SCOTTISH NATURAL HERITAGE

COMMISSIONED REPORT

Commissioned Report No. 100

Trends in Atlantic salmon: the role of automatic fish counter data in their recording

(ROAME No. F01NB02)

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SCOTTISH NATURAL HERITAGE

COMMISSIONED REPORT Summary

Trends in Atlantic salmon: the role of automatic fish counter data in their recording

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Background

Since 1952, information on the abundance of wild Atlantic salmon (*Salmo salar*) in Scottish waters has come primarily from the monthly rod and net catches. Although useful, these catch data suffer from a number of limitations. Automatic fish counters are a possible complementary method for assessing Atlantic salmon abundance.

A variety of counters are in operation across Scotland. Until now the usefulness of these counters has been assessed on a piecemeal and largely local basis. This report attempts firstly to provide a nationwide assessment of the present state of Scotland's fish counters and secondly to use reliable trends in the counters to draw conclusions about the state of Scottish Atlantic salmon populations.

Main findings

- Twenty-nine fish counters are in active operation in Scotland, some of which have been providing data since the early 1950s.
- Eighteen of the counters have provided more than ten years of data prior to 2002. Of these 12 are appropriately sited, well maintained and regularly validated and are considered reliable by their operators.
- Eleven of the 12 long-term counters, which are considered reliable, have trends that are broadly congruent with the rod catch.
- Of the 12 reliable counters, 3 show a 2-fold increase in the 50 years of data collection. Six show an average decrease of 2-fold or more. The remaining three have been relatively constant.
- Counters on small rivers or tributaries like the Clunie, Dundreggan and Invergarry are likely to be documenting the trend in individual populations.
- The counters demonstrate that Atlantic salmon in neighbouring tributaries may be undergoing divergent trends in abundance. Counters on the mainstem of a river monitor the average trend in a set of tributaries. This trend could mask the decline and even extinction of individual populations.
- Due to the limited number of reliable, long-term counters, the biases in their distribution and the disparity of their trends, the counters cannot be used to draw conclusions about Scottish Atlantic salmon in general – only the population groupings whose abundance they measure.
- Where practical, Atlantic salmon should be monitored and conserved at the smallest geographical scales consistent with population structure. New counters should be sited accordingly to complement any existing information, particularly the rod catch data.

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Glossary

Alevin:	Recently hatched juvenile salmon
Anadromous:	Fish that migrate from the marine to the freshwater environment to breed
Freshet:	Intentional release of water from a reservoir
Fry:	Juvenile salmon less than one year old
Grilse:	Adult salmon returning to fresh water after one winter at sea
Kelt:	Spawned salmon returning to sea
Parr:	Juvenile salmon more than one year old and residing in fresh water
Redd:	Disturbance in gravel produced by spawning female(s)
Smolt:	Juvenile salmon migrating to sea

Abbreviations

CCTV:	Closed Circuit Television
cSAC:	candidate Special Area of Conservation
DSFB:	District Salmon Fishery Board
FRS:	Fisheries Research Services
MWGA:	Ministerial Working Group on Aquaculture
SEPA:	Scottish Environment Protection Agency
SFCC	Scottish Fisheries Coordination Centre
SNH:	Scottish Natural Heritage
SSE:	Scottish and Southern Energy plc

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1 INTRODUCTION

The Natural Heritage Trends series aims to provide an electronic library of information about the changing state of Scotland. This report reviews the utility of automatic fish counters to estimate the abundance of wild adult Atlantic salmon (*Salmo salar*) in Scottish rivers. The report assesses Scotland's fish counters, and compares the long-term counts in twelve counters which have been well-sited and regularly monitored to the rod catch in the relevant fishery district. Obstacles to drawing a Scotland-wide picture of the status of Atlantic salmon from counters alone are discussed and a framework within which all relevant information could be integrated is outlined.

The wild Atlantic salmon is an important part of Scotland's natural heritage. However, the number of adults returning to many spawning areas has declined severely in recent decades, raising concerns that egg deposition is now insufficient in some places. In order to conserve and manage this migratory salmonid, data about the historical and current status of populations is required. Such data are available from seven sources that differ in their informativeness (with respect to adult abundance), scale, coverage and the life-history stage monitored (Table 1).

Table 1 The different sources of data about Atlantic salmon abundance and their informativeness (with respect to adult abundance), scale, coverage and the life-history stage monitored.

Source	Life-stage monitored	Informativeness	Scale	Coverage
Electrofishing	juvenile	low	site	extensive
Smolt trap	juvenile	low	tributary – catchment	c.14 sites
Net Catch	adult	intermediate	catchments	historically extensive
Rod Catch	adult	intermediate	catchment	extensive
Adult trap	adult	high	tributary	c.16 sites
Counte	adult	high?	tributary – catchment	29 sites
Redd Count	adult	low	tributary	limited

The challenges facing Atlantic salmon researchers are how to integrate the sources of data so as to produce a Scotland-wide assessment of Atlantic salmon status and how to identify factors responsible for any changes in abundance. The biology of Atlantic salmon makes this a challenge for three main reasons. Firstly, due to accurate (<10km) natal homing, fish in neighbouring tributaries can belong to distinct populations which might be undergoing divergent changes in abundance. Secondly, since Atlantic salmon are anadromous, their abundance is affected by a large number of freshwater and marine factors which act at different stages of the life-cycle. Thirdly, due to the high fecundity of the adults and associated high density-dependent mortality of alevins and fry, juvenile density tends not to reflect adult abundance until the number of returning fish has dropped to critically low levels.

Furthermore each type of data suffers from its own particular limitations (Section 2). Thus in order to meet the challenge, researchers need to integrate the data from multiple sources. A vital initial step in this process is to assess the value of each type of data. The current report attempts this for the counter data by testing its congruence with the rod catch. Of the 29 counters currently operating in Scottish rivers, only 18 provided sufficient data for a meaningful analysis. Since the aim of this investigation was to determine whether counters can provide useful information about salmon abundance we limited our analysis to those counters with sufficient data which were correctly sited, regularly validated and which were considered reliable by their operator. Twelve of the 18 counters with long-term time series fell into this category. Data provided by these twelve counters were found to be at least of intermediate informativeness. Once the general validity of a type of data has been established the next step is to begin comparing the patterns of variation with those in the other data sources in order to identify the underlying short- and long-term fluctuations in abundance. In order to achieve this, the ongoing comparisons need to be interspersed with targeted data collection. Section 11 compares the trends in the counter and rod catch data for the populations monitored by the 12 counters and attempts to identify factors which might be responsible for any differences. After explaining why the 12 local assessments cannot be extrapolated into a Scotland-wide summary of the status of Atlantic salmon, section 14 then outlines a possible framework within which all the available information could be integrated so as to begin to produce such a summary. Finally, section 15 overviews the enormous number of factors that might be influencing Atlantic salmon numbers and the difficulties involved in distinguishing between them. This report, which demonstrates the informativeness of the counter data and attempts to identify the long-term trends in abundance in 12 population groupings, is a contribution to the ongoing effort to assess the status of Scottish salmon.

2 STRENGTHS AND WEAKNESSES OF THE AVAILABLE DATA

As discussed in the previous section, the seven different sources of data on adult Atlantic salmon abundance (Table 1) have their own particular strengths and weaknesses. Depending on the question being asked the strengths and weaknesses determine which information should be collected and how it should be integrated. Each of the different sources of information is outlined below.

2.1 Electrofishing

Data about adult Atlantic salmon abundance can be obtained by electrofishing streams and small rivers for fry and parr. Excluding the possibility of human stocking, the presence of juvenile Atlantic salmon indicates that one or more adult females successfully spawned in the vicinity of the electrofishing site. However, due to the high fecundity of the adult females relative to the carrying capacity of the freshwater environment, very few adult females are required to repopulate a section of river. Consequently, the density of fry and parr is relatively insensitive to the number of spawning adults: the number of juvenile salmon only falls when the number of adults has declined to critically low levels. Nevertheless, electrofishing data allows a shortfall of spawning adults to be detected. Electrofishing data are collected by Fisheries Research Services (FRS), Fisheries Trusts and District Salmon Fisheries Boards (DSFBs). Much of it is held in the Scottish Fisheries Coordination Centre (SFCC) database (http://www.sfcc.co.uk/).

2.2 Smolt trap

Fixed or mobile traps capture smolts during their migration to the sea. Like electrofishing data, the average number of smolts is relatively insensitive to adult numbers. However, unlike electrofishing data, and depending on the position of the trap, the individuals captured can originate from widely separated streams. Smolt traps are operated by FRS and various Fisheries Trusts and DSFBs.

2.3 Net catch

Since 1952, all proprietors of net fisheries in Scottish coastal and estuarine waters have been legally obliged to return annually a month-by-month record of the number of adult Atlantic salmon caught in their nets. The data are collated by FRS and the seasonal (Jan–Apr and May–Dec) regional level catches published in their Statistical Bulletin. In recent decades both the number of adult salmon reported and the number of nets deployed have declined dramatically. Historically, the large number of adult Atlantic salmon taken by the nets depressed the number of fish entering Scottish rivers. When attempting to relate in-river trends in the abundance of adult Atlantic salmon to particular factors the influence of the net catch cannot be ignored (Youngson *et al.* 2002).

2.4 Rod catch

Like their netting counterparts, all Scottish rod fishery proprietors must return a monthly account of their catches to FRS. Although collected for individual rod fisheries, to maintain confidentiality the rod catch data are aggregated for entire districts.

As well as changes in adult Atlantic salmon abundance, changes in effort, catchability and reporting all affect the rod catch. However, despite these sources of variation, the temporal and spatial coherence of the monthly district rod catch data indicates that at this level, at least, the data contain useful short and long-term signals for salmon abundance. Since 1997, catch and release, particularly of spring Atlantic salmon, has been adopted increasingly by anglers as a strategy to protect against a perceived fall in numbers. The associated changes in angling practice and philosophy may have altered the basis on which catches are made and reported (Youngson *et al.* 2002). The utility of the rod catch data as an indicator of adult Atlantic salmon abundance is compromised somewhat by the fact that they are only available for the fishing season, which typically runs from February to September. Furthermore, although rod caught Atlantic salmon which have been released typically survive to spawn, a few do not. Consequently, should Atlantic salmon numbers decline to critically low levels, fishing effort may need to be reduced – at precisely the time when information about Atlantic salmon abundance is most needed. In addition, in order to convert a catch into an absolute number of fish the efficiency of the anglers, which is likely to vary between sites, months and years, must be estimated. Finally, since Atlantic salmon in neighbouring tributaries within a single catchment may be undergoing divergent trends in abundance, tributaries of particular concern may need to be monitored separately. In many cases the rod catch for a particular tributary will be too small to analyse.

2.5 Adult traps

Approximately 16 adult traps are regularly operated in Scottish fresh waters. Like counters, these traps provide a count of the number of ascending fish. Since each fish is individually verified, the data do not suffer from the problems of missed, false, mixed and multiple counts (see Section 4) that plague counters. However, traps are expensive to install, time-consuming to operate, and the presence of the trap structure may alter fish behaviour. Adult traps are operated by FRS, Scottish and Southern Energy plc (SSE), Fisheries Trusts and DSFBs.

2.6 Counters

As discussed in Section 4, counter data can be compromised by missed, false, mixed, multiple and by-passed counts. Counters are also expensive to buy and install, are vulnerable to vandalism and theft, and must be associated with a suitable in-river structure. They require regular monitoring, maintenance and servicing to ensure the data generated are reliable. In remote locations such as at Grimersta in the Outer Hebrides this can be difficult. Even in more accessible locations, maintenance issues cause problems for continuity and data quality (Stephen 1999; 2003). In addition, since they require an in-river structure most counters cannot be relocated cheaply or quickly. In open river situations, counters and even the in-river structure itself can be damaged or destroyed by flooding. Nevertheless, counters have a number of strengths: they provide an absolute count, they operate all year round and they can be used to monitor Atlantic salmon abundance from the tributary to catchment level. In addition, since a correctly-sited counter should have little or no impact on the passage and survival of fish it can be used even when the status of the counted fish is precarious. Adult counters are operated by FRS, SSE, Scottish Power, Fisheries Trusts, DSFBs and private individuals.

2.7 Redd counts

DSFBs, Fisheries Trusts and private fishery managers have traditionally estimated the number of spawning females in a section of river by counting the number of redds. A redd is the disturbance in the river gravels produced when a female excavates the depression in the river-bed into which she lays her eggs. The presence of redds indicates the presence of spawning females and the number of redds gives a rough indication of the number of spawning females. However, a single female can lay batches of eggs in multiple redds and multiple females can contribute eggs to a single redd (Taggart *et al*. 2001). In addition some redds are eggless. Furthermore, the relationship between the number of spawning females and the number of redds is unknown and may vary between sites and years.

3 COUNTERS

3.1 Overview of counters in Scotland

3.1.1 History of counters in Scotland

Automatic counters were first developed in the late 1940s. Fishery managers wanted to know whether or not migrating adult salmonids were able to negotiate the fish passes being incorporated into the new hydro-electric dams (Lethlean 1953) and whether the dams were responsible for depressing spawning stocks (Holden 1988). More recently, counters have also been installed to check whether freshets of water released by the hydro-electric companies successfully encourage fish upstream (Stephen 1998).

Up until the late 1970s, the vast majority of counters in Scotland were positioned in fish passes on hydro-electric dams. Recent concern about the Scotland-wide status of migratory salmonid populations has led to the establishment of a further series of counters at locations independent of hydro-electric schemes. Although counters are now sometimes used for fisheries management and managing freshet control (see *Case Study: Atlantic salmon in the Tweed and its catchment*), behavioural research and environmental impact assessment, Scottish counter data remain a largely under-utilized resource.

3.1.2 Counters currently in operation in Scotland

To the best of our knowledge there are 29 fish counters actively functioning in Scotland (Figure 1 and Table 2). Nineteen are associated with, or are close to, hydro-electric schemes. Of these, 17 are owned and operated by SSE (Scottish and Southern Energy plc, formerly the North of Scotland Hydro-electric Board and Scottish Hydro-electric) and two by Scottish Power. Of the remaining 10 counters, five are operated by the FRS (one in association with Robin Davison, Isle of Lewis), two by the Middle Dee project and one each by the Tay DSFB, the Dee DSFB and the Tweed Foundation.

Of the 29 active counters, only seven are located on rivers which flow into the sea off Scotland's west coast. They are the Morar, Lochy, Awe, Doon, Grimersta, Morsgail and Tongland counters. The remaining 22 counters are found on catchments draining to the east. This east coast bias occurs primarily because large-scale hydro-electric schemes require major river systems which in Scotland flow eastwards.

Scotland is divided into eleven Atlantic salmon fishery statistical regions, and 109 districts. The districts are fused to produce 62 combined fishery districts (Anon. 2003). Eight counters are located in the Moray Firth region, six in the East region, five in the North-East region and three in the North region. The West and Outer Hebrides regions each have two counters, while the North-West, Clyde Coast and Solway Firth regions each have one. Orkney and Shetland, are the only regions that have no counters in place.

3.1.3 Future counters in Scotland

A number of new counters (both resistivity and optical) are planned for the future on the Tweed (see *Case Study: Atlantic salmon in the Tweed and its catchment*), the Tay, the Spey and the Kirkcudbrightshire Dee (Table 3). Counters that are no longer in operation are listed in Table 4.

Figure 1 Position of active fish counters in Scotland relative to Atlantic salmon fishery statistical regions. Fish counters analysed are indicated by the use of capitals in the legend.

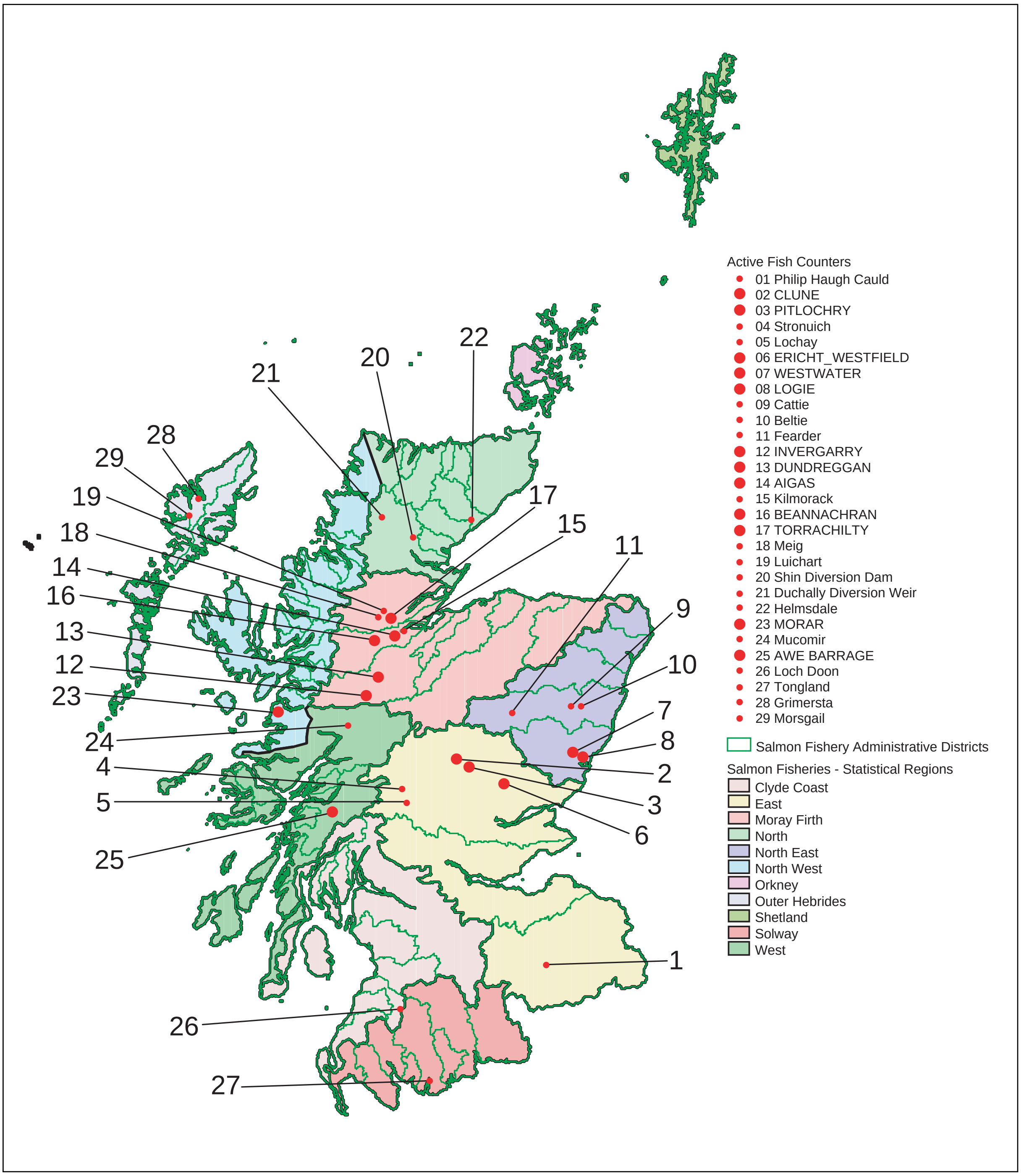

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Table 2 Counters operating currently

No	Counter	River	Counter type (current)	In-river structure	Year installed	Period data available	Counter owner	Catchment	District (uncombined)	Region	Grid reference
1	Philiphaugh Cauld	Ettrick	Optical, Vaki	Fish ladder on weir	1996	1998-present	Tweed Foundation	Tweed	Tweed	East	NT 448 275
2	Clunie	Tummel	Resistivity, Mark 10, 3-electrode	Fish ladder on dam	1953	1953-present	SSE	Tay	Tay	East	NN 885 603
3	Pitlochry	Tummel	Resistivity, Mark 10, 3-electrode	Fish ladder on dam	1953	1953-present	SSE	Tay	Tay	East	NN 935 577
4	Stronuich	Lyon	Resistivity, Mark 10, 5-electrode	Weir, flat, controlled flow	1961	1961-1981 & 1987-1992 & 1994-present	SSE	Tay	Tay	East	NN 512 421
5	Lochay	Lochay	Resistivity, Mark 10, 3-electrode	Borland lift	1960	1960-1978 & 1986-present	SSE	Tay	Tay	East	NN 543 351
6	Ericht	Ericht	Resistivity, Mark 10, 3-electrode	Fish ladder on weir	1990	1990-present	Tay DSFB	Tay	Tay	East	N0 176 463
7	Westwater	Westwater	Resistivity, Logie	Weir, Crump, 3 channels	1990	1990-present	FRS	North Esk	North Esk	North-East	NO 604 663
8	Logie	North Esk	Resistivity, Logie	Weir, Crump, 3 channels	1980	1981-present	FRS	North Esk	North Esk	North-East	NO 698 641
9	Cattie	Cattie	Optical, Vaki	Small dam with 600mm deep x 400mm wide hole	1998	1998-present	Middle Dee Project	Dee (Aberdeen)	Dee (Aberdeen)	North-East	NO 616 961
10	Beltie	Beltie	Optical, Vaki	Small dam with 600mm deep x 400mm wide hole	1998	1998-present	Middle Dee Project	Dee (Aberdeen)	Dee (Aberdeen)	North-East	NO 667 964
11	Fearder	Fearder	Optical, Vaki	Small dam with 600mm deep x 400mm wide hole	2001	2001-present	Dee DSFB	Dee (Aberdeen)	Dee (Aberdeen)	North-East	NO 230 936
12	Invergarry	Garry	Resistivity, Mark 10, 3-electrode	Borland lift in dam	1956	1956-1985 & 1987-present	SSE	Ness	Ness	Moray Firth	NH 276 021
13	Dundreggan	Moriston	Resistivity, Mark 10, 3-electrode	Borland lift in dam	1969	1969-1985 & 1988-present	SSE	Ness	Ness	Moray Firth	NH 358 157
14	Aigas	Beauly	Resistivity, Mark 10, 3-electrode	Borland lift in dam	1963	1963-present	SSE	Beauly	Beauly	Moray Firth	NH 474 437

Table 2 Counters operating currently *(continued)*

No	Counter	River	Counter type (current)	In-river structure	Year installed	Period data available	Counter owner	Catchment	District (uncombined)	Region	Grid reference
15	Kilmorack	Beauly	Resistivity, Mark 10, 3-electrode	Borland lift in dam	1963	1996-present	SSE	Beauly	Beauly	Moray Firth	NH 494 442
16	Beannachran	Farrar	Resistivity, Mark 10, 3-electrode	Borland lift in dam	1963	1963-1986 & 1988-present	SSE	Beauly	Beauly	Moray Firth	NH 326 394
17	Torr Achilty	Conon	Resistivity, Mark 10, 3-electrode	Borland lift in dam	1955	1955-present	SSE	Conon	Conon	Moray Firth	NH 447 545
18	Meig	Conon	Resistivity, Mark 10, 3-electrode	Borland lift in dam	1957	1957-1983 & 1985-present	SSE	Conon	Conon	Moray Firth	NH 376 561
19	Luichart	Conon	Resistivity, Mark 10, 3-electrode	Borland lift in dam	1994	1994-present	SSE	Conon	Conon	Moray Firth	NH 387 579
20	Shin Diversion Dam	Shin	Resistivity, Mark 10, 3-electrode	Borland lift in dam	1988	1988-present	SSE	Shin	Kyle of Sutherland	North	NC 581 051
21	Duchally Diversion Weir	Cassley	Resistivity, Mark 10, 3-electrode	Borland lift in dam	1997	1997-present	SSE	Cassley	Kyle of Sutherland	North	NC 368 203
22	Helmsdale	Helmsdale	Resistivity, Logie	Weir, Crump, 3 channels	1993	2001-present	FRS	Helmsdale	Helmsdale	North	NC 978 185
23	Morar	Morar	Resistivity, Mark 10, 5-electrode & Optical, Vaki	Fish ladder on dam	1960	1960-present	SSE	Morar	Morar	North-West	NM 683 922
24	Mucomir	Lochy	Resistivity, Mark 10, 5-electrode	Borland lift in dam	1963	1963-present	SSE	Lochy	Lochy	West	NN 183 839
25	Awe Barrage	Awe	Resistivity, Mark 10, 3-electrode	Borland lift in dam	1964	1964-present	SSE	Awe	Awe	West	NN 045 288
26	Loch Doon	Doon	Resistivity, Logie	Fish ladder	1981	1981-1983 & 1986-present	Scottish Power	Doon	Doon	Clyde Coast	NS 477 015
27	Tongland	Kirkcud-bright Dee	Resistivity, Logie	Fish ladder on dam	2001	2001-present	Scottish Power	Dee-Ken	Dee (Kirkcudbright)	Solway	NX 702 545
28	Grimersta	Grimersta	Resistivity, Logie	Weir, DIY Crump, 1 channel	1994	no data	FRS	Grimersta	Isle of Lewis	Outer Hebrides	NB 214 297
29	Morsgail	Morsgail	Resistivity, Logie	Weir, flat-bottomed, 3 channels	1991	1992-present	FRS & Robin Davidson	Morsgail	Isle of Lewis	Outer Hebrides	NB 138 224

Table 3 Counters planned for future

No	Counter	River	Counter type (current)	In-river structure	Year installed	Period data available	Counter owner	Catchment	District (uncombined)	Region	Grid reference
1	Gala	Gala	Optical, Vaki	Fish ladder on dam	future	n/a	Tweed Foundation	Tweed	Tweed	East	
2	Gaur	Gaur/ Tummel	to be decided	Fish ladder & Borland lift on dam	2004	n/a	SSE	Tay	Tay	East	NN 464 568
3	Dullan Water	Fiddich	Optical, Vaki	Fish ladder on weir	2004	n/a	Spey FB	Spey	Spey	Moray Firth	NJ 324 390
4	Truim	Truim	Resistivity, Mark 10, 3-electrode	Fish ladder on weir	2004	n/a	Spey FB & SSE	Spey	Spey	Moray Firth	NH 639 835
5	Spey Dam	Spey	Optical, Vaki	Fish ladder on dam	2004	n/a	Spey FB	Spey	Spey	Moray Firth	NH 582 936
6	Earlstoun	Water of Ken	Resistivity, Logie	Fish ladder on dam	future	n/a	Scottish Power	Dee-Ken	Dee (Kirkcudbright)	Solway	NX 613 818
7	Carsfad	Water of Ken	Resistivity, Logie	Fish ladder on dam	future	n/a	Scottish Power	Dee-Ken	Dee (Kirkcudbright)	Solway	NX 605 855

Table 4 Counters operating historically

No	Counter	River	Counter type (current)	In-river structure	Year installed	Period data available	Counter owner	Catchment	District (uncombined)	Region	Grid reference
1	Dunalastair	Tummel	Resistivity	Fish ladder			SSE	Tay	Tay	East	NN 722 591
2	Errochty	Garry	Resistivity	Weir, flow-gauging			SSE	Tay	Tay	East	NN 805 652
3	St Fillans	Earn	Resistivity	Fish ladder on weir			SSE	Tay	Tay	East	NN 698 241
4	Invermark	Water of Mark	Resistivity, Logie	Weir, flat-topped	1995		FRS	North Esk	North Esk	North-East	NO 444 804
5	Whitley	Dee	Resistivity, Logie	Weir, Crump, 8 channels	1992	1992-1998	FRS	Dee (Aberdeen)	Dee (Aberdeen)	North-East	NJ 918 029
6	Collie Pot	Spey	Hydroacoustic, HTI Model 243, Splitbeam	not required	1996	1998-2000	Spey Research Trust	Spey	Spey	Moray Firth	portable
7	Lairg	Shin	Resistivity, Mark 10, 3-electrode	Borland lift in dam	1990	1990-2000	SSE	Shin	Kyle of Sutherland	North	NC 575 069
8	Laggan	Laggan	Resistivity, Logie	Weir, DIY Crump, 3 channels	1994	no data	FRS	Laggan (Islay)	Islay	West	NR 311 569
9	Water of Luce	Luce	Resistivity, Logie	Weir, 4 channels	1995	1995-1998	FRS	Luce	Luce	Solway	NX 192 572

3.2 Types of in-river structure

All but three of Scotland's counters are currently associated with one of three types of in-river structure: weirs, fish ladders and Borland lift fish passes. Such structures, while greatly facilitating the counting process by bringing fish into the range of the counter detectors, need to be carefully chosen. An inappropriately constructed in-river structure will severely impair the correct functioning of any counter. Each of the remaining three counters are positioned in a 60cm by 40cm orifice in a barricade across a small tributary of the River Dee (the Cattie, Beltie and Fearder).

Plate 1. The 'Crump'-type weir with embedded counting electrodes at Logie on the River North Esk (North Esk catchment). Reproduced courtesy of Dan Eatherley.

3.2.1 Weirs

Six counters are currently associated with weirs of varying design. The precise construction of the weir is crucial in determining the effectiveness of the counter. Indeed data generated by counters sited on weirs that are not of the so-called 'Crump' design should be treated with extreme caution. Although originally designed for river discharge monitoring (Crump 1952), well-constructed Crump weirs are ideal locations for siting fish counters, particularly resistivity counters. The triangular profile of the Crump weir, with a 1:2 slope on the upstream face and a 1:5 slope on the downstream face, ensures a rapid, shallow planar flow over the downstream portion of the weir (Plate 1). The speed and depth of this flow forces ascending fish close to the counting array (normally electrodes) embedded in the downstream face. The strong current also prevents fish from lingering which can result in multiple or missed counts (see Section 4).

Plate 2. The fish ladder at Clunie dam on the River Tummel (Tay catchment). Reproduced courtesy of Dan Eatherley.

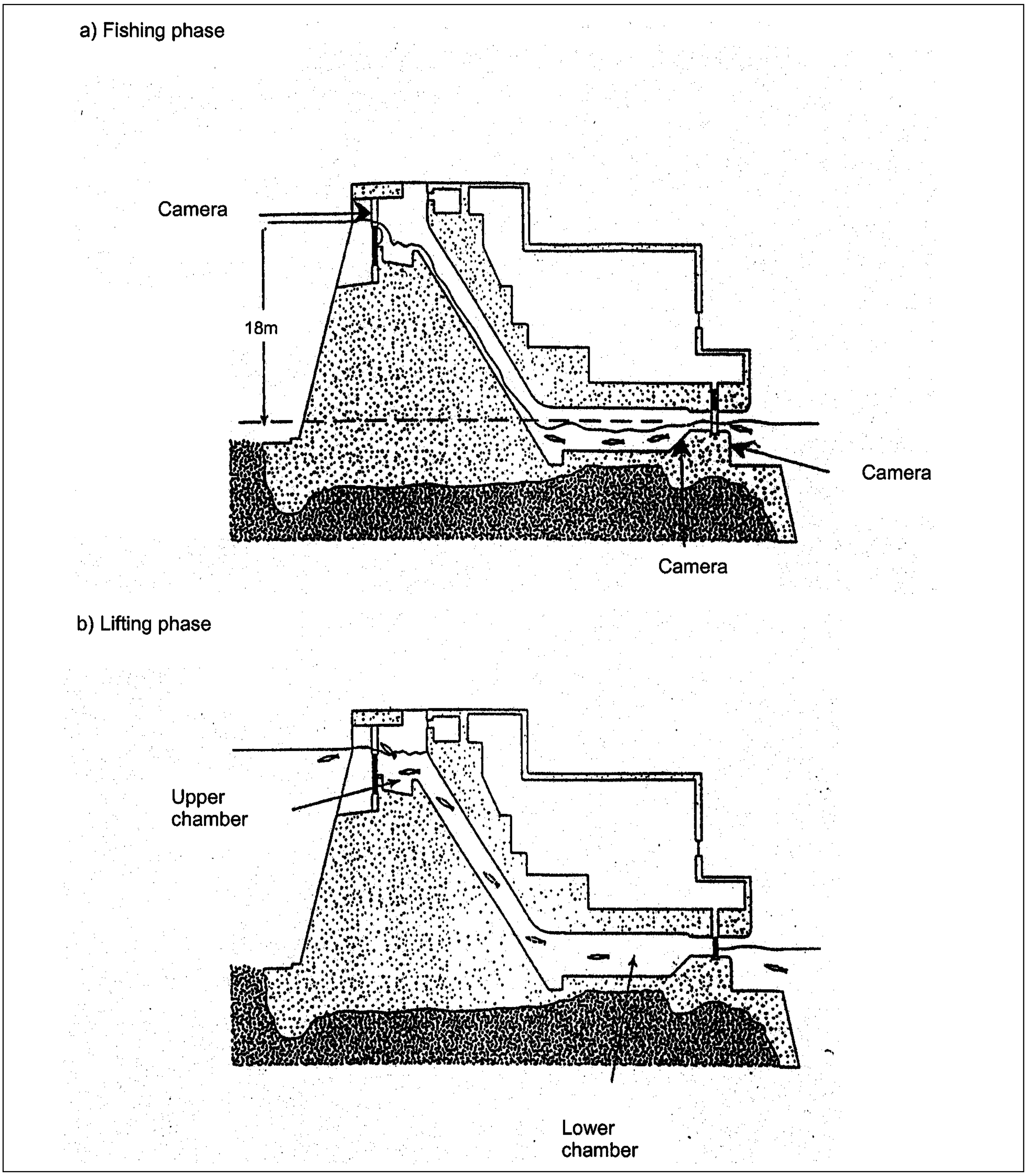
3.2.2 Fish ladders

Seven counters are currently located within fish ladders. Fish ladders consist of a series of stepped pools (Plate 2). The pools are connected either by tubes of varying diameter or by overshot weirs to allow the passage of migratory salmonids up or downstream.

3.2.3 Borland lift fish passes

Thirteen counters are currently incorporated within Borland lift fish passes. Borland lift fish passes were designed to overcome differences in river height or ‘head’ at hydro dams. The Borland lift consists of a lower chamber, situated at the base of the dam at the level of the tailrace, and an upper chamber at the surface of the reservoir (Figure 2). The two chambers are connected by a sloping, or in some cases, vertical shaft. During the ‘fishing phase’, the lower chamber of the Borland lift is open and water flows down through the pass to encourage homing fish to enter the lower chamber. After a set period, the lower chamber is closed and the shaft fills with water. This period is termed the ‘lifting phase.’ Fish inside the lower chamber are then able to swim up the shaft to the upper chamber where they exit into the reservoir or impoundment above the dam. The number and duration of lifting phases depends on the location. Typically the lift will operate on a continuous cycle with the facilities “fishing” for three hours followed by a one-hour lift.

Figure 2 Sectional representation of the Kilmorack Borland lift fish pass. Reproduced with permission from Forbes et al. (2002).



3.3 Types of counter

Three broad classes of automatic fish counting device are currently used or have been used in Scotland: resistivity counters, optical counters and hydroacoustic counters.

3.3.1 Resistivity counters

Resistivity counters operate on the principle that the body of a fish has lower electrical resistance than the surrounding water. Normally, three electrodes, each separated by approximately 45cm, are mounted across the flow of a counting channel. The outer electrodes are energized with a low voltage. The spaces between the two electrodes and the central electrode form two arms of a Wheatstone bridge. A Wheatstone bridge is an electrical balancing circuit used to detect small changes in resistance.

The distance between the electrodes determines the length of fish detected. As a rule of thumb, only fish longer than this distance can cover more than one electrode and trigger a count. In addition the magnitude of the change in resistance provides a rough indication of the size of the fish responsible for the count. The direction of the fish is indicated by the shape of the signal (Figure 3).

In certain locations where the status of sea trout (*Salmo trutta*) is of interest, two resistivity counters can operate side by side. Here the counting array consists of five electrodes each separated by approximately 20cm rather than three electrodes separated by 45cm. SSE installations at Morar, Mucomir and Stronuich currently have five-electrode arrays.

The first resistivity counter in Scotland was installed in one of the tubes near the top of the Pitlochry fish ladder in 1952. A modern version still functions there today. Three stainless steel hoops, which function as electrodes, each separated by approximately 45cm, are mounted on the inner surface of an insulated concrete tube.

In Borland lift fish passes, the resistivity counter is attached to the insulated floor of a counting flume normally located at the exit of the upper chamber. The counting array consists of three parallel stainless steel electrodes positioned perpendicular to the direction of flow. Again, the electrodes are separated by approximately 45cm.

Over the last fifty years, SSE have constantly updated and improved the counters associated with in-river structures. The most recent model, the Mark 10, no longer uses a Wheatstone Bridge to detect changes in resistance. Instead the conductivity between the electrode pairs is monitored directly, reducing the likelihood of false counts.

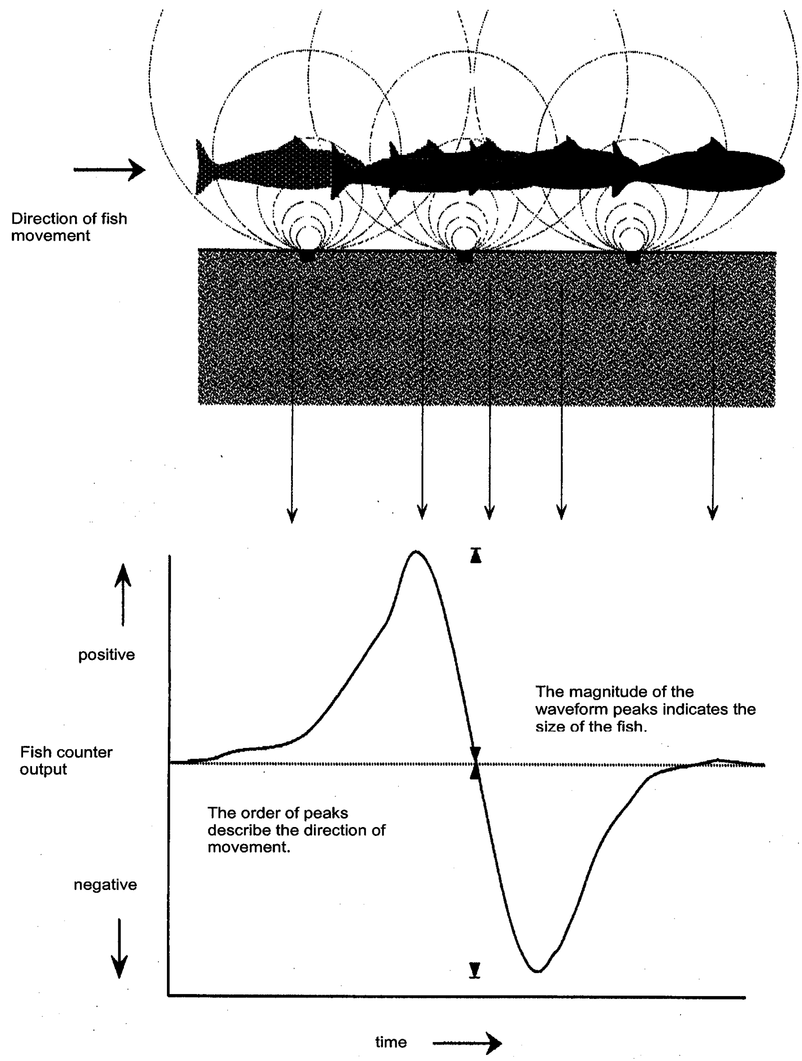
Resistivity counters are the most common type of counter deployed in Scotland. Twenty-four of the 29 active counters record the passage of fish by detecting the change in resistance when a fish swims past. Two models are currently in use in Scotland. The Mark 1 to Mark 10 systems, designed originally by the North of Scotland Hydro-electric Board (now SSE), and the Logie counters developed by Aquantic Ltd.

The Logie counter is named after the location on the North Esk where trials were first conducted (Plate 1). The system is currently manufactured by Aquantic Ltd. Two basic models, are the 1700 series, a single channel counter, and the 2100 series, which can be used with up to four channels. Modern Logie counters use a fish signal discrimination algorithm to reduce the incidence of false counts.

Seventeen Mark 10 resistivity counters are operated by SSE. A Mark 10 counter is also in operation on the River Ericht above Cargill's leap. Five Aquantic Logie counters are owned and operated by FRS Montrose. A further two Logie counters currently operate at Scottish Power installations.

There are plans to install Mark 10 resistivity counters at SSE's dams on the Rivers Gaur (Tay catchment) and Truim (Spey catchment). Scottish Power is currently costing proposals to place Logie counters on the Earlston and Carsfad installations (Dee-Ken catchment).

Figure 3 The passage of a fish over counting electrodes with the resistance change waveform below. Reproduced from Fewings (1994) with permission of The Atlantic Salmon Trust.



3.3.2 Optical counters

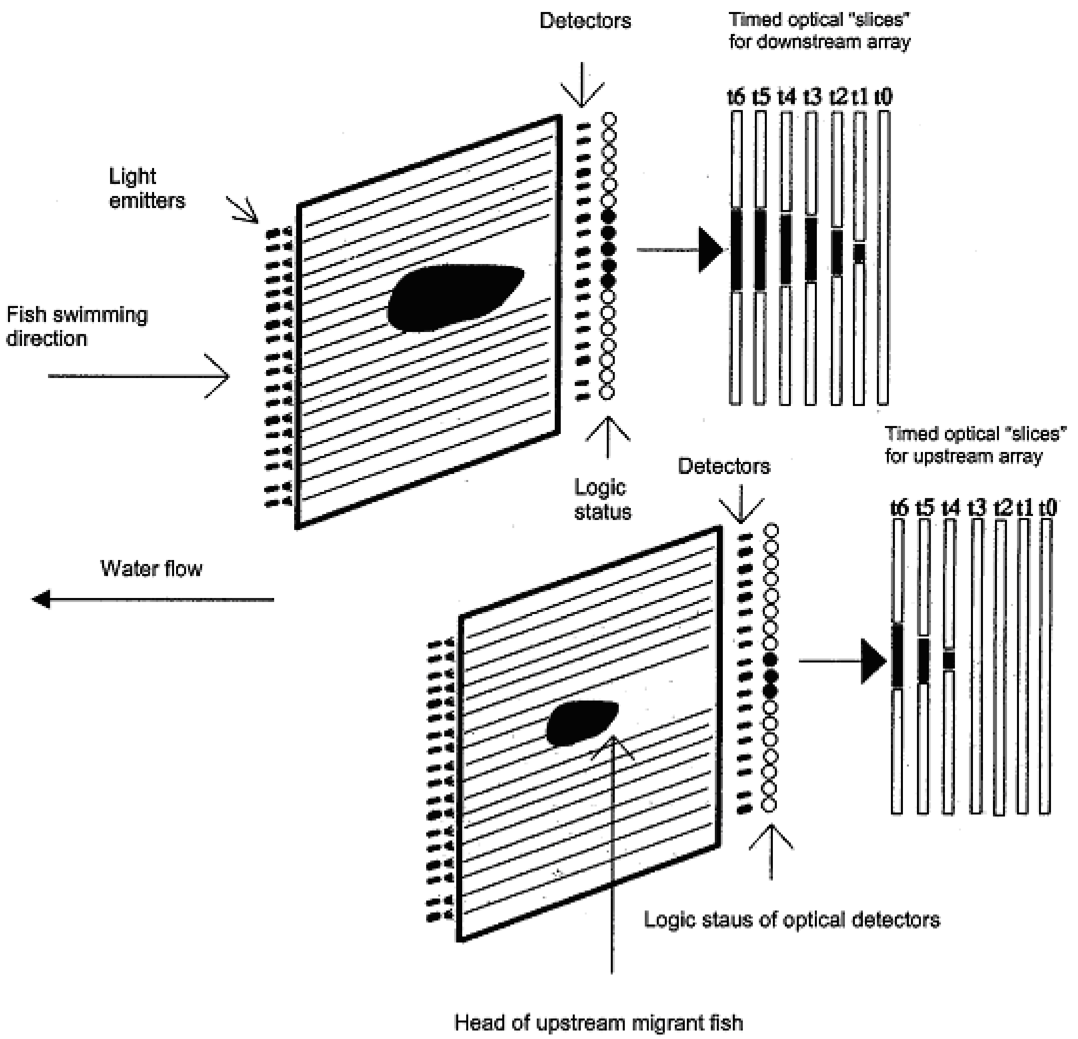
Just one model of optical counter is currently in use in Scotland: the Riverwatcher, manufactured by Vaki Aquaculture Systems Ltd of Iceland. Vaki counters are found on one SSE installation (at Morar), while another three are in operation on the Aberdeenshire Dee. A fifth Vaki counter is in operation on the River Tweed (see *Case Study: Atlantic salmon in the Tweed and its catchment*). Further Vaki counters are planned for the Tweed catchment in the Gala Water and for the Spey, both on the mainstem at Spey Dam and at Dullan Water on the River Fiddich (J. Butler *pers. com.*).

The Vaki Riverwatcher uses a linear sensory array to measure the height (ventral-dorsal) of a fish breaking infra-red light beams emitted from a series of diodes positioned opposite the sensors. As the fish swims forward it breaks a second array of infra-red light beams. From the height of the fish and the rate it moves between the two arrays the counter is able to reconstruct the outline of the fish (Figure 4). This outline is then stored to allow the count to be validated by the operator. A video camera add-on is now also available to eliminate the possibility of false counts.

3.3.3 Hydroacoustic counters

Although fixed-location hydroacoustic counters have been used widely in North American rivers since the 1960s, the only counter of this type in Scotland was the split-beam HTI Model 243 on the Spey between 1996 and 2000. There are currently no firm plans to reinstate this counter (R. Laughton *pers. com.*).

Figure 4 Description of the linear array method of optical fish counting. Reproduced from Fewings (1994) with permission of The Atlantic Salmon Trust.



These two optical arrays are placed one upstream of the other, separated by approximately 10cm. Time delays between corresponding features of the passing objects allow reconstruction of velocity profiles and therefore the spatial separation between adjacent optical "slices" of the object. Subsequent processing enables the calculation of individual fish length and weight in addition to population biomass and length frequency statistics.

Although relatively expensive, modern hydroacoustic counters are highly versatile in that they can operate in the absence of an in-river structure such as a weir. This is certainly an advantage over other types of fish counter although the performance of hydroacoustic counters has often been poor (see Section 8). Other recent advances include the development of more discriminatory post-processing software and the development of multi-beam systems.

4 TYPES OF COUNTING ERROR

As well as the limitations discussed in section 2.6, the accuracy of all types of counters can be compromised by five main types of counting error: missed counts, false counts, mixed counts, multiple counts and by-passed counts. Although somewhat arbitrary the division of counter errors into these five categories is nonetheless useful.

4.1 Missed counts

A missed count occurs when a counter fails to record a passing fish. This occurs when, for example, a fish passes the counter too rapidly for the sensors to detect it. Alternatively, turbulence or turbidity in the water might impair the sensors' function. Missed counts can also occur when two or more fish simultaneously pass the counter but only register as a single count (Dunkley & Shearer 1982). In the case of a counter associated with a fish ladder or Borland fish lift pass this phenomena is known as 'multiple fish exit' (Plate 3).

4.2 False counts

A false count occurs when something other than a fish is registered by the counter. A wide variety of objects passing downstream can lead to false counts including algal mats (Simpson 1978), ice (Dunkley & Shearer 1982), air bubbles (Gray *et al*. 1998; Struthers 1998), otters (*Lutra lutra*) and canoeists (Holden 1988; Struthers 1998).

4.3 Mixed counts

Mixed counts occur when fish other than the type of fish being investigated are counted. For example, the failure to distinguish sea trout from Atlantic salmon, which can overlap in size, often causes mixed counts. This is a particular problem in the Tweed system (see *Case Study: Atlantic salmon in the Tweed and its catchment*) and at Morar (Stephen 2003). More serious are problems caused by escaped farmed fish (see *Case Study: Effects of escaped farmed fish*). The passage of coarse fish, such as pike (*Esox lucius*) and eels (*Anguilla anguilla*), can also cause mixed counts.

4.4 Multiple counts

Multiple counts occur when the same fish is counted more than once. These usually result from a fish swimming back and forth past the counter or simply lingering in the area. Careful design and siting of the in-river structure can reduce multiple counts. With a properly constructed Crump weir or fish ladder, fish are encouraged to swim quickly past the counter. To reduce this possibility counters should not be located too close to spawning grounds where fish exhibiting searching behaviours may travel back and forth across the sensing array.

Counter operators try to reduce the incidence of multiple counts by subtracting the total down-count, which is assumed to be caused by droppers (descending maiden fish) from the total up-count to give the net upstream count. However, in certain situations, descending fish may by-pass the counter (see Section 4.5). Furthermore, kelts also cause down-counts but unlike droppers they should not be subtracted from the total up-count. Counter operators try to separate droppers from kelts by only subtracting the down-count during the summer months. However, in places with an early run of spring Atlantic salmon, for example at Pitlochry, both kelts and droppers contribute to the spring down-count. The dropper season cut-off dates need to be chosen carefully so as to minimise the error. At Pitlochry, down-counts are considered to be droppers from April to December. In situations where the incidence of droppers is considered negligible, such as at the Ericht counter in the Tay catchment, the operator may ignore the down-counts year round (D. Summers *pers. com.*).

Plate 3. An example of multiple fish exit leading to missed counts from the Borland lift fish pass at Meig diversion weir on the River Conon (Conon catchment). CCTV validation reveals eight fish passing over the resistivity counting flume but registering as one. Reproduced courtesy of Dan Eatherley.

4.5 By-passed counts

A by-passed count is similar to a missed count but occurs when a fish negotiates the section of river without passing the counter. The counter is in effect by-passed with no chance of counting the fish however well-validated it is. By-passed counts are most likely on poorly-constructed or inappropriately situated weirs during spates. Counters within Borland lifts or fish ladders associated with large-scale dams cannot be by-passed.

5 VALIDATING COUNTERS

Counting errors are a serious concern and operators should regularly validate their counter to quantify its 'accuracy.' Unfortunately most studies do not define what they mean by accuracy. Under one interpretation the accuracy of the counter is the number of counts divided by the number of ascending fish multiplied by 100%. However, under this definition false counts can compensate for missed counts and could even result in an accuracy of >100%. Alternatively accuracy may be the percent of the ascending salmon that are not missed, but this definition fails to take into account false counts and other types of counting error. To be most useful the validation exercise should attempt to assess the frequency of all five types of counting error – not just missed and/or false counts – under a range of river conditions and run sizes. The magnitude of each type of counting error should be presented separately. However, most studies provide a single percentage and fail to define precisely what it means. In the following section we give some published assessments of 'accuracy' since, despite their shortcomings, they nevertheless provide some indication of the performance of a counter.

5.1 Visual validation

Counters have been traditionally validated by direct visual observation where the counts are compared with the observed passage of fish (either naturally moving or towed) across the counter array.

In recent times, closed-circuit television (CCTV) has been used as the main validation method at many counter sites (eg Dunkley & Shearer 1982; Fewings 1998 and Forbes *et al*. 1999a,b; 2000). It is important to be aware that validation based on a video or stills camera, which is triggered by a registered count, will fail to record missed counts leading to an over-estimate of counter accuracy. To avoid this problem one or more video cameras should be kept running continuously throughout the course of the validation exercises and all tapes carefully scrutinised.

All visual validation methods are themselves subject to error, particularly if the water is turbid, or there is low-light intensity or glare (Struthers 1998). During periods of extremely high flow, resistivity counters on weir structures cannot be validated by visual methods at all.

5.2 Signal analysis

The ability of a counter to discriminate between false and true counts can in some cases be determined by examining the signals generated by the counters and comparing them to the signals produced by fish and known objects.

5.3 Traps

Unlike visual methods, fish-traps positioned up and downstream provide a means to validate counters in turbid water (Reddin *et al*. 1992). They also allow the accuracy of the counter with respect to all types of counting error to be quantified. However, this method requires frequent trap inspections and there is a danger that the presence of the trap structures alters the behaviour of the fishes.

6 PERFORMANCE OF RESISTIVITY COUNTERS

6.1 Missed counts in resistivity counters

6.1.1 Missed counts in weirs

A major limitation of resistivity counters is that they can only detect fish swimming relatively close to the sensors. In deep water, fish that swim high in the water column may not be counted. This problem is most acute in open channel situations particularly when counters are placed on weirs. The design of the in-river structure is crucial in overcoming this problem.

Even a well-designed Crump weir will not eliminate missed counts altogether. For resistivity counters, there is always likely to be an underestimate of the down-count because fish moving downstream do not need to fight the current. These fish tend to be scattered throughout the water column, sometimes out of range of the electrodes and occasionally at oblique angles to the electrode array (Smith *et al.* 1996; Johnstone *et al.* 1998).

6.1.2 Missed counts in fish ladders

Missed counts are less likely in fish ladders than they are in weir situations. Here, fish are forced through a relatively narrow gap and, hence, normally within range of the electrodes. Multiple fish exit is unusual because the size of the gap discourages simultaneous passage of fish (Struthers 1998).

6.1.3 Missed counts in Borland lift fish passes

Most of Scotland's resistivity counters are currently sited on Borland lift fish passes rather than Crump weirs or fish ladders. The counting electrodes are normally positioned on a flat-bottomed flume at the top of a fish pass. The height of water flowing over the counting flume is precisely controlled using ultrasonic sensors. Resistivity counters in these situations are less likely to suffer missed counts due to fish swimming out of the range of the electrodes. However, missed counts due to multiple fish exit can occur on resistivity counters associated with a fish lift pass since the fish become bunched during the lifting phase.

6.2 False counts in resistivity counters

Wave action over counting electrodes can produce both false counts (by temporarily increasing conductivity between the electrodes) and missed counts (by allowing ascending fish to pass out of the range of the electrodes). Strong winds can generate turbulence particularly when river height is low. In Scotland, this problem affected the first Logie counter on the North Esk and more recently the counter at the Lairg Power Station (Stephen 2003). Both of these sites are vulnerable to severe local weather conditions at particular times of year. Even in the absence of wind, turbulence can result from badly designed flow channels or a rough river bed upstream (Gray *et al.* 1998).

Later models of resistivity counter are better able to discriminate genuine fish signals from many of the false events described above, especially when associated with an appropriate in-river structure (Fewings 1994; Gray *et al.* 1998). SSE's Mark 11 counter which is still in development should avoid the problem of false counts entirely by providing digital images of the detected object whenever a count is triggered.

6.3 Mixed counts in resistivity counters

Resistivity counters are particularly susceptible to mixed counts, especially when sited in locations with fish of a comparable size to Atlantic salmon, such as large sea trout. Other fish, particularly those from fish farms, can also lead to mixed counts. For example, since 1997 counts at SSE's Mucomir dam have been invalidated by escapes of rainbow trout (*Oncorhynchus mykiss*) from the fish farm at nearby Loch Lochy (Stephen 1997; 2003).

6.4 Multiple counts in resistivity counters

Like all counters, the vulnerability of resistivity counters to multiple counts depends on the in-river structure, the siting of the counter and timing of the kelts relative to the spring run.

6.5 By-passed counts in resistivity counters

Problems with by-passed counts will depend on the design of the in-river structure. For example, during periods of high flow fish can swim around the weir at Grimersta, avoiding detection.

6.6 Performance of resistivity counters

Several studies have assessed the performance of resistivity counters in a variety of situations. In 2001, CCTV validation found the Pitlochry tube counter to be 97% accurate for up-counts of spring Atlantic salmon, confirming the accuracy of previous visual tests (Stephen 2002). The accuracy was lower, however, for down-counts and summer grilse. As discussed above, multiple fish exit can lower the accuracy of a resistivity counter. Forbes *et al*. (1999a), for example, found a significant negative relationship between numbers of fish ascending the Borland lift at Kilmorack Power Station and the accuracy of the associated Mark 10 counter. Nevertheless, even when there were many instances of multiple fish exit, overall accuracy levels remained greater than 90%.

Studies on the North Esk revealed that the Aquantic Logie counter associated with the weir at Logie counted more than 90% of the ascending fish detected by CCTV and time lapse video (Dunkley 1992). However this study was not conducted in spate conditions. Studies in northwest England show that the counting efficiency of a Logie counter in a weir situation declines with increasing water depth (Fewings 1998). Further support for the Logie counter comes from Newfoundland where Reddin *et al*. (1992) demonstrated with traps above and below the counter that the upstream accuracy was 100%.

7 PERFORMANCE OF OPTICAL COUNTERS

7.1 Missed counts in optical counters

Perhaps the key drawback of optical counters, and especially those using infra-red light, is the relatively short distance over which the beams can penetrate through water. This limits their use to fish ladders, passes and river areas where the navigable flow is concentrated through a small area. The increased attenuation of light caused by turbidity can also limit the ability of optical counters to detect passing fish (Campbell 1998; Struthers 1998).

7.2 False counts in optical counters

Optical counters such as the Vaki Riverwatcher suffer less than current resistivity counters from false counts since an outline of the object responsible is recorded for the operator to verify. A video-camera add-on can reduce the possibility of false counts.

7.3 Mixed counts in optical counters

Since optical counters can estimate the size of each fish with a reasonable degree of accuracy, they are more reliable than resistivity counters for distinguishing between Atlantic salmon and sea trout.

For this reason, SSE decided to withdraw their Mark 10 counter from use on the River Morar and replace it with a Vaki Riverwatcher, which is operated by the local Fishery Trust (Stephen 2003). A Vaki counter is also used at Philiphaugh Cauld on the Tweed system (see *Case Study: Atlantic salmon in the Tweed and its catchment*) and planned for Dullan Water on the Spey (J. Butler *pers. com.*) for similar reasons. However, like other automatic counters, optical counters cannot discriminate between farmed and wild Atlantic salmon.

7.4 Multiple counts in optical counters

Like all counters, the vulnerability of optical counters to multiple counts depends on the in-river structure, the siting of the counter and the time of the year when droppers are discriminated from kelts.

7.5 By-passed counts in optical counters

Problems with by-passed counts will also depend on the in-river structure.

7.6 Performance of optical counters

Tests conducted by the Icelandic Institute of Freshwater Fisheries on the River Blanda found the Vaki counter to be 98.9% accurate (Fewings 1994), whilst a more recent time-lapse video validation study on the Itchen in England found the counter to be 93% accurate in counting fish. Furthermore, when debris, turbidity and air bubble entrainment were kept to a minimum the accuracy increased to 100% (Fewings 1998).

8 PERFORMANCE OF HYDROACOUSTIC COUNTERS

8.1 Missed or by-passed counts in hydroacoustic counters

Missed or by-passed counts are a major problem for hydroacoustic counters. The 'sound beam' of hydroacoustic counters cannot be directed close to the river bed as solid objects interfere with the echoes. However, since fish swimming upstream tend to hug the river bed they often pass 'under the sonar.' Like all counters, site selection is paramount when using a hydroacoustic device. However, in some rivers no suitable sites will exist naturally. Possible solutions to this problem are to make the river bed level using sand bags or to incorporate a screen to guide fish into the beam (Enzenhofer & Olsen 1996; Brotherston 2002). Hydroacoustic counters can also miss counts when there are high levels of background noise caused by entrained air bubbles or turbulent water (Laughton 1998).

8.2 False counts in hydroacoustic counters

A wide variety of objects carried downstream can cause false counts in hydroacoustic counters, particularly the earlier models (Laughton 1998).

8.3 Mixed counts in hydroacoustic counters

With only a limited ability to judge fish size, mixed counts are very likely.

8.4 Multiple counts in hydroacoustic counters

Like all counters, the vulnerability of hydroacoustic counters to multiple counts depends on the siting of the counter and the time of the year when droppers are discriminated from kelts.

8.5 Performance of hydroacoustic counters

Validations of split-beam hydroacoustic counters using fish-traps have revealed a detection rate of 71% (Fewings 1994). CCTV validation of hydroacoustic counters is difficult as water turbidity limits underwater vision, however video validations on the Spey (Brotherston 2002) and on the Wye in England (Gregory *et al.* 1998) found that between 50 and 80% of passing salmonids were detected.

Other studies have been less encouraging. Bray *et al.* (1997) found that a hydroacoustic counter tested on the River North Esk missed almost 94% of upstream migrants which passed under the beam. However, in this instance the suitability of the site was constrained by the river profile in the vicinity of the independent verifying counter. Laughton (1998) found the hydroacoustic counter on the Spey to have similar difficulties during early tests.

9 SITING COUNTERS

The choice of site and in-river structure are the two most important factors determining both the performance of a counter and the utility of the data it produces. The importance of this decision cannot be overstated. Below we discuss six factors that need to be considered when siting a counter. However, in some rivers a suitable site may not exist and some in-river engineering may be required, adding significantly to the cost of the project.

9.1 In-river structure

The in-river structure, be it a Crump weir or a Borland lift, must be carefully engineered from appropriate materials.

9.2 Tributary specific

The decision of where to locate a counter in a catchment depends on the question (or questions) the counter is being installed to answer. If, for example, conservationists are interested in the rate of recolonisation of an entire catchment then a counter on the lower part of the mainstem may be of greatest value (see *Case Study: Atlantic salmon range changes in the Clyde catchment*). However, a counter placed on the mainstem monitors the mean trend in the upstream mainstem and tributaries. This trend can mask the decline and even extinction of individual populations at the sub-catchment level. Where a particular population or populations are of concern, a counter on the associated tributary (see *Case Study: Atlantic salmon in the Tweed and its catchment*) will be most useful.

9.3 Proximity to spawning grounds

Counters should not be located too close to spawning grounds because fish exhibiting searching behaviour may trigger multiple counts by swimming back and forth across the counter's sensing array (Holden 1988).

9.4 Spates

When a river is in spate, expensive equipment or even the in-river structure itself can be damaged or destroyed. The design should be such that the in-river structure will avoid damage or destruction during high spate conditions. In rivers where spates are common, some consideration may be given to the installation of semi-permanent structures.

9.5 Turbulence

Ideally, water flow should be as smooth as possible at all times, especially in weirs. The strength and direction of the prevailing winds must also be taken into account, as wind can generate turbulence and even waves (Gray *et al*. 1998). In weir situations, the substrate must be stable to prevent gravel build-up and consequent upstream movement of the standing wave (Holden 1988; Struthers 1998).

9.6 Electrical requirements

Counters require an uninterrupted electricity supply either from a battery, solar-panels or the mains. Appropriate Health and Safety measures should be adopted to minimize the risk of electric shock to the operators.

10 COUNTER DATA ANALYSIS

Here we use the Atlantic salmon rod catch data to test the reliability of the counters. Agreement between counts and catches indicates that both measures reflect the underlying salmonid abundance whereas lack of agreement demonstrates inaccuracies in one or both.

10.1 Methods

Of the 29 counters currently functioning in Scotland, 18 provided sufficient data for analysis – having been successfully operating for more than ten years prior to 2002 (Table 5). All 18 are resistivity counters. Of these 12 were considered by the operators to consistently provide reliable counts (Table 5). These are: Awe Barrage, Aigas, Beannachran, Torr Achilty, Morar, Dundreggan, Invergarry, Logie, Westwater, Clunie, Ericht and Pitlochry.

Table 5 Status of counters

No	Counter	Years Data Prior to 2002	Type	Considered Reliable	Analysed
1	Philiphaugh Cauld	4	optical	?	No
2	Clunie	49	resistivity	Yes	Yes
3	Pitlochry	49	resistivity	Yes	Yes
4	Stronuich	35	resistivity	No	No
5	Lochay	35	resistivity	No	No
6	Ericht	12	resistivity	Yes	Yes
7	Westwater	11	resistivity	Yes	Yes
8	Logie	21	resistivity	Yes	Yes
9	Cattie	4	optical	?	No
10	Beltie	4	optical	?	No
11	Fearder	2	optical	?	No
12	Invergarry	45	resistivity	Yes	Yes
13	Dundreggan	31	resistivity	Yes	Yes
14	Aigas	39	resistivity	Yes	Yes
15	Kilmorack	6	resistivity	?	No
16	Beannachran	38	resistivity	Yes	Yes
17	Torr Achilty	47	resistivity	Yes	Yes
18	Meig	44	resistivity	No	No
19	Luichart	8	resistivity	?	No
20	Shin Diversion Dam	14	resistivity	No	No
21	Duchally Diversion Weir	5	resistivity	?	No
22	Helmsdale	2	resistivity	?	No
23	Morar	42	resistivity	Yes	Yes
24	Mucomir	39	resistivity	No	No
25	Awe Barrage	38	resistivity	Yes	Yes
26	Loch Doon	21	resistivity	No	No
27	Tongland	2	resistivity	?	No
28	Grimersta	0	resistivity	?	No
29	Morsgail	10	resistivity	?	No

Data for each of these 12 counters were compared to the rod catch (including all caught and released Atlantic salmon) data for the fisheries district in which the counter is located. Since monthly counts were not, in most cases, readily available, we limited ourselves to an analysis of annual counts only. For the majority of the counters, the annual counts were compared to the annual rod catch for the district. However, the Beannachran, Dundreggan, Invergarry, Clunie, Ericht and Pitlochry counters are sited on tributaries producing significant numbers of spring Atlantic salmon. For a more meaningful comparison the annual counts, for these counters, were compared to the spring (February to May) rod catch. It should be noted that the rod catches which are published annually in the Fisheries Research Services Statistical Bulletin are for the combined districts with the spring catches covering the period January to April. Rod catch data for each district are available from 1952. However, to increase the comparability of the trends only catch data since the start of the counter data time series were considered in each case.

To ensure the variation about the trend remained constant (Chatfield 1996), a prerequisite of the statistical analysis, the rod catch and counter data were square-root transformed. Occasionally, the annual down-count exceeded or equalled the up-count producing negative or zero net upstream counts. Non-positive counts were treated as missing values. To ensure the square-root transformed rod catches and counts were comparable they were divided by their respective means prior to construction of the trends and reference band. To aid interpretation the trends, confidence band and reference band were back-transformed to the original scale prior to plotting. The direction and magnitude of change in a counter or rod catch time series was quantified as the n-fold increase or decrease per half century in the back-transformed trend. Under the terms of the 1951 Act, fishery catches are provided in confidence. The rod catch times series, trend lines and confidence bands were standardised so as to disguise the absolute value of the district catches.

The trend was estimated by fitting a smoother (cubic smoothing spline) to each time series (Hastie & Tibshirani 1990). Each smoother was fitted with three, two or one degrees of freedom depending upon whether the time series was greater than 30 years in length, greater than 15 or less than or equal to 15 years, respectively. This amount of variation in the smoothers captured the underlying trend and left negligible autocorrelation (Chatfield 1996; Pyper & Peterman 1998) in the residuals (year-to-year variation about the trend) which could be taken to be independently and normally distributed with constant variance.

Approximate pointwise 95% confidence (Hastie & Tibshirani 1990) and reference bands (Bowman & Azzalini 1997) were constructed using generalised additive models (Hastie & Tibshirani 1990). A pointwise confidence band provides an indication of the uncertainty surrounding the location of a trend line at each point in time while a pointwise reference band indicates the uncertainty surrounding the difference between multiple trend lines at each point in time.

Trends were compared by plotting each pair of time series with the pointwise 95% reference band represented by a shaded area. As a general rule, the counter and catch trends differ significantly when they lie outside the reference band. The residuals (inter-annual fluctuations around the trend) were compared by plotting a dispersion diagram and calculating Kendall's correlation coefficient. The significance of each correlation was determined under the directional hypothesis that the residuals are positively correlated. Since each correlation represented a test of an independent hypothesis, the p-values were not adjusted for the number of comparisons.

A summary of the method and the main findings can be found in Box 1.

10.2 Results

10.2.1 Automatic counter trends

The time series for the 12 most reliable counters, together with their trends and pointwise 95% confidence bands, are plotted in Figure 5. Six counters (Awe, Aigas, Torr Achilty, Morar, Invergarry and Westwater) show a twofold or more decrease per half century of (Table 6). Three show a twofold or more increase per half century (Logie, Clunie and Ericht), while the remaining three (Beannachran, Dundreggan and Pitlochry) have, on average, remained relatively constant.

Table 6 Various characteristics of the 12 counters and related rod catch including the n-fold increase or decrease per half century (N-fold change), the significance of the correlation between the short-term variation (Residuals correlated), the significance of the difference between the long-term variation (Trends different) and the percent of the counter trend that lies within the reference band (Percent in band).

Counter	District	Season	Years	N-fold change	Residuals correlated	Trends different	Percent in band
Awe Barrage	Awe	Annual	38	-2	p < .001	p < .001	68
Aigas	Beauly	Annual	39	-3	p < .001	p < .001	23
Beannachran	Beauly	Spring	38	-1	NS	NS	100
Torr Achilty	Connon	Annual	47	-2	p < .05	p < .001	40
Morar	Morar	Annual	42	-13	NS	p < .001	50
Dundreggan	Ness	Spring	31	-1	p < .05	NS	100
Invergarry	Ness	Spring	46	-17	p < .01	p < .001	57
Logie	N. Esk	Annual	21	2	p < .01	p < .001	38
Westwater	N. Esk	Annual	11	-3	NS	NS	100
Clunie	Tay	Spring	49	4	p < .05	p < .001	18
Ericht	Tay	Spring	12	3	NS	NS	100
Pitlochry	Tay	Spring	49	1	p < .001	p < .005	84

10.2.2 Congruence between counter and rod catch trends

The counter trends are compared to the corresponding rod catch trend in Figure 6. Four of the counters, the Beannachran, Dundreggan, Westwater and Ericht counters, have trends which are not significantly different from the relevant rod catch trend (Table 6). As expected these four counters have trends that fall within the reference band in all years. The Ericht does show discordant trends with the Tay rod catch, but the time series are too short for the differences to be significant. The Awe, Morar, Invergarry, and Pitlochry counters have trends that fall within the reference band in 50% or more of the years. Of the remaining four counters, three have trends that are concordant with the rod catch trend in the sense that they both increase or decrease together. Only the Clunie counter and the Tay spring rod catch show discordant trends that are significantly different.

10.2.3 Correlation between counter and rod catch residuals

The correlation between the year to year variation (residuals) in the counter and rod catch data is compared in the dispersion diagrams in Figure 7. In only four cases (Beannachran, Morar, Westwater and Ericht) are the counts not significantly correlated with the catch. In the case of the Beannachran and Morar the rod catch is so small that any 'signal' for Atlantic salmon abundance is likely to be masked by 'noise.' The remaining two have only been operational for just over a decade so that there are relatively few residuals with which to detect a correlation.

Box 1 Summary of trend analysis

Of the 29 salmon counters in Scotland, 12 have been operating for 10 years or more and are considered to provide reliable counts. The aim of this analysis is to compare trends in these counters with those for rod catch in the surrounding fisheries district. The extent to which both data sources show the same trends facilitates an assessment of the degree to which they reflect salmon abundance in the area. Lack of agreement indicates that one or both sources of data are not representative of local abundance.

Method summary

Step 1. Square root transformation of the data

The variability of count data usually increases as the size of the counts increases. A square root transformation tends to reduce or remove this dependence, which would otherwise invalidate assumptions needed to estimate confidence bands and to test for trends.

Step 2. Standardising of data

After transformation, the rod catch and counter data are divided by their respective mean values. Re-scaling them to the same average level allows trends to be compared, as in Figure 6.

Step 3. Fitting the trend curves

Generalised additive models use smoothers to fit a trend curve to the rod catch and counter data. The particular smoother used was a spline. A spline is a function made up of segments of polynomials joined together to form a smooth but flexible curve. Smoothers can reveal complex underlying trends without having to assume that the trend takes a particular form.

Step 4. Summarising trends

The trend curves in Figure 5 summarise the shape of counter trends, but the overall change is presented as the n-fold increase or decrease between the first and last counts, rescaled over 50 years. For example, an increase from 1000–2000 over 50 years would be a 2-fold increase and a reduction from 2000–1000 would be a 2-fold decrease. To make the shorter time series comparable with the longer ones the changes are presented over 50 years. Thus a 2-fold increase over 25 years, from say 1000–2000 is presented as a 3-fold increase over 50 years from 1000 to 3000. In Table 6 the n-fold changes have been rounded to the nearest whole number.

N-fold change is used in preference to the percentage change as the latter is not symmetric for increases and decreases. Thus, a percentage decrease is always less than 100%, but a percentage increase can take any value. N-fold changes allow increases and decreases to be compared on equal terms.

Step 5. Comparing trends in counter and rod catch

Counter data and rod catch fluctuate for a variety of reasons which cannot be included in the models. This results in uncertainty as to where the true trend line should go and this is illustrated by confidence bands. These indicate that we are 95% confident that the true trend line falls within these bands.

The reference band defines a range such that we are 95% confident that the two trend lines would fall within the band if they are showing the same trend. The middle of the reference band is the average of the two trend lines. The test comparing the trends (Table 6) indicates whether the trends are significantly different for at least one year.

Step 6. Examining the within-year correlation between counter and rod catch

The residuals from the models are the differences between the counts and rod catches and their respective trend lines. They indicate whether the value for that year was above or below that expected from the trend. A significant correlation between the residuals (Figure 7 and Table 6) indicates that if the counter is relatively high the rod catch will also tend to be relatively high, and *vice versa*, suggesting that factors independent of the underlying trends affect both sources of data in the same way.

Results summary

- Of the 12 counters, six have shown a two-fold or greater decrease per half-century and three have shown a three-fold or greater increase.
- Four counters have trends that are not significantly different from the matching rod catch trend. One of these, Ericht shows discordant trends with the Tay rod catch, but the time series are too short for the differences to be significant.
- Trends in 10 of the 12 counters are broadly similar to those for rod catch. Only the Clunie counter and the Tay district rod catch show significantly different and completely discordant trends.
- Eight counters show a within-year correlation with rod catch. The rod catch for two of the remaining four was very small resulting in a lot of 'noise' in the residuals. The time series for the other two may have been too short to detect a correlation.

Counter and rod catch data can provide information about the abundance of salmon in particular rivers. This information can help fisheries managers and conservations ensure sufficient Atlantic salmon spawn in Scotland's rivers to repopulate the freshwater habitat with young fish. Individual rivers and significant tributaries within those rivers contain separate populations of Atlantic salmon. Fish belonging to populations that spawn high in catchments tend to return earlier in the year whereas fish belonging to populations that spawn closer to the river mouth return later. Consequently, the utility of the information that can be extracted from counter and rod catch data would be increased by considering the trend in each month individually.

Figure 5 Net upstream annual counts for the automatic fish counters

The continuous line is the trend and the dashed lines are pointwise 95% confidence bands. The counters are arranged according to the name of the district in which they occur.

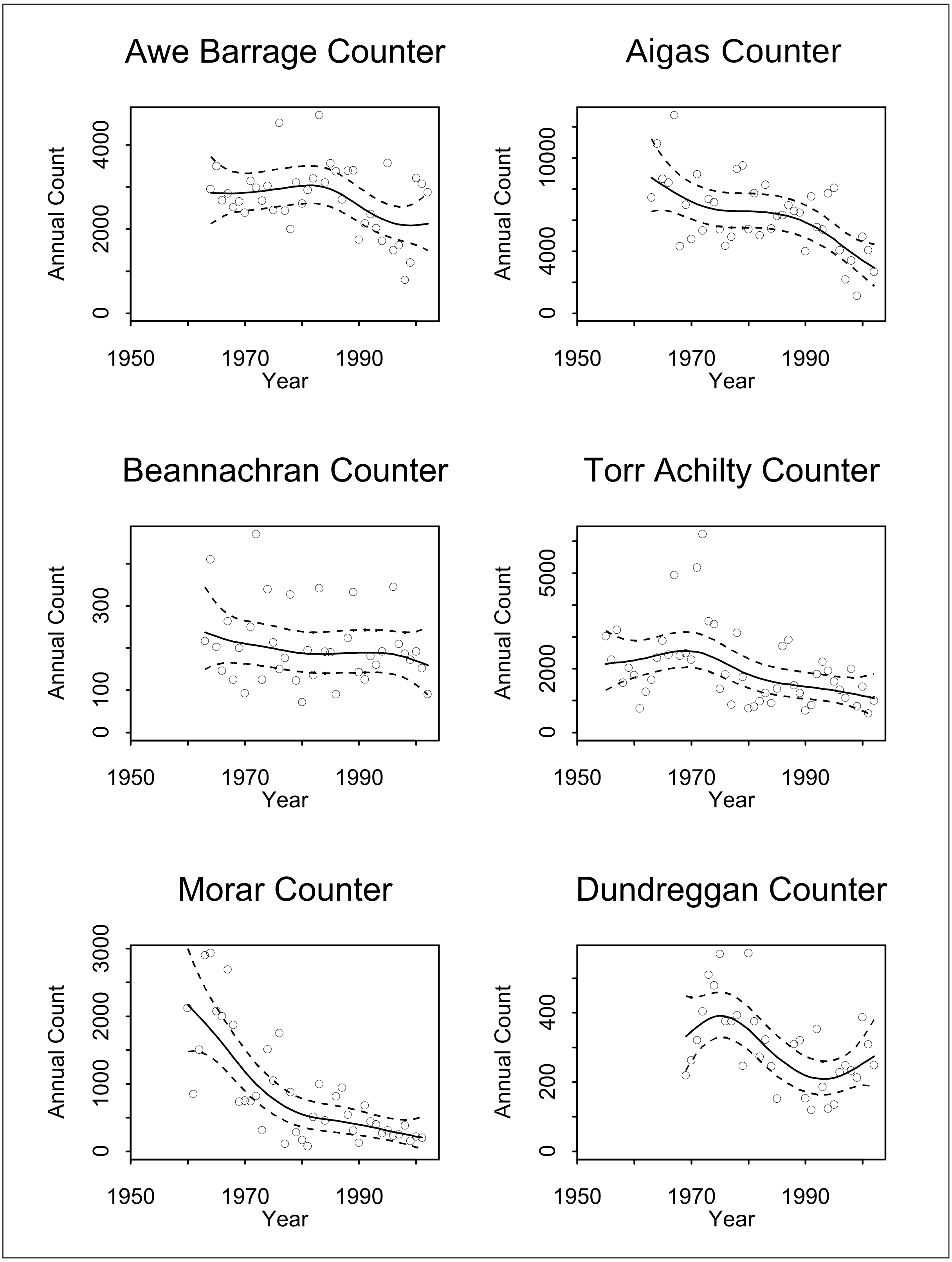


Figure 5 Net upstream annual counts for the automatic fish counters *(continued)*

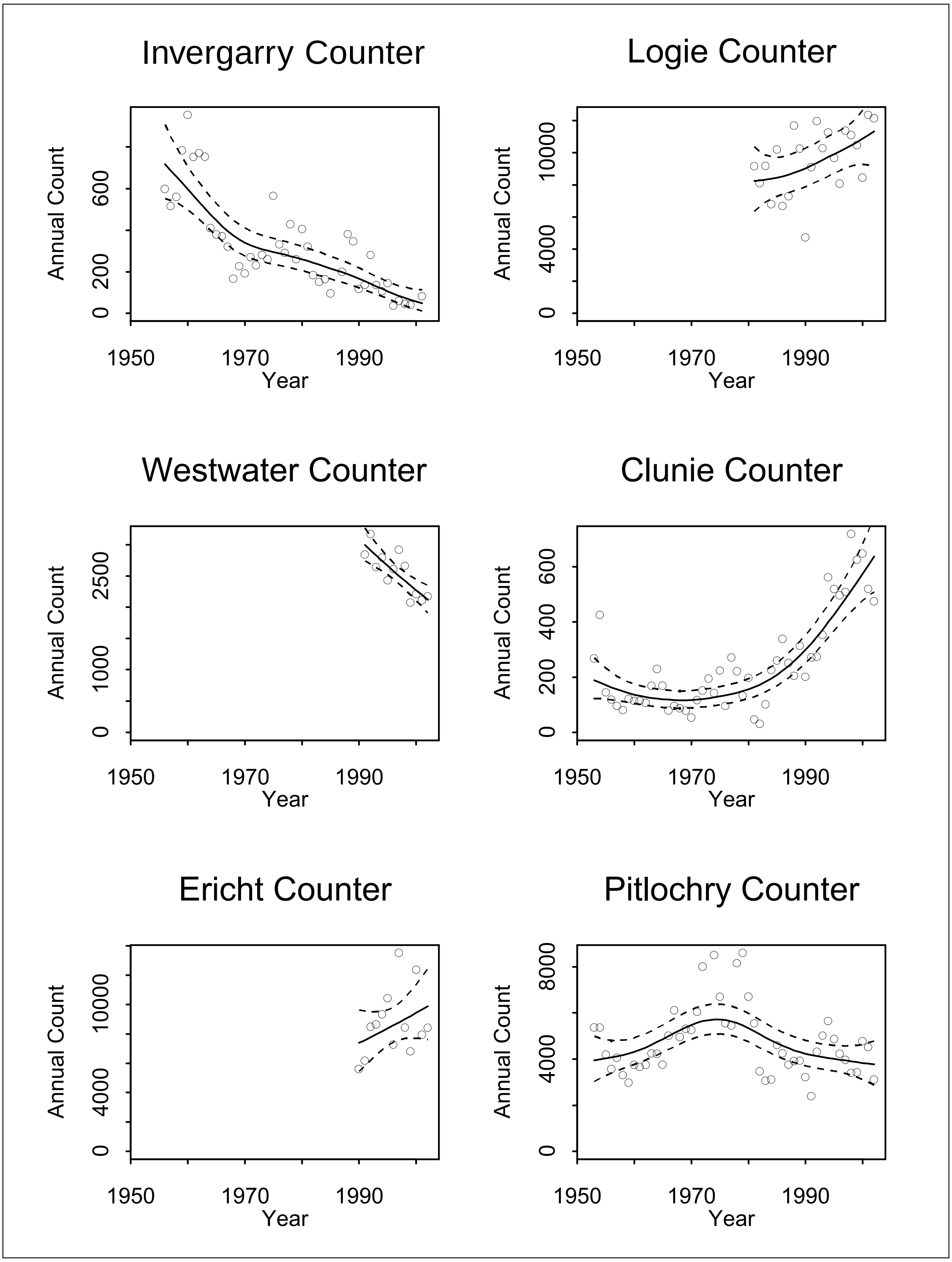


Figure 6 Net upstream annual counts for the fish counters compared to the relevant district's annual or spring rod catch

The continuous line is the counter trend and the dashed line the rod catch trend. The circles and crosses are the counts and rod catches, respectively. The shaded area is a point-wise 95% reference band.

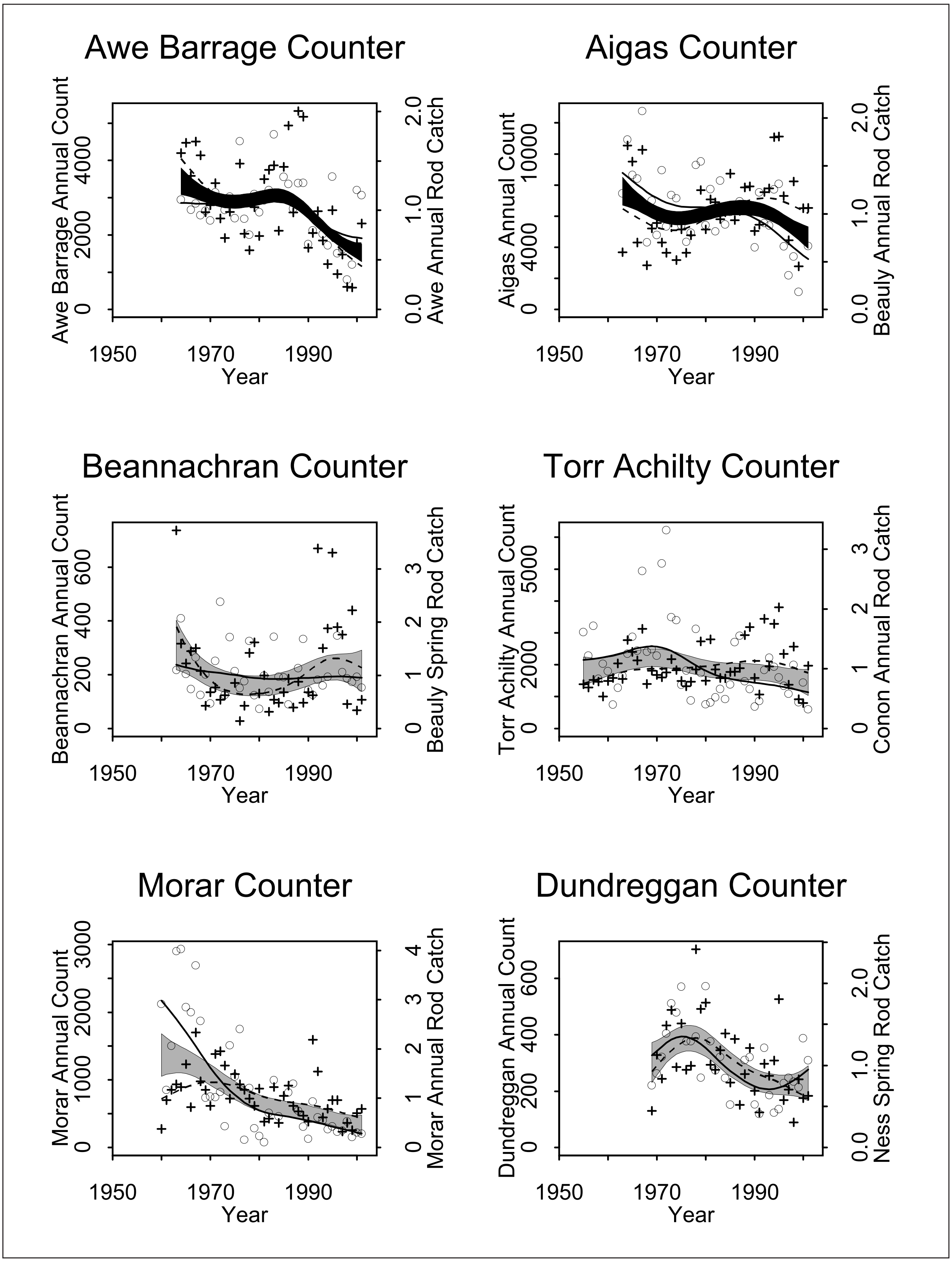


Figure 6 Net upstream annual counts for the fish counters compared to the relevant district's annual or spring rod catch *(continued)*

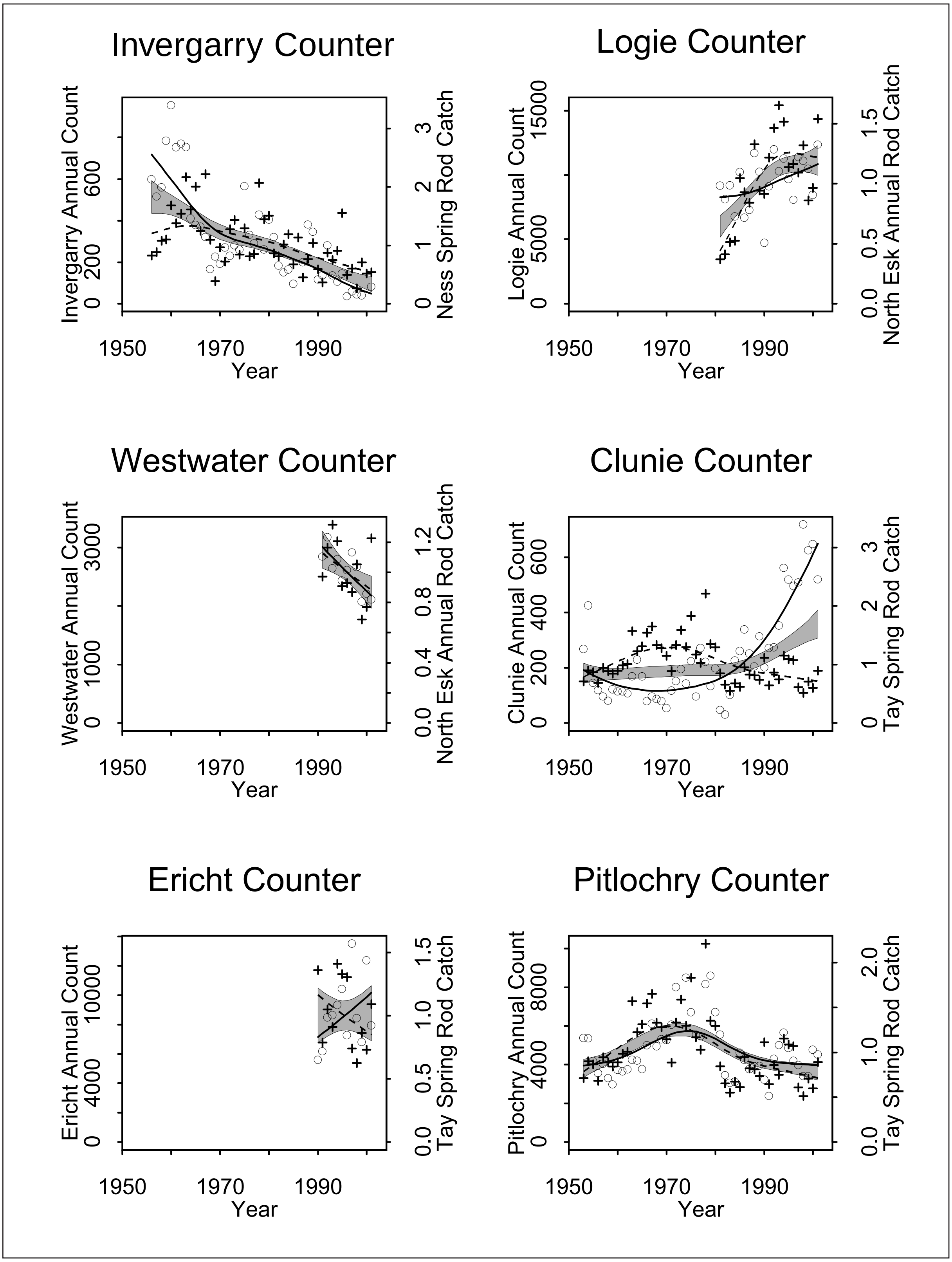


Figure 7 Residual net upstream annual counts for the fish counters compared to the relevant district's annual or spring residual rod catch

The p-value indicates the significance of Kendall's non-parametric correlation coefficient. In each significant correlation the least-squares regression line is plotted to make the relationship easier to see.

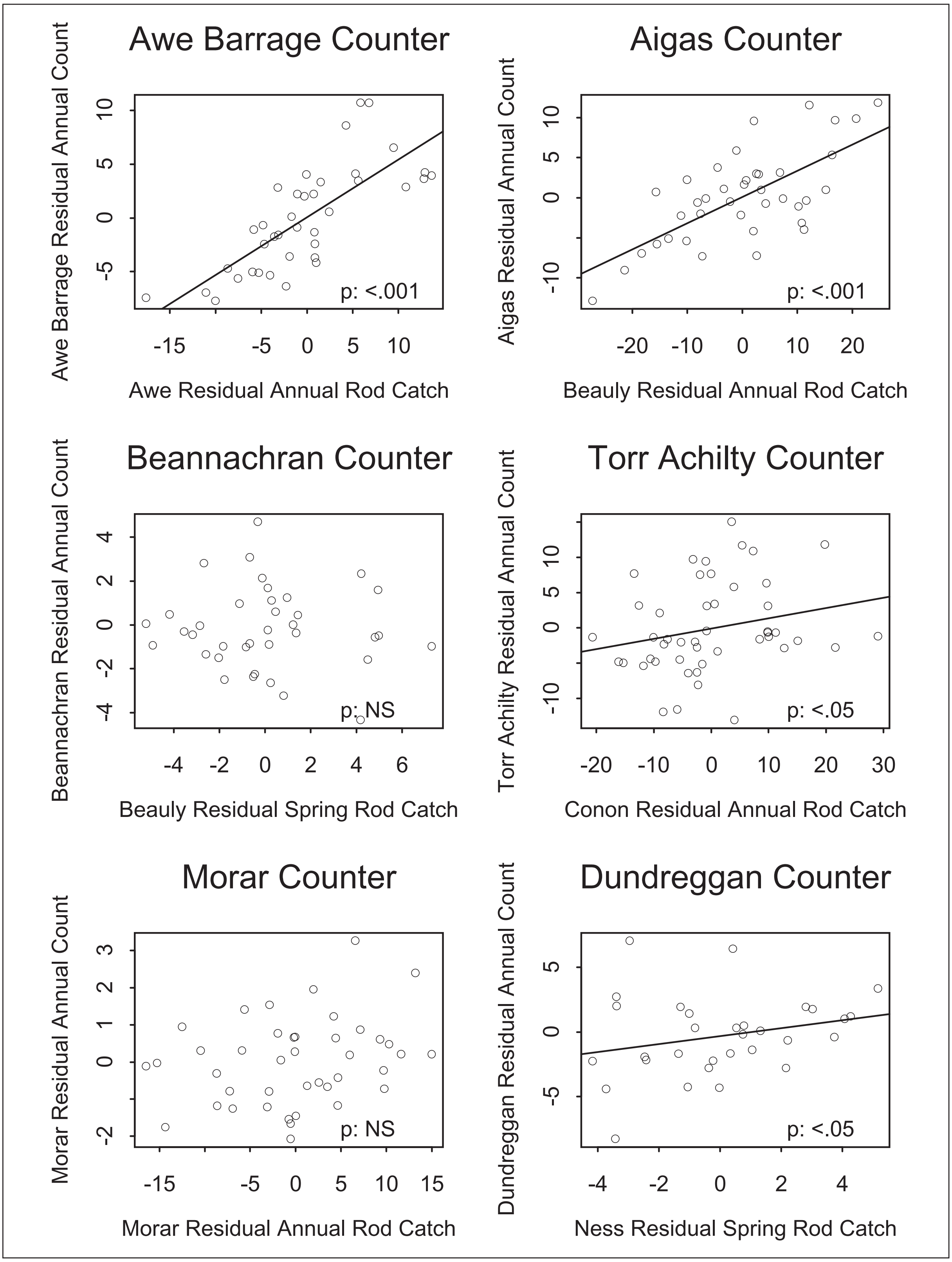
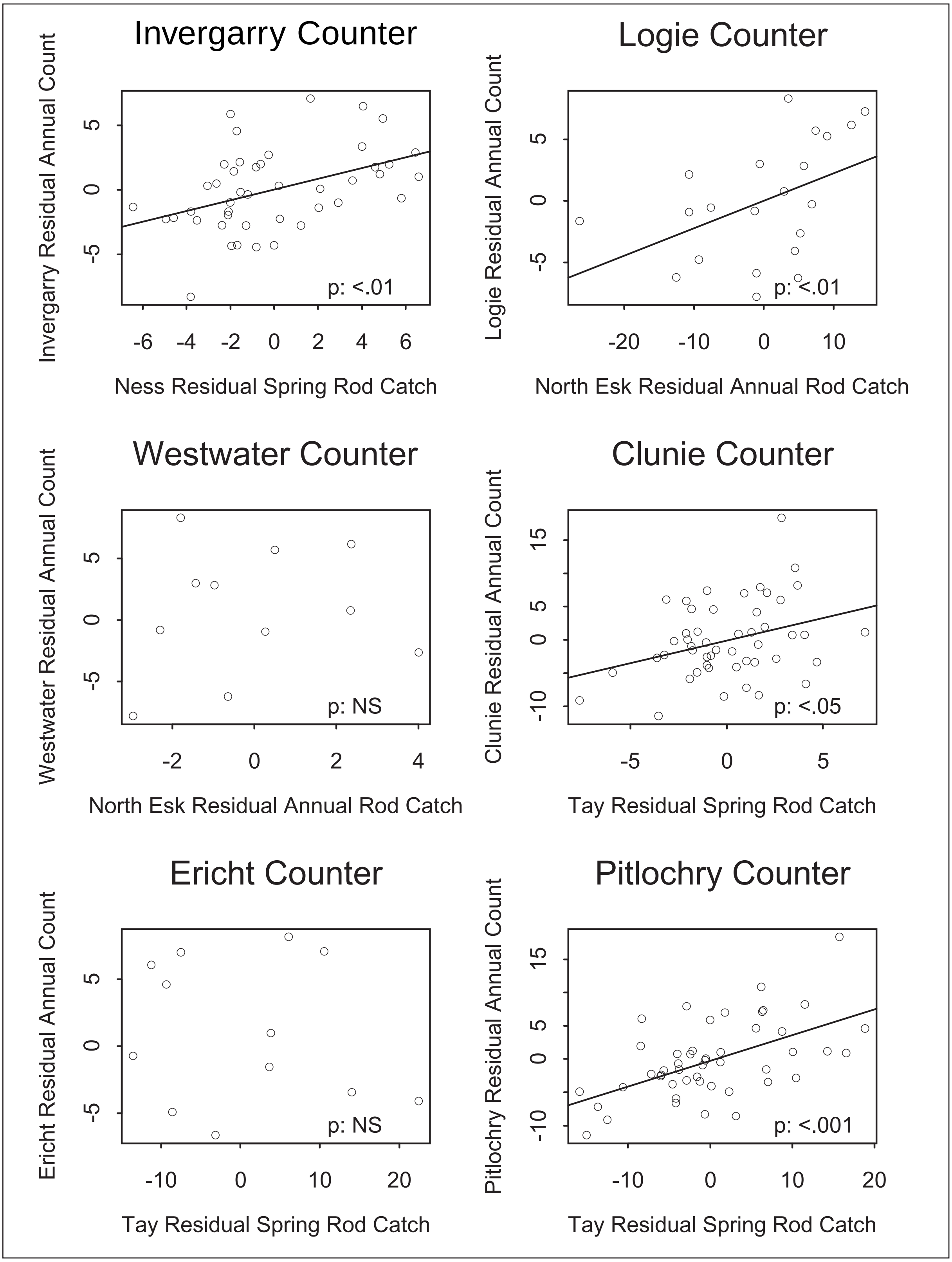


Figure 7 Residual net upstream annual counts for the fish counters compared to the relevant district's annual or spring residual rod catch *(continued)*



10.3 Discussion

The trends in Scotland's counter and rod catch data are broadly congruent in 11 of the 12 comparisons. This is a noteworthy result given that only the district level rod catches are considered. Due to the homing behaviour of Atlantic salmon, rivers in the same district, and even the same catchment, often contain distinct populations which may be experiencing divergent trends. We would expect that comparing the counter data to a more local sub-catchment-level rod catch trend will increase the congruence between the two sources of information. Indeed, the discrepancy between the trends in the Clunie counter and the Tay spring rod catch can be explained, at least in part, by events local to the Clunie counter (see Section 11). However, an improvement in the fit between the counter and catch trends will only occur if the increase in the rod catch local abundance signal is not swamped by the increase in noise associated with the reduction in the size of the rod catch.

The analysis of the counter data demonstrates that resistivity counters which have been correctly sited on an appropriate in-river structure and which are regularly validated and continually monitored, provide useful information about Atlantic salmon abundance. Unfortunately, there are currently insufficient data to conduct a similar comparison for the optical counters. In the following section we consider each of the 12 counters and discuss background information relevant to the interpretation of their trends.

11 THE COUNTERS AND THEIR TRENDS

In order to identify factors which might be responsible for the differences between each of the counter and rod catch trends the available background information is discussed. All the counters are of the resistivity type and, with the exception of the Logie, Westwater and Ericht are owned and operated by SSE.

11.1 Awe Barrage Counter (Awe District)

The Awe counter trend remains relatively constant from the 1960s onwards before beginning to gradually decline in the 1980s. The Awe Barrage counter is a situated on a large hydro-electric dam on the mainstem of the Awe, a West coast river, about four kilometres from the sea.

11.2 Aigas Counter (Beauly District)

The Aigas counter trend falls from over 8000 in the 1960s to under 3000 by the start of the millennium. The Aigas counter is sited on the mainstem of the River Beauly about 10km from the Beauly Firth estuary. Most Atlantic salmon on the Beauly are caught below the counter. The most productive beats were once owned by a single proprietor and were exposed to a relatively low angling pressure. In 1999, the beats were bought by a syndicate, the Beauly Fishery Company. Following the change in ownership the effort expended by Atlantic salmon anglers has increased dramatically. This at least partly explains the different slopes in the Aigas counter and Beauly rod catch trends. Further support for this conclusion is provided by the highly significant correlation ($p<0.001$) between the year-to-year variation in the counts and catches (the residuals). Such a correlation could only occur if the counter and rod catch are both responding to short-term changes in abundance irrespective of any long-term biases in the trends.

11.3 Beannachran counter (Beauly District)

The Beannachran counter is sited about 30km from the sea on the River Farrar, a spring tributary of the Beauly. The Beannachran counter and the Beauly spring rod catch trends remain relatively constant, from the 1960s to the present.

11.4 Torr Achilty counter (Conon District)

The Torr Achilty counter trend shows a gradual decline from around 1970 to the present. The Torr Achilty counter is positioned 10km from the coast on the mainstem of the River Conon. In 1986, the existing resistivity counter was replaced by a Mark 10 resistivity counter. Validation exercises, together with corroborating evidence from PIT-tagging and fish traps, have revealed that the new counter is consistently only about 50% accurate with respect to missed counts. To compensate for this underestimation all counts from 1986 onwards were doubled prior to the analysis.

11.5 Morar counter (Morar District)

The Morar counter trend falls dramatically from over 2000 in 1960 to under 500 in the 1990s. The Morar counter is positioned on a hydro-electric dam at the foot of Loch Morar. The dam is less than 1km from the mouth of the river. The difference between the counter and catch trends in the 1950s and 60s may be due to mixed counts: the counter could not discriminate between small Atlantic salmon and large sea-trout. In the 1970s, the problem was largely rectified when the 3-electrode array was replaced by a 5-electrode array. A Vaki Riverwatcher was installed at Morar in 1999.

Since the 1970s, the Morar counter and catch trends have declined in parallel. A factor contributing to this downward trend may have been the historically high mortality rate of smolts passing through the dam's turbines. Studies have shown that when the dam is generating electricity between 15% and 40% of the smolts are killed. Since the early 1990s SSE have stopped generating electricity during the smolt run. Despite the changes the count and catch have continued to decline.

11.6 Dundreggan counter (Ness District)

The Dundreggan counter trend peaks in the 1970s and then falls until about 1990 before beginning to increase. The Dundreggan counter is located on the River Moriston, one of two major spring tributaries of the Ness. The other, the River Garry, is home to the Invergarry counter (see Section 11.7). The trends in the Dundreggan counter and the Ness spring rod catch are not significantly different. Nonetheless the count shows an upturn in recent years that is not mirrored by the spring rod catch. The explanation for this discrepancy appears to be an increase in the number of summer grilse passing through the counter.

11.7 Invergarry counter (Ness District)

The Invergarry counter is sited on the River Garry the other major spring tributary of the Ness (see Section 11.6). The Invergarry counter trend shows a severe decline which is not apparent in the Ness spring rod catch. The discrepancy between the two abundance measures may be explicable at least in part by local factors including an increase in forestry. The Garry Atlantic salmon run has declined substantially while the Moriston Atlantic salmon, which continue to return in robust numbers, have ensured the overall Ness spring rod catch has been shielded from these changes.

11.8 Logie counter (North Esk District)

The Logie resistivity counter situated on the main stem of the River North Esk (Plate 1) is run by the Montrose Field Station of the Fisheries Research Services Freshwater Laboratory. In the 1980s there was a steady increase in annual counts at Logie mirroring rod catches for the North Esk district. Since the 1990s although rod catches have begun to decline the count has continued to increase.

11.9 Westwater counter (North Esk District)

In sharp contrast to the Logie, the Westwater counter, which is sited on a tributary of the North Esk, indicates a slump in fish numbers. This is another example of two counters on the same system exhibiting divergent trends.

11.10 Clunie counter (Tay District)

The Clunie counter is situated in a fish ladder (Photograph 2), associated with a hydro-electric dam on the River Tummel, a spring tributary of the River Tay. The trend in the Clunie count is almost diametrically opposed to the trend in the Tay spring rod catch: while counts have risen, rod catches have dropped.

A possible explanation for the discrepancy appears to be the changes that have taken place at the Clunie Dam over the last 25 years. The smolt pass on the Clunie dam is positioned such that migrating smolts have difficulty locating it. In 1979, after detailed research, the North of Scotland Hydro-electric Board (now SSE) removed the smolt screens so that smolts were able to exit the loch through the turbines. Although an estimated 20% of the smolts passing through the turbines die, the removal of the smolt screens led to an increase in the number of smolts successfully migrating downstream. All other things being equal this will have led to an increase in the number of adults returning to the upper Tummel, relative to other parts of the Tay.

The Clunie dam is situated about 4km upstream of the Pitlochry dam. The refitting of the adult screens to the Pitlochry dam in 1990 (see Section 11.12) should also have led to an increase in the number of adults ascending the Clunie dam. Despite their widely divergent trends, the year to year variation in the Clunie counts is nonetheless correlated with the residual spring rod catch for the entire Tay district.

11.11 Ericht counter (Tay District)

An upward trend in fish counts is indicated by the Mark 10 resistivity counter on the River Ericht, approximately 40km from the Tay estuary. The counter is operated by the Tay District Salmon Fishery Board.

11.12 Pitlochry counter (Tay District)

The Pitlochry counter trend rises from around 4000 counts in the 1950s to a peak of over 5000 in the 1970s before gradually declining to just under 4000 by the start of the millennium. The Pitlochry counter is situated on the fish ladder of the Pitlochry dam, which lies on the Tummel – a tributary of the Tay that produces high numbers of spring Atlantic salmon. The counter and Tay spring rod catch are remarkably similar when either trends or residuals are compared.

Atlantic salmon have few difficulties finding the downstream entrance to the fish ladder, provided the tail-race area downstream of the adjacent turbines is screened. For a variety of reasons during the 1970s and 1980s the screens were not installed. In 1990, Scottish Hydro-electric (SSE's immediate predecessor) began refitting the adult screens. This may partially explain the increase in the Pitlochry counts relative to the Tay spring rod catch post 1990.

In addition a greater proportion of the Atlantic salmon ascending the system are now released by anglers or evade capture altogether. The reasons are three-fold. Firstly, catch and release, particularly of spring Atlantic salmon, is now widely practiced on the Tay. Secondly, shrimp and prawn fishing has been banned on the Tay reducing angling efficiency (D. Summers *pers. com.*). Thirdly, the average water temperature below the dam has increased so that Atlantic salmon now experience the minimum body temperature required to ascend the ladder earlier in the year.

12 CASE STUDIES

12.1 Introduction

In this section we consider three case studies. The first, on the Tweed, illustrates how the appropriate siting of a Vaki counter has demonstrated the importance of catch and release on the Tweed. The second considers the fall and on-going rise of salmon numbers in the Clyde catchment – a situation where one or more counters might provide useful information. The third and final case study considers the limitations of using counters to monitor wild populations where the adult runs contain significant numbers of escaped farmed fish.

12.2 Atlantic salmon in the Tweed and its catchment

From its source at Tweed's Well, 520m above sea level, the River Tweed flows 156km to Berwick on the southeast coast of Scotland. With a total catchment area of approximately 5000km^2 the Tweed provides around 15% of Scotland's freshwater Atlantic salmon habitat (Gardiner 1989). Importantly, the Tweed system is composed of six major tributaries, four of which: the Ettrick, the Whiteadder, the Teviot and the Till, are big enough to be considered 'rivers' in their own right.

In order to assess the abundance of Atlantic salmon in their system, the River Tweed Commissioners decided in the early 1990's to investigate the possibility of installing one or more automatic fish counters, in addition to existing fish-traps. The choice of the location is crucial particularly in a large catchment like the Tweed where fish entering the river belong to different spawning populations experiencing diverse environmental pressures. A single counter sited on the main stem near the mouth of the Tweed, although providing an overall count, would not be as useful as one placed on a tributary where links could be made to data collected within the catchment.

To reduce costs, a number of locations with existing in-river structures were investigated as possible locations to trial fish counters. Two suitable fish ladders were identified, on the lower reaches of the Ettrick and Gala tributaries, respectively. Scale reading studies have revealed that the Ettrick is an important producer of spring Atlantic salmon. This was further confirmed by a radiotracking study which showed that over a third of all spring Atlantic salmon tagged at Berwick return to this tributary. For this reason, the first counter was trialled on the River Ettrick, at Philiphaugh Cauld fish ladder near Selkirk (N.B. *cauld* is a local term for a weir or low dam).

In-river structures such as the Philiphaugh Cauld fish ladder are considered particularly good places for counters. The velocity of the water passing over the weir and the shape of the weir itself ensure that only a negligible number of fish moving upstream can swim up over the weir without using the fish ladder. This reduces the chances of missed upstream counts. Missed counts are more likely among the downstream data, because fish can travel downstream at any point across the width of the weir and do not need to use the fish ladder. However in the case of the Philiphaugh Cauld, local managers believe that kelts are the only fish to do this in significant numbers. Maiden fish which have been observed dropping downstream have done so within the fish ladder almost immediately after ascending.

Initially, an Aquantic Logie resistivity counter was considered. However two local factors influenced the eventual decision to use a Vaki optical counter. Firstly, the high quantity of metal used in the construction of the Philiphaugh Cauld fish ladder would have interfered with electrical signals in a resistivity counter. Secondly, a Vaki counter which provides silhouetted images of the fish and reliable length estimates, would enable improved discrimination between Atlantic salmon and sea trout. This is particularly important on the Tweed, where there is a considerable overlap in size between the two species.

Although the total river width of the Ettrick at Philiphaugh Cauld is 60m, the fish ladder is just 2m in width and funnels fish through internal channels in some places as narrow as 65cm. The fact that fish are concentrated through a narrow pass is ideal for the Vaki counter which utilizes a short range infra-red detection system.

After initial trials in 1997, the Vaki counter first started to produce reliable data in 1998. For upstream counts, underwater video validation indicates that the Vaki counter is almost 100% accurate at detecting and identifying all fish exceeding 40cm in length which pass through the counter. The downstream count is only 88% accurate, probably because fish moving downstream can travel at a much faster speed and at an oblique angle with respect to the counter. For fish between 30 and 40cm the efficiency falls to 64% (Anon. 1999).

The siting of the counter on the Ettrick has proven to be very useful not only for fisheries management purposes, but also potentially for conservation management. In 1998 a catch-and-release scheme was introduced on the Tweed in response to concerns about spring Atlantic salmon. Before 30 June, anglers are encouraged to release the first Atlantic salmon they catch. The second can be kept, but then the third should be released and so on. The voluntary scheme has proven to be very effective. For example, 57% of the 2400 spring Atlantic salmon which fell to rod and line in 2001 were released. The counter revealed that the number of Atlantic salmon entering the Ettrick was generally just above the level currently deemed necessary to repopulate the stream with fry in most years. In one year the escapement level would not have been reached without the contribution made by released fish.

The counter data from the Ettrick are important for three reasons. Firstly, river managers can monitor the success of their policies. Secondly, by demonstrating the necessity of catch-and-release anglers are encouraged to comply with the necessary codes. Thirdly, conservationists are able to gather useful and relevant information on the abundance of Atlantic salmon in the Tweed cSAC (candidate Special Area of Conservation).

More recently, data from the counter have been used to obtain emergency releases of reservoir water to help fish ascend the Ettrick. Very low rainfall throughout much of 2003 greatly reduced the flow in the Ettrick and prevented many fish reaching their spawning grounds. Indeed, the count for September 2003 was only 97 as opposed to the five-year average of 1631. This information was made available to the Scottish Environment Protection Agency (SEPA) who persuaded Scottish Water to provide a three day emergency water release in mid-October from the Meggat Reservoir in the headwaters of the Ettrick (Campbell *pers. comm.*).

Data obtained from the Ettrick counter have also revealed interesting behavioural patterns among the Atlantic salmon in response to daylight and temperature (Anon. 2000b). The counter confirmed that throughout the year upstream-migrating Atlantic salmon primarily enter the fish ladder during daylight hours although there are some interesting seasonal variations in the movement of Atlantic salmon during crepuscular periods, particularly sunrise. In June, Atlantic salmon swim up past the counter immediately following sunrise but in November the fish respond more slowly. Water temperature and fish physiology is thought to be the key factor. At temperatures below 5°C the Atlantic salmon cannot swim against the current to ascend the fish ladder. Later in the year the water takes longer to breach this threshold temperature, and may indeed fail to do so at all. The temperature barrier at weirs such as the Philiphaugh Cauld may effectively filter out late-running fish, perhaps explaining why Atlantic salmon in the Ettrick are essentially early-running (Campbell *pers. com.*). Such findings could affect future management decisions such as the timing of in-river construction works, as well as predicting the impact of climate change.

Recent improvements to the Ettrick counter include its connection to mains electricity and there are proposals to install a permanent underwater camera at the site, together with a visitor centre, thanks to assistance from Philliphaugh Estate, SNH and the Heritage Lottery Fund. Following the success of the Ettrick counter, plans are now underway to install a second Vaki counter at the Skinworks Cauld fish ladder on the Gala Water.

12.3 Atlantic salmon range changes in the Clyde catchment

During the 18th century Atlantic salmon were present in all accessible stretches of major rivers in the central lowlands of Scotland. In the 1790s the Clyde estuary was said to "*abound with salmon, smelts and trouts which are caught in great plenty*" (Sinclair 1791).

However by 1900 industrial and urban expansion had led to a large fall in Atlantic salmon numbers in lowland rivers. Pollution from factories such as bleach and dye works, coal washeries, tanneries, and distilleries as well as the discharge of raw sewage was responsible for much of the decline. The dredging of rivers and the construction of mills, dams and weirs, such as the weir at Blantyre also caused problems. Rivers worst hit were those such as the Clyde draining industrialized catchments with dense human populations. Throughout the 19th and 20th century the only viable Atlantic salmon populations in the Clyde were to be found in the Loch Lomond and River Leven system, which drains into the estuary at Dumbarton.

Efforts to control the pollution in rivers such as the Clyde began as long ago as the 1860s with the appointment of two Royal Commissions resulting in the 1876 Rivers Pollution Bill. However, the powerful industrial lobby ensured that key recommendations were watered down, limiting the bill's effectiveness.

Meanwhile the state of the rivers continued to deteriorate. By the 1920s Scottish rivers were in a worse condition than they had been in 1872. The Clyde was deemed the most polluted river basin in Scotland.

Clean-up measures only started to be effective in the mid 20th century with the 1951 Rivers (Prevention of Pollution) (Scotland) Act preventing any new unauthorised discharge. The 1967 Act went further, extending powers of water purification authorities to cover existing as well as new discharges. Further laws have been introduced since then, and SEPA was set up under the Environment Protection (Scotland) Act 1990 to enforce them. A decline in polluting industries, such as paper-making and tanneries, coupled with improvements in sewage treatment, led to an improvement in river water quality. Within a few years the Atlantic salmon started to respond.

In 1978 an adult Atlantic salmon and a sea trout were found trapped on cooling screens on Renfrew Power Station on the Clyde. A few years later, fish started to appear along much of the length of the river, including stretches in the centre of Glasgow. Spawning sites in the River Kelvin and in the Black and White Cart

Waters were identified in the early 1990s. The construction of fish passes, such as at Blantyre weir in 1995, assisted in the recovery. By 2003, all accessible tributaries of the Clyde had been re-colonized by Atlantic salmon to varying degrees, except for the North, South and Rotten Calder Waters.

The majority of these Atlantic salmon are likely to have originated from wild Atlantic salmon straying from the neighbouring Leven and Loch Lomond system. Fish farm escapees, as well as stocked Atlantic salmon, may also have contributed.

The return of Atlantic salmon resulted in the establishment of the Clyde Fisheries Management Trust in 1984 to protect and promote this valuable resource. However management decisions were hampered by a lack of scientific information. The Clyde River Foundation was set up in 1999 to address this problem (Doughty & Gardiner 2003).

The fitting of one or more fish counters on appropriate in-river structures on the Clyde would be advisable. Although counters sited on tributaries would help fisheries managers and conservationists monitor different Atlantic salmon populations in this system, at this early stage of sporadic re-colonisation and with limited funds, a single counter fitted on the main stem may be of greater value.

12.4 Effects of escaped farmed fish

Automatic fish counters cannot distinguish wild from farmed Atlantic salmon. Accordingly, in river catchments with lots of escaped farmed fish, the numbers of wild Atlantic salmon cannot be monitored by counters alone.

Scottish aquaculture production has grown exponentially, from an annual Atlantic salmon production of around 600t in 1980, to 138,000t in 2001 (Anon. 2002). Current production of Atlantic salmon in the North Atlantic is estimated at 700,000t per year.

Although the vast majority of Scottish fish farms raise Atlantic salmon, in 2001, 57 farms produced almost 5,500 tonnes of rainbow trout (Anon. 2002). Few regulations govern the release of this species. Although rainbow trout are unlikely to produce self-sustaining populations in Scottish waters (Walker 2003) and cannot hybridize with native species, released rainbow trout can invalidate fish counts. For example, since 1987 counts at Scottish and Southern Energy's Mucomir dam on the River Lochy have been compromised by escapes from a nearby fish farm (Stephen 2003).

Escapes from fish farms are usually caused by storm damage to holding facilities, human error during routine handling operations, vandalism and criminal damage, and seal activity. Fish can escape as fry, parr, smolts or adults. Quantifying the extent of escaped farmed fish in Scotland is difficult, although published figures state that 16 escapes of Atlantic salmon and three of rainbow trout were reported in 2002 involving almost 450,000 fish. However escapes may go unnoticed and/or unreported.

In the absence of reliable statistics for escaped Atlantic salmon, scientists attempt to measure their frequency directly in the wild. There are a number of techniques for distinguishing reared from wild Atlantic salmon. These include morphological defects (Lund *et al*. 1989), scale and otolith reading (Lund & Hansen 1991), genetic analysis (Crozier 1993) and carotenoid analysis (Craik & Harvey 1987). Studies conducted in rivers in northwest Scotland using this latter technique revealed that the proportion of eggs and alevins containing canthaxanthin (a pigment used in aquaculture) averaged at about 5% and in one case reached 20% (Webb *et al.* 1993). Although this gives an indication of the proportion of escaped farmed Atlantic salmon it is likely to be an underestimate as only females can pass on the canthaxanthin and some escapees do not contain the pigment.

Escaped farmed Atlantic salmon can breed with wild Atlantic salmon, adversely affecting the wild populations. Research in Ireland by McGinnity and colleagues (2003) indicates that farmed Atlantic salmon and the hybrids of farmed and wild Atlantic salmon, competitively displace wild parr in the freshwater environment, but have a much lower survival at sea. Moreover, many of the eggs produced by spawnings between returning hybrids die in the stream. Over several generations the cumulative effect of fish farm escapes could lead to the extinction of vulnerable wild populations (McGinnity *et al.* 2003).

The potentially serious effects of escaped farmed Atlantic salmon on wild populations in Scotland has important implications for any conservation management plan reliant solely on fish counters. Since counters cannot distinguish reared from wild fish the proportion of fish of farmed origin in vulnerable rivers should be monitored by other means. Such information can then be used to reduce the total count accordingly. However, due to the negative impacts of farmed fish the inferred wild count should perhaps be reduced still further to reflect the consequences for the wild populations. In this sense, farmed Atlantic salmon represent negative counts.

A joint industry and government working group on farmed fish escapes chaired by the Scottish Executive Rural Affairs Department made a number of recommendations for tackling the problem of escapes. These involve improvements to cage design, early accurate notification of escapes, the fitting of anti-predator devices, tagging of fish and appropriate steps for recapture (Anon. 2000a). Following this, legislation was introduced in May 2002 which makes the reporting of incidents of escapes, or suspected escapes, mandatory.

Issues of escapes and containment were addressed by the Ministerial Working Group on Aquaculture (MWGA), made up of representatives of main stakeholder groups with an interest in the industry. The *Strategic Framework for Scottish Aquaculture* which was published by the MWGA in March 2003 set out a number of priorities for tackling issues such as the location of sites, prevention of escapes and the further development of containment guidance. In future these measures may be expected to reduce the frequency of escaped farmed fish in rivers and therefore the obstacles they present to the accuracy of wild Atlantic salmon assessment.

13 THE STATUS OF SCOTTISH ATLANTIC SALMON

13.1 Utility of counter data

The analysis of the counter and rod catch data demonstrates that the two sources of information are mutually supportive. Both the district-level rod catches and counts from the suitably-sited, regularly monitored and validated resistivity counters considered in this report broadly reflect the local abundance of Atlantic salmon at the relevant scale.

13.2 Interpreting the trends

Given the reliability of the data, what do the trends in the counters tell us about Atlantic salmon in Scotland? As discussed in Section 10, of the 12 counter time series analysed, six (the Awe, Aigas, Torr Achilty, Morar, Invergarry and Westwater) show an n-fold decrease per half century of −2 or more, three show an n-fold increase of 2 or more (the Logie, Clunie and Ericht) and the remaining three (the Beannachran, Dundreggan and Pitlochry) have remained relatively constant (Table 6).

How are we to make sense of the different trends? For example, are all the declines occurring on counters positioned on rivers that produce a high proportion of spring Atlantic salmon? Alternatively, are the declines limited to the West Coast? Table 7 attempts to answer these and similar questions. It shows a breakdown of the trends by various categories. A cursory examination of Table 7 reveals that the number of counters is too small to allow any general conclusions to be drawn. The inadequate sample size is not, however, the only obstacle to the inference of a Scotland-wide picture of the status of Atlantic salmon from counters alone. We discuss each of these obstacles below.

Table 7 The number of counters in each category showing an n-fold increase of 2 or more per half century, an n-fold decrease of −2 or more or remaining relatively constant. Counters were classified as East Coast if the mouth of the river on which they are sited is on the East Coast, Small River if the maximum count was < 1,000, Spring River if a early-running Atlantic salmon make up a substantial proportion of the run and Hydro River if the counter is on a hydro-electric dam.

		Coast		River Size		Spring River		Hydro River	
	Total	**East**	**West**	**Small**	**Big**	**Yes**	**No**	**Yes**	**No**
Increasing	3	3	0	1	2	1	2	1	2
Constant	3	3	0	2	1	3	0	3	0
Decreasing	6	4	2	1	5	1	5	5	1
Total	12	10	2	4	8	5	7	9	3

13.3 Independence in Atlantic salmon populations

Since they home to their natal areas, Scottish Atlantic salmon do not constitute a single population whose fortunes can be summarised in a single trend line. Neighbouring tributaries may vary independently due to a wide range of pressures that differ among locations and with time. Such pressures include habitat change, predation and targeted fisheries. In addition, tributaries may contain genetically distinct populations, which may respond differently to some or all of these pressures. A good example of this independence can be seen by comparing trends at the Dundreggan and Invergarry counters on the Ness catchment. While the Dundreggan population is relatively stable, the Invergarry population separated by just 25km is in marked decline. Clearly, combining data from populations to produce an average trend can mask the decline and even extinction of individual populations (see also the *Case Study: Atlantic salmon in the Tweed and its catchment*).

In general we recommend monitoring and managing spatial groupings of Atlantic salmon at the finest geographical scales consistent with the population structure. Unfortunately, in most cases population boundaries cannot yet be adequately identified. Even if this was possible, the potentially large number of populations would probably make the monitoring of individual populations impractical. Fortunately, for management and conservation purposes, despite the potential for divergence, populations in geographically adjacent areas may show similar trends. If this can be established then it may not be necessary to monitor all the populations individually but rather a subset of 'indicator populations.'

Only those counters on small rivers or tributaries like the Clunie, Dundreggan and Invergarry counters are likely to be documenting the trend in individual populations. Counters positioned on the mainstem of large rivers, like the Aigas and Ericht counters, probably chart the 'average' trend in a collection of populations. As discussed above, such 'average' trends need to treated with caution. The difficulties of interpretation can be reduced if, instead of considering the annual trend, a separate trend is produced for each month or season. Such a temporal decomposition of the trend is useful because run-timing reflects population membership (Stewart *et al*. 2002). In other words, early-returning Atlantic salmon and later-running fish belong to different populations. Unfortunately, most of the counts were only readily available on an annual basis. A recommendation of this report, therefore, is that in future counter data are compiled on a month-by-month basis to support more detailed analysis.

13.4 Biases in the counter data

The 12 counters analysed in this report do not represent the trends in a random sample of populations, rather, the sample is strongly biased. Nine of the 12 counters are situated on hydro-electric dams which will have altered the flow regime and associated ecology of the river. Furthermore the majority of Scottish rivers which are large enough for electricity generation empty onto the East Coast. Consequently, the majority of the counters record Atlantic salmon trends in East Coast rivers. Only two of the 12 counters are located on West Coast rivers. General conclusions regarding all Scottish Atlantic salmon and all Scottish rivers cannot be drawn from such a biased sample.

13.5 Decline in netting effort

Finally, coastal and estuarine nets around Scotland used to catch large numbers of Atlantic salmon that were destined to return to the rivers. With the falling price of Atlantic salmon and diminishing catches the netting effort has reduced dramatically in recent decades. When considering trends in Atlantic salmon abundance this decline needs to be borne in mind. A stable rod catch may actually mask a drop in the abundance of Atlantic salmon returning to the coast (known as the pre-fishery abundance). Since the number of spawners is determined by the pre-fishery abundance minus the fishery catch, conservationists and managers alike need to assess carefully both these measures. Counters like the rod catch can only track changes in the in-river abundance.

14 A FRAMEWORK FOR INTEGRATING ATLANTIC SALMON DATA

As discussed in the previous section, counter data alone are insufficient to provide a Scotland-wide assessment of the status of Atlantic salmon. To achieve this all the available data need to be integrated and used to inform a targeted programme of further data collection. In our opinion assessments are best done within a GIS environment where data can be viewed at a range of scales from the national to the sub-population level. The hierarchical structure of the river catchments provides a natural framework for sub-dividing Scotland at each scale. Questions which have been identified as useful include 'what is the average status of the populations?', 'what is the direction of the long-term trend?', 'is a particular year anomalously low?' and 'what is the absolute abundance (with respect to a critical level)?'. Insufficient information to answer a question for a particular area would become readily apparent and be used to stimulate further data collection. FRS researchers have already begun to explore the technical and statistical issues that need to be overcome if such an assessment scheme is to become a reality.

15 INTERPRETING CHANGES IN ABUNDANCE

Due to their anadromous life-cycle, Atlantic salmon occupy a wide-range of ecologically diverse and geographically disparate environments. Identifying the primary factors responsible for changes in the abundance of Atlantic salmon has proven extremely difficult. In 2001, a report was published which evaluated the possible causes of the decline in the pre-fishery abundance of North American Atlantic salmon (Cairns 2001). The comprehensive report identified 62 hypotheses for the decline. The hypotheses applied to six life-stages (returning adult to egg, egg to hatch, hatch to smolt, smolt at migration, ocean life, adult return through estuaries) in eight categories (fisheries, aquaculture, disease, predation, life history, chemical environment). Consistent with the widely held view that the decline of Atlantic salmon in general is due to low survival at sea, 10 of the 12 top-ranked hypothesized factors impacted salmon in the estuarine or marine environments. However, it was concluded that the reliability of the ranking system was constrained by inadequate knowledge.

A similar conclusion can be drawn for Scottish Atlantic salmon. Consistent with the range-wide decline of Atlantic salmon, the most common view is that in many populations the primary factors act in estuaries or the open oceans. What these factors are is unknown. Evaluating the informativeness of the available data, comparing the data so as to identify the true underlying trends and integrating the available data into a fine-scale, nation-wide assessment of the status of Scottish salmon are all first steps in the on-going effort to identify the primary causal factors.

16 SUMMARY

Resistivity counters which have been suitably sited and regularly monitored and maintained can provide useful information about trends in Atlantic salmon populations or population grouping(s). Of the 29 fish counters in active operation in Scotland, 18 provide sufficient long-term data for meaningful analysis. Of these, 12 counters were considered by their operators to provide reliable data. The time series for these 12 counters are, on the whole, congruent with the relevant district rod catch, indicating that they contain information about the abundance of Scottish Atlantic salmon. Future analyses should also examine the remaining six long-term counter time series to see if they also contain signals.

The 12 counters analysed only provide information about the trends in a small biased sample of population groupings from mostly hydro-affected east coast rivers. These counters, and counters in general, cannot be used to draw conclusions about Scottish Atlantic salmon in general, only the population groupings whose abundance they measure. In order to provide a Scotland-wide assessment of the status of Scottish salmon, all the available information should be integrated into a GIS system which can be queried by area and scale. The outputs should also be used to drive a programme of focused data collection.

Changes in salmon abundance appear to be primarily driven by factors acting in the marine or estuarine environment but what these factors are remains elusive. A fine-scale nationwide assessment framework would not only provide fisheries managers and conservationists with an invaluable tool but would aid attempts to identify the principal factors responsible for changes in Atlantic salmon abundance.

Finally, the site of any future counters should be chosen carefully so as to complement available data of other kinds, and especially perhaps the rod catch data. In particular, counters will be most useful when managers and conservationists require knowledge of the absolute number of fish (for example, where populations are reaching critically low levels), trends in individual populations or trends for populations that are not exploited (for example, very late-running Atlantic salmon). However, a counter should only be installed when there is a suitable site available plus sufficient funds to ensure it is regularly validated and monitored.

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