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Scottish Marine and Freshwater Science Vol 7 No 30

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marine scotland

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Published by Marine Scotland Science

ISSN: 2043-7722
DOI: 10.7489/1879-1

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This report presents the results of marine and freshwater scientific work carried out by Marine Scotland Science.

Assessing the status of Atlantic salmon in the Aberdeenshire River Dee from electrofishing data

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Executive Summary

Salmon fry densities on the river Dee were estimated from juvenile electrofishing data using a capture probability model initially developed in 2015. The resulting density estimates were compared to two potential reference levels that also varied by habitat; (1) a mean National Reference, and (2) a Dee Reference. The biological reality of the different reference levels was assessed by determining whether observed fry densities were above or below the reference levels in the Girnock Burn for each year between 2001 and 2016 and comparing this to an independent measure of catchment health (Smax: that indicates whether maximum emigrant production is likely to be sustained) obtained from stock-recruitment data. The local Dee Reference was found to be in greater agreement with assessment made using Smax than the National Reference which was considerably too low for the Girnock Burn. When salmon fry densities across the whole Dee catchment were compared to the Dee Reference, it was found that the catchment was close to maintaining maximum production in 2012 (a high spawner return year), but considerably below reference in 2016. A number of limitations of the current data, models and monitoring are identified and discussed alongside future developments and directions. Despite the limitations of the current approach, it provides useful insights into status of salmon on the River Dee and with future developments will offer a useful assessment to complement those based on adult returns.

Introduction

In 2015, Millar *et al*. produced a report outlining a two stage approach for modelling Atlantic salmon fry abundance from GIS derived habitat covariates and electrofishing data. This involved (1) modelling spatio-temporal variability in capture probability, and (2) modelling spatiotemporal variability in fish counts using the modelled capture probability as an offset. In 2016, a paper was published that illustrated a national capture probability model for Atlantic salmon fry and parr and outlined the strengths of this approach over other options that assumed constant capture probability or modelled capture probability on a site visit by site visit basis (Millar *et al*., 2016). More recently, work has begun to refit the capture probability model using an updated and quality controlled electrofishing dataset, and to develop a juvenile salmon density model that incorporates both fry and parr lifestages in a single model, carrying error from the capture probability model. At present, this most recent modelling work is incomplete. Consequently, this report focuses on the earlier work reported by Millar *et al*. (2015) and is likely to be superseded in due course.

Following the publication of Millar *et al.* (2015), there was substantial interest in the application of the reported fry models for assessing the health of juvenile salmon populations from electrofishing data. The potential of this approach was first illustrated on the South Esk (Orpwood *et al*., 2016), but was also used to assess the health of salmon fry populations on the River Dee in 2015.

This report provides a brief overview of the potential application of these early models for assessing the health of river catchments from electrofishing data using the models outlined by Millar *et al*. (2015), together with some of the strengths and limitations. It also considers the application of two alternative metrics for defining “reference condition” or “health”. These metrics of “health” are compared with an independent measure obtained from a detailed stock-recruitment relationship for the Girnock Burn, an MSS index monitoring site on the upper Dee. Finally, the report assesses the health of the River Dee salmon stocks, based on fry abundances obtained from electrofishing in 2012 (a year driven by relatively high spawner returns in 2011, where both the Girnock and Baddoch Burns in upper Deeside were at carrying capacity) and 2016.

This report has the following objectives:

- Provide a brief overview of the salmon fry density model developed by Millar *et al*., (2015) and the some of the underlying limitations
- Describe two alternative approaches for establishing “reference conditions” which could be considered indicative of a “healthy catchment”

- Compare reference conditions for fry abundance with an independent measure of health obtained from detailed stock-recruitment data on the Girnock Burn.
- Compare assessments of "health" for the River Dee catchment in 2012 (preceded by a relatively high spawner year) with those for 2016
- Provide an assessment of the health of the Dee Catchment in 2016 based on salmon fry abundance.

Data and model limitations

Ideally, expected salmon fry densities (reference densities) would be modelled from a dataset that was representative of all available habitats in Scotland (unbiased), in years where adult returns from all fish stocks in the preceding years were sufficient to fully stock available freshwater habitat. The dataset would also exclude any sites affected by anthropogenic impacts except where these effects could be identified from GIS predictors. Under these circumstances the estimated densities in each catchment would represent true "reference conditions".

In reality the dataset compiled by Millar *et al*. (2015) included data collected by MSS, SEPA, Fisheries Trusts and boards for a variety of purposes. It is therefore possible that the dataset could contain biases towards high or low density sites depending on the objectives and experimental design employed. Site selection could introduce regional or temporal biases to the fry density model if data providers predominantly electrofished areas that they thought were failing to perform, or areas they thought were doing well. Further negative bias could be introduced if there were no years with sufficient adult returns from all stock components to fully stock available habitat, or if particular regions received unusually low returns.

Unfortunately at this stage it is impossible to determine how or where such biases exist and it seems unlikely that the ideal combination of requirements identified above can be met without further carefully structured fish surveys. Under such circumstances, the fry density model was fitted to the best available data, removing locations that were affected by impacts such as impassable barriers or stocking.

The fry density model

Full details of the fry density model are provided by Millar *et al*. (2015). However, for completeness the partial effects of covariates are illustrated in Figure 1. The main habitat drivers of density at the largest spatial scales are Distance to sea (higher densities are predicted for greater distances to sea, up to ca. 100km), Upstream Catchment Area (lower densities predicted for low and high values < ca. 50 km^2 and > ca. 350 km^2) and Altitude (densities predicted to decline with increasing altitude).

Additional variability occurs in response to channel width, gradient and land-use. The overall effect of these variables is that the highest densities would be predicted for low altitude rivers, a long way from the sea, with intermediate catchment sizes and moderate channel widths. The lowest densities would be predicted for high altitude rivers, close to the sea with very low or very high channel widths. In reality these extreme cases rarely occur and high model predictions tend to occur in tributary rivers at low altitudes in the lower part of a catchment or moderate altitudes in the upper catchment. Small, very high altitude rivers are never associated with high density predictions.

Predicting expected or “reference” fry densities

Expected fry densities can be predicted from the national model for a given location, or set of locations. In the latter case, it is also possible to estimate an average density for the catchment which can be compared to the average density from electrofishing sites. Providing that the electrofishing sites are representative of the catchment this could provide an overall assessment of catchment health.

When specifying the model parameters that are used to predict “reference” conditions at a particular location, some decisions are relatively straight forward. For example, habitat covariate values should be set to the values observed at the site where predictions are required (e.g. altitude, channel width, gradient, etc.) and known pressure variables such as urban land-use or conifer forest (largely expected to be plantation forestry) should be set to zero. Furthermore, because the model aims to predict fry densities under saturated spawning conditions, predictions should be made for the year with the highest observed densities (at the national scale) on an assumption that other factors affecting production are constant across years.

Other decisions require more consideration, with less obvious solutions. For example, average salmon densities vary between catchments and this is captured in the fry density model as “catchment effects” (Figure 1). If a local catchment only contains data on fish densities for years where there have been low spawner returns, then the local catchment coefficient would be too low, resulting in an under-prediction of the local reference condition. Similarly, where there is insufficient local electrofishing data, the estimate of the local catchment effect could be too uncertain to be useful (See Figure 1, top panel). Therefore, in both these circumstances, it could make sense to borrow data on expected mean densities (having accounted for habitat variability) from across Scotland or from nearby catchments. One potential option would be to use the mean of the catchment coefficients from the density model. In contrast, where there is a large amount of locally derived electrofishing data that results in a precise estimate of the catchment effect, and this has been collected in a representative manner that avoids bias in the density estimates, it may be desirable to use a local catchment coefficient. Depending on the difference between the mean and local catchment effects (coefficients), substantial differences in the "reference" densities could arise.

This report explores two potential metrics of "reference" condition for the River Dee, the first using the mean catchment coefficient for Scotland (hereafter "National Reference") and the second using the catchment effect estimated for the River Dee (hereafter "Dee Reference"). In simple terms these can be thought of as the mean national expectation for fish density in a good year, for a particular set of habitat characteristics, or the expectation for the River Dee in a good year for a particular set of habitat characteristics. The different catchment coefficients underpinning these different reference conditions are highlighted in Figure1 (top panel). The resulting differences in expected fish densities are shown in Figure 2, where the Dee Reference predictions result in higher expected densities than the National Reference predictions.

Comparison of fry abundance reference conditions with those developed from stock-recruitment data for the Girnock Burn

The Girnock Burn has detailed information on numbers of adult spawners, production of emigrants, fish sizes and ages. These data can be used to derive a stock-recruitment relationship, from which it is possible to determine the number of female spawners required to maximise emigrant production (Smax, Fig. 3, top panel). These data were analysed by Bacon *et al*. (2015) and are updated annually at http://www.gov.scot/Topics/marine/Salmon-Trout-Coarse/Freshwater/Monitoring/Traps. From these data it is possible to determine the years in which the Girnock is estimated to be at carrying capacity and compare this with the estimates of "catchment health" obtained from juvenile electrofishing.

It is estimated that the number of females returning to the Girnock Burn has only exceeded Smax (carrying capacity) in three of the last 16 years (2004, 2010 and 2011 spawning years which equate to 2005, 2011 and 2012 fry production years). In contrast, observed fry densities exceeded the National reference condition in all but 3 years (2013, 2015, and 2016). This would seem to indicate that the mean national expectation is too low for a catchment such as the Girnock. However, there was good agreement between the estimate of "health" obtained from Smax and that obtained by comparing Girnock fry densities to the Dee reference conditions, where average densities only met or exceeded reference in 2005 and 2012 (Fig. 3 middle panel).

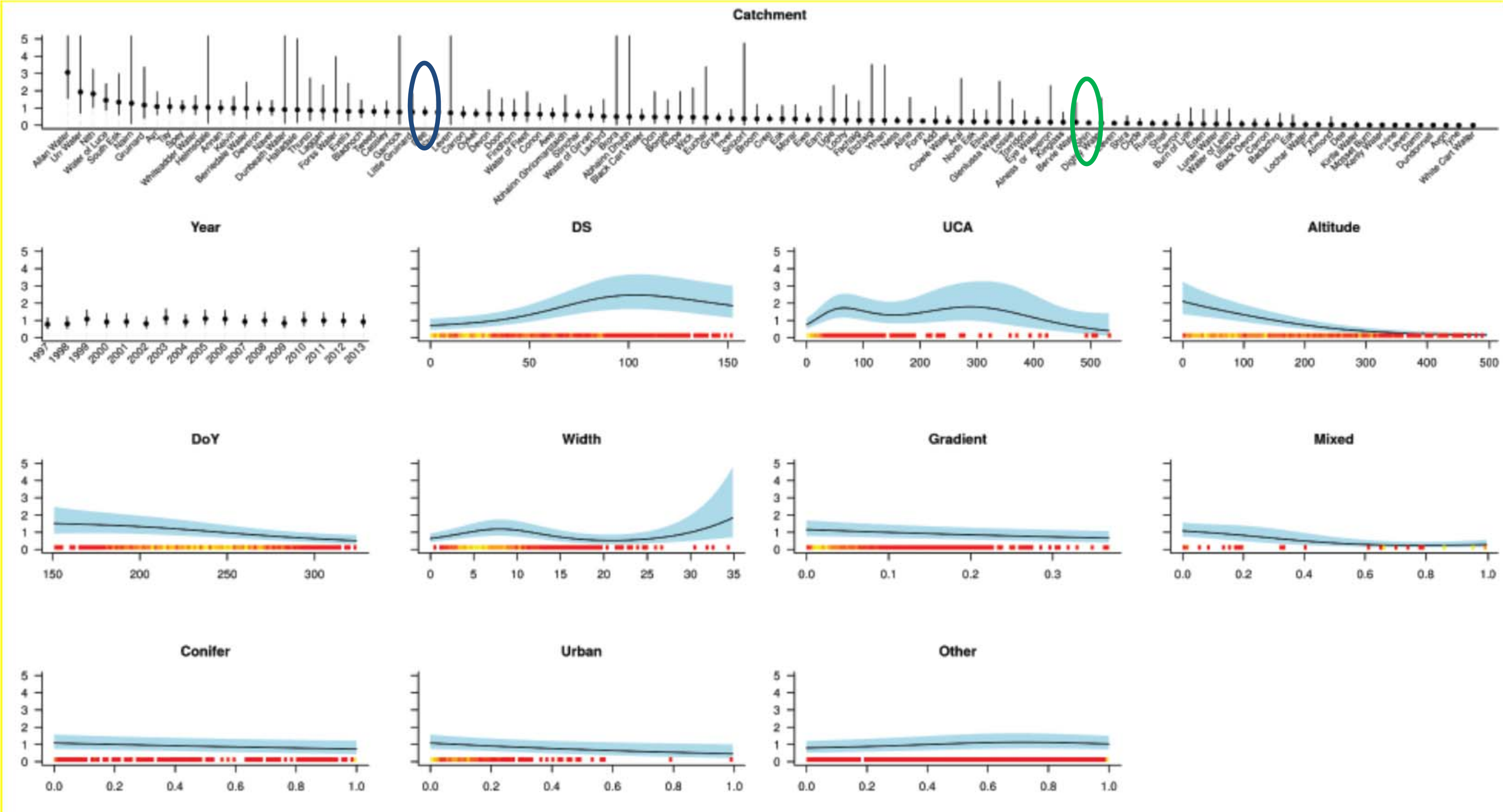
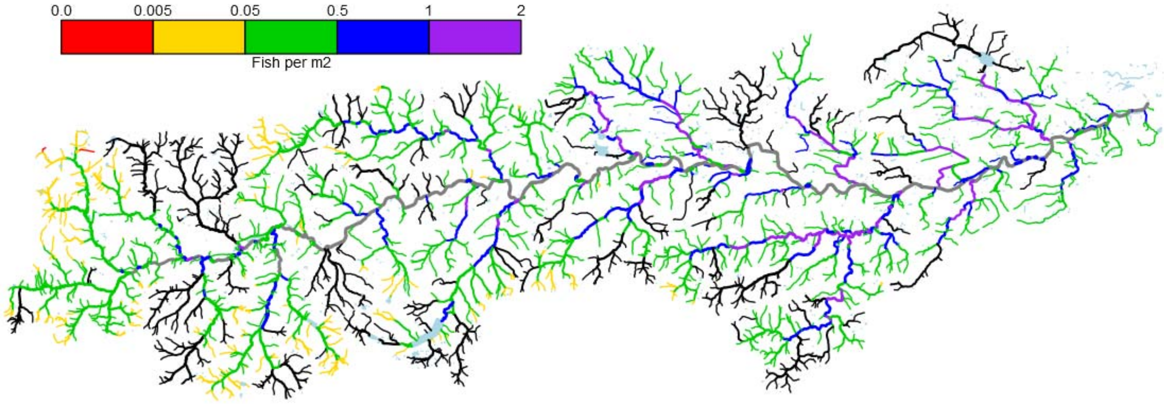


Figure 1: (after Millar *et al*., 2015). Relationship between fish density and covariates. Plots conditioned on Catchment “Tay”, Year “1996” and median values for remaining covariates. 95% pointwise confidence intervals are in blue. “Rugs” on the x-axis indicate data availability with yellow areas indicating greater observation density. Catchment effect “Dee” is highlighted with a blue ellipse. The approximate mean catchment coefficient is highlighted in green. Distance to Sea (DS); Upstream Catchment Area (UCA); Day of Year (DoY). Riparian landuse characterised as % Conifer, Mixed (woodland), Urban or Other.

(a) Dee Reference predictions



(b) National Reference predictions

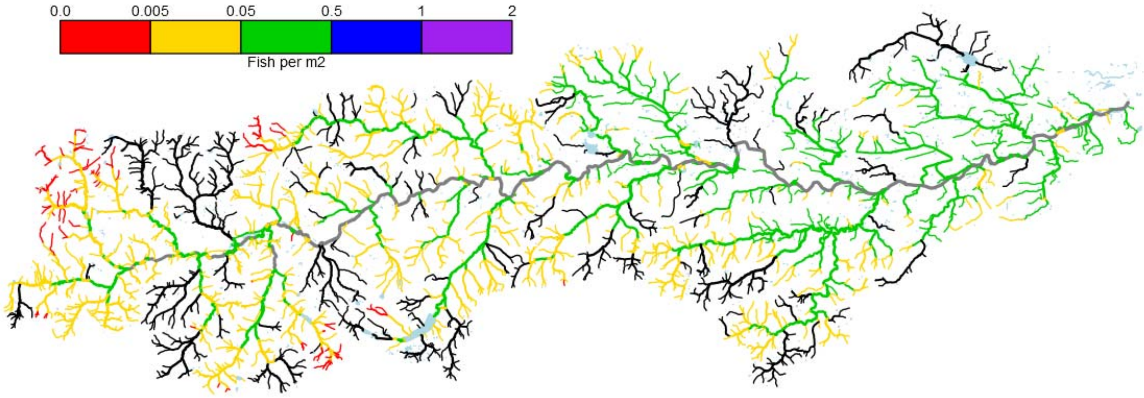


Figure 2: Maps showing predicted reference (expected) densities (a) using the Dee specific catchment coefficient or (b) a national average catchment coefficient. It was not possible to predict expected densities for watercourses shown in grey as their site characteristics were outside of the environmental range of the national electrofishing dataset. No predictions are produced for rivers shown in black as these are above impassable barriers for salmon. Based on digital spatial data licensed from Centre for Ecology and Hydrology, © NERC. © Crown copyright. Licence 100024655.

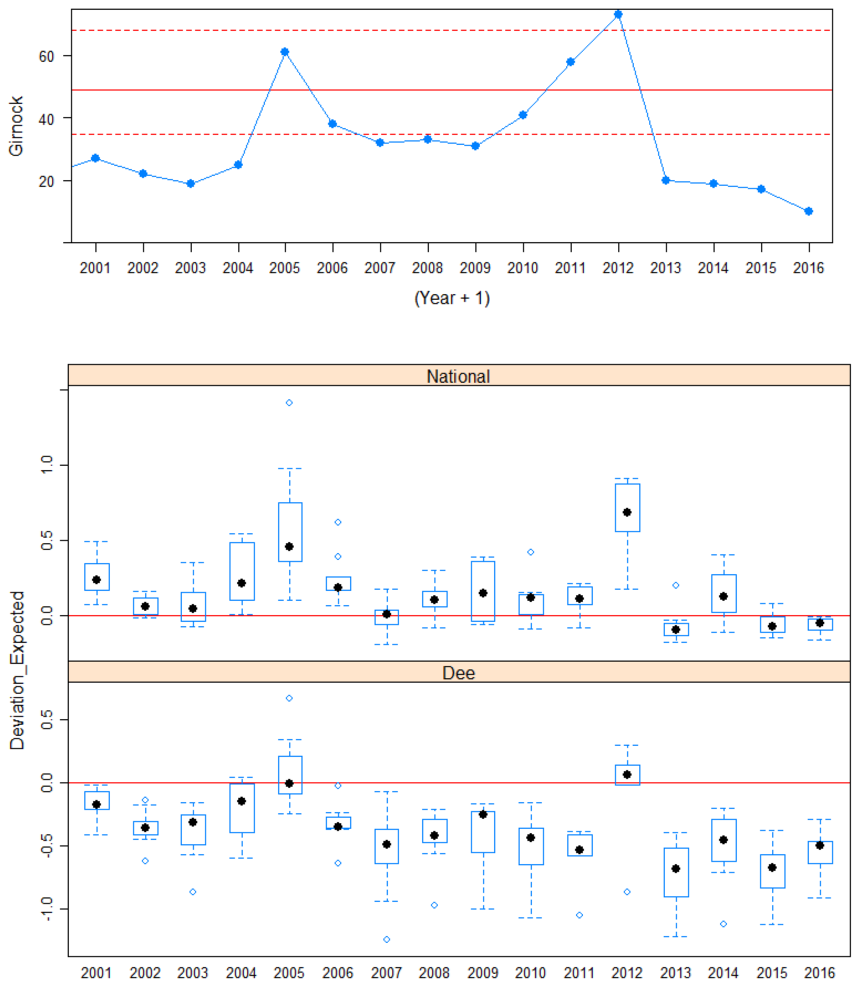


Figure 3: Plots showing *Top panel*: the number of adults returning to the Girnock trap (blue lines and points) together with the estimated number of female fish required to fully stock the Girnock (Smax, solid horizontal red line, with 95% confidence limits, horizontal dashed red lines) *Middle panel*: Box and whisker plot showing the difference between observed and “reference” fry densities for Girnock Burn electrofishing sites using a mean national expectation. Horizontal red line indicates no difference between observed and expected densities. Where black dots are above the red horizontal line, this indicates that on average observed densities exceeded “reference densities” and the catchment could be considered “at reference” based on current definitions. Where black dots are close to, but below the line, this may still be considered acceptable depending on the degree of deviation and exact definitions of reference. *Lower Panel*: Box and whiskers plot repeated using “Dee reference” densities.

Assessment of River Dee fry densities against the National and Dee reference levels for 2012 (high spawner year) and 2016

Rod catches provide a useful, if indirect, indicator of fish abundance. Figure 4 (top panel) shows the temporal trends in rod catch between 1952 and present. Spring salmon catches have declined across much of the time series, although a slight increase was observed between ca. 2000 and 2011 when catches were at their highest level since 1989. In contrast, summer / autumn catches increased between ca. 2000 and 2010 before declining thereafter. As spring and later running salmon are thought to spawn in different parts of river catchments, the 2011 spawning year (2012 fry year), probably represents the best chance of observing catchment-wide fry abundances close to carrying capacity in the last 20 years.

The median observed salmon fry density was substantially higher than the National Reference level in 2012 (0.147 fry (number) per metre squared (nm^{-2})) and slightly lower in 2016 (-0.043 nm^{-2}). However it was slightly lower than the Dee Reference level in 2012 (-0.095 nm^{-2}) and very substantially lower in 2016 (-0.303 nm^{-2}; Fig. 4, lower panel). In this respect, the comparison of reference levels at the scale of the Dee appears broadly comparable with that at the scale of the Girnock indicating that a Dee specific reference condition appears more appropriate.

The spatial distribution of the performance of individual sites can be seen in Figure 5. Any sites affected by impassable or only recently removed barriers have been removed from the above analysis and from the maps to avoid negative bias in the assessment. Unfortunately, once these sites were removed, there were limited electrofishing data available from the lower catchment in 2012, and thus most of the assessment is driven by sites in the upper catchment. The performance of sites in the lower catchment was generally less than expected relative to both the Dee (Fig. 5a) and National (Fig. 5b) reference conditions. Sites in the upper catchment were approximately equally distributed either side of the Dee Reference (Fig. 5a) as would be expected if the target were being met. There were no obvious patterns indicating that certain tributaries were doing substantially better or worse than might be expected. However, almost all the sites in the upper catchment performed better than the National Reference (Fig. 5b), again indicating that this may be too low a performance target for the Dee.

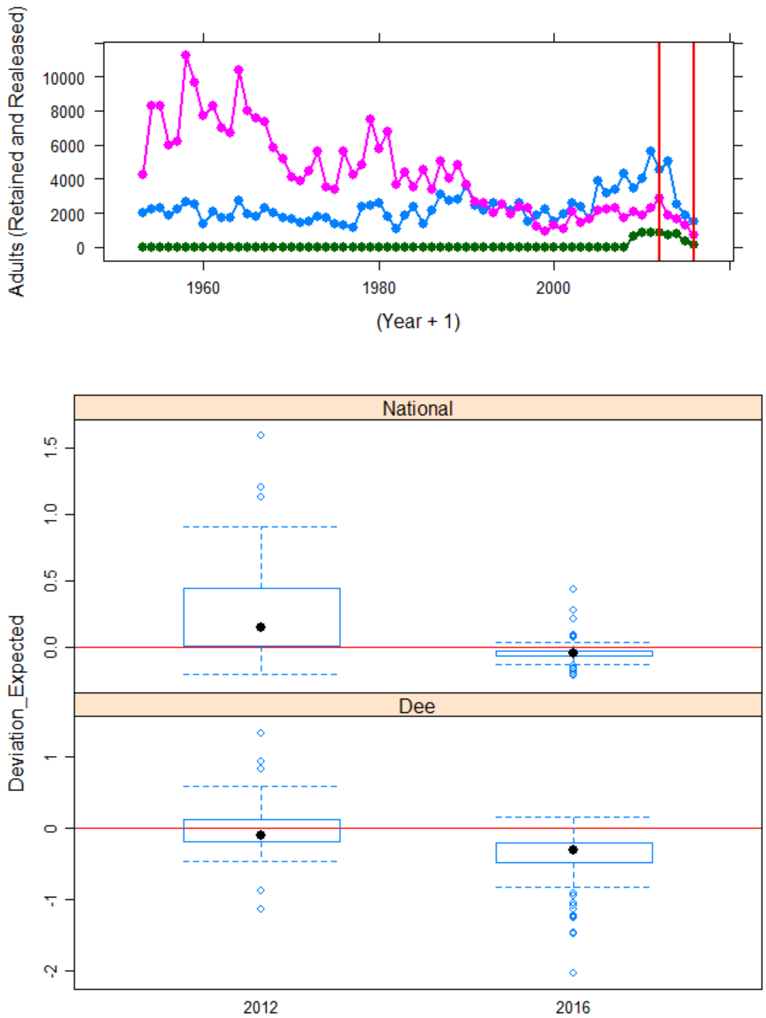
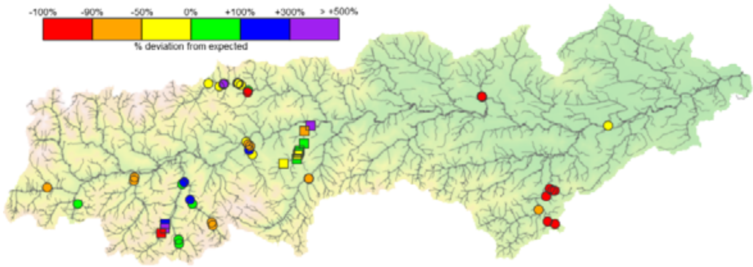
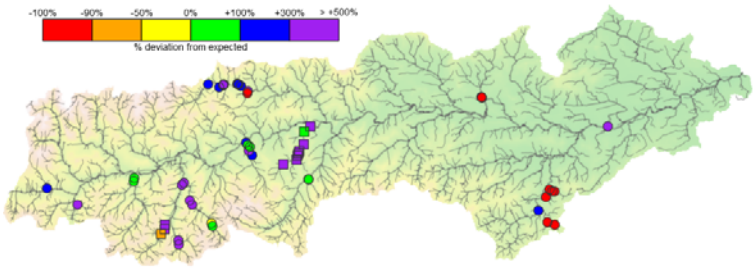


Figure 4: Plots showing *Top panel*: the number of adult salmon (caught and retained) on the River Dee in Spring (February to May, purple points and line), Summer / Autumn (June to September blue points and line) and October, since 2008 (green points and line). Vertical red lines indicate 2011 and 2015 spawner years that equate to 2012 and 2016 fry years. *Middle panel*: Box and whisker plot showing the difference between observed and “reference” fry densities for River Dee electrofishing sites using a mean national expectation. Horizontal red line indicates no difference between observed and expected densities. Where black dots are above the red horizontal line, this indicates that on average observed densities exceeded “reference densities” and the catchment could be considered “at reference”. *Lower Panel*: Box and whiskers plot repeated using “Dee reference” densities.

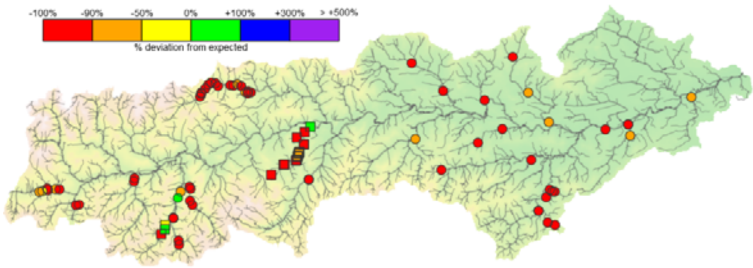
(a) Dee Reference fry densities: 2012



(b) National Reference fry densities: 2012



(c) Dee Reference fry densities: 2016



(d) National Reference fry densities: 2016

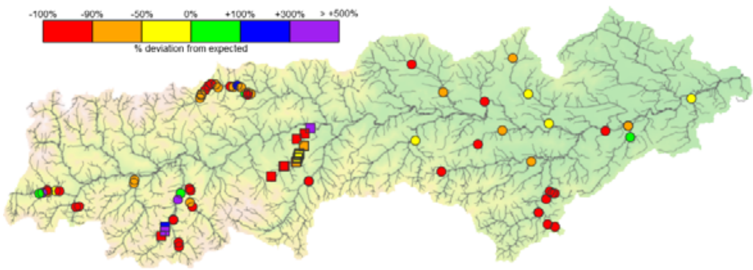


Figure 5 Percentage differences between observed and expected fry densities in 2012 (a, b) and 2016 (c, d) using National (b, d) and Dee (a, c) reference conditions. Based on digital spatial data licensed from Centre for Ecology and Hydrology, © NERC. © Crown copyright. Licence 100024655.

The spatial coverage of electrofishing sites in the lower catchment was substantially improved between 2012 and 2016. The performance of individual electrofishing sites in both the upper and lower catchment was almost uniformly poor against the National Reference (Fig. 5d) with only a few sites performing as, or better than expected. The picture was therefore even worse against the Dee Reference conditions (Fig. 5c), with most sites containing less than 10% of the expected fry numbers.

Summary and Discussion

This report explored potential options for assessing the health of salmon stocks on the river Dee by comparing observed juvenile numbers from electrofishing to reference conditions obtained from a national fry density model (Millar *et al.*, 2015). Two potential reference conditions were explored (1) a mean National Reference condition that used the mean catchment coefficient from the density model and (2) a Dee Reference condition that used the catchment coefficient estimated for the Dee. The two reference conditions were compared with an alternative metric of catchment health (Smax) based on an analysis of stock-recruitment data for the Girnock Burn. Smax provides an estimate of the number of spawners required to maximise emigrant production at the Girnock Burn. The two juvenile reference conditions were intended to represent maximum expected fry production under conditions of saturated spawners. The two measures of catchment health are therefore conceptually similar and focussed on setting a target that maximises production. By comparing Girnock adult returns to the estimate of Smax, it was possible to determine which spawner years would likely maximise emigrant production in the Girnock. Similarly it was possible to determine in which years fry densities (on average) met or exceeded the two fry reference conditions. Ideally we would expect these two alternative metrics of catchment health to be broadly coherent. It was found that assessments of fry using the Dee Reference were in strong agreement with the assessments using Smax, but that the assessments of status using the National Reference were too low, resulting in the sub-catchment meeting this target in all but three of the last 16 years. Given this observation, the amount of electrofishing data available on the Dee and the low uncertainty in the Dee catchment coefficient, it is suggested that the status of the Dee catchment be assessed relative to the Dee Reference. This would not be possible for other catchments with limited electrofishing data where the estimate of the catchment effect (Figure 1 top panel) was highly uncertain, or where there were no years with high (saturated) spawner returns.

Assessment of the status of the Dee relative to the Dee Reference indicated that the catchment was close to maximising fry production under conditions of high spawner returns in 2012, i.e. the average observed density (median 0.21 nm^{-2}) was close to the reference density (median 0.27 nm^{-2}). However, even in 2012 overall performance was reduced by a number of poorly performing sites in the lower catchment, compounded by sparse data coverage. In 2016, the data coverage in the lower catchment was much improved, but the catchment failed to perform adequately against the Dee Reference and even the lower National Reference, with almost universally lower than expected densities. Indeed, average fry densities in 2016 were only around 5% of the Dee Reference expectation or 27% of the National Reference. This would seem to indicate that fry production in the Dee is substantially lower than it could be. While one weak year class on its own will not necessarily have an effect on smolt production due to compensatory mechanisms (e.g. Bacon *et al*., 2015), a succession of years of low fry density will undoubtedly cause a reduction in the numbers of emigrating salmon.

At first appearance this assessment of catchment health using juvenile data would appear to contrast with the results of recent adult assessments under the conservation regulations where the River Dee is assessed as Grade 1 (http://www.gov.scot/Resource/0051/00510536.pdf). These differences potentially arise for a number of reasons. Firstly, the assessment in this report was based on fry data for 2016 alone, whereas the adult assessment uses the last five years of adult returns that included the relatively high 2011 and 2012 spawner years. It is also worth noting that the result of the adult assessment for the 2015 spawner year is less favourable than previous years (<80% probability of meeting CL). Secondly, the metrics of health used in the juvenile assessment model are consistent with maximum production (and thus Smax), whereas the adult assessment uses Maximum Sustainable Yield (or MSY) which is a less demanding target commonly used by ICES for managing exploited fish stocks. Finally, the Dee Reference which was explored in this report allows for local (catchment scale) variability in average fry densities, even after accounting for the effects of physical habitat. This has the effect of allowing fry reference levels (productivity) to vary between catchments based on observed production. Such an option could be considered reasonable where there are sufficient data to define local catchment productivity and where the underlying model contains years where the catchment was fully stocked. This was arguably true in the case of the Dee and indeed the independent comparison with data from the Girnock suggests it was appropriate. In the case of the adult based conservation assessment, it is assumed that all catchments require the same level of egg deposition and it is therefore possible that the target is lower than required for a salmon river like the Dee which is thought to be characterised by higher than average productivity.

Although there appears to be fairly strong evidence suggesting that fry production in the Dee is substantially below carrying capacity, the underlying limitations of the models, reference conditions, model input data (discussed previously) and monitoring data should also be considered. This exercise used a preliminary pair of capture probability and density models developed for salmon fry (Millar *et al*., 2015). Since then there has been further quality control of the underlying datasets and improvements to the capture probability model (Millar *et al*., 2016). Work is now underway to improve the juvenile density model and to extend it to include both fry and parr in a single model that should provide a more robust estimate of catchment health from juvenile data. Investigations are also underway to explore options for designing spatially balanced, unbiased electrofishing monitoring strategies. While juvenile monitoring on the Dee is more comprehensive than many catchments, it still potentially suffers from bias. For example, some sub-catchments contain many electrofishing sites while other areas contain no data. If data coverage has been inadvertently located in good or poor areas this could result in biased assessments of overall catchment performance. Such spatial bias is unsurprising given that much of the data has been collected to meet other objectives. However, there is an argument for a specifically designed monitoring plan for assessing catchment health in future years if juvenile assessment becomes routine or contributes towards assessments that underpin conservation regulations. A further limitation of the current juvenile models is their dependence on electrofishing data that is obtained only on wadeable rivers. This means that quantitative assessments cannot be obtained for larger rivers (see grey shading Fig. 2) that include much of the main stem. While the development of methods for assessing larger rivers (and indeed lochs) should be considered a priority, it seems unlikely that such data will become available soon. Given this constraint, juvenile assessments in the short term will probably need to be focussed on rivers where electrofishing is possible.

Although there are a number of limitations to the current assessment, it is also clear that juvenile methods offer a potentially valuable complimentary approach to adult based assessment methods once the next round of modelling is complete, and issues over sampling design, data collection methods and sampling intensity can be overcome. Work is underway to resolve these issues in collaboration with local fisheries trusts and future trialling of new approaches will be essential. In the longer term, assessments of catchment health that use both adult and juvenile assessment methods would seem to be better than any single assessment, given the (different) limitations of the two approaches. Finally, it is useful to note that juvenile assessment methods can provide not only an assessment of overall catchment health, but could also be used to assess sub-catchments (as seen here for the Girnock) or stocks, providing that relevant areas can be reliably defined. This finer scale application is useful in identifying areas of catchments that are not performing as expected, allowing further investigation or management action as required.

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