dempson et al., 2002; Thorstad et al., 2003; Thorstad et al., 2008). Temperature will be important to monitor in the future for Irish river systems where catch and release is allowed, particularly on rivers where stocks have not been meeting their conservation limits. Webb and Walsh (2004) study suggested that global warming is likely to be detrimental to the habitat of cold water species and by increasing the number of sites investigated and considering more detailed inter-regional information on climate change, would permit better predictions of river temperature response. The relationship between air and water temperature has been tested by several authors such as Pilgrim et al. (1998) where they demonstrated that the strength of the relationship was not adversely affected by a relatively large separation of river and climatological stations (Webb & Walsh, 2004). Future studies for other Irish rivers should be able to locate a nearby climatological station to determine river specific relationships with environmental data. However, the installation of in-river equipment within the catchment for the collation of environmental data is promoted, a total weather station is costly but the cost will be easily offset by the gains.

**The Influence of Discharge on adult Atlantic salmon Migration and Stock Assessments, River Deel**

No clear relationship between the daily mean water level, daily mean flow and adult fish migration were found. Bivariate analysis, by definition, cannot control for additional factors and was used to gain a broad view of potential inter-relationships in the data. River discharge plays a major role in creating the riverine environment and thus has an effect on the life cycles of the fish species that inhabit them. The dropping flow that followed flood events were thought more important for the bulk of salmon migration, particularly in the winter months. Seasonal migration patterns were thought to be influenced by hydrological and meteorological changes resulting in the differences in migration rates on a yearly basis. This method of analysis was used as the multivariate analysis regression carried out showed a high degree of multicolinearity. The bivariate analysis applied will not separate seasonal patterns
eg. summer and winter seasonal peaks in the run as a result of i.e. water temperature. An alternative approach that allows the interactions between migrating salmon and environmental parameters is recommended.

Thorstad et al. (2008) discussed in detail the effects of water discharge on migration and the complex synergy that exists between other factors. There can be a large individual variation among salmon in their response to variation in water discharge at any given site and any given time. This complexity can make it impossible to predict the effects of water discharge on upstream migration, and to define threshold values (Hawkins & Smith, 1986; McKinnell et al., 1994; Thorstad et al., 2008). McKinnell et al. (1994) found no effect of river flow on salmon migration. No correlations were found between changes in discharge and changes in smolt or adult migration on the River Deel, however, these factors were observed to be important but not impacting directly on salmon migration or the size of migrating salmon. This became more apparent in the monthly breakdowns, where relationships were determined between adult salmon migration and discharge but these were very complex relationships.

Consistently high water discharges were experienced on the River Deel during the operation of the DIDSON and this may have masked the relationship; this was also a limitation of Hawkins and Smith (1986) study. No gauge data were available from the EPA data logger for the 29th October 2008 to the 11th December 2008 due to a battery failure at Knockadangan Bridge site, where 44 days of data went unrecorded and this may have affected the outcome of results. Similar to the results of Smith et al. (1994), the results showed that specific studies that rely on investigating only the relationship between Atlantic salmon migration and river discharge are unreliable but can provide good information on possible migration patterns. Erkinaro et al. (1999) showed that during active migration of Atlantic salmon increasing discharge was associated with increased swimming activity of salmon, especially in late summer and that increasing air temperature was also associated with enhanced migration activity. On the River Deel increased swimming activity was noted towards the end of the summer of 2008 and early autumn, particularly during periods of low rainfall (therefore low flows) and following heavy rainfall. This was in line with Dunkley and Shearer (1982) where the number of fish movements increased during periods when discharge was decreasing after
flood events. This was also observed during data processing on the River Deel using the DIDSON.

Another factor that should be considered is that adult fish were counted numerous times migrating upstream past the DIDSON due to the nature of milling fish in this region as described earlier. This was confounded by the near proximity of the site to the mouth of the River Deel and Lough Conn. This may have resulted in the relationship being less significant as fish tended to mill when water levels were stable. The results may have also been influenced by how long adult fish remained in Lough Conn prior to migration. Thorstad et al. (2008) noted that they could find no information on the migration patterns or speeds of Atlantic salmon through lakes. Adult fish are known to mill and hang in nearby pools prior to migration which was likely to be a facet of seasonality. Jensen et al. (1986) suggested that increasing flows stimulated salmon to ascend and that they continue to ascend over a period of time regardless of any changes in river flow. This could be indicative of what was happening on the River Deel.

Orell et al. (2007) study showed that both smolts and adults migrated mainly during decreasing discharge in the River Tana. However, like this study on the River Deel, daily variation in the rate of smolt or adult Atlantic salmon migration did not correlate with changes in discharge but the migration activity of adults appeared to be related to increasing discharge late in the season. Again, the gap in hydrometric data during the peak adult run may have affected the result. Orell et al. (2007) concluded that at times of low seasonal flow, migration of both smolts and adults may be associated with freshets but during higher flow the migration is independent of increases in flow (Smith et al., 1994; Davidsen et al., 2005; Orell et al., 2007). This was indicative of findings from this study. The response of adults to either increasing or decreasing flow appears to depend on the stage of migration, increased flow can increase movement into a river from an estuary (Orell et al., 2007), whereas Atlantic salmon migrating within the river have been shown to prefer decreasing flow (Trépanier et al., 1996; Erkinaro et al., 1999).

Individual salmon can have different responses to river discharge depending on the data collection site and this was also thought to be a facet of seasonality (Thorstad et al., 2008).
However, there was very little gradient change between the DIDSON site and the hydrometric station located at Knockadangan Bridge (approximately 100 m downstream of the DIDSON site) (OPW). The complex relationship between river discharge and other factors made the effects of water discharge on upstream migration very difficult to define and obtain threshold values for upstream migration (Thorstad et al., 2008). It was hoped that threshold values for migration could be detected for discharge and used for the automatic triggering of the DIDSON to record only data where fish were migrating. This in turn would reduce the quantity of data for analysis and ease of processing, where only specific run components were being target, e.g. spring run, summer run etc.

Studies have shown that peak migrations can occur after the peak flood (Lilja & Romakkaniemi, 2003). Peak fish migration past the DIDSON did not coincide with peak flow. The first spring flood on the River Deel occurred 28 days before the first increase in salmon migration, with the second flood occurring 29 days before the second larger peak in spring migration. The general assumption is that increases in flow stimulate Atlantic salmon to ascend a river (Jensen, 1986; Mills, 1989; Laughtoon, 1991; Trépanier, 1996). This was not the case at the River Deel DIDSON site; however, seasonality will have also played a role regarding the spring migration. The general assumption for the majority of Irish rivers is that fish migrate with dropping flow and not in flood waters. DIDSON observations did show in-river fish migration during heavy flood conditions. A complex relationship exists between flow and fish migration on the River Deel, as observed correlations existed at certain times of the year but not over the 14 month study period as a whole. Lilja and Romakkaniemi (2003) found that a short-term variation in the flow rate might have a smaller role in migration in large northern rivers where the flow decreases steadily after pronounced, regular, annual, peak floods in spring. Short-term variations observed in flow on the River Deel during winter months when the bulk of fish were migrating, could be the reason for the complex relationship between flow and fish migration in this river.
Influences of Discharge and Average Daily Water Temperature on the Migration of Atlantic salmon Smolts and Stock Assessments, River Deel

Water temperature generally appeared to be the most important environmental factor for smolt migration which was also noted by Orell et al. (2007). However no significant correlations were found between smolt migration in 2007 and 2008. Smolt migration in the River Deel was shown to have an upper water temperature limit, where smolt migration was significantly reduced above 15 °C in both study years. The influence of water discharge on smolt migration on the River Deel was thought to be related to water temperature, whereby lower water discharges lead to increases in water temperature. No significant correlations were noted between the number of smolts migrating and changes in water level and water flow for both years. However, where very low flows existed, the smolt trap efficiency was reduced and thus fewer smolts were trapped even if they were migrating. The River Deel study has shown that screw trap data is not suitable for comparison with environmental data as the trap efficiency can interfere with the consistent collection of smolts at extreme and low flows. However, key observations were possible using these data in relation to the River Deel temperature window for smolt migration and the determination of the timing of the peak smolt migration for both study years. The significance of the concurrent timing for smolt runs has been described by McCormick et al. (1998) as an adaptation to the area’s prevailing environmental conditions.

Previous studies on salmonid smolt migration have been carried out using trap data on the Burrishoole catchment (Byrne et al., 2003; Whelan et al., 1993; Poole et al., 1996). Byrne et al. (2003) study of sea trout smolt output from the Burrishoole system showed that the timing and duration of the sea trout smolt run was not found to vary significantly over the three decades. Timing and duration of the smolt run did not change over the two year study period on the River Deel. The results show that the peak of the smolt run for both 2007 and 2008 occurred over a nine day period at similar temperatures. This information could be used where resources were limited and a smolt mark-recapture programme could be carried out during the peak of the run. Where such baseline data existed this method could reduce the man-power and operational time to obtain a smolt count for the river on a yearly basis (as previously discussed above). In contrast to the findings of Byrne et al. (2003), the RESCALE
(2010) analysis of the smolt run data from the Burrishoole catchment since the 1970s, indicated that there has been a significant trend towards earlier commencement of the salmon smolt run (measured as 5 % of the fish migrating), by almost 10 days since records began (ICES, 2010), coinciding with increased water temperatures over a similar period. A similar trend was found for the River Bush in Co. Antrim, Northern Ireland, which was believed to be linked to changes in river water temperature (ICES, 2010). Future temperature changes could have implications for salmon smolt migration run timings on the River Deel.

Where there is a reduction in the outward migration of smolts from a river system, this can affect the migration pattern in the river system. Several authors have documented the affect of the social structure of smolts due to changing environmental conditions and that this in turn can affect the run, as smolts migrating from further upstream of a system stimulate the migration of the smolts further downstream creating shoals (Hvidsten et al., 1995; Byrne et al., 2003). Results for the River Deel showed similar results where shoaling behaviour occurred during peak migration, as shoals were observed actively entering the trap during sampling of peak runs. McCormack et al. (1998) stated that temperature may be a controlling factor in smolting and has a role in the timing of smolt development, thus temperature will have serious implications for smolt survival in the wild. Several studies found that increasing water temperature in the spring was strongly correlated with the initiation of the smolt run. This was not shown statistically on the River Deel, but observations of the data showed that increasing temperature coincided with smolt migration. Other studies have shown that downstream migration of smolts of Atlantic salmon and Brown trout occurs at approximately 10 °C or slightly above (White, 1939; Mills, 1964; Osterdahl, 1969; Solomon, 1978; Whelan et al., 1993) and this concurred with the River Deel findings. Ruud-Hansen (1985) showed that only water temperature and no other environmental factors influenced the timing of Atlantic salmon smolt migration in the River Imsa. The results of this study also concurred with their findings, with an average temperature over both study years of 10.2 °C during the peak migration on the River Deel. Studies have shown that smolt runs may only be initiated when water temperatures have reached a certain threshold (Fried et al., 1978; McCleave, 1978). The temperature window of migration for River Deel salmon smolts was found to be between 8.04 °C and 15.72 °C in 2007 and 6.86 °C to approximately 16 °C in 2008. Smolts were trapped on the first day of sampling on the 7th April 2007 at a temperature of 8.5 °C,
thus the smolt trap was installed in March 2008 and the initiation temperature of the 2008 smolt run was at 6.86 °C on the 22nd March 2008.

Jonsson and Ruud-Hansen (1985) showed that the run may be initiated by a pattern of temperature variation over a prolonged period of time. However, other studies have shown that there is no temperature threshold triggering smolt migration, but instead it is controlled by a combination of temperature increase and temperature condition in the river during spring (Orell & Romakkaniemi, 2003; Jonsson & Rudd-Hansen, 1985; Byrne et al., 2004; Zydlewski et al., 2005). As described above, the River Deel temperature related ‘smolt windows’ determined the most suitable temperatures for salmonid smolt migration. This reinforces the finding of Zaugg (1982) Whelan et al. (1993) and Byrne et al. (2003). On river systems where temperature related ‘smolt windows’ have been determined, any subsequent delays in their migration will decrease smolt survival (McCormick et al., 1998).

Like Orell and Romakkanemi (2003), the River Deel study showed that changes in discharge had no significant effect on smolt migration. The River Deel smolts migrated more quickly at high water flow than low and this was in line with the findings of Youngson et al. (1989). Flow affected the operation of the screw trap and it was necessary to adjust its location to ensure it was located in the main stream of flow at all times. Hansen and Jonsson (1985) discussed the active movement of smolts into the main current of the river flow showing their active migration downstream. Their findings and that of the River Dee study, emphasises the need to ensure that the screw trap is in the main flow at all times to ensure trap efficiency and is indicative of the complex relationship that exists with flow and smolt migration.

**8.1.4.1 Climate Change and Predicted Future Changes in Environmental Factors**

Atlantic salmon are not currently limited by temperature conditions in Ireland or the UK (Webb & Walsh, 2004). Climate change may have an indirect and less readily predictable affect on future thermal regime through impacts on river flow, groundwater inputs and temperatures and the nature and extent of the riparian zone (Cooter & Cooter, 1990; Meisner, 1990; Jager et al., 1999, Webb & Walsh, 2004). Limited studies have been undertaken on the affects of water temperature on salmon both nationally and internationally, particularly in relation to the possible effects of climate change. However, Atlantic salmon being a cold
water species suggests that any significant changes in water temperature will have an effect on its life cycle. Predicting the effects of possible future changes in water temperature will be of greater difficulty where rivers are significantly influenced by groundwater. Mackey and Berrie’s (1992) study of two UK rivers suggested that a rise of 2 - 4 °C in monthly mean air temperature would result in a corresponding increase in monthly mean water temperatures of 1.8 - 3.6 °C for a surface fed river, but only 1.1 - 2.2 °C for a spring fed river.

Temperature is a very significant and complex variable affecting many stages of Atlantic salmon life cycle and the ecology of a river. Air and water temperature were determined to be the most significant factor to adult salmon migration on the River Deel from the bivariate analysis. Thus, the predicted future temperature changes will have possible serious effects on the salmon population, whether they are naturally occurring or due to the onset of climate change. Temperature is affected by low flows and increasing summer temperatures and / or low winter flows and colder water temperatures, which could have significant affects on salmon populations. Biro et al. (2007) has identified that temperature-dependant physiology and compensatory feeding behaviour as proximate mechanisms for substantial climate-induced mortality in young rainbow-trout (*Oncorhynchus mykiss*) at a scale of entire populations and waterbodies.

Low flows are vital with respect to discharges within the catchment and were observed in the summer of 2006 to affect the run-timing of salmon migrations on the River Moy. The timing of upstream migration and spawning appear to be under separate control, as migration timing should be affected by the conditions experienced by the adult on the river, whereas, spawning should be timed to optimise the condition that will be experienced by the progeny (Quinn et al., 1997). This was clearly observed on the River Deel, where fish migrated past the DIDSON counter site in some instances well before spawning commenced but this was inconclusive and telemetry studies would be required to confirm these observation. Studies of this nature should include an estimate of the availability of salmon downstream prior to upstream migration (Smith et al., 1997; Thorstad et al., 2008). The River Deel study was atypical and fish migrations into and out of Lough Conn made the assessment of adult salmon migrations in this study more difficult.

Prediction of future conditions suggests that higher river temperatures in winter will be
detrimental to spawning and egg incubation, especially under Webb & Walsh (2004) high climate change scenario (. Like other studies (Orell & Romakkaniemi, 2003; Jonsson et al., 1991), the River Deel study showed that different mechanisms may function in different rivers depending on adaptations to local environmental factors. It is not yet known how this may affect salmon migrations upstream and if this will result in changes in run timings and the timing of spawning. Delays in migration could make counting just the summer/autumn runs more difficult. This could affect the selection of fish counters for rivers where the bulk of migration takes place in autumn and winter, as on the River Deel, thus obtaining only a summer count for a stock estimate will no longer be representative of the rivers stock where migrations become delayed due to increases in temperatures and low flows. Fish counters will have to be operational later in the season to obtain the bulk count. This would also be a factor where discharge showed significant correlations with salmon migration and where salmon migration followed increases in discharge later in the season. Thus, counters would be required to operate at higher water levels to obtain a stock assessment. The only counter shown to consistently have the ability to do this in Irish river systems is the DIDSON (ICES, 2009; Brennan et al., in prep.).

Factors that affect salmon migration can cause increased energy consumption during upstream migration which could reduce the survival of kelts after spawning, and the number of MSW fish in some rivers (Thorstad et al., 2008). Solomon et al. (1999) found that during two dry autumns in relatively small rivers in South West England, the geographical distribution of spawning was severely truncated due to low flows. In these low autumn flows fish migration was delayed particularly at mills and weirs. This could be indicative of future problems for some Irish rivers were low flows may delay migrations at weir mounted counters that have been installed in recent years. For the comparisons with environmental data Thorstad et al. (2008) recommend further research with a high resolution in time and space, larger sample size along with detailed information on hydraulic and environmental factors. DIDSON can provide a vastly greater sample size (on a 12 month basis) than that obtained from exiting counters operational in Ireland today or from telemetry studies.
Due to the sensitivity of salmonids they are of particular importance in providing an early warning to changes in individual river systems. The results for the River Deel have shown the river specific nature of how Irish river systems can be influenced by changes in environmental factors and emphasises the importance of continued long-term monitoring of Atlantic salmon and environmental data. These data could then be used in turn for providing an indicator and a measure of local environmental change and the possible effects of climate change.

Adult Atlantic salmon in the Burrishoole system typically spawn in late November, December and early January (RESCALE, 2010), as with the River Deel. Many fish species have shown the ability to adapt to changing temperatures when exposed gradually to such increases (Graham & Harrod, 2009). As described earlier, McGinnity et al. (2009) concluded that over a long period of time, wild salmon populations may be able to adapt to projected increases in temperatures. To detect possible future changes in the smolt run on the River Deel and other important salmon catchments continued monitoring of the smolt run and environmental factors of air and water temperature and discharge are required. Findings by Jonsson and Jonsson (2009) and results for the Burrishoole system (RESCALE, 2010), have shown that smolt run timings for salmon and sea trout have been predicted to show future general trends for smolt runs that start earlier and the earlier start time is likely to be linked to warmer water temperatures during the preceding winter. Some years also showed a delay in the later part of the smolt run for the Burrishoole system due to drought conditions (RESCALE, 2010). Jonsson and Jonsson (2009) also observed that smolt migrations took place over shorter time periods in mild years.

8.1.5 Evaluation of Stock Assessment Methods Tested
There is a need for Ireland to manage its rivers in such a way that does not interfere with the hydrology of our rivers as part of meeting the objectives of the EU Water Framework Directive. Any physical modifications of the river must be limited and the use of DIDSON technology as a counter for Ireland is and will be more applicable for enumeration of our salmon stocks into the future. Even small weirs have been shown to delay upstream migration (Thorstad et al., 2003; Thorstad et al., 2005; Croze, 2005). One advantage over
other counters when taking cost into consideration is that DIDSON is mobile and can be moved from catchment to catchment. Weir installations for resistivity and infra-red counters can cost more than twice the cost of a DIDSON. Increased discharge did make the operation and effective fishing of the smolt trap difficult but the shorter migration and/or counting period for smolts is an advantage provided suitable conditions exist for the operation of the screw trap. Thus, the counting of juveniles may become increasingly important where fish counters are not suitable for installation and/or resources are not available for the purchase and operation of a DIDSON. Using the point observation method, DIDSON stock assessments have the advantage of providing large sample size of the number of fish migrating for longer, consistent sampling durations, as shown in this study. This methodology could be complemented by telemetry studies to determine the number of fish available for migration prior to passing the DIDSON. Telemetry would also confirm observations that the installation of the fish fence at the DIDSON site did not delay migration on the River Deel.

The methodology tested using the DIDSON count and length data advanced existing methodology using length and date cut-offs applied by the Standing Scientific Committee for Irish rivers. DIDSON data allowed greater analysis using fish length data and run timings to determine specific date cut-offs specific to the River Deel using DIDSON, where DIDSON allowed direct observations of fish migrations. Modelling of the DIDSON length data allowed for species apportionment and counts to be obtained for both salmon and trout. However, the simple length cut-offs applied were just as effective in this study and provided reliable estimates for the 2008 cohort.
CHAPTER 9

9.0 Conclusions and Recommendations

Counter data is used in preference to rod catch data where both exist for a particular river (Anon., 2008b). DIDSON has been shown to provide accurate estimates of the salmon stocks in the River Deel and the combined use of the DIDSON and GSI has now provided a novel and affective methodology for stock assessment data to be obtained for a large river system (with discrete genetic structure) from count data from one index system. This method allows for the annual productivity of the entire River Moy to be determined from obtaining one count of one tributary for the purpose of comparison to Conservation Limits. The River Deel and River Moy case study should be applied to rivers where discrete genetic Atlantic salmon populations have been identified. Stock assessment programmes should be carried out using DIDSON in combination with Genetic Stock Identification to estimate the stock composition of these large Irish rivers. DIDSON is recommended as the counter of choice for future studies of this nature for Irish river systems. This study provides the basis for the development of such methodology for the determination of Atlantic salmon stock cohorts for other large Irish rivers. Where multiple stock components exist, it is essential to be able to produce stock estimates for each stock component for the purpose of their conservation. The objective of the management of Irish salmon fisheries must be to provide the diversity and abundance of salmon stocks and this method suggests a way forward for the future of stock assessment in Ireland.

9.1 Adult Stock Assessment, DIDSON, River Deel and Combined DIDSON-GSI Technique, River Moy

The research findings indicate that the best method for Atlantic salmon stock assessment is the use of a combination of direct and indirect counting methods using DIDSON for calculating the conservation limit of a large river catchment. The combined DIDSON-GSI methodology is transferable to other river systems that have resolvable discrete populations in other parts of the country. Where discrete populations have not yet been successfully separated or identified, new genetic markers are being used to separate out these populations. The River Moy is not unique in terms of its genetic structure within Ireland but it does have
very discrete populations because of the lacustrine system (Dillane et al., 2008). It was not genetically possible to separate the eastern populations of the River Moy; however, the method does show the significant productivity of this region of the Moy catchment. This difference in the production potential between east and west Moy is due to the wetted area. As has previously been noted by Dillane et al. (2008), population differentiation within the eastern catchment of the River Moy, while statistically significant, is low and insufficient for reliable stock discrimination to different tributary populations in this area. However, the tributaries of the River Deel, Clydagh and Manulla show marked and substantial differentiation from each other and from the rest of the River Moy tributaries, and individual estimates were thus possible for these three tributaries. These genetic characteristics were effectively used by obtaining a total yearly count for one discrete population and using these data and GSI to establish the total yearly count for the whole system. DIDSON readily facilitated the ability to obtain a yearly count in an Irish river system and combined with the use of GSI has shown its potential for its use in other large river catchments, where discrete populations have been identified. There were several practical issues with working on index river systems and this study has shown that it was easier to operate equipment on smaller tributaries to determine stock densities due to the lower number of fish to count and debris loadings.

Sampling the run throughout the year would allow for the determination of the genetic proportions of the run on the River Moy and would help improve the accuracy of the estimate in terms of the proportions of the various stock components run timings upstream on the River Moy. A larger sample size would also improve the assessment as the sample size was relatively small, i.e. 257 fish. Sampling was not undertaken throughout the year on the River Moy due to the inability to operate the traps in flood conditions and man-power restrictions. Therefore, there could be numerous River Deel fish migrating upstream from January to May that were not sampled and these fish require sampling and quantification regarding their tributary of origin. This would also increase the sample size particularly for breaking down these data on a monthly basis. The sample taken in this study was technically too small for breaking down the data by month as the estimates become unreliable in the months where fewer fish were captured. Ideally a sample consisting of 1000 - 2000 scale samples.
throughout the year would be more applicable, with the study operated for 2 - 3 years to examine variation between years. Thus, this study also emphasised the importance of the operation of existing traps e.g. Ballina traps, River Moy, for the sampling of fish stocks to enhance the level of information on the run components of Atlantic salmon in Irish rivers. The Ballina traps were only fished successfully in 2007, trapping was less successful in 2008 due to increased flows. Thus, improvements to these traps were recommended to the IFI, Ballina and these improvements have now been completed.

Large spring fish were observed actively swimming upstream and downstream at the end of March and in April 2008 on the River Deel. Future assessment techniques must include more detailed counts of the MSW fish component and the sexing of fish through sampling from, e.g. Ballina Traps, River Moy. Fish length data and scale sampling will also be essential for the aging of fish to determine the 1SW and MSW salmon components, particularly for reference data for comparison with length cut-offs for species apportionment and age analysis. However, where fish traps are already installed they should be developed for the safe sampling and handling of fish to obtain valuable count data. This would allow live length and weight measurements to be taken and to allow for the acquisition of scale data for aging and tissue or scale data for genetic analysis. These data would help improve the methodology and models tested in this study. It must be noted that flood conditions and heavy debris loading on large rivers can make the operation of such traps very difficult and fish should not be trapped where there is a possibility to cause fish damage or mortality where traps become block with debris. DIDSON is the best option for salmon stock assessment in Ireland where no traps exist and where the CLs for a river system are not being met, thus, preventing possible mortality due to handling of important fish stocks on river systems that may have an effect on the remaining population.

DIDSON length data provided accurate length estimates and run timings which allowed for run component determinations for the River Deel. This application could be further used for the protection of MSW and their stock assessments. The availability of temporal samples over several generations is often the limiting resource (Vaha et al., 2008) and continued sample collection is vital for future estimates and genetic stock identification assessments.
Ultimately, the appropriate geographical scale must be determined for management purposes to determine if the within tributaries differentiation is due to genetic drift or as a result of unstable populations or where the differences are driven by natural selection and local adaptation (Vaha et al., 2008). Future studies using the genetic samples of smolts sampled during the 2007 and 2008 screw trap operation on the River Deel, could help determine the possibility of intra-river structuring or temporal changes within the River Deel system itself.

The assessment of the diurnal effects on migration patterns and the affects of turbidity on River Deel salmon migration were beyond the remit of this study but should be considered in future studies to determine if these factors were responsible for changes in salmon migration. Further stock assessment studies should be undertaken on the River Deel, using the DIDSON to obtain count data, in conjunction with telemetry studies to determine salmon movements prior to migrating past the DIDSON. This would assist with further validation of the DIDSON and provide much needed information on the quantity and movement of salmon prior to migrating past a DIDSON counter site. Future applications of DIDSON in Ireland should also include eel stock assessments. This study was the first enumeration of eels in Ireland using a DIDSON. Further work is required to validate DIDSON for eel enumeration.

DIDSON was operated in an Irish river system to provide real time data of fish migrations for the management of in-river quotas. The need for real time data was highlighted by the Independent Salmon Group (Collins et al., 2006). The Standing Scientific Committee also recommends the use of real time counter data but that it should be used in the context of the five year average to allow for seasonal variability in marine and freshwater survival (Anon., 2008b). This study provided a baseline of data for the River Deel and it is a recommendation of this study that DIDSON be operated for a five year study period on the River Deel. Alternatively, another suitable site should be located for the operation of DIDSON particularly in river systems where discrete populations are known to exist, thus allow further testing of the combined use of DIDSON-GSI technique. DIDSON enumeration of Atlantic salmon stocks would greatly improve the quality of stock estimates for the calculation of individual river Conservation Limits.
9.2 Alternative to Adult Atlantic salmon Stock Assessments, Screw Trap Mark-recapture Estimates

From the 2007 screw trap trials, both operational and mark-recapture methodology were further developed in 2008. Mark-recapture methods used in 2007 were altered for 2008 to allow for multiple mark-recaptures through the use of batch marking which allowed for more advance Bayesian modelling to be applied to the 2008 data. To further develop this method for tributaries of large Irish river systems the following are recommended:

- to establish consistent trap operations on a yearly basis at the River Deel site;
- determine the variation in velocity of water through the drum with respect to trapping efficiency; and,
- ensure that the screw trap is in position to enable the start of the smolt run to be determined on a yearly basis (This will highlight changes in migration timings) and to mark smolts in batches of > 50 fish.

From the River Deel data analysis, the classical models provided a more realistic stock estimate for the smolt population on the River Deel in comparison to estimates of the adult run when compared to the individual estimates from the batch data. It was difficult to state which model was the model of choice for future work. The analyses showed that a range of models tested provide enough information to determine the range estimation for the smolt migration but great care is required with respect to choosing a model. These data were used to give the predicted range of the smolt run and the quantity of the run will vary yearly owing to biological factors within this estimated range. The variation in trap efficiency was thought the greatest cause of limiting the number of smolts for marking and recapture but from the mark-recapture data, it was indicative that only a very small proportion of the run was being assessed. It is recommended that Petersen models and Schnabel Regression method with confidence intervals are the most simplistic method of determining the best estimates. However, where experience is available to carry out more sophisticated Bayesian analysis, these should be used in tandem to obtain the best smolt population estimate where no previous smolt population estimates have been carried out. The models of Mäntyniemi and Romakkaniemi (2002) provided the best range of estimates and took into consideration smolt behaviour and environmental factors affect trap efficiency. Rivot and Prévost (2002) model
is recommended for use to predict ‘blind’ data in a distribution where data is sparse between years of smolt migration sampling where a yearly monitoring programme is in place.

Multiple model assessments carried out on the data allowed for a range for the population estimate to be established and were part of the development of the methodology for this type of mark and recapture experiment for Irish rivers. This methodology is recommended as part of any mark-recapture study to enable the best estimate of a salmon smolt population to be determined. High quality flow measurement data and velocities from within the trap should be taken and the continued review and improvement of the sampling protocols and methodology should be undertaken as required. This would allow the optimisation of data collection and improve efficiency of the trap and its operations.

9.3 Combined Information on Both Adult and Juvenile Atlantic salmon Migrations, River Deel

There are a number of challenges facing Ireland with respect to the continued monitoring of Atlantic salmon stocks. New methodology such as DIDSON can produce realistic stock assessment data to enable management decisions to be made for the protection of the species. However, this is made more difficult due to the nature of Irish rivers and the requirement for year round monitoring for complete estimates to be produced. Increased episodes of flash flooding have been shown to make the operation of equipment more onerous nationally, particularly using weir-mounted counters. The DIDSON has been shown on the River Deel to provide a successful alternative to counting salmon even in adverse weather conditions of flash flooding and low flows during draughts. Combining information on both adult and juvenile migrations provides details of freshwater productivity and marine survival, giving valuable information for management. Alternative salmon stock assessment methods are required to provide accurate river specific count data to allow for the continued assessment of stocks for the determination of yearly CL’s where counter technology cannot be installed. Screw trap operations could also be important for stock estimates in smaller catchments and where resources are low and in sensitive areas where in-river works are not permitted, e.g. Freshwater Pearl Mussel Habitats (*Margaratifera margaratifera*).
During this study, increased air and water temperatures on the River Deel were shown to be significant to the upstream migration of adults and were observed to coincide with the outward migration of smolts. Further research is required to determine the possible effects of predicted increased water temperatures over the latter half of this century on Atlantic salmon migration. Analysis of the full impacts particularly on ecosystems is limited due to the absence of long-term monitoring sites. The value of long-term monitoring of salmon migration and environmental data is now evident and a network of long-term ecosystem monitoring sites should be established as part of Atlantic salmon stock assessments nationally. Increased monitoring stations could provide more locally required information which could be gathered at stock assessment sites. This would provide both environmental data for assessment of salmon migration patterns and provide much needed water temperature and river discharge data to determine localised variations. These possible future changes in discharge and temperature due to climate change show that where stock assessments are undertaken in Irish rivers then care should be taken that the counter selection type will not interfere with salmon migration now or in the future. The effects of potential migration barriers, such as weir-mounted counters, on water discharge rates are site specific and specific site investigations will be required to ensure that they are not delaying upstream salmon migrations at high and low flows. There is a need for Ireland to manage its rivers in such a way that does not interfere with the hydrology of our rivers as part of meeting the objectives of the EU Water Framework Directive. Any physical modifications of the river must be limited and the use of DIDSON technology as a counter for Irish rivers has been shown to be non-invasive and does not alter fish migrations. It is and will be more applicable for enumeration of our salmon stocks now and in the future.

The DIDSON has been tested and proven in Irish waters as an effective counter and methodology has been developed making it easy to operate, maintain and obtain count data. For its use in Irish waters, DIDSON operational and processing methods were verified and validated to count and track the migration pattern of salmon in the River Deel-Moy Catchment and to establish a total net upstream salmon count for the Deel tributary. It has a proven ability to count in Irish rivers for twelve months of the year unlike counters already in existence in Ireland, such as the resistivity and Vaki counters which can incur large amounts
of downtime and erroneous counts when operated in flood conditions and turbid waters. Using such approaches to salmon stock estimations will allow for an objective basis for the study of both adult and juvenile (smolt) stocks using hydroacoustic counters and mark-recapture data.

The main limitation for field operations of DIDSON is the large file size which prevents remote downloading. DIDSON was found to be the best method for salmon stock assessment under controlled circumstances. There needs to be an underlying knowledge of the biology of target and non-target species in the river and environmental factors affecting fish movement. DIDSON has been shown to be affective in Irish rivers when installed, operated and data processed as per methodology developed in this study. Investigations were made to determine if the DIDSON counter or other fish counters could be linked to parameters such as water level for the counting of salmon, whereby, the counter would be triggered by a predicted water level relationship with fish upstream migration. The counter could then be set to turn on automatically to count during these specific water temperatures, water levels or flows. This idea was presented to Sound Metrics and is possible in theory to apply to the DIDSON counter technology. However, without specific and defined ‘trigger’ parameters to correlate with fish movement this was not possible for the River Deel and is a recommendation for the future. The technique has a potential solution for other catchments and could result in the saving of valuable resources for operational, maintenance and data analysis for DIDSON and other fish counters.

9.4 Future Management Implications
There are a number of challenges facing Ireland with respect to the continued monitoring of Atlantic salmon stocks. New methodology is required that can produce realistic stock assessment data to enable management decisions to be made for the protection of the species. This in turn is made more difficult due to the nature of our rivers and the requirement for year-round monitoring for best estimates to be produced. Increased episodes of flash flooding have been shown to make the operation of equipment more onerous, particularly using weir-mounted counters. The DIDSON has been shown on the River Deel to provide a successful alternative to count salmon even in adverse weather conditions of flash flooding and low flows.
Fisheries management is now susceptible to budgetary restrictions and this was taken into consideration for the long-term operation of equipment to provide cost-effective strategies for accurate assessments. Resources available should be used for the national development of the DIDSON counter to provide greater information to effectively assess individual salmon stocks, particularly where discrete genetic populations have been identified and to determine the specific run timings of salmon on these catchments. This would allow for more affective protection of the species as a whole. Existing rod catch exploitation restrictions of catch do not go far enough on some rivers for the protection of summer and autumn running MSW fish and for the protection of discrete populations of some tributaries of large river systems. Rod catch data is not sufficient due to low numbers of fish caught for some of these important tributaries such as the River Deel as they cannot be fished sufficiently due to their hydrological characteristics.

ICES (2009) indicated in recent stock forecasts, that the current low sea survival rates will prevail until at least 2013 and priority must be given for conservation rather than catch until there is a noticeable improvement in stock size (Anon., 2010). Accurate stock assessment data are essential for the calculation of Conservation Limits and ensuring that Atlantic salmon stocks are protected. This study now provides the tools to further enhance the ability for managers to determine accurate stock estimates and for the protection of discrete populations.
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