# A review of the National Atlantic Salmon stock assessment process used in England and Wales: recommendations for future implementation and further refinement



Image courtesy of Chris Conroy

Cyfoeth Naturiol Cymru Natural Resources Wales

Environment Agency

Cefas

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# Crynodeb

Mae'r adroddiad hwn yn cyflwyno canfyddiadau adolygiad cynhwysfawr o'r broses genedlaethol o asesu stociau eogiaid yr Iwerydd (*Salmo salar*) a ddefnyddir gan Asiantaeth yr Amgylchedd yn Lloegr a Cyfoeth Naturiol Cymru (CNC) yng Nghymru. Mae'r adolygiad wedi'i gwblhau gan grŵp arbenigol a gynullwyd o staff sy'n cynrychioli Asiantaeth yr Amgylchedd, CNC, a Chanolfan Gwyddorau'r Amgylchedd, Pysgodfeydd a Dyframaethu (Cefas).

Cychwynnwyd yr adolygiad mewn ymateb i ofyniad parhaus i Asiantaeth yr Amgylchedd ac CNC ddiweddaru a gwella eu prosesau o asesu stociau eogiaid yn rheolaidd ar gyfer prif afonydd eogiaid dynodedig o fewn eu hardaloedd awdurdodaeth priodol. Mae'r adolygiad wedi ystyried canllawiau Sefydliad Cadwraeth Eogiaid Gogledd yr Iwerydd (NASCO) ar gyfer rheoli stociau a physgodfeydd eogiaid ac wedi ystyried y prosesau asesu stociau eogiaid a gymhwysir mewn awdurdodaethau eraill yn y DU, ac ar draws Gogledd yr Iwerydd, er mwyn nodi arfer gorau. Mae'r grŵp adolygu wedi ystyried ein dull o reoli pysgodfeydd eogiaid yn y dyfodol a'r defnydd o ddata a thystiolaeth newydd a rhai sy'n dod i'r amlwg mewn perthynas â bioleg eogiaid yr Iwerydd, yn ogystal â'r angen i ddarparu mwy o eglurder a thryloywder wrth ddeillio asesiadau o stociau eogiaid, a'r allbynnau o'r broses hon, i lywio penderfyniadau rheoleiddio pysgodfeydd. Mae'r adolygiad wedi ystyried allbynnau ac argymhellion y Gweithdy Asesu Stociau Eogiaid Cenedlaethol, ynghyd ag adborth mewnol ac allanol a dderbyniwyd drwy weithredu rheoliadau pysgodfeydd eogiaid, yn ogystal ag ymgysylltu â'r Swyddfa Rheoleiddio Ystadegau.

Mae'r adolygiad wedi ystyried y cydrannau canlynol o'r broses asesu stociau eogiaid:

- Y prosesau asesu stociau eogiaid a ddefnyddir gan awdurdodaethau eraill i nodi arfer gorau a chydnawsedd
- Y broses o osod terfynau cadwraeth eogiaid yng Nghymru a Lloegr
- Y paramedrau biolegol a rheoli pysgodfeydd allweddol a ddefnyddir yn y broses o asesu stociau eogiaid
- Y broses ar gyfer amcangyfrif cyfraddau ecsbloetio eogiaid wrth ddefnyddio gwialen yng Nghymru a Lloegr
- Y broses ar gyfer asesu cydymffurfedd â'r terfyn cadwraeth blynyddol ar gyfer eogiaid
- Y strwythur penderfyniadau cenedlaethol ar gyfer rheoli eogiaid a ddefnyddir yng Nghymru a Lloegr i lywio camau rheoli

Mae'r adolygiad hwn yn cynnwys nifer o argymhellion allweddol sy'n ceisio diweddaru ac esblygu'r prosesau cenedlaethol presennol ar gyfer asesu stociau eogiaid a'r fframwaith rheoli cysylltiedig ar gyfer pysgodfeydd eogiaid yng Nghymru a Lloegr. Mae hefyd yn darparu cynigion ar gyfer gwaith yn y dyfodol i ddatblygu

ymhellach y prosesau o asesu stociau eogiaid, gan nodi bod datblygiadau yn y dyfodol yn dibynnu ar adnoddau staff ac ymchwiliadau pellach.

Mae'r paramedrau allweddol sy'n sail i ddeillio amcangyfrifon blynyddol dyddodiad wyau eogiaid mewn afonydd penodol – sy'n ffurfio sail asesiadau cydymffurfedd â therfynau cadwraeth mewn afonydd penodol yng Nghymru a Lloegr – wedi'u hadolygu a'u diweddaru, gan ystyried tystiolaeth newydd a thystiolaeth sy'n dod i'r amlwg ac ymchwiliadau penodol i sicrhau bod unrhyw dybiaethau a wneir yn parhau i fod yn ddilys.

Cyflwynir dull newydd ar gyfer amcangyfrif cyfraddau ecsbloetio eogiaid gan ddefnyddio gwialen mewn pysgodfeydd. Mae hyn yn ymgorffori newidynnau y mae pysgotwyr, rheolwyr pysgodfeydd a gwyddonwyr eogiaid yn credu y gallent ddylanwadu ar ecsbloetio mewn pysgodfeydd â gwialen, megis llif afonydd, ymdrech pysgodfeydd gwialen, a data amcangyfrif stoc sy'n dychwelyd sy'n annibynnol ar bysgodfeydd ac sy'n deillio o gyfrifwyr pysgod awtomataidd. Defnyddir y dull hwn i lywio cyfraddau ecsbloetio â gwialen mewn pysgodfeydd sydd mewn dalgylchoedd afonydd eogiaid nad oes ganddynt raglenni asesu stoc sy'n dychwelyd sy'n annibynnol ar bysgodfeydd.

Mae'r adolygiad hwn yn cyflwyno proses newydd o asesu cydymffurfedd â'r terfyn cadwraeth ar gyfer eogiaid sy'n ystyried perfformiad y stoc eogiaid yn seiliedig ar statws cyfredol y stoc (yn seiliedig ar berfformiad y stoc eogiaid yn ystod y pum mlynedd diwethaf) a statws rhagamcanedig y stoc (gan ystyried perfformiad dros y deg mlynedd diwethaf). Bydd y broses hon yn cael ei defnyddio wrth benderfynu ar y categori y bydd stoc eogiaid afon unigol yn cael ei rhoi ynddo bob blwyddyn.

Argymhellir pwynt cyfeirio uchaf newydd yn seiliedig ar gynhyrchiad gleisiaid uchaf y dalgylch (a fynegir mewn dyddodiad wyau). Mae'r pwynt cyfeirio uchaf yn darparu amcan rheoli sy'n canolbwyntio ar adferiad ac sy'n ceisio adfer poblogaethau eogiaid tuag at eu potensial cynhyrchiol naturiol. Mae'r dull hwn yn blaenoriaethu cynhyrchu cymaint o leisiaid eogiaid â phosibl wrth gynhyrchu gleisiaid dŵr croyw ac felly'r nifer posibl o oedolion sy'n dychwelyd i silio yn y dyfodol er mwyn cynyddu'r cyfle i'r eithaf ar gyfer cynaliadwyedd stociau eogiaid.

Mae hyn yn cynrychioli dull newydd uchelgeisiol sy'n hyrwyddo adfer stociau eogiaid fel y prif amcan rheoli er mwyn gwarchod gallu atgenhedlu ac adferiad stociau eogiaid wrth geisio sicrhau bod pysgodfeydd eogiaid lle defnyddir gwiail yn parhau i fod yn gynaliadwy i'r dyfodol. Y bwriad yw symud y tu hwnt i'r broses reoli bresennol, lle mae'r broses o wneud penderfyniadau o ran rheoli pysgodfeydd wedi ceisio osgoi i'r stoc syrthio o dan y terfyn cadwraeth, i fabwysiadu a chymhwyso pwynt cyfeirio uchaf yn uniongyrchol er mwyn osgoi i'r stoc syrthio o dan y terfyn cadwraeth. Dylid ystyried y terfyn cadwraeth fel terfyn cyfeirio isaf na ddylid caniatáu i'r stoc ostwng oddi tano er mwyn amddiffyn gwydnwch a gallu atgenhedlu'r stoc honno yn y dyfodol. Mae'r dull newydd arfaethedig – sy'n defnyddio pwynt cyfeirio uchaf neu darged rheoli – yn fwy cydnaws â chanllawiau arfer gorau NASCO ar gyfer rheoli

eogiaid. Mae hefyd yn cydnabod yr angen i gymhwyso dull rhagofalus mwy tryloyw tuag at warchod stociau eogiaid sy'n wynebu amrywiaeth ddigynsail o bwysau yn yr amgylchedd dŵr croyw a morol. Mae'r dull arfaethedig hefyd yn gyson ag ymrwymiad Cyfoeth Naturiol Cymru i'r fframwaith ar gyfer Rheoli Adnoddau Naturiol yn Gynaliadwy.

Mae'r adolygiad yn darparu cymhariaeth rhwng asesiadau cydymffurfedd ar gyfer terfynau cadwraeth eogiaid a chanlyniad y broses flynyddol o gategoreiddio stociau ar gyfer yr holl brif afonydd eogiaid cyfredol yng Nghymru a Lloegr yn seiliedig ar y prosesau asesu cyfredol a'r rhai newydd arfaethedig. Mae hyn wedi'i gwblhau er mwyn cefnogi trosglwyddiad clir a thryloyw rhwng canlyniadau'r dulliau asesu stociau eogiaid presennol a'r rhai arfaethedig er mwyn llywio'r broses o wneud penderfyniadau yn y dyfodol.

Y Grŵp Adolygu Cenedlaethol ar gyfer Asesu Stociau Eogiaid

Aelodau craidd y Grŵp Adolygu Cenedlaethol ar gyfer Asesu Stociau Eogiaid ar adeg cyhoeddi yw:

Asiantaeth yr Amgylchedd

- Simon Toms, Arweinydd y Tîm Rheoli Pysgodfeydd Cenedlaethol ac Uwch-gynghorydd, Tîm Pysgodfeydd Cenedlaethol
- Brian Shields, Uwch-arbenigwr Technegol Pysgodfeydd, Gwasanaeth Pysgodfeydd Cenedlaethol
- Brecht Morris, Cynghorydd Pysgodfeydd, Tîm Pysgodfeydd Cenedlaethol

Cyfoeth Naturiol Cymru

- Ben Wilson, Prif Gynghorydd Pysgodfeydd
- David Mee, Cynghorydd Arbenigol
- Bregan Brown, Uwch-swyddog Asesu Amgylcheddol Pysgodfeydd
- Ian Davidson, Uwch-swyddog Asesu Amgylcheddol Pysgodfeydd (wedi ymddeol)
- Peter Gough, Prif Gynghorydd Pysgodfeydd (wedi ymddeol)

Cefas

- Alan Walker, Pennaeth y Parth ar gyfer Pysgod Dŵr Croyw, Ymfudol a Morydol
- Jonathan Gillson, Uwch-wyddonydd Pysgodfeydd Ymfudol
- Stephen Gregory, Uwch-ystadegydd
- Jon Barry, Prif Ystadegydd

# Summary

This report presents the findings from a comprehensive review of the national Atlantic salmon (Salmo salar) stock assessment process used by the Environment Agency (EA) and Natural Resources Wales (NRW) in England and Wales, respectively. The review has been completed by an expert group convened from staff representing the EA, NRW and the Centre for Environment, Fisheries and Aquaculture Science (Cefas).

The review was initiated in response to an ongoing requirement for the EA and NRW to periodically update and improve their salmon stock assessment processes for designated Principal Salmon Rivers (PSRs) within their respective areas of jurisdiction. The review has taken account of the North Atlantic Salmon Conservation Organisation (NASCO) guidelines for salmon stock and fishery management and considered the salmon stock assessment processes applied in other jurisdictions in the UK, and across the North Atlantic, to identify best practice. The review group has considered our future approach to salmon fisheries management, the use of new and emerging data and evidence in relation to Atlantic salmon biology, as well as the need to provide greater clarity and transparency in the derivation of salmon stock assessments and the outputs from this process to inform fishery regulation decisions. The review has taken account of the outputs and recommendations from the National Salmon Stock Assessment Workshop, in addition to internal and external feedback received through the implementation of salmon fishery regulations, as well as engagement with the Office for Statistical Regulation.

The review has considered the following components of the salmon stock assessment process:

- The salmon stock assessment processes used by other jurisdictions to identify best practice and compatibility
- The process of setting salmon Conservation Limits in England and Wales
- The key biological and fishery management parameters used within the salmon stock assessment process
- The process for estimating salmon rod exploitation rates in England and Wales
- The process for assessing annual salmon Conservation Limit compliance
- The national salmon management Decision Structure used in England and Wales to guide management actions

This review includes a number of key recommendations that seek to update and evolve the current national salmon stock assessment processes and the associated salmon fishery management framework for England and Wales. It also provides proposals for future work to further develop the salmon stock assessment processes,

noting that future developments are dependent upon staff resourcing and further investigations.

The key parameters that underpin the derivation of annual river-specific salmon egg deposition estimates, that form the basis of river-specific Conservation Limit compliance assessments in England and Wales, have been reviewed and updated taking account of new and emerging evidence and specific investigations to ensure that any assumptions made remain valid.

A new method for estimating salmon rod fishery exploitation rates is presented. This incorporates variables which anglers, fishery managers, and salmon scientists believe could influence rod fishery exploitation, such as river flows, rod fishery effort, and fishery-independent returning stock estimate data derived from automated fish counters. This approach is used to inform the rod fishery exploitation rates in salmon river catchments that do not have fishery-independent returning stock assessment programmes.

This review presents a new salmon Conservation Limit compliance assessment process that takes account of salmon stock performance based upon both current (based on the last five years salmon stock performance) and projected salmon stock statuses (taking account of the last 10 years performance) that will be used when determining the category into which an individual rivers salmon stock will be placed annually

A new Upper Reference Point (URP) based upon catchment Maximum Smolt production (expressed in egg deposition) is recommended. The URP provides a recovery-focused management objective that seeks to restore salmon populations towards their natural productive potential. This approach prioritises the production of salmon smolts in freshwater and hence the potential number of adults returning to spawn in the future in order to maximise the opportunity for salmon stock sustainability.

This represents an ambitious new approach which promotes the recovery of salmon stocks as the primary management objective in order to conserve the reproductive capacity and recovery of salmon stocks whilst seeking to ensure that salmon rod fisheries remain sustainable into the future. The intention is to move beyond the current management process where fishery management decision making has sought to avoid the stock falling below the Conservation Limit (CL), to adopting and directly applying an Upper Reference Point to avoid the stock falling below the CL. The CL should be considered to be a minimum reference limit below which the stock should not be allowed to fall in order to protect the resilience and future reproductive capacity of that stock. The proposed new approach using an Upper Reference Point or Management Target is more aligned with the NASCO best practice salmon management guidelines. It also recognises the need to apply a more transparent precautionary approach towards the protection of salmon stocks which are facing an unprecedented array of pressures in both freshwater and the marine environment.

The proposed approach is also consistent with Natural Resources Wales' commitment to the Sustainable Management of Natural Resources (SMNR) framework.

The review provides a comparison between salmon CL compliance assessments and the outcome of the annual stock categorisation for all the current PSRs in England and Wales based upon both the current and proposed new assessment processes. This has been completed to support a clear and transparent transition between the outcomes of both current and proposed salmon stock assessment approaches to inform future decision making.

# The National Salmon Stock Assessment Review Group

The core national salmon stock assessment review group members at the time of publication are:

Environment Agency

- Simon Toms, National Fisheries Management Team Leader and Senior Advisor, National Fisheries Team.
- Brian Shields, Senior Fisheries Technical Specialist, National Fisheries Service
- Brecht Morris, Fisheries Advisor, National Fisheries Team
- Graeme Peirson, Senior Fisheries Scientist (Retired)

National Resources for Wales

- Ben Wilson, Principal Fisheries Advisor
- David Mee, Specialist Advisor
- Bregan Brown, Senior Fisheries Environmental Assessment Officer
- Ian Davidson, Senior Fisheries Environmental Assessment Officer (Retired)
- Peter Gough, Principal Fisheries Advisor (Retired)

Cefas

- Alan Walker, Head of Domain for Freshwater, Diadromous and Estuarine fish
- Jonathan Gillson, Senior Diadromous Fisheries Scientist
- Stephen Gregory, Senior Statistician
- Jon Barry, Principal Statistician

# Argymhellion ar gyfer newidiadau i'r broses genedlaethol o asesu stociau eogiaid

Fel y nodwyd yn y crynodeb uchod, mae'r grŵp adolygu wedi datblygu sawl argymhelliad (ar gyfer newid) i'r prosesau cenedlaethol o asesu stociau eogiaid a'r fframwaith rheoli cysylltiedig ar gyfer pysgodfeydd eogiaid. Bwriedir i'r rhain gael eu gweithredu gan Asiantaeth yr Amgylchedd ac CNC. Mae'r rhain wedi'u rhestru drwy gydol y ddogfen ond hefyd wedi'u casglu yma er hwylustod cyfeirio mewn rhestr wedi'i rhifo, gyda rhif yr adran wedi'i nodi hefyd.

Nododd y grŵp adolygu hefyd sawl tasg sy'n deilwng o archwiliad a datblygiad yn y dyfodol, yn amodol ar adnoddau a chyllid. Disgrifir y rhain drwy gydol y ddogfen fel cynigion ar gyfer gwaith yn y dyfodol. Maent wedi'u hamlygu drwy gydol y ddogfen ond hefyd wedi'u coladu fel rhestr yn Atodiad 3.

I grynhoi, mae 'argymhellion' yn newidiadau y mae'r grŵp adolygu yn ystyried y dylid eu gweithredu cyn gynted â phosibl mewn ymateb i ganfyddiadau'r adolygiad hwn, tra bod 'cynigion' yn cynrychioli cyfleoedd ychwanegol yn y dyfodol ar gyfer newid y gellid eu harchwilio neu eu hystyried pan fydd adnoddau ac, mewn rhai achosion, tystiolaeth ychwanegol ar gael.

**Argymhelliad 1**

**Adran 5.2.2**

*Bydd cyfanswm y ddalfa fesul afon yn cael ei amcangyfrif o'r ddalfa ddatganedig drwy gymhwyso ffactor cywiro ar gyfer tan-adrodd. Dylid cyfrifo a chymhwyso ffactor cywiro cenedlaethol ar gyfer dalfa eogiaid â gwialen (Cymru a Lloegr) yn seiliedig ar y fethodoleg a ddeilliwyd gan Small (1991) yn flynyddol er mwyn disodli'r cysonyn a weithredir ar hyn o bryd o x1.10. Bydd y ffactor cywiro hwn yn ystyried newidiadau yn y ffordd y mae dalfeydd eogiaid gan ddefnyddio gwialen yn cael eu hadrodd a newidiadau blynyddol yng nghyfraddau adrodd dalfeydd gan ddefnyddio gwialen.*

**Argymhelliad 2**

**Adran 5.3.1.1**

*Cynhyrchu ffactorau cywiro penodol i oedran y môr ar gyfer cyfraddau ecsbloetio gan ddefnyddio dulliau llyfnhau LOWESS a gymhwysir i arsylwadau, a'r weithdrefn trynewid, yn ôl yr hyn sydd ar gael. Addasu gweithdrefnau i ddeillio a chymhwyso cyfraddau ecsbloetio pysgota ar gyfer eogiaid, fel bod yr amcangyfrif stoc sy'n dychwelyd bob blwyddyn yn deillio o swm yr amcangyfrifon stoc sy'n dychwelyd ar*

*gyfer eogiaid sydd wedi treulio un gaeaf yn y môr (1SW) a'r rhai sydd wedi treulio nifer o aeafau yn y môr (MSW).*

**Argymhelliad 3**

**Adran 5.3.2.4**

*Yn ddelfrydol, dylid deillio amcangyfrif o gyfraddau ecsbloetio eogiaid blynyddol gan ddefnyddio gwialen ar gyfer pob prif afon eogiaid gan ddefnyddio un dull cyson, tryloyw ac ystadegol gadarn fel yr un a gyflwynir yn Adran 5.3. Lle mae allbynnau'r model yn gwrthdaro â thystiolaeth empirig, gellir addasu'r cyfradd ecsbloetio â gwialen flynyddol gan arbenigwyr technegol pysgodfeydd yn yr ardal leol mewn trafodaeth â rhanddeiliaid lleol, ar yr amod bod achos cadarn a chyfiawn wedi'i ddogfennu'n glir a'i gytuno â Grŵp Arbenigwyr Technegol Rheoli Eogiaid Cenedlaethol Asiantaeth yr Amgylchedd. Dylid adolygu a diweddaru'r fethodoleg genedlaethol newydd ar gyfer amcangyfrif cyfraddau ecsbloetio o bryd i'w gilydd er mwyn sicrhau bod y data a'r gweithdrefnau ystadegol mwyaf priodol yn cael eu defnyddio.*

**Argymhelliad 4**

**Adran 5.3.2.4**

*Amcangyfrifon stoc sy'n dychwelyd sy'n annibynnol ar bysgodfeydd, fel y rhai a geir gan gyfrifwyr pysgod a thrapiau pysgod wedi'u dilysu, a data sy'n ddibynnol ar bysgodfeydd ar ddalfeydd ac ymdrech pysgotwyr, yw asgwrn cefn yr asesiad presennol o stociau eogiaid, a dylid gwneud pob ymdrech i ddiogelu eu cyflenwad parhaus, gan gynnwys buddsoddi mewn seilwaith i gasglu, dilysu a storio eu data sylfaenol.*

**Argymhelliad 5**

**Adran 5.8.4**

*Defnyddio data pennu rhyw a ddeilliwyd yn enetig a gafwyd o astudiaethau a gynhaliwyd yn afon Tamar ac afon Dyfrdwy i ddiweddaru'r gyfran amcangyfrifedig o fenywod ar gyfer eogiaid sydd wedi treulio un gaeaf yn y môr a'r rhai sydd wedi treulio nifer o aeafau yn y môr ym mhob prif afon eogiaid arall.*

**Argymhelliad 6**

**Adran 5.9**

*Defnyddio'r berthynas rhwng hyd a ffrwythlonedd a gafwyd o ddata a gasglwyd yn afon Dyfrdwy, afon Clwyd, afon Gwy ac afon Taf i lywio'r berthynas ddiofyn mewn gweithdrefnau i ddeillio amcangyfrifon blynyddol o ddyddodiad wyau ar gyfer Cymru a Lloegr. Yn ogystal, ac yn absenoldeb dewisiadau amgen penodol i'r afon, dylid adnewyddu a chymhwyso'r berthynas rhwng pwysau a hyd ar gyfer eogiaid sydd*

*wedi treulio un gaeaf yn y môr a'r rhai sydd wedi treulio nifer o aeafau yn y môr yn afon Dyfrdwy ac afon Tamar yn flynyddol (yn seiliedig ar y setiau data deg mlynedd diweddaraf) i drosi data pwysau o ddalfeydd â gwialen yn ddata hyd fel rhan o'r gweithdrefnau hyn.*

**Argymhelliad 7**

**Adran 6.5.2**

*Defnyddio atchweliad llinol safonol heb unrhyw ddibyniaeth amserol (cydberthyniad awtomataidd) i werthuso'r duedd mewn amcangyfrifon blynyddol o ddyddodiad wyau fel rhan o'r asesiad cydymffurfedd.*

**Argymhelliad 8**

**Adran 6.6**

*Cynnal yr asesiad blynyddol o statws stociau eogiaid yn seiliedig ar y canlynol:*

- *perfformiad y stoc yn erbyn dau bwynt cyfeirio biolegol penodol i'r dalgylch a ddiffinnir o ran niferoedd wyau (y pwynt cyfeirio isaf = terfyn cadwraeth stoc eogiaid lleiaf, a'r pwynt cyfeirio uchaf = potensial gleisiaid uchaf y dalgylch);*
- *disodli'r asesiad cydymffurfedd presennol o ran dyddodiad wyau rhagamcanedig gyda chynllun dwy haen gan ddefnyddio, yn gyntaf, y cymedr rhifyddol o'r dyddodiad wyau blynyddol amcangyfrifedig o'r pum mlynedd diwethaf (cymedr y gorffennol) ac, yn ail, rhagamcan pum mlynedd ymlaen yn seiliedig ar atchweliad cymedr safonol o amcangyfrifon blynyddol o ddyddodiadau wyau yn ystod y deg mlynedd diwethaf;*
- *mae'r metrigau cymedr y gorffennol a'r rhagamcaniad ymlaen wedi'u dosbarthu i un o dri dosbarth: iach, gofalus neu argyfyngus. Mae'r rhain yn seiliedig ar y tebygolrwydd bod y metrig sy'n cael ei fesur (y cymedr neu'r rhagamcaniad ymlaen) uwchlaw pob un o'r pwyntiau cyfeirio uchaf ac isaf. Yn benodol, mae metrig:*
  - *yn argyfyngus os yw'r tebygolrwydd ei fod uwchlaw'r pwynt cyfeirio isaf yn llai na 0.75;*
  - *yn ofalus os yw'r tebygolrwydd ei fod uwchlaw'r pwynt cyfeirio isaf yn fwy na neu'n hafal i 0.75 a'r tebygolrwydd ei fod uwchlaw'r pwynt cyfeirio uchaf yn llai na 0.75;*
  - *yn iach os yw'r tebygolrwydd ei fod uwchlaw'r pwynt cyfeirio uchaf yn fwy na neu'n hafal i 0.75.*
- *Pennir y dosbarthiad blynyddol terfynol ar gyfer afon gan y dosbarth isaf a gyflawnir gan y metrigau cymedr y gorffennol a'r rhagamcaniad ymlaen,*

*waeth pa un. Mae hyn yn cynrychioli dull rhagofalus ac fe'i cynlluniwyd er mwyn amddiffyn gallu atgenhedlu eogiaid fel blaenoriaeth reoli tra pwysig.*

**Argymhelliad 9**

**Adran 7.11**

*Adolygu'r strwythur penderfyniadau ar gyfer rheoli pysgodfeydd eogiaid yng Nghymru a Lloegr er mwyn sicrhau ei fod yn adlewyrchu'r fethodoleg ddosbarthu newydd ac amlinellu'n glir y camau gweithredu sydd eu hangen i gynnal ac adfer stociau. Byddai hyn yn seiliedig ar raddau afonydd a bennir gan berfformiad blynyddol y stoc fel y'i profwyd yn erbyn y categorïau cydymffurfio stoc cyfredol (cymedr pum mlynedd diwethaf) a rhagamcanedig (rhagamcan pum mlynedd yn y dyfodol). Bydd y categorïau hyn yn cael eu hystyried ar y cyd i bennu un radd afon gyffredinol yn amrywio o 1 i 3. Defnyddir yr isaf o'r ddau gategori asesu i benderfynu ar y safle mewn gradd afon flynyddol derfynol.*

**Argymhelliad 10**

**Adran 9.1.2**

*Disodli paratoi a dadansoddi data â llaw gan ddefnyddio meddalwedd berchnogol, fel llyfrau gwaith, gyda llifoedd gwaith wedi'u sgriptio sydd wedi'u hysgrifennu mewn ieithoedd rhaglennu cyfrifiadurol ffynhonnell agored y gellir eu darparu i'r cyhoedd.*

# Recommendations for change to the national salmon stock assessment process

As noted in the Summary above, the Review Group has developed several recommendations (for change) to the national salmon stock assessment processes and the associated salmon fishery management framework. These are intended to be implemented by the EA and NRW. These are listed throughout the document but also collated here for ease of reference in a numbered list, with the section number specified also.

The Review Group also identified several tasks worthy of future exploration and development, subject to resources and funding. These are described throughout the document as proposals for future work. They are highlighted throughout the document but also collated as a list in Annex 3.

In summary, 'Recommendations' are changes that the review group consider should be implemented as soon as possible in response to the findings of this review, whereas 'Proposals' represent future additional opportunities for change that could be explored or considered when resources and, in some cases, additional evidence, becomes available.

**Recommendation 1**

**Section 5.2.2**

*Total catch per river will be estimated from declared catch by applying a correction factor for underreporting. A national (England and Wales) declared salmon rod catch correction factor based on the methodology derived by Small (1991) should be calculated and applied annually to replace the currently implemented constant of x1.10. This correction factor will take into account changes in the way in which salmon rod catches are reported and annual changes in rod catch reporting rates.*

**Recommendation 2**

**Section 5.3.1.1**

*Generate sea-age specific exploitation rate Correction Factors using LOWESS smoothing methods applied to observations, and the permutation procedure, as available. Modify procedures to derive and apply angling exploitation rates for salmon, such that the annual returning stock estimate is derived from the sum of the*

*returning stock estimates for one-sea winter (1SW) and multi-sea-winter (MSW) salmon.*

**Recommendation 3**

**Section 5.3.2.4**

*Estimation of annual salmon rod exploitation rates (RER) for each Principal Salmon River should ideally be derived using a single, consistent, transparent and statistically robust method such as that presented in Section 5.3. Where model outputs conflict with empirical evidence, the annual RER may be adjusted by local Area Fisheries Technical Specialists in discussion with local stakeholders, providing a sound and justifiable case is clearly documented and agreed with Agency National salmon management Technical Specialists Group. The new national methodology for estimating exploitation rates should be reviewed and updated periodically to ensure that the most appropriate data and statistical procedures are being utilised.*

**Recommendation 4**

**Section 5.3.2.4**

*Fishery-independent returning stock estimates, such as those derived by validated fish counters and fish traps, and fishery-dependent data on angler catches and effort, are the backbone of the current salmon stock assessment, and every effort should be made to safeguard their continued supply, including investment in infrastructure to collect, validate, and store their underlying data.*

**Recommendation 5**

**Section 5.8.4**

*Use genetically derived sex determination data obtained from studies undertaken on the rivers Tamar and Dee to update the estimated proportion of females for one-sea-winter (1SW) and multi-sea-winter (MSW) salmon in all other principal salmon rivers.*

**Recommendation 6**

**Section 5.9**

*Apply the length-fecundity relationship obtained from data collected on the rivers Dee, Clwyd, Wye and Taff to inform the default relationship in procedures to derive annual egg deposition estimates for England and Wales. In addition, and in the absence of river-specific alternatives, weight-length relationships for one-sea-winter (1SW) and multi-sea-winter (MSW) salmon on the rivers Dee and Tamar should be renewed and applied annually (based on the latest 10-year datasets) to convert rod catch weight data into length data as part of these procedures.*

**Recommendation 7**

**Section 6.5.2**

*Apply standard linear regression with no temporal dependence (autocorrelation) to evaluate the trend in annual egg deposition estimates as part of the compliance assessment.*

**Recommendation 8**

**Section 6.6**

*Undertake the annual salmon stock status assessment based on:*

- *stock performance against two catchment-specific biological reference points (BRPs) defined in terms of egg numbers (the Lower Reference Point = a minimum salmon stock Conservation Limit, and the Upper Reference Point = the catchment Maximum Smolt potential);*
- *replacing the current projected egg deposition compliance assessment with a two-tiered scheme using, first, the arithmetic mean of estimated annual egg deposition from the past five years (past mean) and, second, a five year forward projection based on standard mean regression of the last 10 years of annual egg deposition estimates;*
- *both the past mean and the forward projection metrics are classified into one of three classes: Healthy, Cautious or Critical. These are based on the probability that the metric being measured (the mean or the forward projection) is above each of the upper and lower reference points. Specifically, a metric is:*
    - *Critical if the probability that it is above the LRP is less than 0.75;*
    - *Cautious if the probability it is above the LRP is greater than or equal to 0.75 and the probability it is above the URP is less than 0.75;*
    - *Healthy if the probability it is above the URP is greater than or equal to 0.75.*
- *The final annual classification for a river is determined by the lowest class attained by either one of the past mean and forward projection metrics. This represents a precautionary approach and has been designed to protect salmon reproductive capacity as an overriding management priority.*

**Recommendation 9**

**Section 7.11**

*Revise the salmon fishery management Decision Structure (DS) for England and Wales to ensure it reflects the new classification methodology and clearly outline the actions required to sustain and restore stocks. This would be based on river grades determined by the annual performance of the stock as tested against both the current (past five-year mean) and projected (future five-year projection) stock compliance categories. These categories will be considered in combination to determine a single overall river grading ranging from 1 to 3. The lower of the two*

*assessment categories will be used to determine the placement into a final annual river grade.*

**Recommendation 10**

**Section 9.1.2**

*Replace manual data preparation and analysis using proprietary software, such as workbooks, with scripted workflows written in open-source computer programming languages which can be made available to the Public.*

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# 1 Introduction

## 1.1 The National Salmon Stock Assessment Review for England and Wales

The National Salmon Stock Assessment Review has been commissioned by the Environment Agency (EA) and Natural Resources Wales (NRW) to update and, where necessary, revise or modify the current national salmon stock assessment and reporting processes.

The review team was led by the EA and NRW, and included the Centre for Environment, Fisheries and Aquaculture Science (CEFAS) who have provided independent salmon fisheries science and statistical analysis expertise. The review team was also supported by Game and Wildlife Conservation Trust (GWCT) through the SAlmonid Management Round the Channel (SAMARCH) project (https://www.samarch.org/) who supported the development of the salmon rod exploitation rate model between 2018 and 2021.

The need for this review and its scope have been built upon six fundamental considerations:

1. The 1998 Ministerial Direction which requires an annual assessment of the status of salmon stocks and a periodic review and update of the stock assessment processes to reflect advice from NASCO. The current methodology has been in constant use since 2003, with revisions to elements as and when required
2. Recognition that there have been profound changes in salmon stock composition and abundance, reflecting sustained and critical declines throughout the North Atlantic since the 1980s
3. There is an opportunity to make better use of our data and analytical techniques to assess stock status
4. The recommendations of the National Salmon Stock Assessment Workshop (Atlantic Salmon Trust, 2017)
5. Feedback received during Net Limitation Order (NLO) and migratory salmonid byelaw consultations in England and in Wales, and
6. Continued adherence to NASCO guidance and best practice procedures for managing salmon stocks

The review process has sought to take account of, and apply, NASCO salmon management guidance, with a further requirement to develop a clear and transparent decision-making process that is consistent with the Precautionary Approach (NASCO 2009). The commitment to undertake this review is reflected within the

NASCO salmon management implementation plan for England and Wales NASCO Implementation Plan (IP) 2019-2024.

The overall objective of the review is to ensure that the EA and NRW are using a stock assessment methodology based on the best available data and techniques, and which provides them and their stakeholders further confidence in the evidence being used to support management decisions. There is a recognition that the outcome of the annual salmon stock assessment process needs to be clearly and transparently communicated to stakeholders in a timely manner. The assessments need to underpin clear and consistent fisheries management advice including exploitation controls, as well as catchment management actions that are considered necessary to protect salmon stocks and support future stock sustainability.

In considering the above drivers, the review team identified the following areas within the scope of the review:

1. A review of the data and methods currently used for CL setting and compliance assessments in E&W alongside consideration of alternative data sources and methods developed in other jurisdictions (Sections 2 & 3)
2. A review of the data that underpin the development of BRPs (Section 4)
3. A review of the data that underpin the stock assessment process (Section 5)
4. A review of the statistical approach used to assess stock status (Section 6), and
5. A review of the Decision Structure and management measures linked to stock assessment outcomes (Section 7)

The basis of our process to assess stock status against predefined BRPs is to gather data to inform that assessment, analyse those data, and present the results. The results are used by the regulators (EA and NRW) to make decisions about fisheries management. The structure of this review follows that order. It describes the present system, investigates and considers alternatives that might improve the approach and reflect on stakeholder feedback, examines how BRPs are set and how this might change, examines how data collection might change and how data analysis might evolve, and then examines how the management decision making process might change to reflect our proposals. Each section in this review was completed at different stages of the process and contained the latest data at the time of writing. Unless it was considered relevant to a particular point, description, or explanation, river names have been anonymised to encourage focus on the wider points being considered, e.g., the details of methods, etc.

This review seeks to inform, among other things, the salmon stock assessment methodology, reporting and management decisions in both the EA and NRW. This may include activities in fulfilment of national and international obligations. Implementation of the ‘recommendations for change’ described in this review will require appropriate levels of scrutiny and approval within each organisation as determined by their respective governance procedures.

The duration of the review has reflected its complexity, its wide-ranging scope and scale, and the skilled specialist resource availability within each organisation. As this is a constantly developing topic area influenced by evolving environmental, ecological, technological and human behavioural aspects, this review has not been able to fully address all the initially foreseen tasks and has generated new questions that require further investigation. Some considerations will thus take longer to develop and implement and so will form a subsequent tranche of additional measures, and further work to gather data and develop approaches will continue thereafter. These future proposals are considered in Section 9 of this review.

## 1.2 Background to salmon fisheries management in England and Wales

The Department for Environment, Food and Rural Affairs (Defra) and the Welsh Government have overall policy responsibility for diadromous and freshwater fish stocks in England and Wales. A review of salmon and freshwater fisheries published by the Ministry of Agriculture Fisheries and Food (MAFF) considered one objective of Government involvement in the conservation of salmon and freshwater fish and the management of associated fisheries should be “to ensure the conservation and maintain the diversity of freshwater fish, salmon, sea trout and eels and to conserve their aquatic environment” (MAFF, 2000). Defra and Welsh Government work closely with the EA and NRW, which are responsible for operational management and regulation in England and Wales, respectively. NRW was established on 1 April 2013 and assumed responsibility for the functions previously undertaken by the EA within Wales.

Defra has key ministerial priorities to promote the sustainable management and use of marine resources, and to achieve Good Ecological Status (GES) in fresh and transitional waters, through protecting and enhancing biodiversity and limiting significant adverse impacts of human activities. These obligations are shared by Welsh Government and NRW. The implementation of conservation measures for diadromous fish species delivers on both these marine and freshwater policy areas.

Defra and the Welsh Government have set objectives for the EA and NRW to:

- Promote the conservation and maintain the diversity of migratory and freshwater fish, and to conserve their aquatic environment
- Enhance the contributions migratory and freshwater fisheries make to the economy, particularly in remote rural areas and in areas with low levels of income
- Enhance the social value of fishing as a widely available and healthy form of recreation, and

- For Wales, contribute to the Welsh Government's aims and objectives for freshwater fisheries management using the principles of Sustainable Management of Natural Resources (SMNR).

The Salmon and Freshwater Fisheries Review (MAFF, 2000) noted that the first of these objectives should carry the greatest weight. Thus, the general management objective for all diadromous fish species is to ensure the conservation of existing stocks and the restoration of stocks that have been lost or are depleted and this is enshrined in a variety of legislation and policy documents. Socio-economic factors are also taken into account when activities are planned that may affect the conservation status of species or when new management measures are considered. This may influence the nature and balance of controls affecting different stakeholder groups and the rate of stock recovery that can be achieved.

The EA and NRW have a statutory duty under section 6(6) of the Environment Act 1995 "to maintain, improve and develop fisheries of salmon, trout, eels, lampreys, smelt and freshwater fish". This role encompasses the protection of fish stocks and their environment as well as provision of a service to anglers paid for from the rod licence duty to manage fisheries.

## 1.3 International obligations for salmon management

The North Atlantic Salmon Conservation Organisation (NASCO) is an international organisation, established by an inter-governmental Convention in 1984. The objective of NASCO is to conserve, restore, enhance and rationally manage Atlantic salmon through international co-operation taking account of the best available scientific information. While NASCO's initial focus was on developing management measures for the distant-water fisheries at West Greenland and the Faroe Islands, it is widely accepted that conservation and restoration of salmon stocks cannot be achieved by these measures alone. Following the adoption of the Precautionary Approach (NASCO, 1998), and the Next Steps process (NASCO, 2005), NASCO has developed several guidelines, agreements and resolutions relating to the management of salmon fisheries, habitat protection and restoration, and aquaculture and related activities.

The UK has been an independent Party to the NASCO convention since 2020 and represented by the UK devolved Government administrations covering England, Wales, Northern Ireland and Scotland.

Although salmon fisheries management responsibilities are devolved between England and Wales, these jurisdictions are combined as a single reporting unit for submissions to international bodies. Both jurisdictions are committed to apply the international best practice guidance for salmon fisheries management produced by NASCO (NASCO, 2009), which requires individual member states to define and set

biological reference points (BRPs), such as Conservation Limits (CLs) and Management Targets (MTs). This objective enables member states to achieve effective fisheries management and implement exploitation controls in a timely manner to ensure that salmon stocks remain resilient and sustainable in the longer term. Conservation Limits are regarded as the minimum biological acceptable limit for a stock to attain to ensure continued sustainability. The MT is set above the CL to ensure that action is implemented at an early stage to inform the extent of management interventions that may be required to avoid the stock falling below the CL. Thus, the CL should be considered as the minimum stock target level below which the salmon stock should not be allowed to fall, owing to the risk of longer-term decline in the numbers of returning adults. More information on the role and work of NASCO is available from the following link: http://www.nasco.int/index.html.

The International Council for the Exploration of the Sea (ICES) provides biological information and advice on a wide range of fish stocks to help fisheries managers maintain viable fisheries within sustainable ecosystems. Information is compiled and assessments are conducted by Working Groups, which are comprised of national experts on the specific fish stocks. The Working Group reports are passed to the Advisory Committee (ACOM) for peer review and to provide the formal advice to managers. For Atlantic salmon, ICES provides advice relating to a list of questions posed by NASCO each year. The assessment of salmon stocks and their fisheries presents particular problems to the ICES scientists both because of the highly migratory nature of the fish and because they comprise many distinct river stocks which must, to some extent at least, be managed separately. Further information on the ICES Working Group on North Atlantic Salmon (WGNAS) is available at: https://www.ices.dk/community/groups/pages/wgnas.aspx.

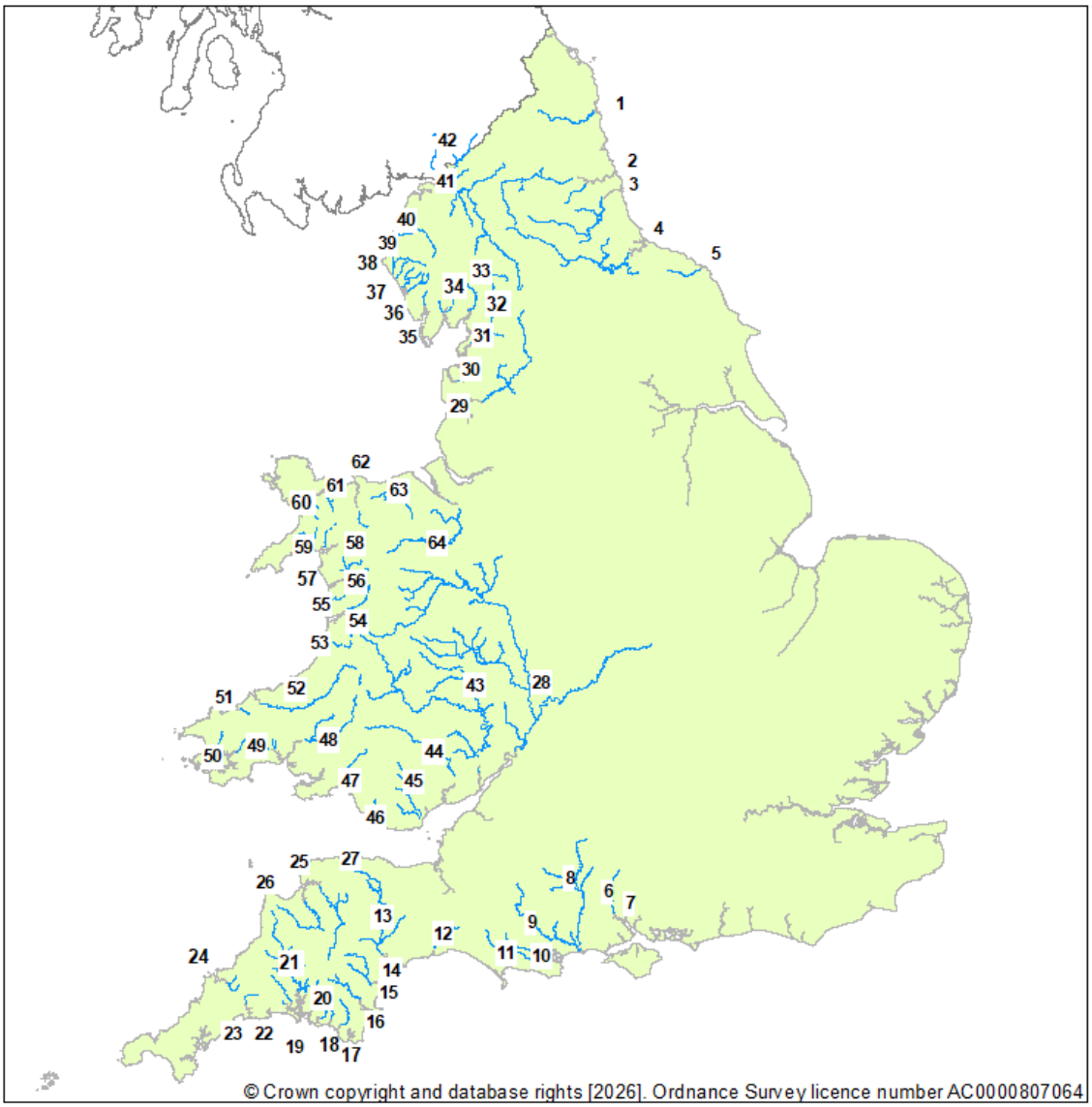
## 1.4 National obligations for salmon management

In England and Wales, there are 64 Principal Salmon Rivers (PSRs; Figure 1.1) designated under a Ministerial Direction in 1998 (the Direction) (Annex 1). This Direction required/s the EA and NRW to:

a) prepare Salmon Action Plans by 2002
b) develop and set spawning targets for each river (in this context spawning targets equate to CLs as defined by NASCO)
c) review compliance of stock levels with these targets annually, giving due regard to stock characteristics such as age composition and run timing, and take appropriate action
d) ensure that target setting and compliance assessment procedures are regularly revised to take account of improvements in methodologies and new data

e) take account of the compliance stock levels with spawning targets when initiating and conducting reviews of Net Limitation Orders and byelaws for salmon fisheries, and
f) maintain a comprehensive and complete data archive of catches and other assessments, reporting definitive stock and fishery assessments annually.

Stock compliance assessments are fundamental to the management of salmon fisheries in England and Wales, allowing the EA and NRW to identify poorly performing salmon stocks and therefore fisheries and take timely and proportionate actions to protect and restore stocks. This report sets out how the EA and NRW currently undertake annual stock compliance assessments and make decisions about managing fisheries, as set out in section c) of the Direction. It also describes how that methodology has been reviewed and revisions proposed in accordance with requirement d).




**English Principal Salmon Rivers**

1 Coquet
2 Tyne
3 Wear
4 Tees
5 Esk (Yorkshire)
6 Test
7 Itchen*
8 Avon (Hants)*
9 Stour (Dorset)
10 Piddle
11 Frome
12 Axe
13 Exe
14 Teign*
15 Dart*
16 Avon (Devon)
17 Erme*
18 Yealm
19 Plym
20 Tavy*
21 Tamar
22 Lynher
23 Fowey
24 Camel*
25 Taw*
26 Torridge
27 Lyn
28 Severn
29 Ribble
30 Wyre
31 Lune
32 Kent
33 Leven
34 Crake
35 Duddon
36 Esk (Cumbria)
37 Irt
38 Ehen*
39 Calder
40 Derwent*
41 Eden*
42 Esk (Border)

**Welsh Principal Salmon Rivers**

43 Wye*
44 Usk*
45 Taff
46 Ogmore
47 Tawe
48 Tywi
49 Taf
50 E & W Cleddau
51 Nevern
52 Teifi*
53 Rheidol
54 Dyfi
55 Dysynni
56 Mawddach* & Wnion
57 Dwyryd
58 Glaslyn
59 Dwyfach& Dwyfawr
60 Seiont
61 Ogwen
62 Conwy
63 Clwyd
64 Dee*

*Figure 1.1. Map of England and Wales showing the Principal Salmon Rivers which have Salmon Action Plans and those designated as Special Areas of Conservation (*) in which salmon must be maintained or restored to favourable conservation status.*

## 1.5 Current approach to salmon stock assessment and management

Work to define BRPs for salmon in the form of spawning targets and CLs in England and Wales began in the mid-1990s, guided by advice received from Regional Fisheries, Ecology and Recreation Committees (RFERACs) and external stakeholder consultation. This requirement was later underpinned by a need to apply NASCO best practice salmon management guidance (NASCO, 2009). This required countries to develop catchment specific CLs and associated MTs to enable the annual assessment of salmon stock status in PSRs.

The status of individual river stocks is evaluated annually against these criteria using egg deposition estimates. In essence, CLs describe the minimum desirable spawning stock level below which the salmon stock and therefore the fishery, is not considered to be sustainable – in ICES terms, if the CL is not being achieved, the stock is suffering reduced reproductive capacity to the extent that the catchment is unlikely to be able to sustain the population and the fishery in the longer term. Management interventions are required to bring the stock back into a sustainable state. The river-specific CL is set at a stock size (defined in terms of the number of eggs) below which further reductions in spawner numbers are likely to increase the risk of reductions in the number of juvenile fish produced by the next generation. Sections 2, 4 and 5 of this report review the current approaches used in E&W to set river-specific CLs and derive annual egg deposition estimates for compliance assessment. A full account of the current salmon stock assessment used in E&W is set out within the annual salmon stock assessment reports and the supporting background reports (Cefas, Environment Agency and Natural Resources Wales, 2024 a,b).

The regulators (EA and NRW) make decisions on how to manage salmon fisheries according to the findings of the annual stock status assessments, alongside additional information. This decision-making process is informed by a Decision Structure framework, as per recommendations from NASCO (NASCO, 2009).

Some elements of the stock assessment process, alongside descriptions of the fisheries and other impacts, are reported to ICES and NASCO.

# 2 Original Conservation Limits for English and Welsh salmon stocks

The principles and drivers for the salmon management system currently operated in England and Wales are described in Section 1, above. Key to the aims of this management system is the establishment of consistent and objective biological

reference points against which to assess the status of salmon stocks in individual rivers. In its simplest terms, to attempt to answer the question “How many salmon should our river produce?”. In Section 2, we explore the principles and basis of how BRPs were set for Principal Salmon Rivers in England and Wales. Following this, in Section 3, we review the approaches developed and adopted by neighbouring UK nations and Ireland to identify whether these provide approaches that could be used to advance methods in England and Wales.

## 2.1 Biological Reference Points for salmon

All Principal Salmon Rivers (PSRs) were required, under Ministerial Direction (1998, see Annex 1), to have Salmon Action Plans (SAPs), and an essential part of these was to set Conservation Limits (CLs). The CL is selected to protect the long-term sustainability of the stocks and the fisheries they support.

The principle is straightforward. The number of salmon a river can produce (and consequently the catches that the stocks support) is a function of the quality and quantity of accessible spawning and rearing area. This is why, in general, big rivers have larger catches and have correspondingly bigger total spawning requirements than small rivers. Thus, for any given river and level of harvest by the fisheries, there should be an optimum level of stock which management seeks to protect.

The Environment Agency (EA) and Natural Resources Wales (NRW) define CLs in terms of minimum spawning levels, expressed in terms of egg deposition (eggs laid per 100 $m^2$, or the total number of eggs per river). This is because egg deposition is regarded by salmon biologists as the primary factor controlling the number of smolts likely to be produced in a river system. Typically, more eggs deposited means more smolts produced, up to some level beyond which smolt output levels off or may even decrease. This ‘levelling off’ occurs because young salmon are strongly territorial and there is a maximum number that a river system can support – this is referred to as density-dependence and is driven by competition for limiting resources. This maximum level of juvenile production is often referred to as the carrying capacity.

If data are available, then for a given river a curve can be plotted showing the change in ‘recruitment’, e.g., expressed as the number of smolts leaving a river system or the number of adults returning, and the ‘stock’ level, e.g., as the number of adult spawners in the parent generation or the eggs they deposit. This curve is known as a "stock-recruitment" (S-R) curve. The other essential component of the process of setting CLs, where recruitment is expressed in terms of smolt numbers, is the Replacement Line, which includes the density-independent marine survival rate of post-smolts to the point of return to homewaters as adults. The Replacement Line represents an estimate of survival at sea including accounting for any losses due to offshore fisheries (fisheries beyond the assessed river). If, for instance, marine survival from smolts to returning one-sea-winter (1SW) adults was 10%, then a pair

of spawning salmon would need to generate ~20 outgoing smolts to ensure that two adults came back to spawn in a year's time (to 'replace' the original two spawners).

Typically, plots of data points relating levels of stock and recruitment show considerable scatter because of the influence of complex and variable biological and environmental processes. Several models have been developed to describe fish S-R relationships, each summarising the underlying complexity and variability by defining the 'average' state (represented as a curve fitted to the data). Among these relationships, the dome-shaped Ricker curve is frequently applied to salmon data because it can take account of the density-dependent mortality of young salmon which can occur when the nursery stream carrying capacity is exceeded.

An example of a Ricker S-R curve is shown in Figure 2.1. In this case, the 'stock' (X-axis) is represented as adult spawners, and the 'recruits' (Y-axis) as numbers of smolts produced. The Ricker S-R curve is shown by the blue line and the Replacement Line by the red line. At any point on this line, the number of surviving adults equals the number of spawners in the previous generation. Here it represents a 10% survival rate from smolts to adults. The stock-recruitment curve lies above the replacement line at low stock levels, and the distance between the replacement line and the stock-recruitment curve is the number of fish that may be caught without reducing the population, often referred to as the harvestable/exploitable surplus. The Replacement Point equates to the point where the population would settle (on average) under stable environmental conditions and in the absence of losses to homewater fisheries and/or other anthropogenic factors. The CL is set at the point where (under this set of stable conditions) catches to homewater fisheries can be maximised (defined as the 'Maximum Sustainable Yield' or MSY). This yield, or surplus, depends on the positions of the S-R and Replacement Lines, and will vary as they do.

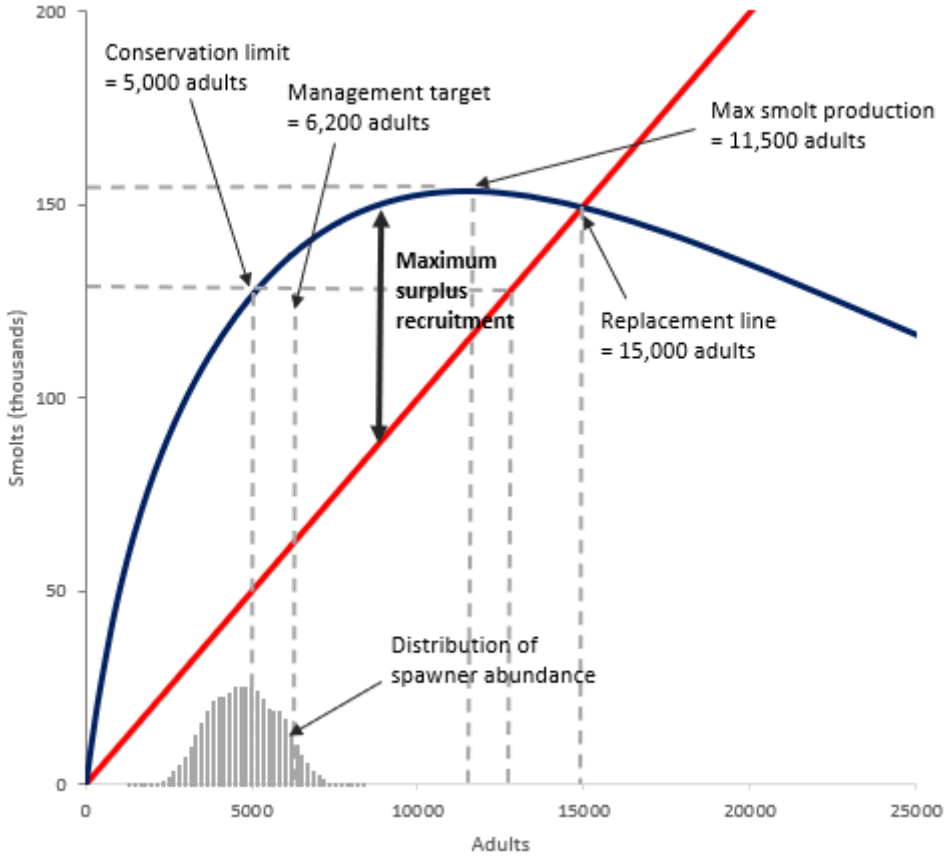



*Figure 2.1. An idealised Ricker – type stock-recruitment curve (blue line) for salmon, the replacement line (red), and various biological reference points shown along the curve.*

The CL (at MSY) is the reference point recommended by the International Council for the Exploration of the Sea (ICES) and the North Atlantic Salmon Conservation Organisation (NASCO) for salmon stock assessment and has been adopted for all PSRs in E&W. From the S-R curve in Figure 2.1., the CL is the point at which the difference between the Replacement Line and the S-R curve is at its greatest.

The exploitation rate represents the proportion of the whole adult salmon run that is harvested by the fisheries. If the harvest by the fisheries (i.e. the retained catch, or fishing mortality) increases so that it exceeds the MSY, then fewer salmon will be available to spawn than the number required to achieve the CL. Although the catch may temporarily increase, the stock (and future catch) will eventually reduce. Thus, the CL represents a lower limit on spawning for a stock, below which the risk of stock collapse progressively increases.

If the fishery was managed so that the stock achieved its CL value, on average, then for about 50% of the time it would be below the CL and, depending on the degree of natural annual variation, it could be considerably and dangerously below it.

Accordingly, to reduce the risk of harm to stocks, the current compliance procedure in E&W is designed to ensure that average stock levels are held some way above the CL. The Management Objective (MO) is that the frequency of being below the CL is no more than one year in five (i.e. 20% of the time). A Management Target (MT) is set as the average spawning stock level (egg deposition) required to achieve the MO. This follows from NASCO guidelines (NASCO, 2009), wherein Section 2.4e states that:

*"Management targets should also be established at a level above the CL to assist fishery managers in ensuring that there is a high probability of stocks exceeding their CLs".*

As such, the MT can be considered as an Upper Reference Point (URP), and although it is the CL that is most closely related to the characteristics of the river and its stock, it is the MT that is the primary reference point used in applying the annual management review using the Decision Structure (as explored further in Section 7). Section 6.3.2.2 details how river-specific MTs are estimated for E&W.

Managing to the MT and MO should be regarded as an acceptable level of insurance to meet the primary aim of protecting stocks while seeking sustainable levels of exploitation by the fisheries. However, given the concerning decline in salmon numbers in recent years, it is now recognised that higher levels of protection might be justifiable for stocks deemed to be at higher risk.

Figure 2.1 is an idealised representation of a S-R curve. In practice, the individual points around which such a curve is fitted (each point being a measure of the stock and recruitment levels associated with each year class of fish) would, invariably, show a high degree of scatter around the curve. This is usually the case even when numbers are accurately and precisely measured, reflecting the wide variation in recruitment which occurs at any one stock level, which in turn reflects the effects of a variety of environmental factors influencing survival, such as river flow, temperature, water chemistry changes and predation, etc. as well as measurement error. An example of this is shown below for the Girnock Burn, an intensively studied sub-catchment of the Aberdeenshire Dee (Figure 2.2).

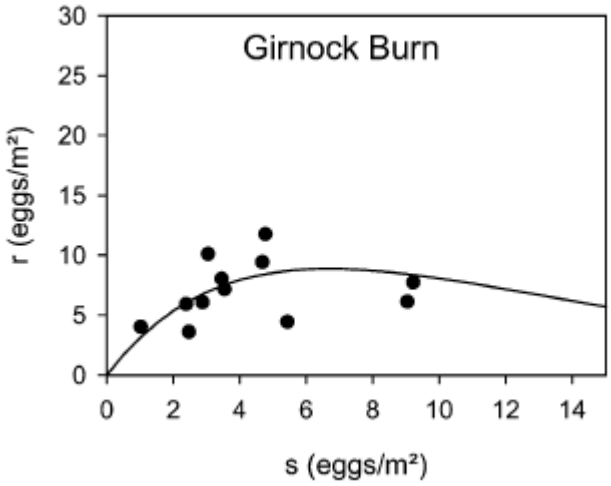



*Figure 2.2. A stock-recruitment curve for the Girnock Burn (from Prevost et al., 2003). S and r are the stock and recruitment variables expressed as eggs per square metre of wetted areas accessible to salmon.*

To fit an S-R curve, such as that on the Girnock Burn (Figure 2.2), requires a lot of data collected over many salmon generations. Such data sets are not available for most rivers (except on the few rivers where estimates of outgoing smolts or returning adults are obtained using counters or traps). This was the case for all salmon rivers in E&W in the 1990s such that the procedures used to derive S-R curves and CLs in E&W (Wyatt and Barnard, 1997a) utilised S-R data collected from the River Bush in Northern Ireland, (Kennedy & Crozier 1993) where intensive, comprehensive monitoring of salmon over a long period has generated a working model of the relationship between spawners and smolts. The shape of S-R curves, particularly the value at the peak of the curve (equating to the maximum smolt production predicted for the river), is controlled by the productivity of the freshwater habitat, and its extent, whilst the survival rates at different stages of the freshwater parts of the life-cycle of the salmon influence the initial gradient of the curve. Parameters defining elements of the Bush S-R relationship have been applied ('transported') in the modelling of S-R curves for rivers in E&W (e.g. the initial gradient of the curve reflecting density-independent survival). Other aspects of the S-R modelling, however, rely on data specific to the rivers in E&W for which S-R curves and CLs were derived (e.g. estimates of juvenile production which relate to the height of the S-R curve). These aspects of the 'transportation model' are described further below.

## 2.2 The transportation model

The transportation model (Wyatt and Barnard, 1997a) was used to derive first an (egg-smolt) S-R curve and secondly a (smolt-egg) Replacement Line for salmon

rivers in E&W. In turn, these two relationships were used to define the CL for any given river.

The model combined the following:

1) The Bush S-R curve, which defines the initial or density-independent mortality (DIM) rate – i.e. the gradient of the ascending limb of the S-R curve, and the smolting rate – i.e. the proportion of fry and parr which go on to smolt aged 1-year (S1) and older, respectively
2) A Habitat sub-model to predict carrying capacity (or the height of the S-R curve) for fry and parr

The Habitat sub-model was based upon:

- Altitude
- Stream order
    - both of which were obtained from 1:250,000 GIS (Geographical Information System) data
- Mean fry densities and mean parr densities predicted for each stream order/altitude category using England and Wales data sets collected for the HABSCORE model (see below)

The HABSCORE model (Milner *et al.,* 1998) was initially constructed from fry and parr abundance data collected by quantitative electric fishing from what were considered pristine sites – where recruitment was not thought to be limited by anthropogenic factors e.g. habitat and water quality, and when/where availability of adult spawners was similarly not constrained – thus indicating the optimum numbers of juvenile salmon that would be assumed to lead to maximal smolt output.

For each catchment, the GIS was used to extract the total length of stream in each category from a matrix of altitude-stream order cells. This matrix was then multiplied by equivalent matrices containing default values for:

- Mean stream width estimated (from the HABSCORE data set) for the respective stream order and altitude categories - to generate stream area estimates
- Predicted fry and parr densities for each category (again, based on the HABSCORE data set)

Thus, enabling determination of the likely maximum carrying capacity of the catchment for fry and parr.

Subsequently, the transportation model was used to derive separate egg-smolt S-R curves for each altitude by stream order (reach) class. Individual S-R curves were then combined (weighted by the proportion of stream area in each reach class) to produce a composite S-R curve for the whole catchment.

Replacement line values, to convert from the number of smolts leaving the river to the numbers of adult spawners and the consequent egg deposition, were based on:

- Marine survival estimates from smolt to adult salmon returning to homewaters. Current default values are 11% for One-Sea Winter (1SW) salmon and 5% for Multi-Sea-Winter (MSW) fish based on the survival rates reported in ICES (2001)
- Mean percentage 1SW fish in the stock - used to weight the default marine survival values to produce a single estimate for the whole stock
- Mean percentage females – used to define the egg producing component in the stock
- Mean fecundity - used to define the numbers of eggs carried by female fish in the stock

The efficacy of the transportation model was checked by comparison with the Bush system. Wetted area estimates derived from the habitat sub-model were 92% accurate when compared to independent estimates specific to the Bush. Similarly, the transportation model produced a S-R curve that provided a close visual approximation to a Ricker curve fitted to the actual stock and recruitment data (egg and smolt estimates) collected on the Bush system. An equivalent validation exercise on the Girnock Burn in Scotland also produced an accurate (96%) estimate of wetted area and resulted in an S-R curve representative of the observed data.

Hence, the transportation model (Wyatt and Barnard, 1997a) has been used to generate Ricker (egg-to-smolt) S-R curves and associated (number of smolts required to replace the adult population) Replacement Lines for all PSR stocks of salmon in E&W, and associated reference points derived from these.

## 2.3 Key limitations in the current England and Wales CL-setting procedure

Despite consideration of volumes of data from salmon rivers in the UK and elsewhere, many scientific publications on salmon ecology and inputs from salmon fishery scientists from around the North Atlantic, there remains uncertainty in outputs from current protocols for setting biological reference points for salmon. Aspects of this were discussed at the National Salmon Stock Assessment Workshop (Atlantic Salmon Trust, 2017). The main issues were considered, at that time, to be:

1) The Bush S-R curve. Even within the context of the River Bush, the Ricker curve that has been derived from the Bush data gathered in the late 1980's and early 1990's may not represent the situation in that river through more recent times: data from a similar number of years during a different time period might generate a different shaped curve, due to varying environmental conditions in both the freshwater and marine environments

2) In combining the original Bush S-R curve with data from the E&W HABSCORE database to derive individual S-R relationships for individual river reaches, it was assumed that the densities of salmon fry and parr in pristine English and Welsh rivers were comparable with similar river reach types represented in the Bush catchment. If, however, the parr densities in the Bush were on average higher than those in the HABSCORE database, then estimates of smolt production from English and Welsh rivers would be too high
3) The HABSCORE database itself was compiled from electric fishing and habitat surveys of what were considered to be pristine juvenile salmonid nursery areas (i.e. that neither water quality nor availability of adult spawners was considered to be limiting) in a selection of relevant catchments throughout E&W in 1992 and 1993. It is important to understand if the juvenile salmon densities from those surveys genuinely represented peak levels of abundance and can therefore be considered to represent potential juvenile carrying capacity, or if higher levels of abundance have been recorded in subsequent surveys
4) The Bush S-R curve and the salmon fry and parr densities from HABSCORE were used to generate what are now the default values for fry-parr survival and for smolt production used in the Bush model that have been transported to English and Welsh rivers. As with the S-R curve, these values represent those for the Bush at the time. It is accepted that these survival rates would vary markedly in time and between rivers and sites, and that the default values are only estimates of likely means. It is possible however that survival has changed substantially since these values were derived, due for instance to direct impacts of climate change (Jonsson & Jonsson, 2009; Bernthal *et al*., 2022) and via climate-driven changes in stream productivity (Hannesdottir *et al*., 2013)
5) Estimates of accessible stream wetted area made for English and Welsh rivers in the late 1990's / early 2000's used a 1:250,000 map scale that, by nature of the mapping resolution, would not have included all of the lowest order, especially first order, streams that would be included in higher resolution maps. This was considered appropriate at the time as salmon rarely spawn in such small streams but any such known examples could be included if local audit considered it appropriate. In addition, since the original wetted area estimates were calculated, significant additional lengths of river may now be accessible to spawning salmon in some catchments due to barrier removal/amelioration but not yet accounted for in modelling S-R curves and CLs. Hence, in these catchments, spawner requirements to fully utilise all the available habitat may be underestimated by the current CL
6) The point on the classic Ricker S-R curve at which the CL occurs is highly dependent on marine survival rates from smolt to returning adults. It needs to be established whether marine survival rates have undergone a substantial change from default values used at present and what the implications might be for CL-setting and subsequent management action. Similarly, size-, sex-

and sea-age composition of the run and fecundity all have implications for the slope of the Replacement Line. There is therefore a need to investigate whether current values used on each river for these parameters are still appropriate.

However, given the significant data and resource requirements for these investigations, it was not possible to fully address all these issues in this review phase. A future standalone project would be the best approach to ensure effective delivery.

Therefore, in this review, we will address the following aspects of the CL-setting process:

1) A comparison of CLs for salmon rivers derived by jurisdictions in the UK and neighbouring countries (Section 3.1.4), which examines the degree of consistency in the absolute values of these reference points on similar sized river systems where CLs have been produced using different methodologies
2) An update of the accessible wetted area estimates in a selection of river catchments, using higher resolution mapping software, OS MasterMap Water Network Layer (Section 4.1)
3) A preliminary examination of whether salmon fry and parr densities in the HABSCORE database are fully representative of the range of pristine conditions in English and Welsh rivers (Section 4.2)

# 3 Stock assessment in England and Wales compared with neighbouring jurisdictions

## 3.1 Comparison of biological reference points throughout UK and Ireland

### 3.1.1 Introduction

Methods to set Conservation Limits (CLs) for individual river-stocks of Atlantic salmon have been developed by most jurisdictions across the species range (ICES, 2024). The CLs arising from these methods underpin procedures to assess and protect stocks and help ensure associated fisheries and environmental resources are managed sustainably.

This review focuses on the derivation of CLs in the neighbouring jurisdictions of the United Kingdom (UK) and the Republic of Ireland based on the assumption that their proximity means the salmon stock production dynamics and fisheries will be most similar to those of England and Wales.

Over the last 20-30 years, jurisdictions operating in the UK and the Republic of Ireland have developed separate approaches for estimating CLs on their main salmon rivers. These sit alongside methods to assess compliance (i.e., procedures to derive spawner and egg numbers and evaluate performance against the CL) and protocols to inform the management response (e.g. to address 'failing' stocks, etc). These procedures are well documented – see for example:

- England and Wales (E&W): Wyatt & Barnard (1997a,b); Milner *et al*. (2000); Environment Agency (2003); Cefas, Environment Agency & Natural Resources Wales (2021a,b)
- Scotland: https://scotland.shinyapps.io/sg-salmon-conservation-detailed/
- Northern Ireland: Kennedy *et al.* (2019)
- Republic of Ireland: White *et al.* (2016); Gargan *et al.* (2021); White *et al*. (2023)

### 3.1.2 Purpose and approach

This section of the report examines relationships between river-specific CLs set by different jurisdictions in the UK and the Republic of Ireland, and common measures of river size (namely accessible wetted area and catchment area). This approach is

used to explore the extent to which CLs and related measures are comparable between systems.

It was not possible to directly apply each country's CL methodology to other countries because of fundamental differences in the types, formats and quantities of input data used in each different methodology. However, CL estimates for rivers in E&W derived (opportunistically) using the methodology developed in the Republic of Ireland (White *et al*., 2016) are compared with the equivalent CLs produced using the E&W methodology.

### 3.1.3 Data sources and results

Various published sources available for each jurisdiction were examined to collate data on CLs and measures of river size. Information utilised in the analysis presented here is summarised in Table 3.1 (below).

*Table 3.1. Summary of published sources of salmon CLs and related information examined in this study.*

| Variable | Country | Notes | Source |
|---|---|---|---|
| Accessible wetted area (hectares) | E&W | | Cefas, Environment Agency & Natural Resources Wales (2012) |
| | Scotland | | https://scotland.shinyapps.io/sg-salmon-conservation-detailed/ |
| | N. Ireland | No information | |
| | Ireland | Fluvial area only – area of accessible lacustrine habitat given but not included | Anon (2010) |
| Latitude and Longitude | E&W | | NASCO (2018a) |
| | Scotland | | NASCO (2018d) |
| | N. Ireland | | NASCO (2018c) |
| | Ireland | | NASCO (2018b) |
| Catchment area ($km^2$) | E&W | | NASCO (2018a) |
| | Scotland | No information | |
| | N. Ireland | | NASCO (2018c) |

| Variable | Country | Notes | Source |
|---|---|---|---|
| | Ireland | | NASCO (2018b) |
| CL (Eggs per 100m$^2$) | E&W | | Cefas, Environment Agency & Natural Resources Wales (2012b) |
| | Scotland | | https://scotland.shinyapps.io/sg-salmon-conservation-detailed/ |
| | N. Ireland | | Kennedy *et al*. (2019) |
| | Ireland | Not applicable | |
| CL (eggs millions) | E&W | | Cefas, Environment Agency & Natural Resources Wales (2012b) |
| | Scotland | | https://scotland.shinyapps.io/sg-salmon-conservation-detailed/ |
| | N. Ireland | | NASCO (2018c); Kennedy *et al*. (2019) |
| | Ireland | | NASCO (2018b); de Eyto *et al*. (2015) |

### 3.1.4 CLs and accessible wetted area

As expected, there are statistically significant ($p<0.001$) positive linear regression relationships between river-specific CLs and accessible (fluvial) wetted area estimates in England & Wales, Scotland, and the Republic of Ireland (Figure 3.1). Notwithstanding differences between regressions for each jurisdiction (e.g., intercept and/or slope estimates), they revealed strong similarities among jurisdictions suggesting that a measure of available habitat (e.g., wetted area) is widely expected to be an important descriptor of expected egg deposition estimates and thus derived CLs.

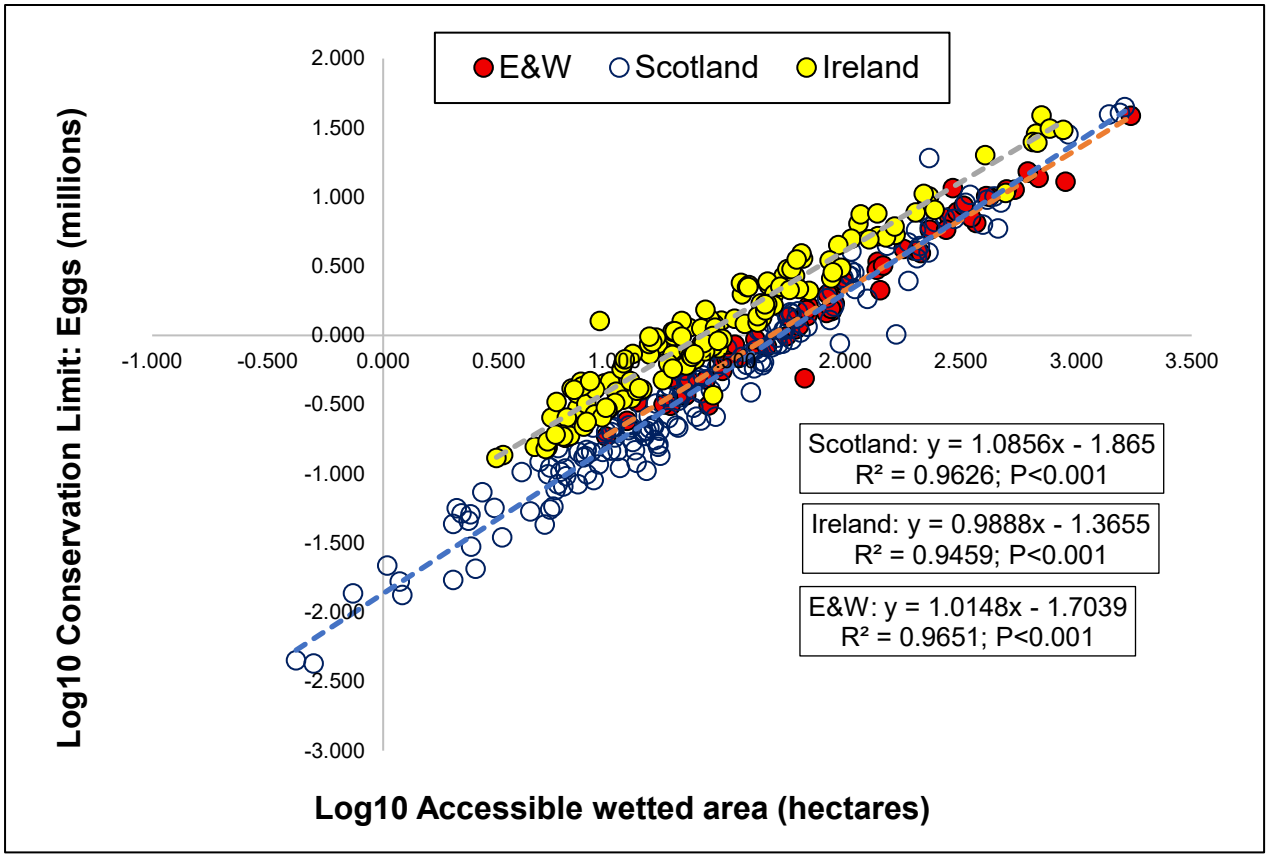



*Figure 3.1. Relationships between CLs derived for individual river stocks of Atlantic salmon and accessible wetted area estimates in E&W, Scotland, and the Republic of Ireland. Data sources: Cefas, Environment Agency & Natural Resources Wales, (2021a and b), White et al. (2016); Gargan et al. (2021).*

CL values predicted from these relationships (expressed as millions of eggs) are compared across a range of accessible wetted area categories in Table 3.2. This indicates that, for rivers of equivalent wetted area, CL values derived for Irish rivers

are consistently greater than those for E&W or Scotland – by factors averaging (overall) ×1.90 and ×1.86, respectively.

The same comparison between E&W and Scotland indicates that CLs from both these jurisdictions are broadly equivalent across the range of wetted area categories. However, for rivers with wetted areas below ~200 hectares, CLs in E&W are, on average, up to ×1.17 greater than those in Scotland. In contrast, for rivers with wetted areas of ~200-2000 hectares the position is reversed with CLs in Scotland being ×1.05 to ×1.18 greater than those in E&W (Table 3.2).

*Table 3.2. Comparison of CLs in E&W, Scotland, and the Republic of Ireland predicted from linear regression relationships with accessible wetted area (see Figure 3.1).*

| Accessible wetted area (hectares)_Class | >0 to <20 | >20 to <40 | >40 to <60 | >60 to <80 | >80 to <100 | >100 to <150 | >150 to <200 | >200 to <400 | >400 to <600 | >600 to <1000 | >1000 to <1500 | >1500 to <2000 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Accessible wetted area (hectares) | 20 | 40 | 60 | 80 | 100 | 150 | 200 | 400 | 600 | 1000 | 1500 | 2000 | All |
| Log10 Accessible wetted area (hectares) | 1.3010 | 1.6021 | 1.7782 | 1.9031 | 2.0000 | 2.1761 | 2.3010 | 2.6021 | 2.7782 | 3.0000 | 3.1761 | 3.3010 | All |
| **E&W** | | | | | | | | | | | | | |
| No. Sites | 6 | 14 | 5 | 6 | 8 | 5 | 2 | 9 | 4 | 4 | 0 | 1 | 64 |
| % Sites | 9.4 | 21.9 | 7.8 | 9.4 | 12.5 | 7.8 | 3.1 | 14.1 | 6.3 | 6.3 | 0.0 | 1.6 | 100.0 |
| Cumulative % | 9.4 | 31.3 | 39.1 | 48.4 | 60.9 | 68.8 | 71.9 | 85.9 | 92.2 | 98.4 | 98.4 | 100.0 | |
| Predicted CL $P_{2.5}$ (Eggs millions): | 0.28 | 0.56 | 0.85 | 1.14 | 1.43 | 2.14 | 2.86 | 5.86 | 8.72 | 14.73 | 22.28 | 30.04 | |
| Predicted CL $P_{50}$ (Eggs millions): | 0.42 | 0.83 | 1.26 | 1.69 | 2.13 | 3.19 | 4.29 | 8.70 | 12.98 | 21.87 | 33.04 | 44.24 | |
| Predicted CL $P_{97.5}$ (Eggs millions): | 0.61 | 1.24 | 1.87 | 2.51 | 3.14 | 4.71 | 6.42 | 12.90 | 19.33 | 32.36 | 49.08 | 65.50 | |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Scotland** | | | | | | | | | | | | | |
| Number of rivers | 85 | 23 | 22 | 4 | 6 | 7 | 5 | 13 | 4 | 1 | 1 | 2 | 173 |
| % Rivers | 49.1 | 13.3 | 12.7 | 2.3 | 3.5 | 4.0 | 2.9 | 7.5 | 2.3 | 0.6 | 0.6 | 1.2 | 100.0 |
| Cumulative % | 49.1 | 62.4 | 75.1 | 77.5 | 80.9 | 85.0 | 87.9 | 95.4 | 97.7 | 98.3 | 98.8 | 100.0 | |
| Predicted CL $P_{2.5}$ (Eggs millions): | 0.20 | 0.43 | 0.67 | 0.91 | 1.16 | 1.80 | 2.46 | 5.25 | 8.15 | 14.05 | 21.83 | 29.48 | |
| Predicted CL $P_{50}$ (Eggs millions): | 0.35 | 0.75 | 1.17 | 1.58 | 2.02 | 3.12 | 4.28 | 9.15 | 14.12 | 24.49 | 38.07 | 52.48 | |
| Predicted CL $P_{97.5}$ (Eggs millions): | 0.61 | 1.30 | 2.03 | 2.78 | 3.51 | 5.54 | 7.60 | 15.77 | 24.49 | 43.01 | 66.36 | 91.00 | |
| **Ireland** | | | | | | | | | | | | | |
| Number of rivers | 66 | 30 | 17 | 6 | 5 | 6 | 3 | 5 | 2 | 6 | 0 | 0 | 146 |
| % Rivers | 45.2 | 20.5 | 11.6 | 4.1 | 3.4 | 4.1 | 2.1 | 3.4 | 1.4 | 4.1 | 0.0 | 0.0 | 100.0 |
| Cumulative % | 45.2 | 65.8 | 77.4 | 81.5 | 84.9 | 89.0 | 91.1 | 94.5 | 95.9 | 100.0 | 100.0 | 100.0 | |
| Predicted CL $P_{2.5}$ (Eggs millions): | 0.51 | 1.01 | 1.52 | 2.02 | 2.52 | 3.77 | 5.02 | 9.90 | 14.59 | 24.49 | 36.72 | 48.64 | |
| Predicted CL $P_{50}$ (Eggs millions): | 0.83 | 1.66 | 2.49 | 3.27 | 4.10 | 6.13 | 8.10 | 16.21 | 24.00 | 40.20 | 59.48 | 79.19 | |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Predicted CL $P_{97.5}$ (Eggs millions): | 1.35 | 2.73 | 4.01 | 5.39 | 6.62 | 10.08 | 13.10 | 26.60 | 39.22 | 65.29 | 96.68 | 127.92 | |
| Ratio CL EW:Scotland ($P_{50}$) | 1.17 | 1.12 | 1.07 | 1.07 | 1.05 | 1.02 | 1.00 | 0.95 | 0.92 | 0.89 | 0.87 | 0.84 | 1.00 |
| Ratio CL EW:Ireland ($P_{50}$) | 0.50 | 0.50 | 0.51 | 0.52 | 0.52 | 0.52 | 0.53 | 0.54 | 0.54 | 0.54 | 0.56 | 0.56 | 0.53 |
| Ratio CL Scotland:Ireland ($P_{50}$) | 0.43 | 0.45 | 0.47 | 0.48 | 0.49 | 0.51 | 0.53 | 0.56 | 0.59 | 0.61 | 0.64 | 0.66 | 0.54 |

There were notable differences in the distribution of rivers among the wetted area categories identified in Table 3.2, with, for example 75% and 77% of salmon rivers in Scotland and the Republic of Ireland having wetted area estimates of 60 hectares or less, compared to only 39% of Principal Salmon Rivers (PSR) in E&W.

### 3.1.5 E&W CLs estimated using the Republic of Ireland methodology

The CLs were estimated directly for 51 of the PSRs in E&W using the Republic of Ireland methodology (White *et al*., 2016). The Irish approach combines stock-recruitment data from a number of index rivers with information from rod catch and catchment characteristics from non-monitored rivers. The resulting values (White *pers comm*) – expressed as millions of eggs (Figure 3.2) - were much closer to those using the current E&W method than those estimated purely based on wetted area (see above section). For example, the CLs derived using the Irish method were on average ×1.05 greater (95% Confidence Intervals (CI): ×0.95 to ×1.20) than those from the current E&W method. This indicates that the CL predictions based on accessible wetted area alone (Figure 3.1 and Table 3.2) exaggerate the differences, at least in the case of E&W and the Republic of Ireland. This may be because wetted area can only serve as a fairly coarse, catchment-scale indicator of productive potential and so fails to reflect more subtle effects. On some individual rivers plotted in Figure 3.2, it is evident there are large differences between CLs estimated using the E&W and Republic of Ireland methodologies, although it is not clear, from this level of analysis, why these differences occur.

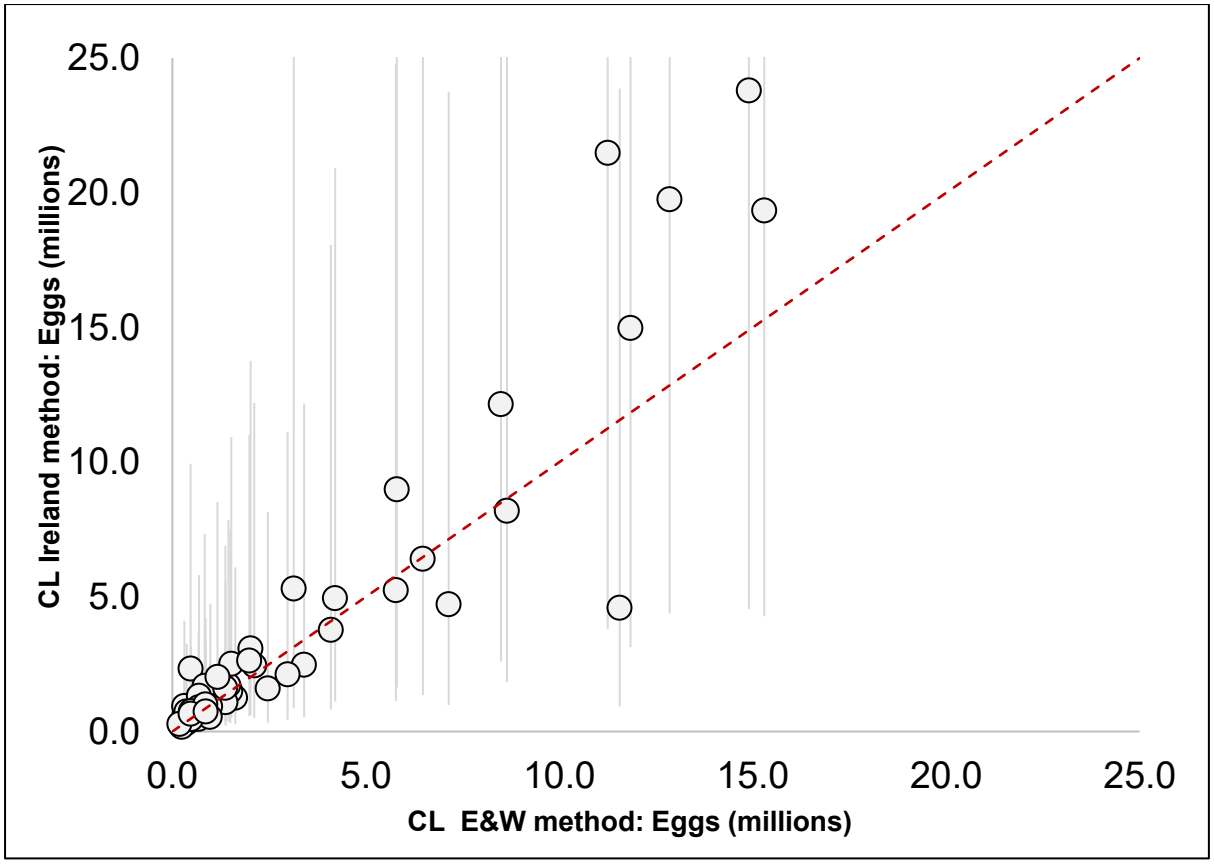



*Figure 3.2. Comparison of CLs derived for 51 Principal Salmon Rivers in E&W using the E&W and the Republic of Ireland methodologies [vertical bars indicate 80% Confidence Intervals for the latter estimates; red dashed line is the line of parity].*

### 3.1.6 Accessible wetted area and catchment area

River-specific estimates of CLs are dependent on map-derived measures of river reaches accessible to salmon spawners, including estimates of wetted area.

Comparison of accessible wetted area estimates with an alternative measure of catchment size – namely catchment area – provides a means of examining the degree of consistency between jurisdictions in procedures used to obtain wetted area estimates (or at least consistency in the outputs of those procedures).

Statistically significant ($P<0.001$) positive linear regression relationships were evident between estimates of accessible wetted area and catchment area for rivers in E&W and the Republic of Ireland (Figure 3.3) (data from Scotland were not available to make these comparisons).

Again, these regression relationships were different in terms of their slope and intercept. They indicate that, for catchment areas above ~500 $km^2$, wetted area estimates in E&W are on average increasingly greater than those in the Republic of

Ireland by factors ranging from ×1.25 to ×2.05 (corresponding to catchment areas of 1,000 and 5,000 km$^2$, respectively; Table 3.3). The opposite is true of smaller rivers with catchment areas less than ~500 km$^2$ where wetted area estimates for Irish rivers tend to be greater than rivers in E&W of equivalent size. The majority of the rivers included in this analysis had catchment areas $\leq$ 500 km$^2$ ($\log_{10}$ = 2.699): ~55% and 89% of rivers in E&W and the Republic of Ireland, respectively.

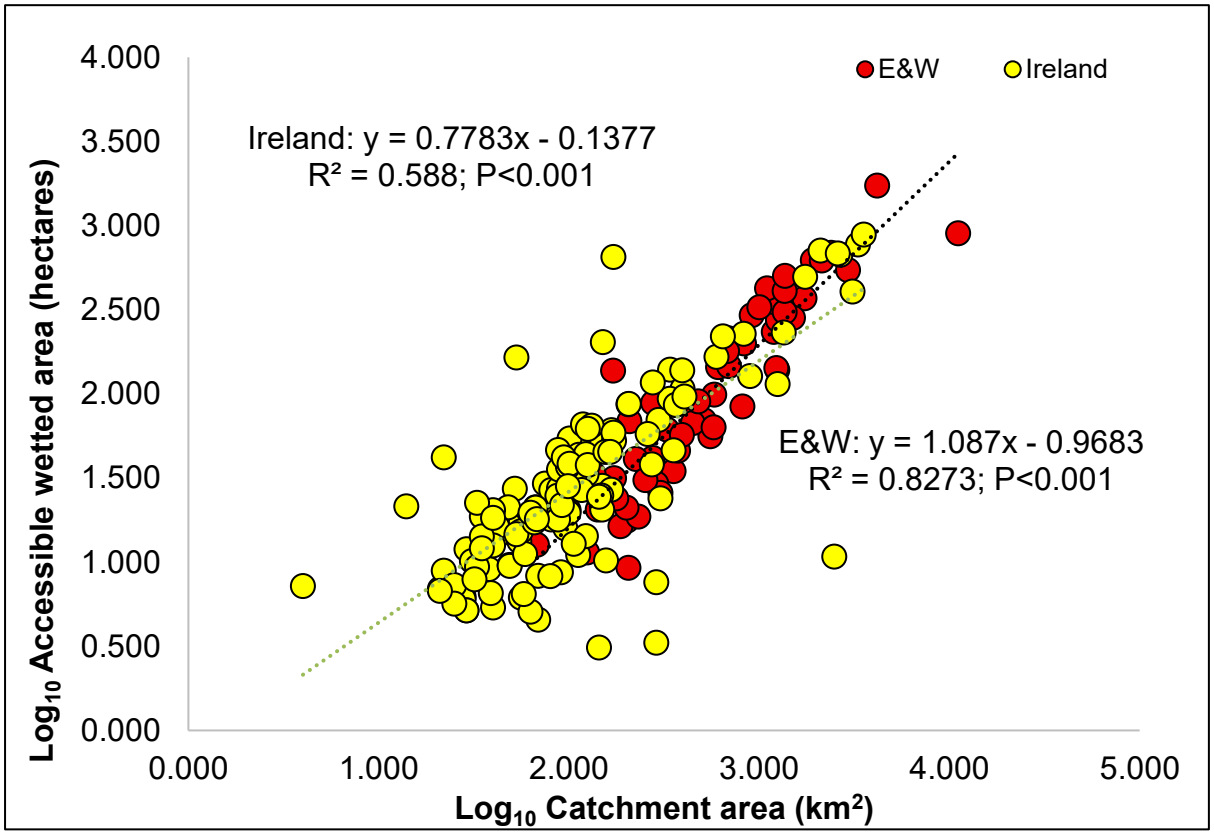



*Figure 3.3. Relationships between accessible wetted area estimates and catchment area for rivers in E&W and the Republic of Ireland.*

*Table 3.3. Comparison of accessible wetted areas in E&W and the Republic of Ireland predicted from linear regression relationships with catchment area (see Figure 3.3). # Average ratio over all wetted area categories.*

| Catchment area_Class ($km^2$) | >0 to <100 | >100 to <300 | >300 to <500 | >500 to <1000 | >1000 to <1500 | >1500 to <2000 | >2000 to <2500 | >2500 to <3000 | >3000 to <3500 | >3500 to <4000 | >4000 to <4500 | >4500 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Catchment area ($km^2$) | 100 | 300 | 500 | 1000 | 1500 | 2000 | 2500 | 3000 | 3500 | 4000 | 4500 | 5000 | All |
| Log10 Catchment area ($km^2$) | 2.00 | 2.48 | 2.70 | 3.00 | 3.18 | 3.30 | 3.40 | 3.48 | 3.54 | 3.60 | 3.65 | 3.70 | |
| **E&W** | | | | | | | | | | | | | |
| Number of rivers | 2 | 22 | 11 | 11 | 10 | 3 | 2 | 1 | 0 | 0 | 1 | 1 | 64 |
| % Rivers | 3.13 | 34.38 | 17.19 | 17.19 | 15.63 | 4.69 | 3.13 | 1.56 | 0 | 0 | 1.56 | 1.56 | 100 |
| Cumulative % | 3.13 | 37.50 | 54.69 | 71.88 | 87.50 | 92.19 | 95.31 | 96.88 | 96.88 | 96.88 | 98.44 | 100 | |
| Predicted Wetted area (Hectares) $P_{2.5}$: | 6.78 | 22.10 | 40.14 | 84.91 | 128.26 | 177.42 | 226.25 | 277.49 | 323.91 | 377.56 | 429.11 | 485.97 | |
| Predicted Wetted area (Hectares) $P_{50}$: | 16.13 | 53.01 | 91.82 | 197.28 | 301.13 | 419.01 | 523.71 | 648.16 | 758.48 | 882.25 | 1007.27 | 1128.08 | |
| Predicted Wetted area (Hectares) $P_{97.5}$: | 38.04 | 125.67 | 216.26 | 460.82 | 720.35 | 965.38 | 1216.73 | 1521.69 | 1768.64 | 2101.36 | 2346.05 | 2652.35 | |

| **Ireland** | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Number of rivers | 69 | 38 | 8 | 4 | 2 | 1 | 2 | 2 | 2 | 1 | 0 | 0 | 129 |
| % Rivers | 53.49 | 29.46 | 6.20 | 3.10 | 1.55 | 0.78 | 1.55 | 1.55 | 1.55 | 0.78 | 0.00 | 0.00 | 100 |
| Cumulative % | 53.49 | 82.95 | 89.15 | 92.25 | 93.80 | 94.57 | 96.12 | 97.67 | 99.22 | 100.00 | 100.00 | 100.00 | |
| Predicted Wetted area (Hectares) $P_{2.5}$: | 6.79 | 16.54 | 23.82 | 40.91 | 56.23 | 70.73 | 85.03 | 99.47 | 111.53 | 118.64 | 136.09 | 146.85 | |
| Predicted Wetted area (Hectares) $P_{50}$: | 26.28 | 61.16 | 93.80 | 157.32 | 213.01 | 274.17 | 321.81 | 380.10 | 419.71 | 460.32 | 513.50 | 551.41 | |
| Predicted Wetted area (Hectares) $P_{97.5}$: | 98.95 | 238.73 | 341.90 | 597.04 | 805.65 | 1033.83 | 1205.22 | 1430.57 | 1613.96 | 1749.88 | 1849.90 | 2122.36 | |
| Ratio wetted area (Hectares) $P_{50}$ EW:Ireland | 0.61 | 0.86 | 1.01 | 1.25 | 1.41 | 1.54 | 1.65 | 1.75 | 1.83 | 1.91 | 1.98 | 2.05 | 1.49 |

### 3.1.7 Summary

Linear regression relationships between CLs derived for individual river stocks of Atlantic salmon and estimates of accessible wetted area in E&W, Scotland, and the Republic of Ireland identified similarities as well as differences between jurisdictions.

Predictions from these relationships indicate that CL values for Irish rivers are on average ~×1.90 higher than those set for rivers in both E&W and Scotland when corrected for accessible wetted area. Differences between CLs for rivers in E&W and Scotland were less marked, with values close to parity overall.

However, direct comparison of CLs derived for rivers in E&W using E&W versus the Republic of Ireland methodologies found estimates for the latter to be, on average, less than ~×1.10 greater. This suggests the differences between the two countries identified using the former wetted area-based comparisons are exaggerated - at least when using the method from the Republic of Ireland.

There may be good reasons for jurisdictional differences in CL estimates, e.g. linked to factors such as geography and salmon stock biology, as well as methodological differences in the procedures used to derive CLs. The reasons for these differences are not examined in detail here because the underlying drivers are multi-faceted, including differences in the knowledge base, data availability, resources, and expertise at the time of development. However, the commonalties suggest that procedures to derive CLs in E&W, although different to those developed in neighbouring countries, generally appear to result in similar outcomes in terms of the CL values they generate.

A more limited comparison of linear regression relationships between accessible wetted area estimates and catchment area estimates for rivers in E&W and the Republic of Ireland also highlights similarities as well as differences. From an E&W perspective, this comparison does not suggest that accessible wetted areas are systematically underestimated in E&W compared to the Republic of Ireland (except, perhaps on the smallest systems, and even here – for the most part - the differences tend not to be great).

Since our interest was around similarities and differences in derived CLs between jurisdictions rather than descriptions of relationships within jurisdictions, we elected to use only linear regressions, neglecting any non-linearities that might have been useful to describe CL variations within jurisdictions.

## 3.2 Estimating adult salmon returns and egg deposition in the UK and Ireland

### 3.2.1 Overview of national approaches

The purpose of this review is to explore the initial parts of the salmon stock assessment process in the UK and the Republic of Ireland, specifically the procedures to estimate the numbers of adult salmon returning to rivers and egg deposition as depicted in the dashed boxes in Figure 3.4. The review concludes with an evaluation of the scope to apply aspects of these procedures in England and Wales.

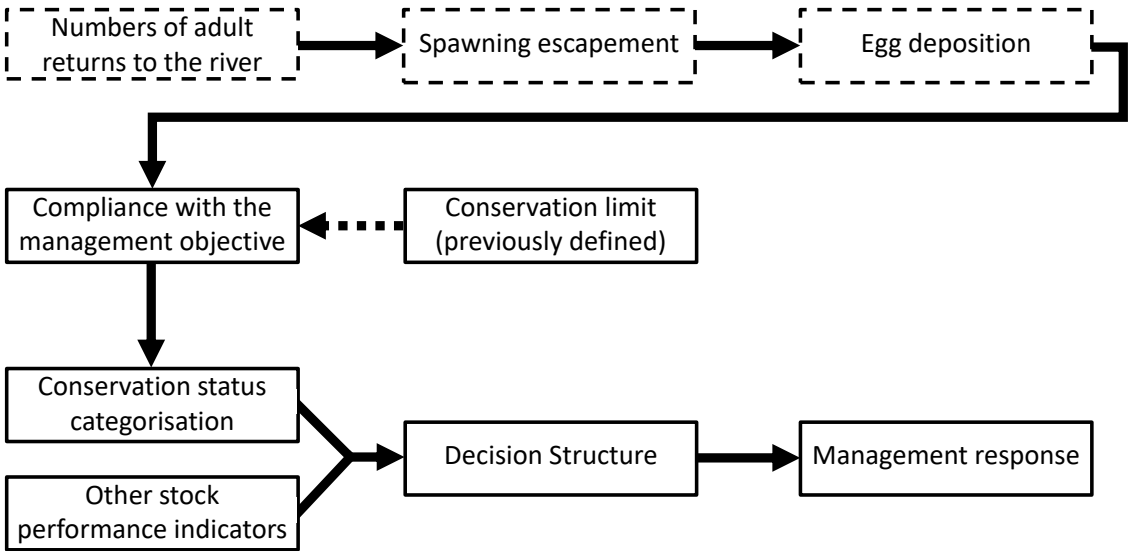



*Figure 3.4. General salmon stock assessment process in the UK and the Republic of Ireland. The dashed boxes indicate the aspects of the process explored in this review.*

#### *3.2.1.1 England and Wales*

The numbers of adult salmon returning to the 64 PSRs in E&W, prior to exploitation in rod fisheries, are estimated annually for stock assessment purposes (Cefas, Environment Agency, and Natural Resources Wales, 2024a). The key steps in this procedure, which differ depending on whether data are available from fish counters and traps or only rod catches, are outlined in Figure 3.5, and then briefly described in the following text. More details about the procedure are available in Cefas, Environment Agency, and Natural Resources Wales (2024a,b).

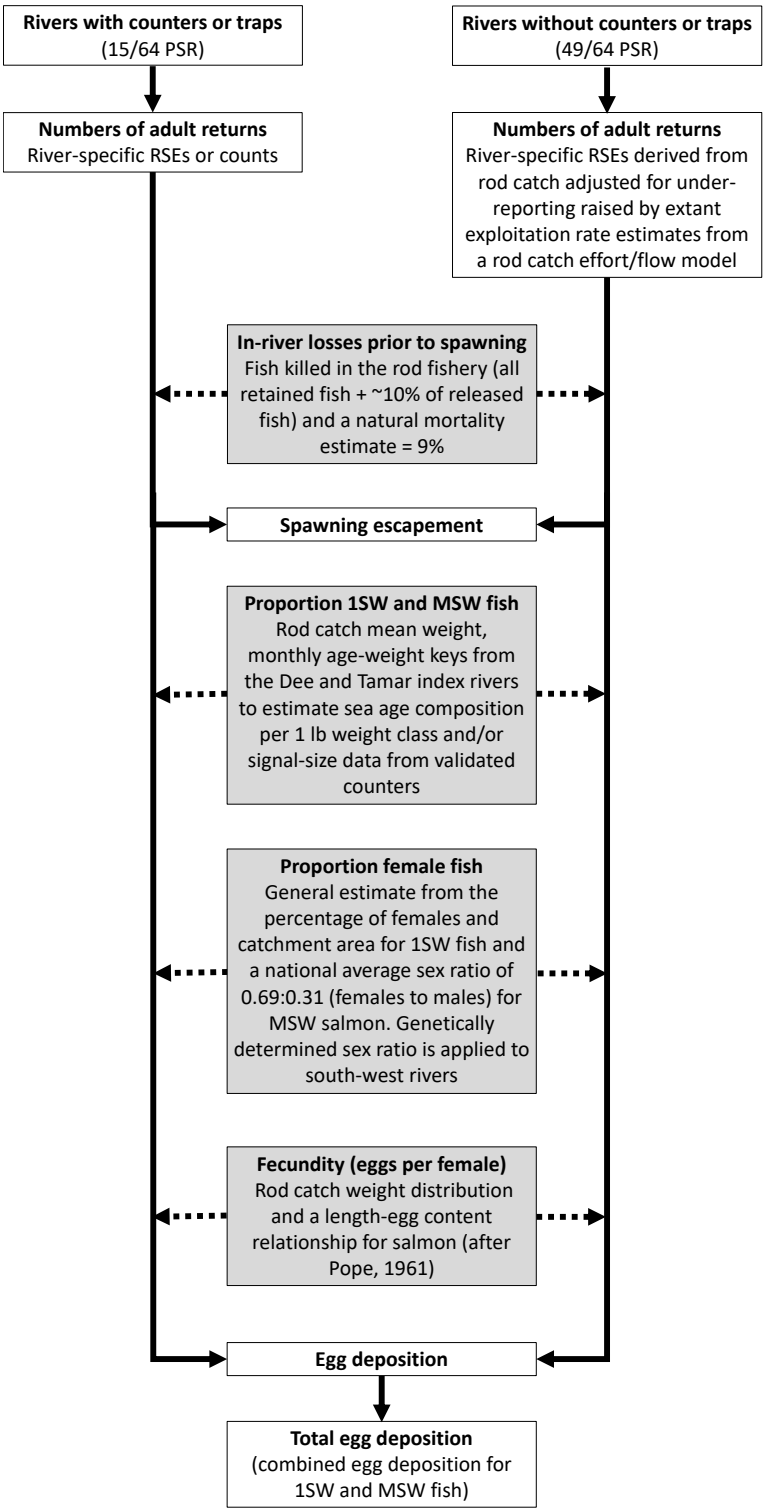



*Figure 3.5. Procedures to generate adult return and egg deposition estimates in England and Wales.*

#### *3.2.1.1.1 Numbers of adult returns*

Validated fish counters or traps have operated on twelve 'monitored' rivers (Tyne, Itchen, Test, Hants Avon, Frome, Fowey, Tamar, Lune, Leven, Kent, Dee and Teifi) to provide annual Returning Stock Estimates (RSEs) for adult salmon. RSEs are verified records of adult returns, corrected for counting inefficiencies and losses to rod fisheries downstream of the counter. A further three rivers (Tees, Taff, and Caldew) have produced annual counts of adult salmon, which are almost equivalent to RSEs. These three rivers are also classed as 'monitored' for present purposes. However, these annual counts provide indices of abundance that have not been adjusted for counting inefficiencies.

Fish counters are also operated on the rivers Ribble, Wear, Exe, and Afon Tanat (a tributary of the Severn), but their siting within the catchment and/or their accuracy in terms of distinguishing fish species mean that they do not provide a RSE for those catchments. Work is underway to upgrade and improve the resilience of the salmon counter network.

In those 49 PSRs lacking validated fish counters or traps, the annual numbers of adult returns are derived from rod catches raised by extant exploitation rates (the proportion of the returning stock of salmon before, during and after the fishing season caught by angling). Rod catches are adjusted for under-reporting using a correction factor of ~10% based on the approach devised by Small (1991). Extant rod exploitation rates used in the derivation of adult returns are modelled from catch and stock estimates obtained from the counted rivers along with measures of angling effort as a key predictor of fishing success (Environment Agency, 2003). However, in some instances, local fishery technical specialists have adopted fixed estimates of extant rod exploitation rates to derive adult returns from declared rod catches. At present, these procedures do not account for the effects on rod exploitation rates of inter-annual variation in fishing effort, river flow, or repeat captures due to catch-and-release fishing and therefore have the potential to over- or underestimate actual exploitation rates. A new national model to estimate annual exploitation rates, based on relationships between rod exploitation rates and angler effort (declared days fished), successful angler effort (proportion of declared days fished for which a salmon was caught), the proportion of salmon returned to the river after capture, mean river flow, and wetted area accessible to spawners, has been developed (Gregory *et al*., 2023) and is being considered for future implementation (see Section 5.3).

Uncertainty in the annual numbers of adult returns is not currently estimated.

#### *3.2.1.1.2 Numbers of spawning fish*

The numbers of returning adult salmon surviving to spawn (hereafter spawning escapement) are estimated by first subtracting the number of fish killed in the rod

fishery (estimated as all retained fish, adjusted for under-reporting, plus 10% of released fish) from the numbers of adult returns, and then subtracting the amount of fish expected to die of natural causes (9%: Milner *et al*., 2000) prior to spawning.

Uncertainty in the numbers of spawning fish is not estimated in the current assessment.

#### *3.2.1.1.3 Egg deposition*

Egg deposition estimates (the number of eggs spawned throughout the river) are a fundamental component of the stock assessment process, serving as the unit of spawning success when assessing compliance with river-specific CLs defined in numbers of eggs. Egg deposition is estimated according to the weight of the female returning salmon, and their fecundity – the relationship between the size of the female salmon and the number of eggs it produces.

In 'monitored' rivers, egg deposition estimates are derived separately for 1SW and MSW salmon according to the size and sex of returning fish, based on either local information (including trap-based sampling programmes) or default relationships.

In salmon rivers where adult returns are derived from rod catches, size composition data from rod catch returns and monthly age-weight keys obtained from index river monitoring on the rivers Dee and Tamar are used to estimate numbers of 1SW and MSW spawners and their egg contributions. The Tamar age-weight key is applied to rivers in the south and south-west regions of England since it is the most representative for southern river stocks, while the Dee age-weight key is applied to rivers in the north-east and north-west of England, and Wales. Both age-weight keys account for the timing and size of returning fish and their likely sea age and are used to estimate the proportion of one-sea-winter (1SW) and multi-sea-winter (MSW) salmon in each one-pound weight class (imperial units of weight are used here as the weights of rod-caught fish are primarily reported by anglers in these units).

Estimates of egg deposition by weight class are based on sex ratio and size-fecundity relationships. The proportion of females (sex ratio) is based on (i) the negative relationship between the percentage of females and catchment area for 1SW fish, because female grilse tend to be less dominant in large versus small rivers, and (ii) a national average sex ratio of 0.69:0.31 (females to males) for MSW salmon (Environment Agency, 2003), or (iii) genetically determined sex ratios for 1SW and MSW salmon based on sampling from the River Tamar (King *et al*., 2023) – the latter has been applied to south-west rivers in recent years. The size-fecundity relationship is that of Pope *et al*. (1961) which utilised data on egg number and wild salmon body size from six Scottish rivers sampled in 1957, 1958 and 1959. Egg deposition per sea age is derived by multiplying expected numbers of female spawners by the mean number of eggs per female. Total egg deposition is then estimated by combining the data for each sea-age class.

Uncertainty in egg deposition is estimated by considering variation in regression parameters using a Bayesian hierarchical regression model fitted with Markov Chain Monte Carlo (MCMC) sampling during the latter stages of the stock assessment process when evaluating compliance with river-specific CLs (Environment Agency, 2012). The uncertainties in the estimates of the egg deposition distribution parameters are obtained as 95% credible intervals based on 60,000 samples drawn using bootstrapping techniques.

#### *3.2.1.2 Scotland*

In Scotland, annual estimates are made of the numbers of adult salmon returning to 173 ‘assessable’ rivers or groups of rivers. The procedural steps, which differ depending on whether data are available from fish counters, traps and tagging studies or only rod catches, are shown in Figure 3.6 and briefly described in the text below.

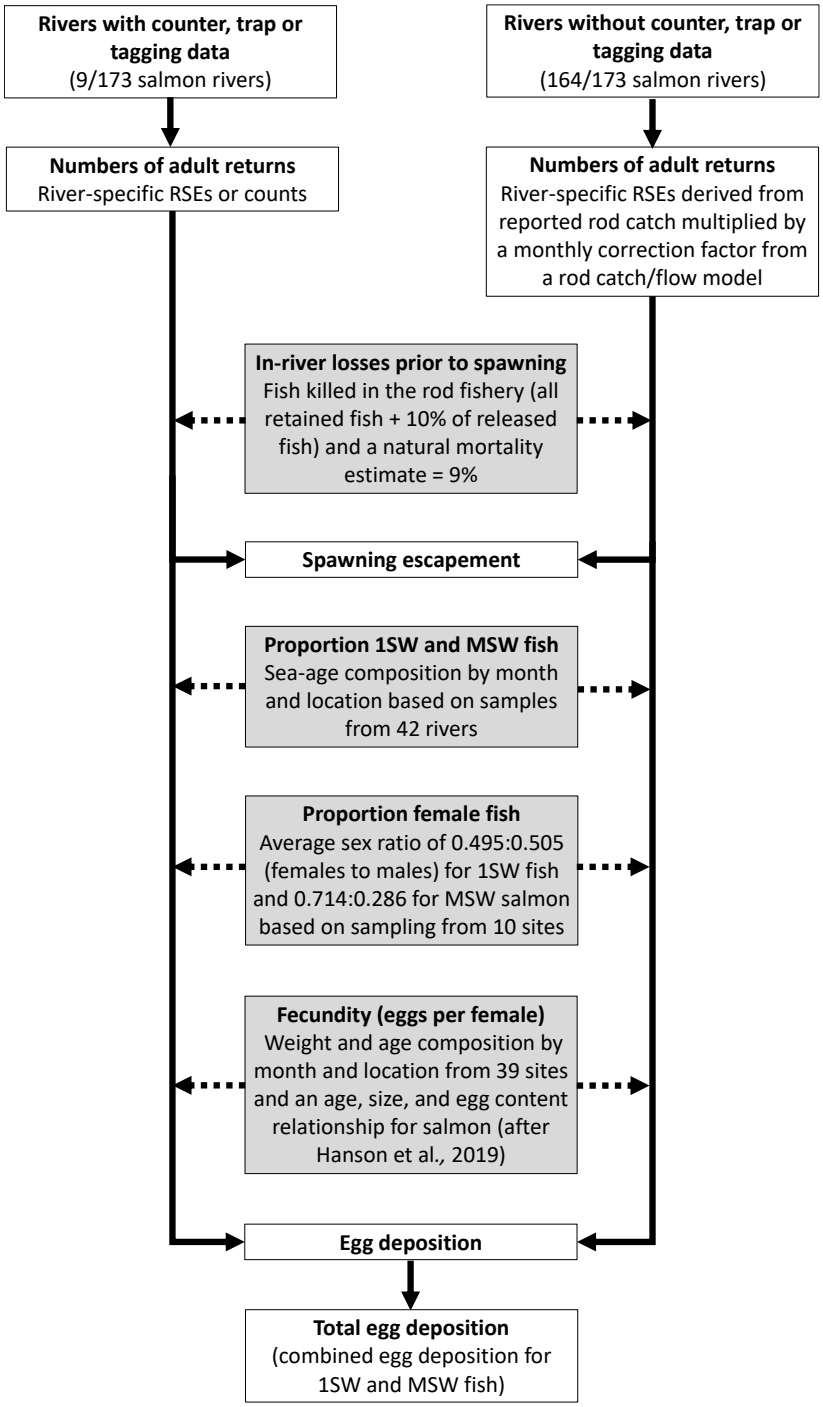



*Figure 3.6. Procedures to generate adult return and egg deposition estimates in Scotland.*

#### *3.2.1.2.1 Numbers of adult returns*

Monthly fish count data, and rod catches from fisheries situated upstream of fish counters, are available for seven salmon rivers (Marine Scotland Science, 2020). Rather than directly deriving the numbers of returning adult salmon, a correction

factor based on the monthly exploitation rate is produced using the fish count data and rod catches from these seven rivers, allowing adult returns to be derived for two further rivers with tagging data. Generalised linear mixed models with binomial errors are used to examine the relationship between the correction factor and both month and river flow. The models operate by adjusting the RSE to account for changes in catchability (defined by the correction factor) linked to month and flow conditions. Rod effort has only been collected since 2019 and therefore these data were not available for inclusion in the model at the time of its inception but are expected to be incorporated in subsequent model developments (Middlemass, pers comm).

Adult returns for the 164 salmon rivers without fish counter or tagging data are estimated by multiplying reported rod catch (adjusted for under-reporting) with the modelled monthly correction factor. Given that there are no rod catch data outside of the fishing season but there may still be salmon returning to the river, the numbers of adult returns during the fishing season are raised by the relative seasonal distribution of fish established from counter data to estimate the total annual return by combining the in-season and out-of-season adult returns.

#### *3.2.1.2.2 Numbers of spawning fish*

Spawning escapement is estimated from the numbers of adult returns minus the number of fish killed in the rod fishery (all retained fish + 10% of released fish: Webb, 1998) and those lost to natural mortality in rivers (9%: Milner *et al*., 2000). The numbers of spawners by sea-age class are derived by multiplying spawning escapement by the proportion of 1SW and MSW fish based on sampling data on sea-age composition from 208,457 salmon collected from 42 rivers between 1963 and 2018 (Marine Scotland Science, 2020). The spawner numbers by sea-age class are then converted to the number of female spawners using sex ratios from wild salmon sampled at 10 sites throughout Scotland from 1966 to 2016, where 49.5% of 1SW and 71.4% of MSW salmon were found to be female based on genetic sexing or fish trapping data.

#### *3.2.1.2.3 Egg deposition*

Egg deposition estimates are derived from the numbers of female spawners using data on the sizes and ages of 205,544 salmon collected from 39 sites throughout Scotland between 1963 and 2018 to estimate the egg content of individual females based on relationships between smolt age, sea age, adult size and fecundity (Hanson *et al*., 2020). These estimates of the egg contents of individual females are applied to the spawning escapement of females for each sea-age/month combination and summed to estimate total annual egg deposition.

A Monte Carlo simulation model is used to estimate uncertainty in the numbers of adult returns, female spawners and egg deposition. Uncertainties in the distributions

of these parameters are expressed as 95% confidence intervals based on 10,000 samples drawn using bootstrapping techniques.

#### *3.2.1.3 Northern Ireland*

Annual estimates of spawning escapement in 16 ‘primary salmon rivers’ are the foundation of the stock assessment methodology in Northern Ireland, serving as the unit of spawning success when assessing compliance with river-specific CLs and determining the availability of a harvestable surplus (Kennedy *et al*., 2015).

Three approaches are used to estimate the numbers of returning adult salmon, depending on data availability: (1) counts of adult returns at validated fish counters or traps, (2) an annual tagging study, or (3) rod catches raised by extant exploitation rates. The key steps in the procedure are outlined in Figure 3.7 and briefly described in the following text.

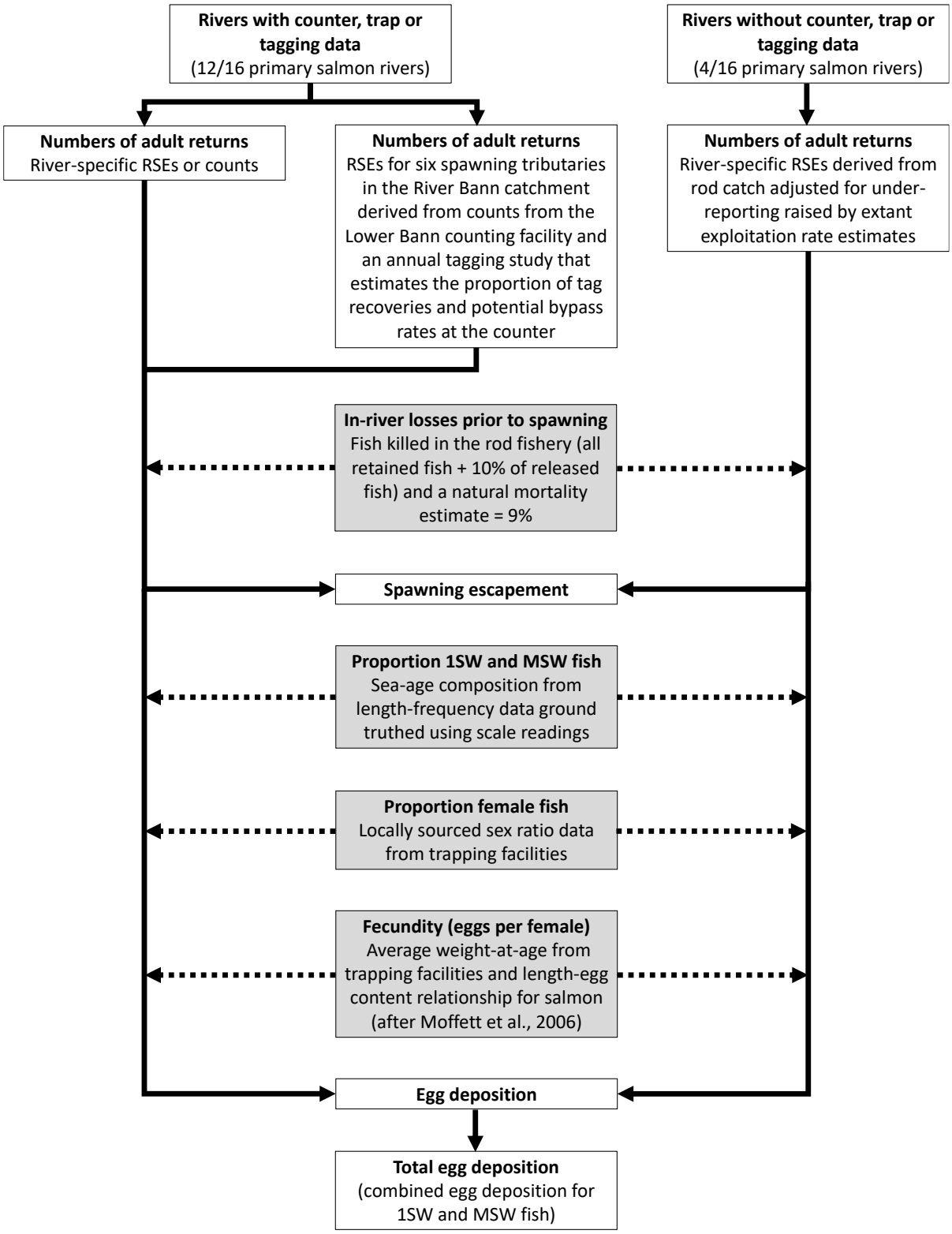



*Figure 3.7. Procedures to generate adult return and egg deposition estimates in Northern Ireland.*

#### *3.2.1.3.1 Numbers of adult returns*

Validated fish counters or traps provide the numbers of adult returns for six rivers (Bush, Clady, Erne, Glendun, Lower Bann, and Shimna) covering the vast majority (~90–95%) of total salmon production in the region (Kennedy *et al*., 2015).

An annual tagging study is undertaken throughout the River Bann catchment to track the spawning migration of adult salmon (Kennedy *et al*., 2015; Kennedy and Allen, 2016). This tagging study facilitates the derivation of adult returns for six spawning tributaries (Ballinderry, Blackwater, Main, Moyola, Sixmile, and Upper Bann) by determining the potential bypass rates at the Lower Bann counting facility.

The numbers of adult returns for four salmon rivers without validated fish counters or traps (Agivey, Ballycastle, Glenarm and Melvin) are derived using rod catches raised by extant exploitation rates (Kennedy *et al*., 2015). Although catch returns from anglers are mandatory, the return rates have declined following the introduction of catch-and-release fishing, which has increased uncertainty in the assessment outputs. Rod catches are adjusted for under-reporting using a correction factor of 10% based on the approach devised by Small (1991). Precautionary estimates of exploitation rates for the Agivey, Ballycastle and Glenarm rivers are derived from the upper 95% confidence interval around the long-term exploitation rate on the River Bush (Kennedy *et al*., 2015). These exploitation rates are precautionary because they are assumed to be higher than the long-term average. For the cross-border Melvin catchment, the exploitation rate is estimated by the Republic of Ireland.

#### *3.2.1.3.2 Numbers of spawning fish*

Spawning escapement for salmon rivers with fish counters or traps is estimated from the numbers of adult returns upstream from the counter or trap, corrected for in-river losses due to natural and fishing mortality prior to spawning (Milner *et al*., 2000).

For each spawning tributary in the River Bann catchment, spawning escapement is estimated by adjusting adult returns using a raising factor for the Lower Bann counter, minus in-river losses prior to spawning due to natural and fishing mortality based on carcass tag returns and an estimate of non-reported catch, multiplied by the proportion of tagged fish recovered in each tributary.

Spawning escapement for salmon rivers without fish counters, traps or tagging data is estimated by multiplying reported rod catch (raised for under-reporting and adjusted for repeat captures due to catch-and-release fishing by deducting a percentage of the catch return) with extant exploitation rates, minus in-river losses due to natural and fishing mortality.

#### *3.2.1.3.3 Egg deposition*

Egg deposition in rivers with validated fish counters or traps is estimated by splitting the spawning escapement according to locally derived sea-age class proportions and the sex ratio (Kennedy *et al*., 2015). Routine biological monitoring of adult salmon is undertaken on most rivers, whereby a sample of fish are trapped or electric fished during the migratory season and their age, length, weight, and sex are recorded. The sea-age composition of each river stock is estimated from length-frequency data, ground-truthed using scale readings, with direct measurements of sex and weight. The numbers of 1SW and MSW females are multiplied by the average weights-at-age derived from trapping facilities and relationships between age, size, and fecundity from 118 wild stripped female salmon trapped at Bushmills Salmon Station between 2000 and 2002 (Moffett *et al*., 2006).

For each of the six spawning tributaries in the River Bann catchment, egg deposition is derived using a combination of adult returns from the Lower Bann counting facility, tagging data, locally derived biological characteristics and the age-length-fecundity relationship described above (Kennedy *et al*., 2015).

Where adult returns are derived from rod catches on salmon rivers without fish counters or traps, egg deposition is estimated using the same approach applied to rivers with validated fish counters or traps (Kennedy *et al*., 2015).

Uncertainty in egg deposition estimates is not quantified, but minimum estimates of this parameter are used in the stock assessments as a precaution against overestimating egg deposition. This is related to the use of maximum extant exploitation rate estimates in the stock assessments as a precaution against underestimating salmon exploitation by rod fisheries.

### *3.2.1.4 Republic of Ireland*

Time-series estimates of annual numbers of adult salmon returning to 141 rivers prior to exploitation in rod fisheries are the keystone of the stock assessment methodology in the Republic of Ireland (TEGOS, 2019). Stock management decisions for the forthcoming fishing season are based on forecasts of adult returns in rivers using fish counter and trap data (if available) or rod catches raised by extant exploitation rates, which are taken from the most recent five-year time-series (SSCS, 2016). The procedural steps are shown in Figure 3.8 and briefly described in the text below.

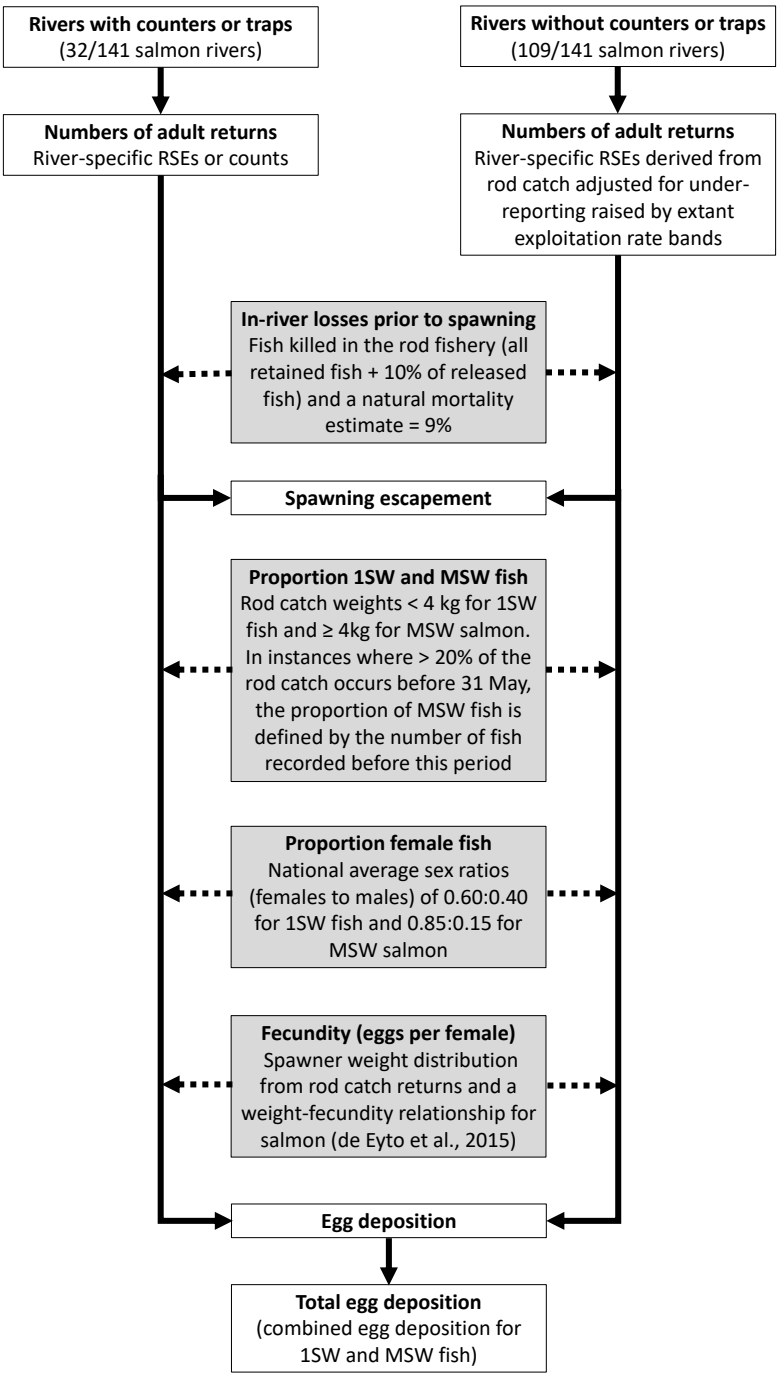



*Figure 3.8. Procedures to generate adult return and egg deposition estimates in the Republic of Ireland.*

#### *3.2.1.4.1 Numbers of adult returns*

Thirty-two rivers operate validated fish counters or traps that monitor the numbers of returning adult salmon (TEGOS, 2019). For the 109 salmon rivers without validated fish counters or traps, adult returns are derived from rod catches raised by extant exploitation rates. Rod catches may be adjusted for under-reporting using a

correction factor of 10% based on the approach devised by Small (1991). Extant rod exploitation rate bands are derived from salmon rivers with fish counters or traps, supported by information from the scientific literature and the national coded wire tagging and tag recovery programme. Salmon rivers dominated by 1SW (< 4kg) stocks are assigned into low, medium, and high exploitation rate bands (Table 3.4). In contrast, salmon rivers dominated by MSW (≥ 4kg) stocks are classified into low or high exploitation rate bands. No medium exploitation rate band is defined for salmon rivers dominated by MSW stocks because examples of medium exploitation rates are lacking. This procedure is analogous to using confidence intervals in uncertainty situations.

A review of salmonid exploitation rates in the Republic of Ireland concluded that rates were generally consistent or lower than historic estimates of exploitation (Millane *et al*., 2017). For example, the recent estimate of exploitation on the River Erriff (17.9%) was in line with the reported rate of 19.3% (Gargan *et al*., 2001), whereas exploitation on the Burrishoole system at 4.4% was lower than the 15% reported previously (Whelan *et al*., 2001).

*Table 3.4. Rod exploitation rates applied to salmon rivers without validated fish counters or traps to estimate stock size. These values were derived in 2006 using observed values from 18 salmon rivers with fish counters and rod catch data (Millane et al., 2017).*

| River stock | Intensity | Minimum | Midpoint | Maximum |
|---|---|---|---|---|
| 1SW | Low | 1 | 5 | 12 |
| | Medium | 7 | 15 | 35 |
| | High | 10 | 33 | 50 |
| MSW | Low | 6 | 12 | 27 |
| | High | 15 | 31 | 46 |

In salmon rivers without fish counters or traps, and limited or no catch data, a juvenile salmon abundance threshold, defined as either 15 or 17 fry per five-minute electric fishing survey (mean of surveys across the catchment), is used as the threshold for managers to decide whether the rivers can be opened for catch-and-release only fishing.

#### *3.2.1.4.2 Numbers of spawning fish*

Spawning escapement is estimated from the numbers of adult returns upstream from the fish counter or trap, adjusted for in-river losses due to natural (9%: Milner *et al*., 2000) and fishing (all retained fish + 10% of released fish) mortality prior to spawning (SSCS, 2016).

#### *3.2.1.4.3 Egg deposition*

Spawning escapement is converted to egg equivalents using the proportions at sea-age, the average fecundity of each age class based on rod catch weights for the two sea-age classes, and the proportion of females in each sea-age class (White *et al*., 2016).

Where catches are higher than 100 salmon per year, reported river-specific proportions at sea-age are used (SSCS, 2016). For salmon rivers with smaller catches, national average proportions at sea-age are applied. Frequency distributions of rod catches are constructed from the median and standard deviations of salmon < and ≥ 4 kg. The $10^{th}$, $50^{th}$ and $90^{th}$ percentile catch weights are then taken to form the weight ranges (minimum, median and maximum) of 1SW and MSW salmon for each river stock.

Most Irish stocks are dominated by 1SW salmon and assessed as single age units – this assumes that MSW salmon contribute only a small proportion of egg deposition (White *et al*., 2023). Where historic information suggests that MSW salmon contribute at least 20% of the salmon 'run' or catch, the catch until 31 May is assumed to be MSW, and 1SW and MSW components are assessed independently.

The proportion of females in each sea-age class is based on mean values for national data: 0.60 for 1SW fish and 0.85 for MSW salmon (Ó Maoiléidigh *et al*., 2004). Fecundities for 1SW and MSW salmon expressed as eggs per fish, and their $10^{th}$ and $90^{th}$ percentiles, are estimated using a weight-fecundity relationship for 336 salmon sampled from Irish rivers between 1992 and 2011 (de Eyto *et al*., 2015) and the normal distribution of mean rod catch weights with corresponding $\pm 90^{th}$ percentiles (White *et al*., 2016). The average fecundities applied are 3441 eggs for 1SW and 6059 eggs for MSW salmon.

A Monte Carlo simulation model is used to estimate uncertainty in egg deposition drawn from triangular distributions (a continuous probability distribution with lower limit, median and upper limit). The model runs 75,000 samples based on randomly selected values of egg deposition to calculate a probability distribution. The egg deposition estimates are thereafter described as the number of eggs with the associated confidence interval (White *et al*., 2023).

### 3.2.2 Comparison of national approaches

Commonalities and differences exist in the procedures to generate adult return and egg deposition estimates across the UK and the Republic of Ireland. All the procedures use rod catch, counter and trap data to derive adult return and egg deposition estimates for salmon rivers. However, there are differences in aspects of data collection and analysis, which are described in more detail below.

#### *3.2.2.1 Data collection*

All countries operate validated fish counters or traps on a proportion of rivers to monitor adult salmon returns. Northern Ireland has the most extensive counter network, covering 75% of salmon-assessed rivers, although there are comparably fewer of these rivers (16 assessed rivers: 6 counters but one covers 7 assessed rivers and spawning tributaries) than in the other countries. England and Wales, Scotland, and the Republic of Ireland have more fish counters or traps (15, 7, 32 respectively) but a larger number of assessed rivers (64, 173, 141, respectively), so the percentages of rivers with fish counters or traps are lower (23%, 5%, 23%, respectively).

Each country uses rod catch data to estimate adult returns in those salmon rivers without validated fish counters or traps. Rod catch data are reported by anglers (a requirement of the rod licencing system in England and Wales, for example) and some fishery owners.

A notable procedural difference is that biological monitoring data on the age, size, and sex of adult salmon are more routinely collected on a wider range of rivers outside England and Wales.

#### *3.2.2.2 Analysis*

Multiple analytical approaches are used on salmon rivers with and without fish counters or traps to generate adult return and egg deposition estimates. Most approaches are common among the countries but there are some differences.

All countries estimate spawning escapement by correcting the numbers of adult returns for in-river losses due to fishing (all retained fish + ~10% of released fish) and natural mortality prior to spawning.

The key differences in the analytical approaches among the countries are as follows.

- Scotland is the only country that estimates adult returns in salmon rivers without validated fish counters or traps by adjusting rod catches using a modelled correction factor based on month and river flow. All the other

countries correct rod catch for under-reporting using the approach based on Small (1991) and then raise the corrected rod catches by extant exploitation rates to derive adult return estimates in these salmon rivers
- The Republic of Ireland is the only country to raise rod catches by extant exploitation rate bands, as opposed to discrete value estimates, to estimate adult returns in salmon rivers without validated fish counters or traps
- Only in England and Wales is the relationship between the percentage of females and catchment area used as one of the methods to estimate the proportion of female 1SW fish. All the other countries, and E&W in other rivers, estimate this proportion using fixed or variable sex ratios obtained from historic or recent sampling data
- All countries estimate uncertainty in egg deposition using Monte Carlo methods, except Northern Ireland where minimum estimates of this parameter are used in the stock assessments. This means that Northern Ireland takes a more cautious view about egg deposition in their rivers than other countries, but how that affects fisheries management depends on the options for control and the decision making in each country

### 3.2.3 Conclusion

Our review of the approaches applied elsewhere in the UK and the Republic of Ireland suggests several aspects the Stock Assessment and Management Approach that might benefit from new data or methods. Some of those were relatively straightforward to examine, and therefore these investigations are reported in later sections of this report, as follows:

- Section 5.2 examines the raising factor used to correct rod catch for under-reporting devised by Small (1991) and considers whether and how this could be refined to more accurately represent current levels of undeclared catches in salmon rivers
- Section 5.3 describes a new statistical model developed to refine the rod exploitation rate model to better account for inter-annual variation in fishing effort, river flow, and catch-and-release fishing
- Section 5.8 describes the consideration of whether the relationship between the percentage of females and catchment area is still appropriate using more recent information and including an additional 11 rivers to estimate the proportion of female 1SW fish and testing the resultant change in egg deposition estimates
- Section 5.9 describes tests of whether the fecundity estimates for salmon based on Pope *et al*. (1961) remain appropriate when comparing them against more recent fecundity estimates from England and Wales and elsewhere and examining the resultant scale of change in egg deposition

This phase of the project was unable to fully explore other aspects, because they would require new data, methods, resources, or a combination of these challenges. These aspects are considered in Section 9 for future phases of this project.

## 3.3 Potential best practice in assessment and management approaches

### 3.3.1 Overview

Assessment and management approaches for Atlantic salmon stocks have been devised using similar principles, yet their means of application differ amongst North Atlantic Salmon Conservation Organisation (NASCO) jurisdictions. Accordingly, this part of the review process had two objectives: 1) to present a synopsis of the assessment and management approaches for Atlantic salmon stocks in NASCO jurisdictions, and 2) to summarise the advantages and disadvantages of the current approaches to identify potential best practice to improve the robustness of the stock assessments in England and Wales.

A synopsis of the assessment and management approaches for Atlantic salmon stocks in NASCO jurisdictions is presented below. Regional examples from neighbouring countries have been given particular emphasis, because their proximity means that Atlantic salmon stocks and fisheries in these countries are expected to exhibit similar characteristics, which provides an ideal opportunity to evaluate the advantages and disadvantages of the stock assessment and management approaches.

Many commonalities exist in the stock assessment and management approaches amongst NASCO jurisdictions. Approaches typically focus on compliance with CLs and Management Targets (MTs) to maintain spawning stock size at maximum sustainable yield ($S_{MSY}$) in accordance with the requirements of NASCO (NASCO, 1998). This is consistent with the application of a precautionary approach to salmon fishery management as adopted by NASCO. Stock status (CL compliance) is assessed annually based on estimated adult returns compared to CLs expressed in terms of eggs deposited and/or spawning escapement. For salmon-producing rivers without CLs, temporal trends in catches and/or pre-smolt abundance are used as indicators of stock status. Approaches are river- and region-specific, depending on data availability and stock status.

Catch data are the foundation of most stock assessments. Principally (in the context of this review) they provide the main data source for estimating of numbers of adult returns, spawners, and egg deposition on rivers without fish counters or traps. In contrast, several methods are deployed to enumerate adult returns by more direct

(largely fishery-independent) means. These include the use of validated fish counters/traps, dive/snorkel and redd surveys, and mark-recapture experiments.

Egg deposition is estimated from spawning escapement and the biological characteristics of the population (e.g., sex ratio, size, and fecundity data). The CLs are generally derived by transporting stock-recruitment (S-R) relationships from data-rich to data-poor rivers, for example, based on latitude and wetted area (Prévost *et al*., 2003). Over 80% of the jurisdictions have set CLs for their main salmon-producing rivers. In some jurisdictions, river-specific CLs remain under development (ICES, 2024). Progress in Iceland, for example, has been hindered by a lack of field-based measurements of wetted area (Bárðarson, H., *pers. comm*).

Estimates of annual egg deposition and/or spawning escapement are compared against CLs to calculate the compliance probability for each river stock. Requirements for compliance probabilities vary across jurisdictions, with stocks required to meet ×0.75 to ×1.50 of their CL over varying time periods to be deemed compliant (examples for jurisdictions neighbouring England and Wales are shown in Table 3.5, and a full summary for all 16 NASCO jurisdictions is provided in Annex 2). More than 80% of the jurisdictions enter compliance assessment results into a decision structure that assigns stocks into stock status categories and guides the relevant management response. For example, stocks in Scotland with an average probability of less than 0.6 of having met their CL over the last five years are deemed to be exploited unsustainably and therefore mandatory catch-and-release fishing is required for one year (stock status and appropriate regulatory provisions are reassessed annually). Iceland, where there is no formal requirement to estimate compliance with CLs specified in the Icelandic national fisheries legislation, is the only jurisdiction that uses temporal trends in annual catch numbers to guide management.

Many jurisdictions are transitioning from stock assessments based on catches to those incorporating fishery-independent indices of abundance (e.g. pre-smolt abundance, smolt output, and marine survival rates), particularly in instances of data paucity. Uncertainty in some of the catch-based assessments has increased due to reduced stock and catch levels and increasing use of catch-and-release fishing over the last three decades. For instance, rivers closed to fishing or without fish counters in the Republic of Ireland must exceed a minimum average fry abundance requirement of either 15 or 17 fry per five-minute electric fishing survey across the catchment to be considered for catch-and-release only fishing (TEGOS, 2019). Rivers at or near their CLs in the Canadian Maritimes Region must comply with a smolt production requirement of 3.8 smolts per 100 m² to be assigned into the healthiest stock status category. Temporal and spatial trends in indices of juvenile salmon abundance are likely to become increasingly important indicators of overall stock status if adult rod catches continue to decline in the future.

Aside from reviewing assessment methodologies, stock categorisation and associated decision structure actions, there are various issues that would merit

further consideration with regard to assessments in England and Wales. These include: 1) adjusting rod catches to account for the repeat capture of salmon arising from catch-and-release fishing, 2) incorporating other indicators of stock status (e.g. extrapolating from counts and juvenile survey data) in the assessment, and 3) considering the potential for developing a system that might allow annual review and implementation of regulatory measures. These were beyond the practical scope of this phase of this project but are considered briefly in section 9 as aspects to consider in future phases.

*Table 3.5. Examples of the advice basis and stock status categories for Atlantic salmon in the UK and the Republic of Ireland.*

| Jurisdiction | Advice basis | Stock status category |
|---|---|---|
| England and Wales | The probability that the river will comply with the Management Objective (MO) in five years' time. The MO requires that each river meets its CL for four out of five years (i.e. 80% of the time). Management measures reviewed annually but applied as needed | 1) A river with at least a 0.95 probability of meeting the MO five years into the future is classed as 'Not At Risk'. No further management action required<br>2) A river that has a 0.50–0.94 probability of meeting the MO five years into the future is classified as 'Probably Not At Risk'. If the trend in adult returns is not stable and positive, then management actions are required to reverse the decline in spawning escapement within five years<br>3) A river that has a 0.05–0.49 probability of meeting the MO five years into the future is categorised as 'Probably At Risk'. Management actions required to ensure sufficient spawning escapement to achieve more than a 0.5 probability of meeting the MO within five years, including voluntary catch-and-release fishing targets in excess of 90%<br>4) A river that has less than a 0.05 probability of meeting the MO five years into the future is regarded as 'At Risk'. Management actions are urgently required to reduce fisheries exploitation to zero, including mandatory catch-and-release fishing |
| Scotland | The average probability that each river or group of rivers meets its CL over a 5-year period. Management measures reviewed and applied annually | 1) More than a 0.80 average probability that the river or group of rivers has met its CL over the last five years. Sustainable exploitation. No further management actions required<br>2) A 0.60–0.80 average probability that the river or group of rivers has met its CL over the last five years. Management action required to reduce exploitation. Mandatory catch-and-release fishing not immediately required, but subject to annual review<br>3) Less than a 0.60 average probability that the river or group of rivers has met its CL over the last five years. Unsustainable exploitation. Management actions required to reduce exploitation for one year. Mandatory catch-and-release for all fishing methods |
| Republic of Ireland | The probability that the numbers of adult returns for the forthcoming fishing season in the river will meet its CL. Management measures reviewed and applied annually | 1) At least a 0.75 probability of meeting the CL in the following year. Rivers with a harvestable surplus above the CL are open for salmon fishing. The harvest must not exceed the surplus above the CL. Estuarine salmon fisheries are only permitted if all rivers in the embayment have at least a 0.75 average probability of meeting their conservation limits simultaneously<br>2) A 0.75 probability of meeting 50−100% of the CL in the following year, or the river must have an average of either 15 or 17 fry per 5-minute electric fishing survey on average across multiple sites in the catchment. River open for catch-and-release only salmon fishing |

| | | |
|---|---|---|
| | | 3) A 0.75 probability of meeting less than 50% of the CL in the following year, or insufficient data to estimate stock status. River is closed to salmon fishing until stock status improves or more information becomes available |
| Northern Ireland | Commercial fishing: The average escapement or spawning stock relative to the CL in 3 out of 5 of the previous years. Management measures reviewed and applied annually | Commercial fishing:<br>1) Escapement should be at least 125% of the CL in three out of five of the most recent years for which data are available. Rivers with an identifiable surplus over the CL are open to commercial salmon fishing. The commercial harvest must not exceed the surplus above the CL<br>2) Less than 125% of the CL in three out of five of the most recent years for which data are available. Rivers closed to commercial fishing until stock status improves or more data become available |
| | Recreational fishing: The average escapement or spawning stock relative to the CL in 3 out of 5 of the previous years. Management measures reviewed and applied annually. The compliance requirement is lower for recreational than commercial fishing to reflect the lower exploitation efficiency of recreational fishing compared to commercial fishing | Recreational fishing:<br>1) Escapement should be at least 115% of the CL in 3 out of 5 years of the most recent years for which data are available. Harvestable surplus available for recreational salmon fishing. The recreational salmon harvest must not exceed the surplus above the CL<br>2) Less than 115% of the CL in 3 out of 5 years of the most recent years for which data are available. Recreational salmon fishing restricted to mandatory catch-and-release until stock status improves or more data become available |

### 3.3.2 Advantages and disadvantages of stock assessment approaches

Summaries of the advantages and disadvantages of the assessment approaches for Atlantic salmon stocks in England and Wales, Scotland, Northern Ireland, the Republic of Ireland, and Canada, on the basis of stock protection, analytical complexity, and ease of interpretation are presented below. Stock assessment and management approaches applied in Canada have been included because the Department of Fisheries and Oceans (DFO) in Canada invited review group members to critically appraise the robustness of their approaches at the time of writing, thereby giving access to a greater level of detail about their approach than is available for other jurisdictions.

#### *3.3.2.1 England and Wales*

Atlantic salmon stocks are assessed annually against a Management Objective (MO) that requires them to meet their CL for four years out of five (i.e. 80% of the time). Bayesian regression analyses are applied to egg deposition estimates from the last 10 years on the assumption that there might be an underlying linear trend over the period. The method fits a Bayesian 20$^{th}$ percentile regression line to the time-series of annual egg deposition estimates, extrapolates the regression line beyond the current year to project the future performance of the stock relative to its CL, and then calculates the probability that the stock will comply with the MO in five years' time. Stocks are allocated into one of the following four categories based on the probability of meeting their MO: 'Not At Risk' (NAR), 'Probably Not At Risk' (PNAR), 'Probably At Risk' (PAR), or 'At Risk' (AR).

A Decision Structure (DS) guides management action based on these categories. Stocks in the NAR category require no further management action, stocks in the PNAR category might require actions to reverse declines in spawning escapement within five years, those situated in the PAR category require actions to ensure sufficient spawning escapement to achieve more than a 0.5 probability of meeting the MO within five years (i.e. restore them to 'probably not at risk'), and stocks in the AR category urgently require actions to reduce fisheries exploitation to zero.

The Salmon and Freshwater Fisheries Act (1975), the Salmon Act (1986), and the Marine & Coastal Access Act (2009) are the main regulatory frameworks for the management of Atlantic salmon, but several other provisions apply. Most net and fixed engine fisheries are regulated by net limitation orders and byelaws. National spring salmon byelaws (1999) prohibit commercial fisheries from exploiting salmon before 1 June and require mandatory catch-and-release in recreational rod fisheries prior to 16 June. A policy to phase out mixed-stock fisheries in coastal waters and a ban on the sale of rod-caught salmon together with a carcass tagging scheme for salmon retained in nets is in place. Salmon and Sea Trout Protection byelaws came into effect in England in 2019 for a 10-year period, which required the closure of many net fisheries (or the need to release any salmon caught where a fishery is

authorised to continue to operate for sea trout) and for requirements to achieve very high levels of catch-and-release fishing (>90%) in rod fisheries. The 'All Wales' and 'Cross-border (Wye and Dee)' fishery byelaws implemented from 1 January 2020 for a period of 10 years include the mandatory catch-and-release of salmon across Wales and restrictions on angling methods to help maximise the survival of released fish.

The main features of the assessment approach in England and Wales are:

- Stock status at the catchment scale is assessed based on estimated spawning escapement compared to river-specific CLs expressed in numbers of eggs deposited. Fishery-independent data are also collected as an indicator of stock status. For example, juvenile density estimates from electric fishing surveys are used to assess stock status at the sub-catchment scale and identify factors limiting salmon production to inform management
- River-specific CLs have been set for all 64 PSRs using smolt-to-adult return estimates along with Ricker stock and recruitment (S-R) relationships. The latter are derived from (i) river-specific estimates of juvenile production/smolt output modelled from GIS measurements of catchment characteristics and (ii) stock-recruit parameters transported from the River Bush in Northern Ireland
- Compliance with the MO is assessed using Bayesian regression analyses applied to the latest ten-year time-series of egg deposition estimates on the assumption that there might be an underlying linear trend over the period, which is extrapolated five years into the future
- A National Fisheries Classification Scheme (NFCS) is used to group juvenile salmon and trout density estimates from electric fishing surveys into one of six abundance categories (A–F). The scheme compares fry (age-0+ fish) and parr (age-1+) densities from each survey with national baseline densities from early 1990s surveys. NFCS grade A identifies a density that sits within the top 20% of sites nationally for the respective species and age class, while a NFCS grade E identifies a density that sits within the bottom 20% of sites nationally for the respective species and age class. NFCS grade F refers to a site where the species/age class is absent. Sites are classed as 'at or above average' (A–C), 'below average' (D) or 'well below average or fishless' (E–F). The proportion of sites in each class is used to provide an indication of juvenile recruitment.

#### *3.3.2.1.1 Advantages of this approach*

- Provides a system that assesses stock status annually to inform management action based on a pre-agreed Decision Structure, as per NASCO Guidelines
- Projecting compliance with CLs five years forward provides an indicator of possible future stock status and serves as the basis for early management intervention, as per NASCO Guidelines

- Regulations have typically been applied on a multi-annual basis, usually operating for five to ten years, although with intermediate reviews where these are considered appropriate. This regulatory process has been designed to ensure some stability and continuity in the fisheries, while at the same time allowing new management objectives (e.g. restoring the stock above its CL) to be applied over an appropriate time frame
- The assessment methodology complies with international best practice and remains fit for purpose

#### *3.3.2.1.2 Disadvantages of this approach*

- Stock status is assessed annually but does not elicit an annual management response. Several other jurisdictions are moving to a system of annual regulation linked to the latest annual assessment. However, this is likely to carry additional costs
- The assessment methodology and resulting outputs often involve complex processes which are difficult to explain to stakeholders
- Bayesian 20$^{th}$ percentile regression is used to assess stock status based on the probability that the salmon river will meet its MO five years into the future. This categorisation based on projections can suffer from uncertainties associated with projecting estimates of compliance with CLs into the future
- Assessing stock status using Bayesian statistics requires high-level expertise
- Taken together, the compliance assessment and stock status categorisation approach may be less definitive for stakeholders than equivalent frameworks in other jurisdictions. The use of four probability bounds in the compliance assessment, combined with stock status categories that rely on ambiguous terminology (e.g. 'Probably Not At Risk' and 'Probably At Risk'), and management actions characterised by numerous conditional ('if') statements, can reduce clarity in decision-making
- The risk categories applied to the salmon stocks do not adequately convey the level of threat to population viability due to the categorisation process accounting for statistical uncertainty

### *3.3.2.2 Scotland*

Atlantic salmon are assessed and managed on an annual basis by assigning each salmon river or group of assessable rivers into one of three stock status categories, each with its own recommended management actions. There are 173 assessable rivers or groups of rivers in Scotland for which CLs have been set. The Conservation of Salmon (Scotland) Regulations 2020 provides the main regulatory framework for the management of Atlantic salmon. This prohibits the retention of catches in coastal waters, permits the take of salmon in inland waters for stocks with category 1 status (considered sustainable), indicates that management action is needed to reduce

exploitation in category 2 rivers (some take still permitted), but requires mandatory catch-and-release in areas where stocks have category 3 status.

#### *3.3.2.2.1 Advantages compared with the approach in England and Wales*

- Provides a system that assesses stock status and updates regulatory provisions annually. Once the Scottish scientists complete the stock assessment for the upcoming fishing season, officials finalise the stock status categories and seek formal regulatory approval. This annual implementation cycle thus maintains close links between the stock assessment and management response
- Provides transparency in the assessment and management result. Scottish Government update official statistics and stock status information online
- The assessment methodology is probably more understandable for stakeholders. The stock status of salmon stocks is based on the average probability that the salmon river or group of assessable rivers has met its CL over the last five years. This categorisation based on retrospective data is less likely to suffer from the uncertainties associated with methods that project estimates of compliance with CLs into the future
- Uncertainties in estimates of egg deposition, the egg deposition requirement, and wetted area are incorporated when calculating compliance estimates and categorising the stock status of each salmon river or group of assessable rivers. This allows the level of confidence in the estimates to be given greater consideration when making management decisions

#### *3.3.2.2.2 Disadvantages compared with the approach in England and Wales*

- The annual assessment / management response cycle imposes very tight time limits for completing the assessment, consulting, and implementing legal measures prior to the start of the fishing season
- Given the time pressures, catch statistics are not available for the most recent year. The assessment thus runs with a one-year lag (e.g. the measures for the 2021 season were based on the five years 2015 to 2019)

### *3.3.2.3 Northern Ireland*

Atlantic salmon are assessed and managed on an annual basis by categorising each river stock into one of two stock status categories, each with its own recommended management actions. There are 17 rivers in Northern Ireland for which CLs have been defined. Category 1 rivers with an identifiable surplus above the CL are open to salmon fishing of that surplus, and category 2 rivers are closed to commercial fishing and restricted to mandatory catch-and-release for recreational fishing until stock status improves or more data become available. The Fisheries Act (Northern Ireland) 1966 is the main regulatory framework for the management of Atlantic salmon.

Accompanying legislation includes the Fisheries Regulations (Northern Ireland) 2014, which prohibit commercial fishing and require mandatory catch-and-release in recreational fisheries without an identifiable surplus above the CL.

#### *3.3.2.3.1 Advantages compared with the approach in England and Wales*

- The annual implementation cycle maintains close links between the stock assessment and management response
- Regulatory provisions are based on the probability that each river stock has met its CL for three out of five of the most recent years. Rivers without an identifiable surplus above the CL are closed to commercial fishing and restricted to mandatory catch-and-release only fishing
- Salmon stocks must meet or exceed their CLs by differing amounts to be considered for opening for commercial or recreational fishing. The required amount is higher for commercial (≥ 125%) than recreational (≥ 115%) fishing
- Numbers of adult returns are estimated from fish counter data for the Rivers Bush and Bann, along with a scaling factor used to raise the counts to all the other rivers in Northern Ireland based on certain explanatory variables, including a fine scale mapping of salmon-producing habitats that took about 15 years to develop. Salmon populations in the Rivers Bush and Bann represent important indicator stocks that have been monitored since the early-1970s
- Optimal productivity metrics from a stock-recruit analysis for the River Bush are transported to measured habitat parameters for each recipient river to estimate the egg deposition required to achieve MSY
- An index of fry abundance is used as an indicator of stock status to help guide decisions on the need for management measures

#### *3.3.2.3.2 Disadvantages compared with the approach in England and Wales*

- The annual assessment / management response cycle imposes very tight time limits for completing the assessment, consulting, and implementing legal measures prior to the start of fishing seasons
- Uncertainty in the assessment outputs has increased due to the very low number of retained salmon in catches resulting from declines in stock status, the closure of salmon fisheries, and the implementation of mandatory catch-and-release only fishing. As a result, fish counter data are now considered more informative about the number of adult returns than catches, even though these are only available for two rivers
- Collecting an annual index of fry abundance for all the primary salmon rivers as an indicator of stock status is a time consuming and labour-intensive activity
- Applying the Bayesian hierarchical stock and recruitment analyses to assess stock status requires high-level expertise

#### *3.3.2.4 Republic of Ireland*

The assessment and management of Atlantic salmon is based on the classification of each river stock into one of three stock status categories, each with its own recommended management actions. There are 143 rivers in the Republic of Ireland for which CLs have been defined. Category 1 rivers with a harvestable surplus above the CL are open for exploitation of that surplus, category 2 rivers are open for catch-and-release only fishing, and category 3 rivers are closed to all salmon fishing until stock status improves or more information becomes available. The Wild Salmon and Sea Trout Tagging Scheme Regulations are the main framework for the management of Atlantic salmon. They stipulate catchment-specific annual harvest restrictions in rivers exceeding their CL. Accompanying legislation includes the Conservation of Salmon & Sea Trout Byelaws, which specify the rivers closed to salmon fishing or restricted to catch-and-release only fishing with further limits on permissible gears.

##### *3.3.2.4.1 Advantages compared with the approach in England and Wales*

- Provides a system that assesses stock status and reviews management measures annually. Once the Technical Expert Group on Salmon has completed the stock assessment, officials finalise the stock status categories and seek regulatory approval. This annual implementation cycle thus maintains close links between the stock assessment and management response
- The assessment methodology is probably more understandable for stakeholders. Decisions are based on the probability that a river will meet its CL in the following year, based on an average of the last five years
- Uncertainties in estimates of adult returns, fecundity, egg deposition, the egg deposition requirement, and the ratio of 1SW:MSW salmon are considered in the calculation of compliance estimates and stock status categorisations
- An alternative index has been developed as an indicator of stock status where rivers are closed to all fishing. Rivers closed to salmon fishing and without an adult fish counter must exceed a minimum average fry abundance requirement of either 15 or 17 fry per five-minute catchment-wide electric fishing survey to be opened for catch-and-release only fishing

##### *3.3.2.4.2 Disadvantages compared with the approach in England and Wales*

- Given time pressures, catch statistics for the most recent year are very provisional
- For fisheries that are closed to all fishing, alternative measures are required on which to assess the stock status of rivers and make decisions about possible reopening of the fishery

- For rivers without fish counters, the time consuming and labour-intensive activity of deriving an annual index of age-0+ juvenile salmon abundance from catchment-wide electric fishing surveys as an indicator of stock status
- High-level expertise is required to run the Bayesian hierarchical stock and recruitment analyses used for the stock assessment

#### *3.3.2.5 Canada*

Atlantic salmon are assessed and managed on an annual basis by classifying each salmon population into one of three stock status zones, each with its own recommended management actions. Salmon populations classified in the 'healthy' zone are available for exploitation, those situated in the 'cautious' zone require management measures to reduce exploitation and increase stock size, and populations in the 'critical' zone require actions to promote stock growth and reduce fisheries-related mortality to the lowest level possible. The Wild Atlantic Salmon Conservation Policy (Fisheries and Oceans Canada, 2009) is the keystone of the management of Atlantic salmon. Commercial fisheries for Atlantic salmon are prohibited. Only indigenous, recreational, and resident subsistence fisheries are permitted.

The healthy zone is defined as being above an upper reference point (URP) (Management Target), the critical zone is below the lower reference point (LRP), and the cautious zone is between the two reference points.

##### *3.3.2.5.1 Advantages over the approach in England and Wales*

- Provides a system that assesses stock status and reviews management measures annually. This annual implementation cycle thus maintains close links between the stock assessment and management response
- Annual egg deposition estimates are compared to a lower limit reference point and an upper stock reference point
- The assessment methodology is probably more understandable for stakeholders. Stock status is based on the percentage of the CL that a salmon population has met in a given year. A salmon population is classified as 'healthy' when annual egg deposition estimates exceed 150% of the CL, 'cautious' when they are between 100% and 150% of the CL, or 'critical' when they are below 100% of the CL. This categorisation based on retrospective data avoids potential uncertainties which can arise when using methods that project estimates of compliance with CLs into the future. Furthermore, the labels used for the stock status categories are more descriptive and easier to interpret than numbers

#### *3.3.2.5.2 Disadvantages compared to the approach in England and Wales*

- The annual assessment / management response cycle imposes very tight time limits for completing the assessment, consulting, and implementing measures prior to the beginning of the fishing seasons
- There are cost implications for the Government to implement annual changes in management measures
- Collecting indices of abundance as additional indicators of stock status is a time consuming and labour-intensive activity
- Assessing stock status using a Bayesian hierarchical modelling framework requires high-level expertise.

# 4 Refinements to Biological Reference Points for salmon stocks

## 4.1 Stream wetted area: are our original estimates accurate?

Wetted area estimates used to derive Conservation Limits (CLs) undertaken in the late 1990's - early 2000's were originally based on the methodology of Wyatt and Barnard (1997b). Expert opinion at the time considered that the streams identified at the 1:250 000 (hereafter 1:250K) map scale appropriately encompassed the relevant salmon spawning and nursery areas for each catchment. GIS drainage network maps at this scale (with associated reach measurements) were obtained for each Principal Salmon River (PSR) in England and Wales. These were provided to technical specialists within each fisheries management area to refine by identifying any inaccessible reaches to be excluded and accessible reaches not visible on the maps to be included (there were very few of the latter). In addition, models were developed to derive expected densities of juvenile salmon (fry and parr) under 'pristine' conditions (i.e. at carrying capacity) based on the reach characteristics of 'median altitude' and 'stream order' (at 1:250K scale) as model predictors. These models (utilising fish density data collected as part of the HABSCORE dataset) did not include stream orders greater than stream order 4 and streams at altitudes higher than 400 m on the basis that there were too few sites containing salmon with these attributes.

The inclusion of stream order as a predictor of juvenile salmon abundance presents a fundamental and significant problem in this comparison of accessible wetted area at different scales because stream order changes with changing map scales. A first order stream at the 1:250K scale is likely to be identified as a second, third or higher order stream at a higher resolution map scale and that change in stream order is not a simple linear transition. Our previous modelling of stream order (at a given map scale) as a predictor of juvenile production therefore places a significant limitation on our ability to re-assess CLs using higher or lower resolution map scales.

The GIS used by Wyatt & Barnard (1997b) had reach length but not width – both are required to estimate wetted area. Wyatt & Barnard (1997a) used width measurements from 677 HABSCORE sites to model the relationship between wetted widths, altitude, and stream order. In most cases, Area staff also submitted river-specific width measurements to help estimate wetted areas.

Compared to the finer resolution mapping, the original 1:250K GIS may have omitted some of the smaller tributaries in catchments potentially accessible to salmon although local staff were originally asked to identify and include any such instances.

In addition, the 1:250K resolution will have estimated the stream length differently, even of stream reaches that were visible at this scale (see Table 4.1, below). Further, since the original estimates were made, any additional river reaches made accessible to salmon due to barrier removal have, for the most part, not been incorporated into CL estimates. However, CL estimates on some river catchments (e.g., Wye) have been revised to account for barrier removal.

These aspects are examined below utilising higher resolution mapping systems and GIS techniques to re-visit estimates of accessible river length and wetted area and examine the potential consequences for CL setting. However, an important difficulty was encountered in this exercise, in that the original 1:250K stream length measurements were not recorded for individual streams in a manner that allowed those to be reproduced accurately here at either the same map scale or at the higher resolution map scales.

An exercise was undertaken on three Welsh rivers (Tawe, Clwyd and Conwy) utilising reach length measurements obtained using OS Master Map (OSMM) as part of modelling work carried out by Bewes *et al*. (2020)**.** The new length measurements were compared on a like-for-like basis with the equivalent measurements obtained in the 1990s using a 1:250K GIS for the purpose of deriving CLs (Wyatt and Barnard, 1997a; Table 65).

*Table 4.1. Comparison of reach length measurements obtained on the Tawe, Clwyd and Conwy using 1:250K and 1:50K (OSMM) mapping systems applied to identical drainage networks.*

| **Catchment** | **Estimate of stream length (original 1:250K scale), km** | **Estimate of stream length, OS MasterMap Water Network, (1:50k scale), km** | **% increase or decrease of wetted stream length at 1:50k on original** |
|---|---|---|---|
| Tawe | 111.9 | 98.2 | -12.24 |
| Clwyd | 326.7 | 361.2 | +10.56 |
| Conwy | 305.0 | 321.7 | +5.48 |

Proportional differences in stream length were evident for the Welsh rivers when applying these OSMM measurements to derive approximate wetted area and egg deposition estimates, i.e. within, on average, +/-10% of current (1:250K) map-based estimates (again, comparisons were made on a like-for-like basis – covering identical drainage networks at the two map scales) (Table 4.2). It should be noted that in the

Welsh example, wetted area estimates incorporated modelled widths based on generic defaults or actual wetted width measurements taken during surveys, not bank full widths. The same set of wetted width estimates were used to calculate wetted areas for both the 1:250K and OSMM scenarios.

*Table 4.2. Comparison of reach area measurements on the Tawe, Clwyd and Conwy using 1:250K and 1:50K (OSMM) mapping systems applied to identical drainage networks and wetted width estimates.*

| **Catchment** | **Estimate of stream area (original 1:250K scale), $m^2$** | **Estimate of stream area, OS MasterMap Water Network, (1:50k scale), $m^2$** | **% increase or decrease of wetted stream area at 1:50k on original** |
|---|---|---|---|
| Tawe | 878 493 | 842 266 | -4.12 |
| Clwyd | 839 231 | 993 584 | +18.39 |
| Conwy | 630 181 | 667 439 | +5.91 |

The EA used the latest OSMM Water Network to calculate altitude, stream order, wetted stream length and area - mapped at the 1:50K (and, for comparison, highest resolution – 1:10K) for selected English PSRs. The GIS team were provided with the National Grid References for the known upstream limits for salmon access identified by Area fisheries specialists in selected catchments. The river network was re-analysed to generate stream lengths at the more detailed 1:50K scale – this being the scale of the commonly used OS Landranger map. The resulting GIS maps were then reviewed by the fisheries specialists via ArcGIS Online (AGOL) so that stream reaches that are accessible and used by salmon (including sections newly accessible due to barrier removal), could be confirmed, and also that streams visible at 1:50K that are unsuitable for salmon spawning could be excluded from the revised wetted length estimates.

The outputs from these exercises generated the estimates of accessible stream length shown below in Table 4.3. These suggest significant differences between the original 1:250K measurements and those using the 1:50K OSMM, with the new estimates being lower than the originals. The notable exception is the Frome, where significant additional stream sections have recently been found to be used by salmon which were not included in the original estimates made in the late 1990’s. In other catchments examined, increases in accessible length due to barrier removal were relatively slight, for example in the case of the Tamar.

Generally, however, EA Area specialists considered that relatively few of the smallest tributaries visible at the 1:50K scale were used by salmon as they may have regularly completely dried out or had no record of either spawning or juveniles in living memory and the majority of these were excluded from the new calculations.

*Table 4.3. Comparisons of original estimated total stream length accessible to salmon with revised estimates using OS MasterMap Water Network, selected rivers.*

| **Catchment** | **Original estimate of accessible stream length (1:250K scale) (1997-98), km** | **Estimate of accessible stream length, OS MasterMap Water Network, (1:50K scale), km** | **% increase or decrease of accessible wetted stream length at 1:50K on original** |
|---|---|---|---|
| Lune | 346.586 | 302.351 | -12.8 |
| Tyne | 460.571 | 377.531 | -18.02 |
| Coquet | 176.303 | 138.387 | - 21.5 |
| Frome | 75.500 | 124.947 | +65.5 |
| Tamar | 350.676 | 354.403 | +1.1 |

Estimating stream wetted areas using the modern GIS approach presents further challenges. To estimate wetted areas, width measurements are required. The approach recommended by EA GIS specialists for estimating wetted area using the OSMM Water Network Layer uses bank-full wetted width, not the widths measured during fishery surveys which were used in the original calculations at 1:250K scale. Our comparison of stream measurements between the two different scales therefore has to be limited to the estimates of accessible length only, as presented in Table 4.3.

In addition, when moving from the original 1:250K scale to higher resolution mapping and measurements, there may be some differences in the relative proportions of total accessible stream wetted lengths in the respective stream order/altitude categories, illustrated for the Lune in Figure 4.1, and the impact of this upon calculation of egg deposition targets needs further consideration.

Tables 4.2 and 4.3, we consider that any changes in estimated wetted length resulting from the use of higher resolution maps are unlikely to provide, on their own, a sound basis for revising CLs.

More importantly, however, it is evident that there is a requirement to re-examine relationships between salmon fry and parr abundances and measured survey-site habitat variables, excluding stream order which fundamentally differs at differing map scales, (Wyatt and Barnard, 1997a). Consideration should be given to re-working of models using the HABSCORE dataset, preferably replacing stream order with finite measures of stream size such as altitude and width.

The original detail of individual streams and their accessible limits have only been available in basic sketch map form (non-digital), making it impossible to allow a direct comparison of stream length calculations using the original 1:250K resolution and the 1:50K resolution used here.

It should also be noted that changes in accessible wetted area will need to be made when barriers are removed that allow access for salmon to previously inaccessible but otherwise suitable spawning areas. We consider that a greater source of inaccuracy in estimation of salmon-accessible wetted area in rivers relates to the quality of information on the true upstream limits for salmon access.

*Figure 4.1a*

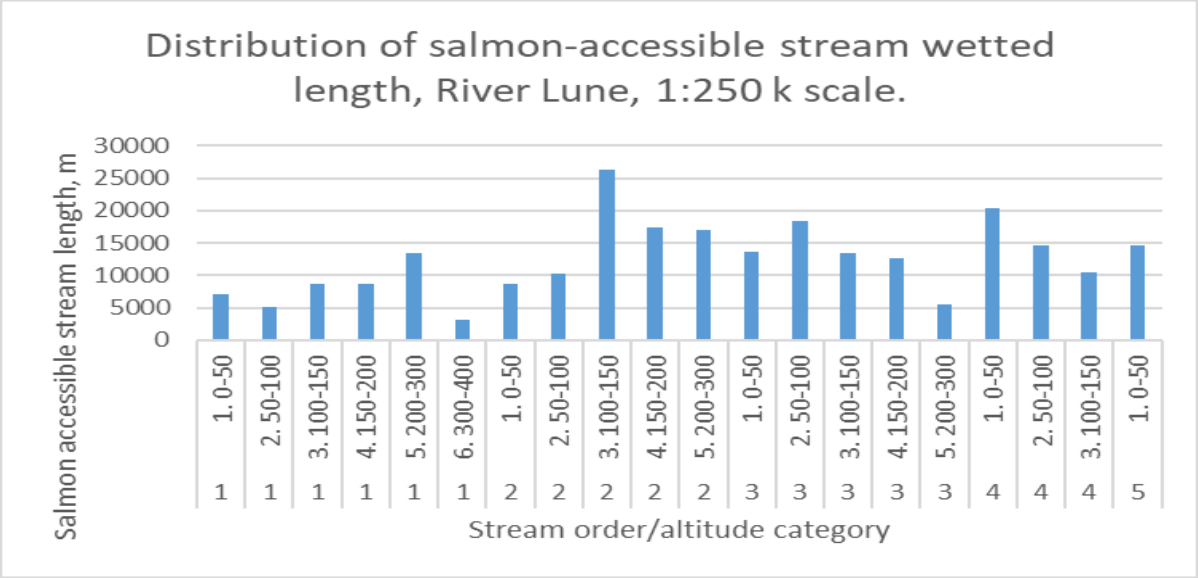



*Figure 4.1b*

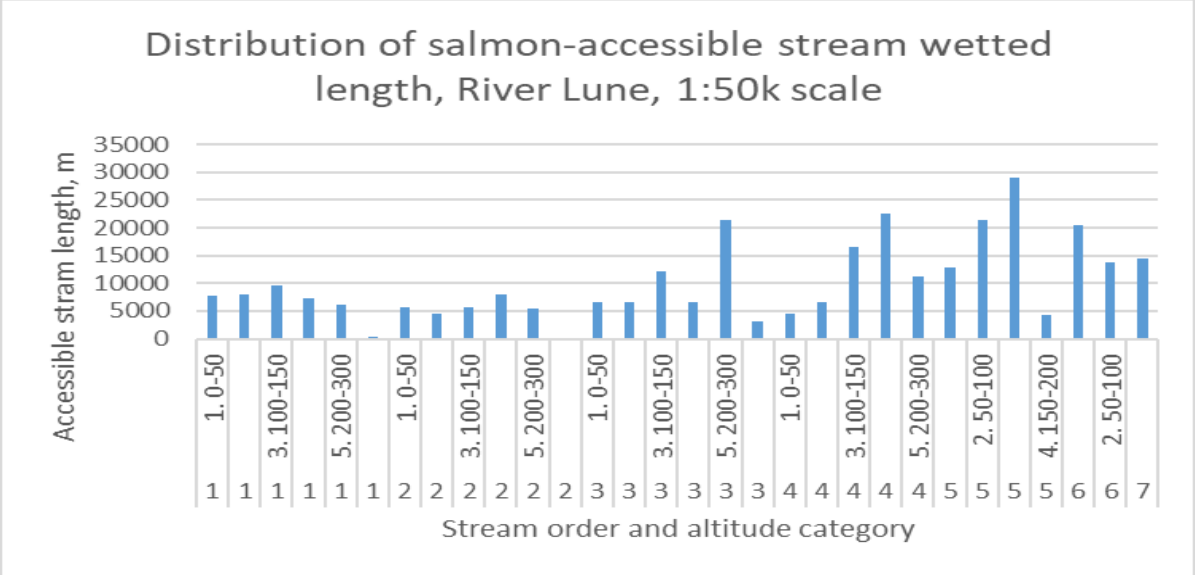



*Figure 4.1. Comparison of wetted lengths in stream order/altitude categories between (a) original estimates at 1:250K scale and (b) OS MasterMap 1:50K scale, for the River Lune.*

At the time of estimating the original accessible wetted areas and associated juvenile production levels, a relatively simplistic method was used to estimate the production levels within online lakes (primarily in Cumbrian catchments). Juvenile salmon production levels in lakes are markedly lower than in rivers and largely focussed on the shallow littoral zones. Specific measurements of relevant littoral areas and

associated likely juvenile production levels were not available at the time, so the equivalent levels of riverine production were substituted for the equivalent length of lake. For example, for a 4 km long lake, the juvenile production was estimated to be the equivalent of a 4 km length of river. Improved data and methods since the original CL setting could be incorporated into any future revision of CLs to better reflect potential levels of juvenile production in lakes, as has been incorporated into methods used by Republic of Ireland and Scotland in recent years.

Reflecting these areas of future investigation:

**Proposal 1**

*For all Principal Salmon Rivers, confirm the full extent of salmon access in each catchment, taking account of newly accessible areas arising from removal of barriers or improvements in water quality, using a nationally agreed, consistent, auditable and reproducible approach.*

**Proposal 2**

*Consider the inclusion of on-line lakes in our estimates of juvenile salmon carrying capacity.*

## 4.2 Fry and parr densities under "pristine" conditions in England and Wales

Estimates of juvenile (age 0+ & >0+) salmon production for categorised river reaches were based on average densities over 398 accessible electric fishing sites across E&W rivers in the early 1990's (Wyatt and Barnard, 1997a). These sites were assumed to represent pristine conditions with no overt impacts of water quality or recruitment at that time.

Juvenile survey data will be available for all PSRs in the intervening 25 years, albeit intermittently for most rivers. It is proposed that time series of fry and parr densities are examined for the more frequently monitored survey sites across all PSRs to determine if those 1990's densities were likely to represent truly maximum or pristine levels of juvenile production. For example, the time series of fry and parr densities from regularly monitored sites on the River Lune are presented in Figure 4.2 below. Some higher fry densities are evident in 2005, 2007 and 2009, and some higher parr densities are evident in 2003, 2005, 2007 and 2010. This suggests that levels of juvenile production may have been higher on this catchment since the original setting of CLs in the 1990's.

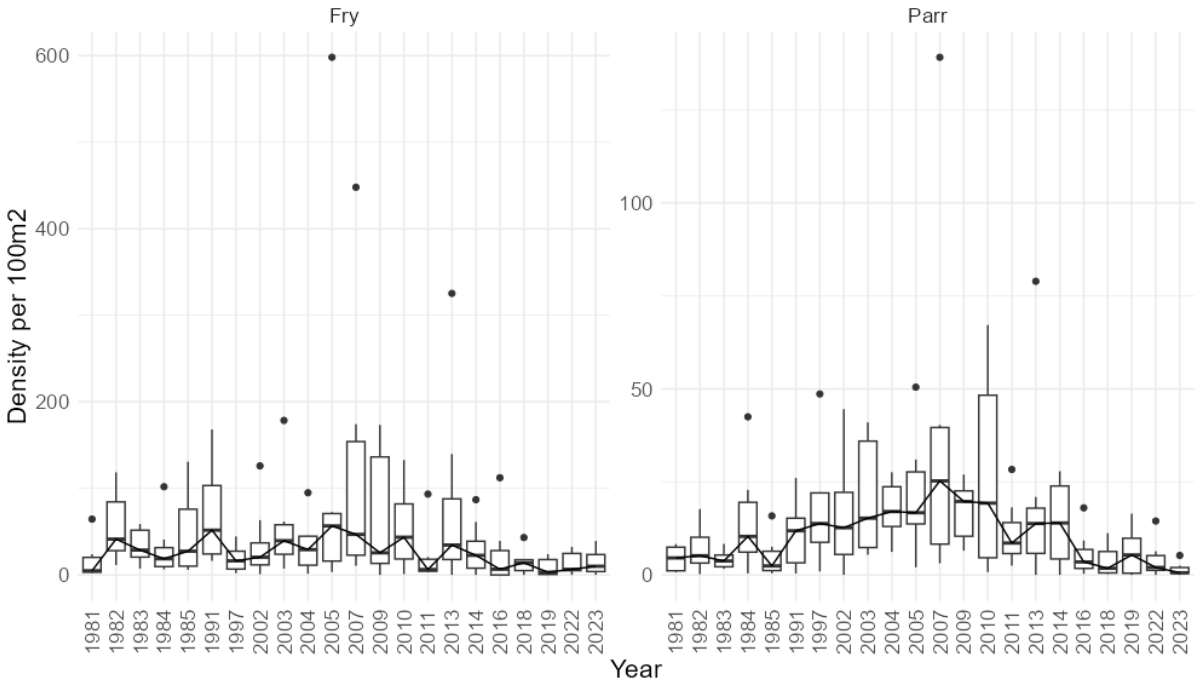



*Figure 4.2. Boxplots of salmon fry and parr densities from consistently monitored sites on the River Lune catchment between 1981 and 2023. Boxes delimit the 25%–75% interquartile range (IQR), the horizontal bar represents the median, whiskers delimit the 1.5 x IQR range, and the black dots represent extreme values.*

**Proposal 3**

*Examine time series of fry and parr densities in the more frequently monitored survey sites across all Principal Salmon Rivers to determine if those 1990's densities were likely to represent truly maximum or pristine levels of juvenile production.*

**Proposal 4**

*Evaluate juvenile survey data for Principal Salmon Rivers contained in the National Fish Population Database to understand and scrutinise levels of abundance over the last 20+ years with respect to potential carrying capacities.*

## 4.3 Changes in in-river survival rates for salmon fry and parr

The transportation model described in Wyatt and Barnard (1997a) includes default values for density-independent survival from egg-to-parr and for proportions of fish

smolting at ages 1 and older, respectively, derived by combining data from the Bush and from England and Wales habitat models.

Survival of salmon fry and parr will vary greatly from year to year due to environmental factors, such as fluctuations in water temperature and river flow, and perhaps others such as predation or competition from other species. However, it is possible that we may see substantial reductions in survival rates due to climate change acting on both water temperature and river flow, as suggested in Solomon and Lightfoot (2009), Clews *et al*. (2010) and Bernthal *et al*. (2022). Similarly, proportions of fish smolting at age 1 have increased compared to older age classes due to a warming climate (Kennedy and Crozier, 2010; Jonsson and Jonsson, 2009; Hedger *et al*., 2013).

Lower levels of in-river survival would mean that more eggs would have to be deposited to ensure the same numbers of smolts leave the river. The impacts of earlier smolting patterns are harder to predict, since if smolting occurs earlier and survival rates remained similar, then more smolts would leave the river from a given number of eggs. However, if younger smolts were smaller fish then their marine survival would be expected to be lower (Jutila *et al*., 2006; Gregory *et al*., 2019; Simmons *et al*., 2022).

Enquiries with Scottish and Irish jurisdictions have revealed that no changes to their CLs have been made in relation to perceived changes in either in-river juvenile survival or smolting rates.

**Proposal 5**

*Investigate whether there have been substantial changes in in-river survival of salmon fry and parr and in smoltification rates and assess whether these could have implications for estimation of biological reference points.*

## 4.4 Changing marine survival rates for salmon

Conservation Limits demarcate the undesirable spawning stock level, below which recruitment would begin to decline significantly – previously referred to as the Minimum Biologically Acceptable Level of the stock.

The current method to derive CLs combines freshwater and marine stages in a relatively simplistic manner to be able to define the stock size that produces the Maximum Sustainable Yield (MSY) of salmon for the fisheries that exploit them. The Replacement Line is based on prevailing marine survival rates at the time of CL setting, and reducing these survival rates produces lower CLs. Such a revision was made in 2003, when the assumed rates were reduced from 25% and 15%, for 1SW

and MSW fish respectively, to 11% and 5%. These are considered still high in view of recent studies suggesting that marine survival rates have reduced further due to changes in the marine environment (Chaput, 2012; ICES, 2024). However, reducing the default values for marine survival used in CL setting would further reduce CLs, which is counter-intuitive to the management imperative to protect and recover stocks that are experiencing higher rates of mortality. If fisheries management continued to focus on such lower CLs, this would theoretically allow continued exploitation of stocks to even lower levels than previously permitted and thus place the population at greater risk of collapse - see Figure 4.3 below. In the face of higher rates of marine mortality, and under a non-stable (dynamic) situation as we experience now, a stock needs to produce more, not less, juveniles to counteract that higher mortality (Atlantic Salmon Trust, 2017).

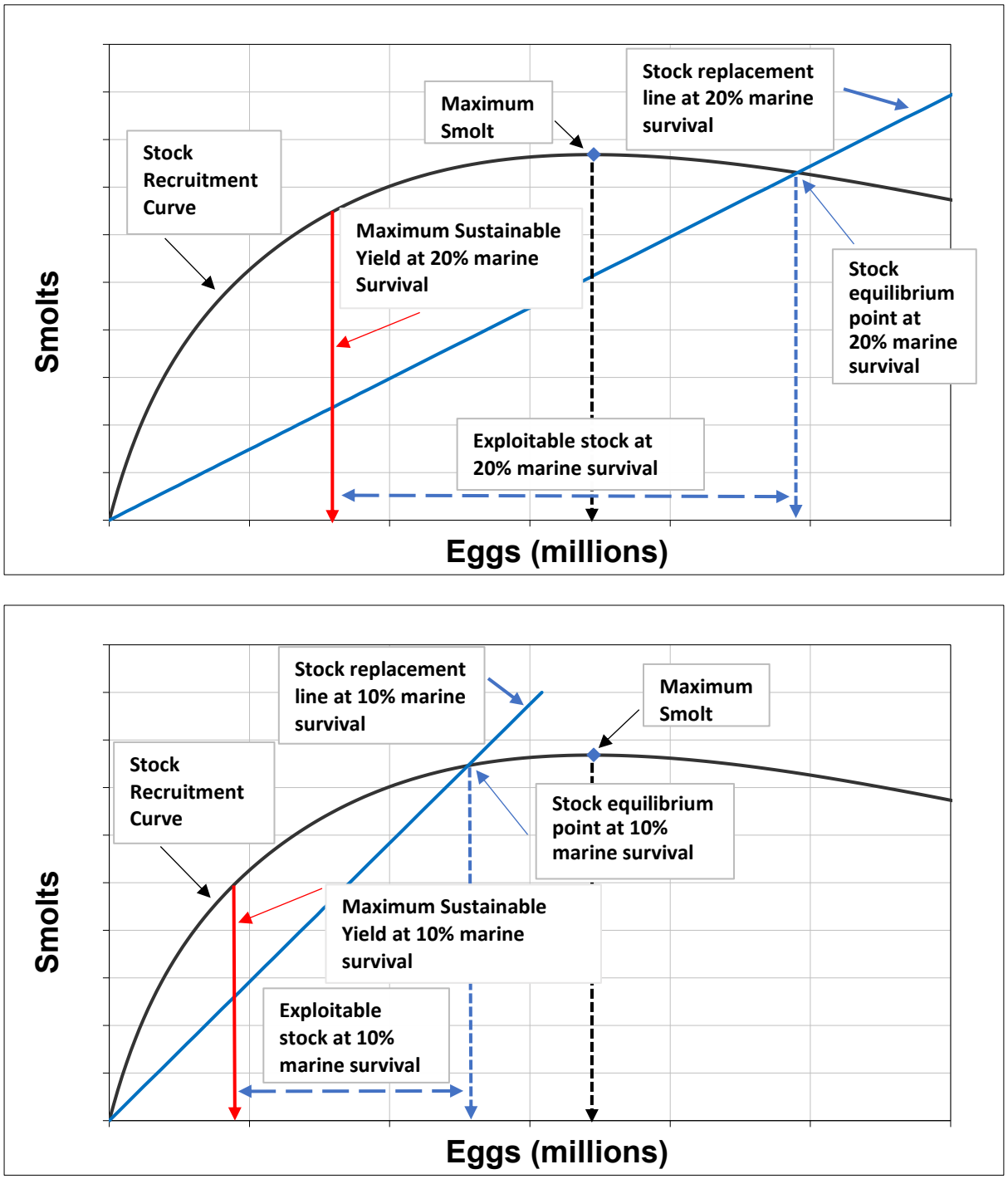



*Figure 4.3. Illustration of potential impacts of lower marine survival rates on CL setting. Reducing estimated marine survival rates from 20% to 10% results in a steeper replacement line, which has the effect of moving the CL point towards the origin, resulting in potential exploitation down to lower stock levels than when marine survival is 20%. It is also noteworthy that the exploitable stock itself reduces.*

In terms of maintaining stock size, increased juvenile production in freshwater would be required to offset the observed increase in marine mortality. The interpretation of stock productivity is sensitive to assumptions about mortality rates. If mortality is lower than assumed, this could support a lower CL. However, from a precautionary perspective, we consider it appropriate to avoid lowering CLs at a time when stocks remain depleted and marine survival is at a record low. Lowering CLs could undermine incentives to address ongoing constraints in freshwater, delay necessary management measures, and run counter to long-term aims to base biological reference points on freshwater production.

Where stocks are failing to achieve their CLs and management measures have been focussed on reducing or eliminating the harvest of salmon by the fisheries, it could reasonably be argued that the upper reference point – the Management Target (MT) - should no longer be derived from the CL but should focus on appropriate levels of freshwater productivity instead. Given the imperative to maximise smolt production, the Maximum Smolt point on the stock-recruitment curve offers such a reference point.

## 4.5 Considering Maximum Smolt as an Upper Reference Point

### 4.5.1 Introduction

Developing biological reference points based on maximising smolt output from rivers has been recommended (Thorstad *et al*., 2021; Gillson *et al*., 2022). Consequently, this study considers the utility of using the egg deposition required to maximise smolt output as an alternative or additional biological reference point to the application of CLs and associated MTs currently used to assess the status of Atlantic salmon stocks in England and Wales. These biological reference points are obtained from combining (i) a modelled adult/egg-to-smolt (Ricker) stock-recruitment curve with (ii) a Replacement line to convert smolts back to returning adults/eggs on a river-by-river basis. In this context, egg deposition is analogous to spawning stock biomass (SSB), while smolt output represents recruitment. The stock-recruitment relationship therefore describes the production of smolts from a given spawning stock, while the replacement line represents the relationship between smolt output and returning adults. This process is summarised in Figure 4.4 and described below:

1) Conservation Limit (CL), which is set at the point of MSY
2) Management Target (MT), which is set above the CL on the ascending limb of the curve. This indicates the average spawning stock level required to achieve the Management Objective (MO) of meeting or exceeding the CL in four out of five years

3) Maximum Smolt (MS), which is set at the asymptote of the stock-recruitment curve. This reference point is the most protective of freshwater production because it seeks to maximise smolt output from a catchment
4) Replacement Point (RP), which is set at the point where the Replacement Line crosses the stock-recruitment curve. This indicates the equilibrium point, where the population would settle based on the expected survival from smolt to returning adult (i.e., marine survival)

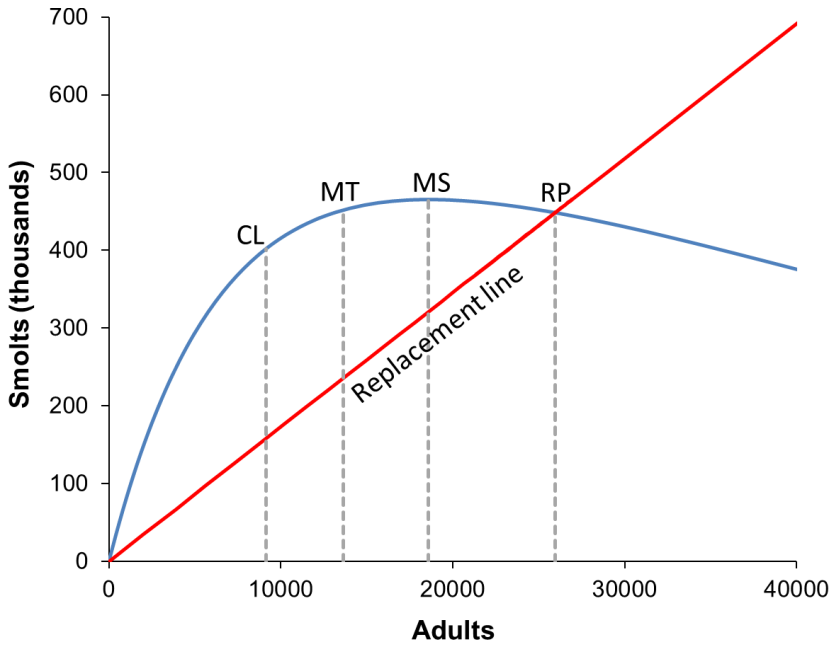



*Figure 4.4. Egg deposition target options derived from the stock-recruitment curve and Replacement line for the River Wye in Wales. CL = Conservation Limit, MT = Management Target, MS = Maximum Smolt, and RP = Replacement Point.*

Stock-recruitment relationships are usually described as being dome-shaped or asymptotic. As such (for the life-stages represented by the curve in Figure 4.4), they allow the point of MS to be defined by the maximum height of the stock-recruitment curve, where the curve asymptote represents the maximum number of smolts a river can support in optimum conditions (i.e. its smolt carrying capacity). The MS can be used to derive an egg deposition target to evaluate the performance of Atlantic salmon stocks and guide protective management measures where required.

It is important to note that the MS point does not represent the maximum adult return; more adults can return to the river but density-dependent processes will mean that they make no additional contribution to future smolt production (see adults to the right-hand side of the RP point in Figure 4.4). The number of returning adults

in excess of that required to achieve MS can be considered as a surplus relative to the reproductive capacity of the catchment.

This surplus can be interpreted differently depending on the management objective depending on whether management is based on maintaining stock levels (i.e., an escapement-based approach) or on maximising fishing opportunities (i.e., an F-based or harvest-based approach). This distinction is fundamental to how biological reference points are interpreted and applied.

Under an escapement-based approach, the surplus spawning stock above MS represents fish available for harvest once spawning requirements are met.

In this study, we adopt a precautionary, escapement-based perspective, placing emphasis on protecting and rebuilding stock levels under non-stable conditions. We do not therefore propose re-evaluating CLs in response to reduced marine survival but instead retain existing CLs while seeking to improve stock status. Furthermore, we emphasise the importance of maximising the productive potential of freshwater habitats, which represent the component of the life cycle most amenable to management intervention.

### 4.5.2 Maximum Smolt estimates for salmon stocks in England and Wales

Estimates of MS for the 64 PSRs in England and Wales are shown in Figure 4.5. Across all rivers, these estimates are highly variable, ranging from 2,165 (Dwyryd) to 503,224 (Wye) smolts. However, these absolute numbers depend on the extent and quality of river habitat available for spawning and rearing, with estimates of smolt output per unit (wetted) area (average 2.62 smolts 100 $m^2$) being far less variable.

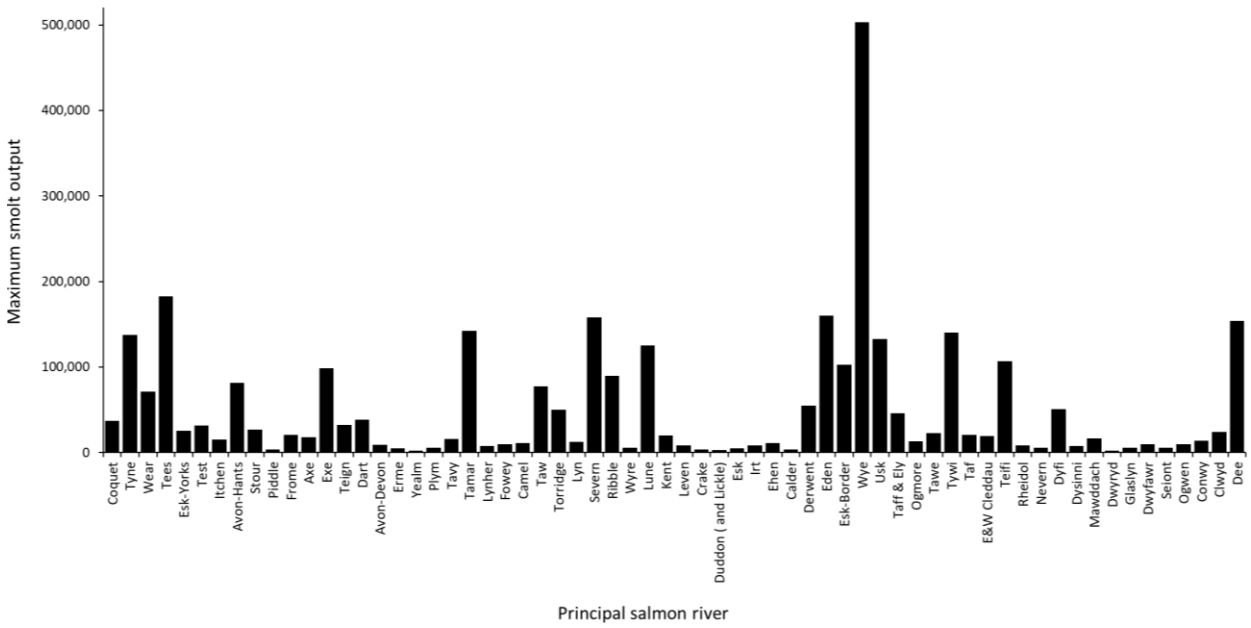



*Figure 4.5. Maximum Smolt estimates for the 64 Principal Salmon Rivers in England and Wales. These were derived using current CL setting parameters.*

### 4.5.3 Assessing compliance with Maximum Smolt targets

It is important to note that although this upper stock reference point (URP) is named Maximum Smolt, it would be defined in terms of eggs deposited and not in terms of smolts produced. This approach has the benefits of (i) both reference points are defined in the same units, and (ii) the URP can be estimated for all 64 PSRs in E&W. The annual ‘run’ of smolts is only monitored in three rivers across E&W (Tamar, Dee, Dorset Frome), and although smolt abundance could be estimated using a standard capture-mark-recapture approach, this is not routinely conducted in any other of these rivers.

# 5 How we gather data for the annual assessment of stock status

## 5.1 Introduction

On 12 Principal Salmon Rivers (PSRs) across England and Wales, Returning Stock Estimates (RSEs) are currently enumerated directly using automated fish counters and/or trapping facilities (see Table 23 in Cefas, Environment Agency and Natural Resources Wales, 2023). On the majority (52) of the PSRs, where there are no fish traps or counters, annual returns of adult fish are derived from rod catches by applying modelled angling exploitation rates to estimate the proportion of fish caught.

Rod catch data along with biological data (the latter including data collected from the counted/index rivers Tyne, Tamar, Dee, and Lune) are used to assign RSEs to 1SW and MSW sea-age classes, evaluate in-river losses, and estimate spawner and egg numbers (the latter to assess compliance with CLs or associated reference points).

This sequence of procedures – starting with the provision of rod catch data and ending with estimates of egg deposition – was well documented when CLs were first applied to salmon assessment and management in E&W (Environment Agency, 2003). This application was also integral to the production of Salmon Action Plans (SAPs) for individual river stocks and a requirement under the Ministerial Direction.

An updated version of these procedures is summarised in the flow-diagram shown in Figure 5.1 below, and has also been described, in general terms, in Section 3.2 of this report – the latter including comparison with equivalent approaches applied by neighbouring jurisdictions in the UK and the Republic of Ireland.

The aim here, in line with this report's overall purpose, is to: (i) review procedures set out in Figure 5.1 (namely those highlighted), (ii) seek to update and improve these where appropriate, and (iii) make recommendations for change.

The procedures concerned are:

- Estimation of rod catch declaration rates
- Application of age-weight keys to estimate proportions of 1SW and MSW fish in declared catches and adult returns
- Modelling of extant rod exploitation rates on salmon of all sea ages
- Derivation and use of extant rod exploitation rates for 1SW and MSW salmon to obtain separate RSEs for these two sea-age groups
- Review of default size-fecundity relationships used to generate egg deposition estimates by weight class
- Review and application of sex ratio defaults to identify the proportion of female spawners

- Review of default estimates of post-catch and release (C&R) mortality
- Review of estimates of natural mortality

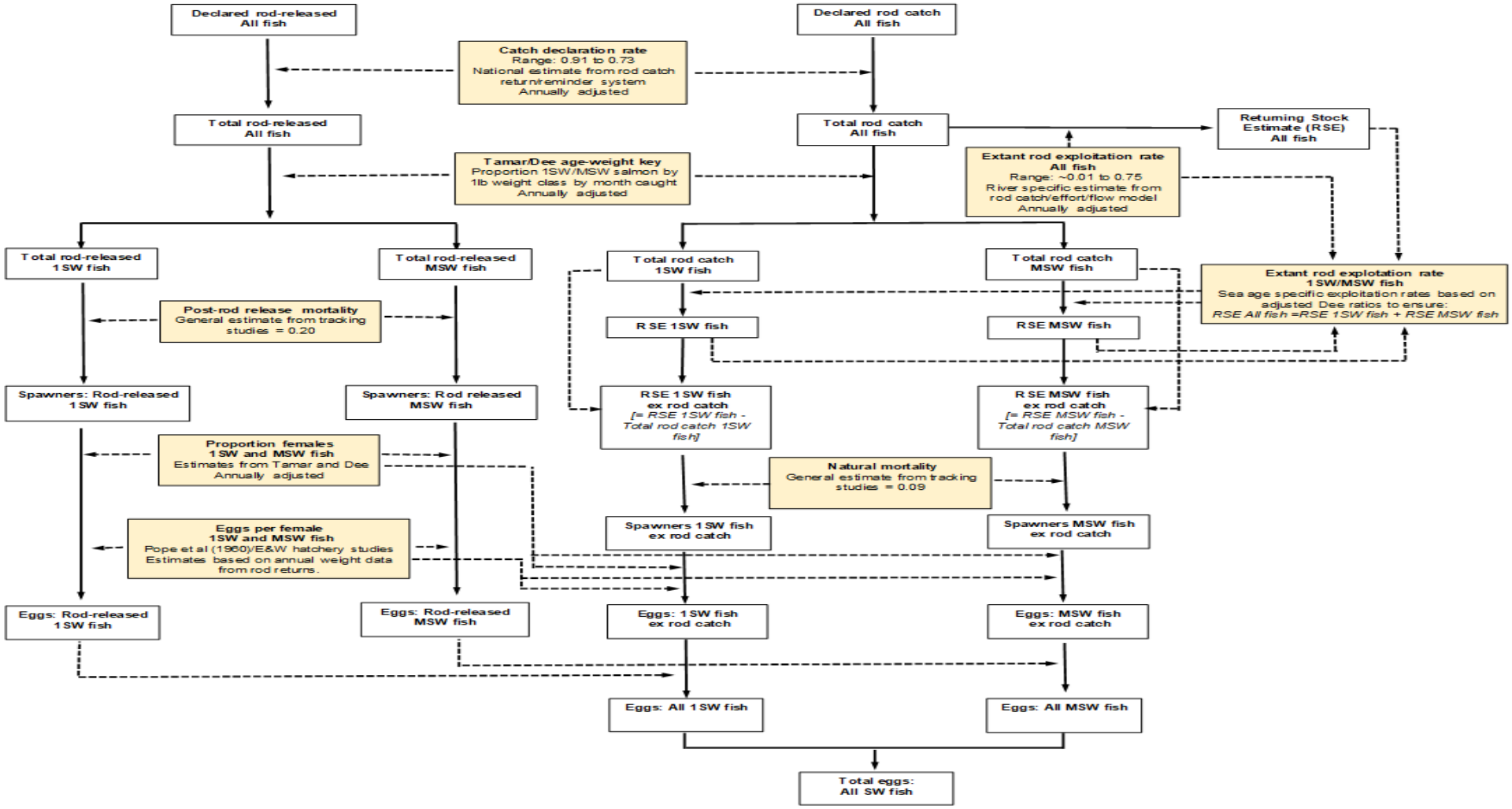



*Figure 5.1. Flow chart summarising default procedures used in England and Wales to derive salmon returning stock estimates, spawner and egg deposition estimates from rod catches.*

## 5.2 Estimation of rod catch declaration rates

### 5.2.1 Introduction

In the absence of validated fish counters or traps to enable the direct enumeration of returning stocks, catch data reported by anglers provide the primary means of estimating stock size for assessment purposes. This includes not only data on the numbers of fish caught but also other fishery (e.g. angling effort) and biological metrics (e.g. individual fish weights) that are used to evaluate stock size and composition.

In England and Wales, angling for salmon and sea trout is a licenced activity managed by the EA and NRW. A single national rod licence for these species, including a catch return reminder system, has been in place in a largely consistent format since 1994. This system requires licence holders to submit an annual catch return (including nil returns: as zero catch or 'Did not fish') to the EA. However, each year a proportion of license holders do not submit a return – currently approximately 30-40%.

As indicated above, on most rivers, rod catch data are integral to obtaining annual estimates of adult returns, spawner and egg numbers – the latter primarily used to evaluate compliance with CLs or associated biological reference points. This requires procedures to estimate total catches from declared catches (i.e. account for any unreported catch). Where no catch return has been submitted, simply raising the declared catch in proportion to the number of missing returns is likely to overestimate the total catch. For example, Small (1991) observed that the more successful anglers are more likely to submit a catch return voluntarily ('unprompted') and generally record the highest catch rates (catch per return). In contrast, anglers prompted to make a return following a reminder tend to report lower catch rates (although this trend may not persist as second or further reminders are issued – see Welsh Water Authority, 1987).

### 5.2.2 Current approach to estimating rod catch declaration rate

A method devised by Small (1991) utilises the decline in catch rate among unprompted and prompted returns to estimate catch declaration rates. This and related methods have been applied by the EA and NRW (and predecessor organisations e.g. Welsh Water Authority, 1981 and 1987) to derive estimates of the total salmon (and sea trout) angling catch from declared catches; the latter obtained through national (and formerly regional) rod licence and catch return/reminder systems (Environment Agency 2003 – Appendix III, Environment Agency 2007).

Application of the method of Small (1991) to rod catch data from 1994 onward is described below, where:

$$Actual\ catch\ =\ Declared\ catch \times\ ((0.3/Return\ rate)\ +\ 0.7)$$

This is derived from Equation 5.1 below:

$$C/Cu\ = Y/Pu\ +\ (1-Y)$$ Equation 5.1

where C is Total rod catch, Cu is Unprompted rod catch, Pu is Proportion of Unprompted effort (as licences returned), Y is 0.3 for salmon (and 0.5 for sea trout) – a constant based on average estimates of Y derived from studies measuring the decline in angling catch rate with repeated reminders (see Small 1991).

In applying Equation 5.1, the EA and NRW have used the total declared catch as the estimate of Cu, and the proportion of all licence returns (adjusted for multiple short-term and junior licences) as the estimate of Pu.

Across the time-series (1994-2020) and rivers available, Equation 5.1 yielded an estimate C/Cu of 1.10, which equates to an average catch declaration rate of 91% (see Figure 5.2). Note that the period 2015-2018 was an exception to this where additional catch correction factors were introduced to account for loss of information associated with the introduction and refinement of a new online national catch reporting system (see Cefas, Environment Agency, Natural Resources Wales, 2023).

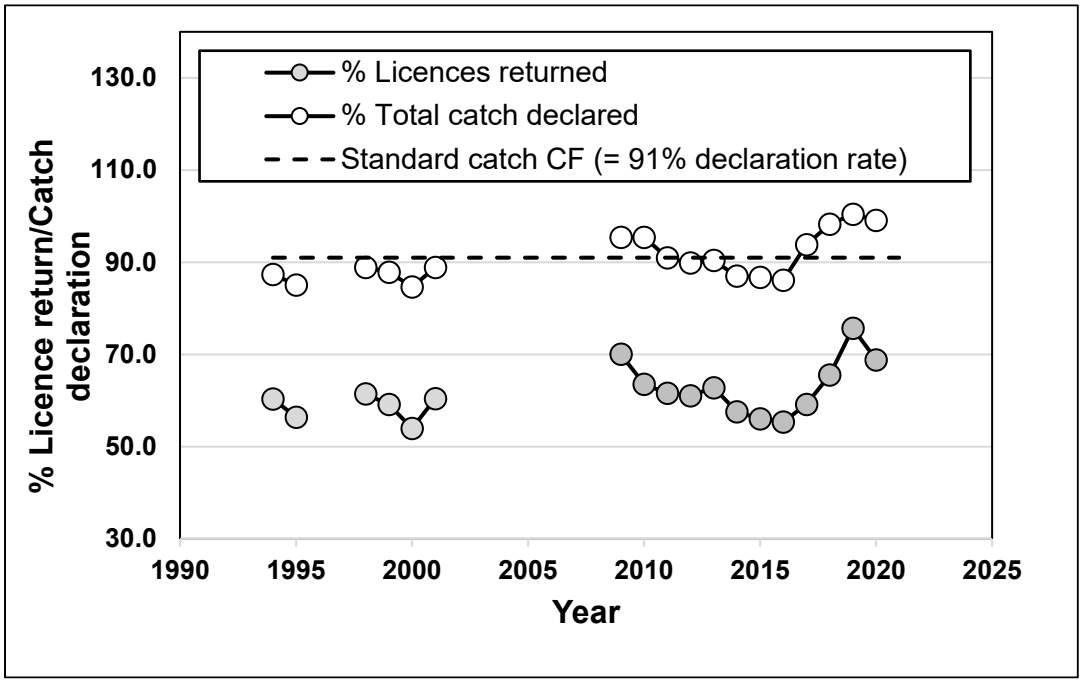



*Figure 5.2. Rod licence return (all licence types) and estimated salmon catch declaration rates for E&W, 1994-2020. A standard catch Correction Factor (CF) for the latter: as 1.10 or a 91% declaration rate, is shown alongside annually adjusted estimates, both the annual and standard catch declaration rates are calculated using the method of Small (1991). This figure does not include additional catch correction factors applied from 2015-2018.*

**Recommendation 1**

*Total catch per river will be estimated from declared catch by applying a correction factor for underreporting. A national (England and Wales) declared salmon rod catch correction factor based on the methodology derived by Small (1991) should be calculated and applied annually to replace the currently implemented constant of x1.10. This correction factor will take into account changes in the way in which salmon rod catches are reported and annual changes in rod catch reporting rates.*

The method of Small (1991), as currently applied, is considered a reasonable approach to estimating undeclared catches at a national (E&W) scale but is not refined enough to capture variation at a finer scale (e.g. by region) where data sets are far more limited. The introduction of the online catch reporting system (which in recent years has accounted for ~80% or more of all licence returns), alongside the facility to send out multiple reminders by text and email (as well as the usual dual postal reminders), provides an opportunity to explore and potentially better utilise catch records. For example, return dates for electronic catch returns (unlike paper

returns) are captured automatically and, if associated with reminder periods, can be used to examine patterns of decline in catch rates through time. The latter information could be applied to the method of Small, or related methods, in more direct ways than has been possible to date and may allow provision of more refined national catch Correction Factors, including, perhaps, greater insight into regional differences. Some initial work has been carried out in this area; however, this requires further exploration.

**Proposal 6**

*Fishery-dependent data on angler catches and effort should be reliable and representative and negate the need for correction factors. Furthermore, fishery-independent returning stock estimates should be available for more Principal Salmon Rivers in England and Wales. For the time being, however, options to better utilise online catch return data, including more direct application of the method of Small (1991) or related methods in generating national catch Correction Factors, should be further explored.*

### 5.2.3 Conclusions

Riparian owner-derived catch returns have been considered as an alternative to help account for undeclared catch and in some instances, this has been useful, particularly where such catches are collated in a robust, accurate and transparent way. However, such accurate and transparent collated returns are not routinely available for the majority of rivers.

The method developed by Small (1991) was based on the statutory catch return system in England and Wales. On balance, it would be most appropriate in future to only use the published statutory national salmon and sea trout catch return statistics as the primary source of rod catch data for salmon fisheries management purposes in England and Wales. This approach would aid transparency and consistency in the derivation of the returning stock estimates and reinforce the need for individual angler catch reporting.

**Proposal 7**

*In future only use the published statutory national salmon and sea trout catch return statistics as the primary source of rod catch data for salmon fisheries management purposes in England and Wales.*

A targeted survey of non-declaring anglers would better quantify the extent of, and understand the current reasons for, the non-declaration of catch returns. Results of

such a survey would be used to help update and improve the catch return process. This approach may lead to future adjustments to the Small method to account for under-declaration or improvements to the way in which anglers are incentivised to make timely and accurate catch returns.

**Proposal 8**

*A targeted survey of non-declaring anglers should be undertaken to better quantify the extent of, and understand the current reasons for, the non-declaration of catch returns. Results of such a survey would be used to help update and improve the catch return process.*

## 5.3 Exploitation Rates

### 5.3.1 Derivation and use of extant rod exploitation rates for salmon

#### *5.3.1.1 Review, recommendation and proposal*

Modelling of extant angling exploitation rates provides annual estimates which apply to all sea age components of each river stock.

This single exploitation rate has been adjusted based on differences between separate 1SW and MSW rates obtained from a tagging and recapture programme on the Welsh Dee and the overall ('All SW') exploitation rate on this river to generate 1SW and MSW rates on all PSRs. This step is required to produce separate RSEs for 1SW and MSW salmon (Figure 5.1).

Current procedures apply two (fixed) sea-age-specific default Correction Factors (CFs) to make these adjustments – both based on the differential between extant angling exploitation rates observed on all sea age components (All SW salmon) on the Welsh Dee in the early 1990s and those recorded for 1SW and MSW fish separately. This is derived from Equation 5.2 below:

$$Extant\ exploitation\ rate_{1SW} = Extant\ exploitation\ rate_{AllSW} \times 0.893$$

$$Extant\ exploitation\ rate_{MSW} = Extant\ exploitation\ rate_{AllSW} \times 1.250$$

Equation 5.2

Time-series of these CFs, generated since the early 1990s, are shown in Figure 5.3, along with the current defaults which were derived at the start of the time-series and have remained unchanged since.

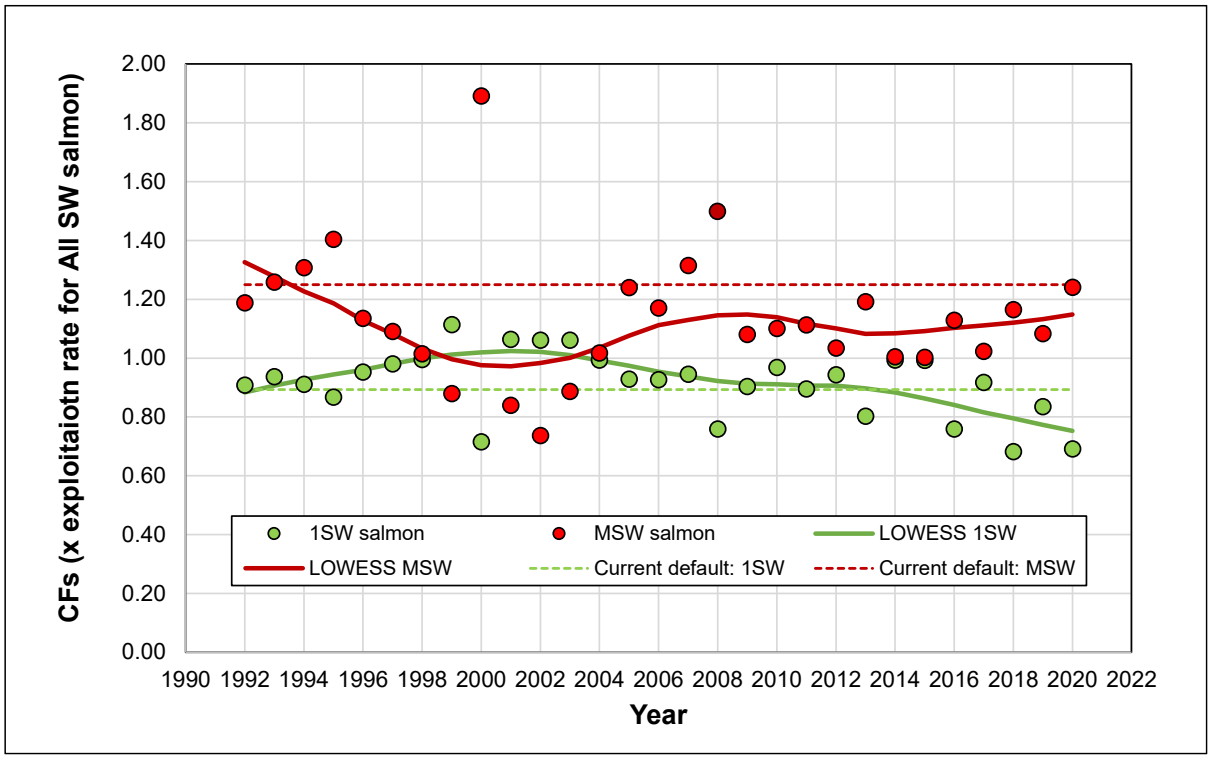



*Figure 5.3. Correction Factors (CFs) to derive extant rod exploitation rates for 1SW and MSW salmon from rates for all SW fish: Welsh Dee, 1992-2020. [Trend lines fitted to 1SW, and MSW time-series were derived using LOWESS or Locally Weighted Scatterplot Smoothing methods: Minitab (2021).]*

Applying separate 1SW and MSW angling exploitation rates (derived as described above) to 1SW and MSW rod catches (as defined by sea age-weight keys – see section 5.7 for more details) has resulted in separate RSEs for 1SW and MSW salmon which, when added together, differ from the RSE generated by applying the overall (All SW) exploitation rate to the total (All SW) rod catch. While this difference is usually small (+/-10%) - and tends to be positive where 1SW salmon dominate catches and negative where MSW comprise the majority - it presents an inconsistency in the current approach.

To address this inconsistency, it is proposed that exploitation rates for separate sea age components are estimated each year applying a procedure that explores permutations as shown in Equation 5.3 below:

$$RSE_All\ SW\ salmon\ =\ RSE_1SW\ salmon\ +\ RSE_MSW\ salmon \quad \text{Equation 5.3}$$

to identify a solution that seeks to minimise the deviation from annually derived CFs. These permutations range from:

$$RSE_1SW\ salmon/RSE_All\ SW\ salmon\ =\ 0.00\ (or\ 0\%)$$

to

$$RSE_1SW\ salmon/RSE_All\ SW\ salmon\ =\ 1.00\ (or\ 100\%)$$

for increments of 0.01 (or 1%) i.e. 101 permutations in total. It follows that:

$$RSE_MSW\ salmon\ =\ RSE_All\ SW\ salmon\ -\ RSE_1SW\ salmon$$

where *RSE_All SW salmon* is a fixed value each year obtained from:

$$RSE_All\ SW\ salmon = Total\ rod\ catch_All\ SW\ salmon/Extant\ exploit\ rate_All\ SW\ salmon$$

where *Total rod catch_1SW salmon* and *Total rod catch_MSW salmon* are fixed values each year, estimated from age-weight keys (see Figure 5.1).

Hence, for each permutation:

$$Extant\ exploit\ rate\ 1SW\ salmon\ =\ Total\ rod\ catch_1SW\ salmon/RSE_1SW\ salmon$$

and

$$Extant\ exploit\ rate\ MSW\ salmon = Total\ rod\ catch_MSW\ salmon / RSE_MSW\ salmon$$

All permutations are examined to identify the solution that minimises Equation 5.4:

$$[(Extant\ exploit\ rate\ 1SW\ salmon / Extant\ exploit\ All\ SW\ salmon) - CF_1SW\ salmon + (Extant\ exploit\ rate\ MSW\ salmon / Extant\ exploit\ All\ SW\ salmon) - CF_MSW\ salmon]$$

Equation 5.4

**Recommendation 2**

*Generate sea-age specific exploitation rate Correction Factors using LOWESS smoothing methods applied to observations, and the permutation procedure, as available. Modify procedures to derive and apply angling exploitation rates for salmon, such that the annual returning stock estimate is derived from the sum of the returning stock estimates for one-sea winter (1SW) and multi-sea-winter (MSW) salmon.*

**Proposal 9**

*Consider automating the optimisation procedures for calibrating the sea-age specific exploitation rate Correction Factors and coupling/embedding this with the exploitation rate model to generate sea-age specific exploitation rates by river.*

#### *5.3.1.2 Implementation and outcomes*

Figure 5.4 below compares 10-year time-series of egg estimates (2011-2020) generated for 20 (northern) PSR stocks using both current procedures ('Control') and a modified approach to deriving extant rod exploitation rates for 1SW and MSW salmon - as set out above ('Test'). This comparison examines the difference in egg estimates obtained from the Test and Control methods where:

$$\%\ Deviation_Egg\ estimates = ((Egg\ estimates_Test - Egg\ estimates_Control)/\ Egg\ estimates_Control)) \times 100$$

From the boxplot in Figure 5.4, it is evident that introducing the modified approach to deriving 1SW and MSW exploitation rates results (in the main) in relatively small changes in egg estimates – on most rivers, within +/- 10% of the egg estimates obtained from the current (Control) procedure. Note the middle 50% of observations for any one river lie within the shaded box with the mean % deviation from the Control indicated by the 'X' symbol.

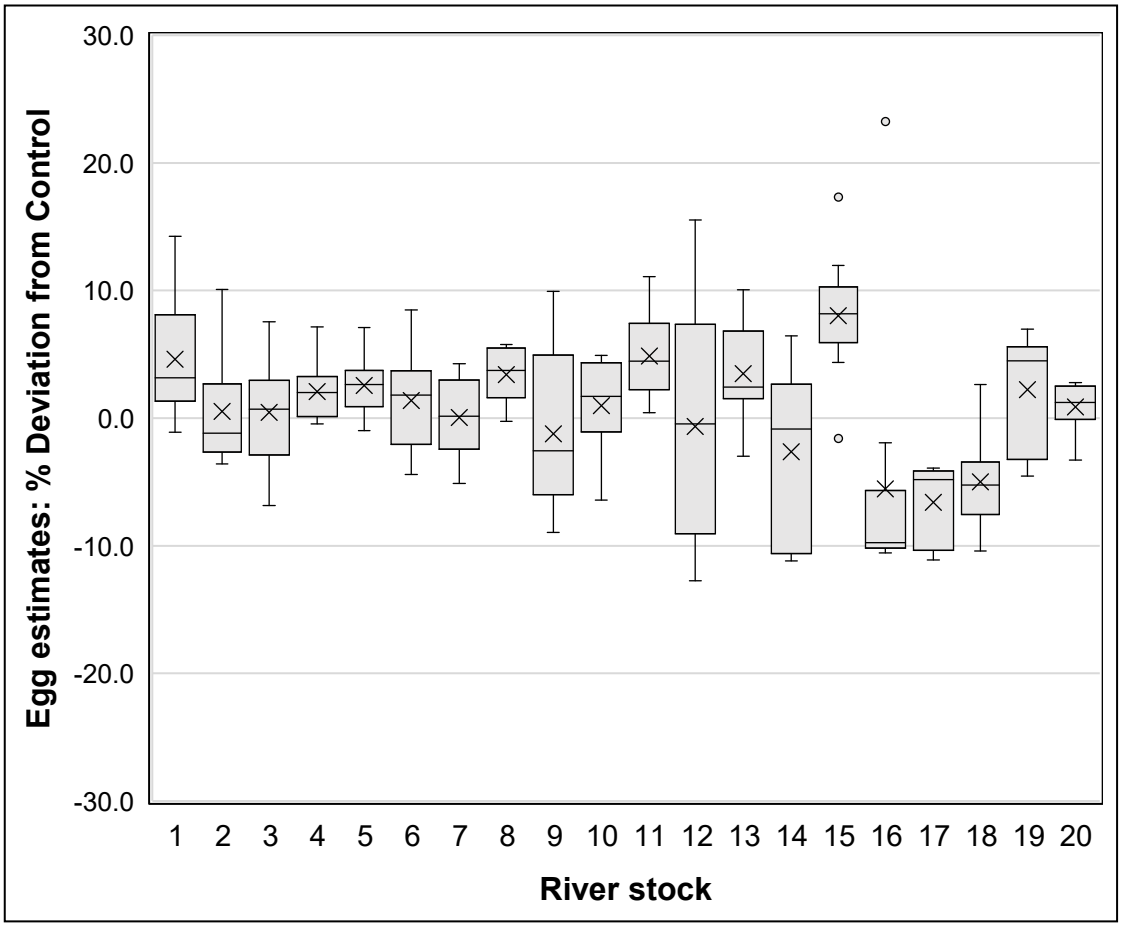



*Figure 5.4. A boxplot comparing the percentage change in egg estimates (10 years x 20 principal river stocks) resulting from current (Control) procedures versus a modified approach (above) to deriving extant rod exploitation rates for 1SW and MSW salmon ('Test'). Boxes delimit the 25%–75% interquartile range (IQR), the horizontal bar represents the median, whiskers delimit the 1.5 x IQR range, the dots represent extreme values ± 1.5 x the IQR, and the 'X' indicates the mean percentage deviation from the control.*

This comparison is extended to an examination of compliance with CL in Table 5.1, applying the current statistical trend-based method to assign a ‘risk’ status to each river stock in 2020 and 2025.

On this basis, and as might be expected from the differences in egg deposition estimates (e.g. Figure 5.4), Control and Test procedures result in very similar outcomes in terms of CL compliance (‘risk status’) and trends in egg deposition estimates.

*Table 5.1. Sea-age specific rod exploitation rates: Comparison of CL compliance outcomes resulting from application of Control and Test procedures (above) to generate annual egg estimates on 20 principal salmon rivers for the 10-year period: 2011-2020.*

**'Control': Current procedure**

| | **Risk' status:** | | **10-year trend in egg estimates: Prob. (p) of upward trend (see key below)** | | |
|---|---|---|---|---|---|
| **River stock** | **Current year: 2020** | **Projected: 2025** | **p** | **Direction** | **Certainty** |
| 1 | At risk | Prob at risk | 0.315 | - | Uncertain |
| 2 | Prob at risk | Prob at risk | 0.146 | - - | Uncertain |
| 3 | At risk | At risk | 0.182 | - - | Uncertain |
| 4 | At risk | At risk | 0.002 | - - - | Down |
| 5 | At risk | Prob at risk | 0.319 | - | Uncertain |
| 6 | At risk | At risk | 0.017 | - - - | Down |
| 7 | At risk | At risk | 0.025 | - - - | Down |
| 8 | At risk | At risk | 0.002 | - - - | Down |
| 9 | At risk | At risk | 0.005 | - - - | Down |

**'Control': Current procedure**

| | Risk' status: | | 10-year trend in egg estimates: Prob. (p) of upward trend (see key below) | | |
|---|---|---|---|---|---|
| **River stock** | **Current year: 2020** | **Projected: 2025** | **p** | **Direction** | **Certainty** |
| 10 | At risk | Prob at risk | 0.287 | - - | Uncertain |
| 11 | At risk | At risk | 0.219 | - - | Uncertain |
| 12 | At risk | Prob at risk | 0.795 | ++ | Uncertain |
| 13 | Prob at risk | Prob at risk | 0.263 | - - | Uncertain |
| 14 | Prob at risk | Prob at risk | 0.383 | - | Uncertain |
| 15 | At risk | At risk | 0.006 | - - - | Down |
| 16 | At risk | At risk | 0.117 | - - | Uncertain |
| 17 | At risk | At risk | 0.217 | - - | Uncertain |
| 18 | Prob at risk | Prob at risk | 0.402 | - | Uncertain |
| 19 | Prob at risk | Prob at risk | 0.398 | - | Uncertain |
| 20 | At risk | At risk | 0.032 | - - - | Down |

**'Test': Inclusion of modified approach to deriving 1SW/MSW exploitation rates:**

| | | | 10-year trend in egg estimates: | | |
|---|---|---|---|---|---|
| | Risk' status: | | Prob. (p) of upward trend (see key below) | | |
| River stock | Current year: 2020 | Projected: 2025 | p | Direction | Certainty |
| 1 | At risk | At risk | 0.233 | - - | Uncertain |
| 2 | Prob at risk | Prob at risk | 0.118 | - - | Uncertain |
| 3 | At risk | At risk | 0.202 | - - | Uncertain |
| 4 | At risk | At risk | 0.003 | - - - | Down |
| 5 | At risk | Prob at risk | 0.347 | - | Uncertain |
| 6 | At risk | At risk | 0.019 | - - - | Down |
| 7 | At risk | At risk | 0.023 | - - - | Down |
| 8 | At risk | At risk | 0.003 | - - - | Down |
| 9 | At risk | At risk | 0.009 | - - - | Down |
| 10 | At risk | Prob at risk | 0.304 | - | Uncertain |
| 11 | At risk | At risk | 0.211 | - - | Uncertain |
| 12 | At risk | Prob at risk | 0.790 | ++ | Uncertain |
| 13 | Prob at risk | Prob at risk | 0.316 | - | Uncertain |
| 14 | Prob at risk | Prob at risk | 0.382 | - | Uncertain |
| 15 | At risk | At risk | 0.010 | - - - | Down |
| 16 | At risk | At risk | 0.104 | - - | Uncertain |
| 17 | At risk | At risk | 0.222 | - - | Uncertain |
| 18 | Prob at risk | Prob at risk | 0.430 | - | Uncertain |

**'Test': Inclusion of modified approach to deriving 1SW/MSW exploitation rates:**

| | Risk' status: | | 10-year trend in egg estimates: Prob. (p) of upward trend (see key below) | | |
|---|---|---|---|---|---|
| **River stock** | **Current year: 2020** | **Projected: 2025** | **p** | **Direction** | **Certainty** |
| 19 | Prob not at risk | Prob not at risk | 0.492 | - | Uncertain |
| 20 | At risk | At risk | 0.034 | - - - | Down |

| Probability (p) of uptrend: | |
|---|---|
| p<=0.05 | --- |
| 0.05<p<=0.10 | --- |
| 0.10<p<=0.30 | -- |
| 0.30<p<=0.50 | - |
| 0.50<p<0.70 | + |
| 0.70<=p<0.90 | ++ |
| 0.90<=p<0.95 | +++ |
| p=>0.95 | +++ |

## 5.3.2 Estimating Atlantic salmon returns from rod exploitation rate

This work has been published in the ICES Journal of Marine Science, as:

Gregory, S.D., Gillson, J.P., Whitlock, K., Barry, J, Gough, P., Hillman, R.J., Mee, D., Peirson, G., Shields, B.A., Talks, L., Toms, S., Walker, A.M., Wilson, B. & Davidson, I.C. (2023). Estimation of returning Atlantic salmon stock from rod exploitation rate for principal salmon rivers in England and Wales. ICES Journal of Marine Science, 80 (10): 2504-2519. https://doi.org/10.1093/icesjms/fsad161.

For this report, data were updated to include 2021-2024 and some method modifications applied to produce updated results, which are presented in section 5.3.3.

### *5.3.2.1 Introduction*

The primary objective of salmon fishery management is to ensure the sustainable exploitation of their stocks (Quinn II and Deriso, 1999), i.e., to ensure that enough spawning takes place to assure the safe state of future generations. To implement appropriate fishery management measures, we must first estimate the size of the

returning adult stock available to the fishery, assess the status of that stock in terms of the numbers of adult fish that are subsequently available to spawn and how this has changed over time. To evaluate status, measures are usually compared to some predetermined standard (or standards). This process usually involves provision of estimates by quantitative modelling, broadly referred to as stock assessment (Quinn II and Deriso, 1999). In E&W, and elsewhere around the North Atlantic basin, salmon stock management is underpinned, following the NASCO guidance (NASCO, 2009), by the application of biological reference points (Potter *et al*., 2003), which are derived from the relationship between the estimated annual spawning stock size and the estimated subsequent recruitment of spawners (or earlier life-stages) due to the reproduction of that estimated annual spawning stock (Prevost *et al*., 2003; White *et al*., 2016). From this spawner–recruitment relationship, various biological reference points can be estimated. In E&W, as in other ICES jurisdictions (White *et al*., 2023), a lower limit spawning stock size is the CL, and an associated fishery MO has been set that a river stock should equal or exceed its CL in at least four years out of five on average (Cefas, EA and NRW, 2020), following the precautionary approach recommended by NASCO (NASCO, 1998) and adopted by the ICES (Davidson *et al*., 2017; ICES, 2023).

Given the purpose of salmon stock assessment and its use in managing fishery exploitation, it is imperative that estimates of the sizes of the adult salmon stock returning to rivers (hereafter salmon stocks), and subsequent spawning stocks, are as accurate, precise and unbiased as possible, and provided with measurements of their uncertainties (Rivot *et al*., 2001; Crozier *et al*., 2003; Prevost *et al*., 2003; Potter *et al*., 2004; Rivot *et al*., 2019). Broadly, estimates of salmon stocks can be obtained by fishery-dependent and fishery-independent methods, and each has advantages and disadvantages (Maunder and Punt, 2013; Bentley, 2015; Maunder and Piner, 2015). Fishery-dependent methods rely on catches by recreational and commercial fishers whose activities cover a large spatial and temporal extent, but whose choices and behaviours can result in complex and potentially subjective indicators of stock size, which is also unavailable if the fishery is closed (Maunder and Punt, 2004; Arlinghaus *et al*., 2007). In contrast, fishery-independent data are collected using specific protocols to enumerate the stock directly, often using devices that include automated resistivity, acoustic or optical fish counters, or the use of partial or total traps – the former includes use of capture-mark-recapture methods to derive full return estimates (Eatherley *et al*., 2005). Typically, these devices are operated with a degree of standardisation and validation, thereby produce a somewhat objective measure of stock size (Dunkley and Shearer, 1982). Their high implementation and ongoing costs, however, mean that they produce data that are restricted spatially and temporally (Cowx and Fraser, 2003; Eatherley *et al*., 2005; but see Smith *et al*., 1996). Hence, for example, only 12 of the 64 PSRs in E&W have reported or continue to report a fishery-independent RSE (Cefas, EA and NRW, 2020).

Around the North Atlantic Area, salmon stocks are estimated using numerous different but related methods depending on, *inter alia*, the management framework, available data, and suitable expertise. A widespread method is to raise declared

salmon catches (adjusted for catch reporting rates and known as total catches: Small and Downham, 1985) to RSEs by applying a measure of stock exploitation by anglers (known as the salmon rod exploitation rate [hereafter RER]: Solomon and Potter, 1992; Milner *et al*., 2001; O'Connell, 2003). An important motivation underpinning the development and adoption of the RER method is the large amount of spatio-temporal fish catch data generated by anglers and collated and reported in a regular and consistent manner (Milner *et al*., 2001). An extension of this approach, including exploitation by commercial fisheries, is used to reconstruct pre-fishery abundances that underpin international stock assessments (Potter *et al*., 2004; Rivot *et al*., 2019; Olmos *et al*., 2020). Where available data are more extensive and accompanied by emerging statistical concepts and increasing computation power, new methods have been developed and are recommended (Milner *et al*., 2001; Ó Maoiléidigh *et al*., 2004), including models that separate ecological from observation processes (Rivot *et al*., 2004; Auger-Méthé *et al*., 2021). For example, some recent salmon stock assessment approaches in France have used quantitative modelling to integrate data from multiple life stages through time, thereby emulating the salmon's life cycle, while accounting separately for the fish counting process (Buoro *et al*., 2019; Lebot *et al*., 2022). Similar models have been partly developed in E&W (Crozier *et al*., 2003).

The primary method of estimating salmon stocks in E&W is based on the RER method (Milner *et al*., 2001), although regional variations include more or less information and assumptions. The decision to use this approach was based on the widespread evidence of a strong and positive relationship between reported salmon catch by rod anglers and stock size (Crozier and Kennedy, 2001; Gargan *et al*., 2001; Hansen, 2001; Whelan *et al*., 2001; Thorley *et al*., 2007), together with the abundance of available spatio-temporal catch data. In E&W, rod catch data for salmon (and sea trout *Salmo trutta*) have been collected in a consistent manner via a single national rod licence return-reminder system since 1994. Similar catch return systems operate in neighbouring jurisdictions, including Scotland (https://marine.gov.scot/sma/assessment/salmon-and-sea-trout), the Republic of Ireland (White *et al*., 2016) and France (Buoro *et al*., 2019; Lebot *et al*., 2022). Such systems, including the E&W rod licence return data, collect information on the amount of effort spent angling on different rivers, and data on individual catches, including the species, size, and method of capture. These data can be used to reduce biases inherent in these fishery-dependent catch data.

To use fishery-dependent data for salmon stock assessment, we must confront and try to overcome some of its biases. There are several practical issues to consider when working with angler catches. They can represent fish (Shelton, 2001a) and angler (Gardiner, 2001) behaviours, and both might be influenced by other variables, such as the prevailing weather conditions (Hendry *et al*., 2007). The fate of captured fishes is important insomuch as a returned fish can be re-captured later, whereas a killed fish cannot, and thus should not thereafter be considered as part of the spawning stock (Leeuwen *et al*., 2020; Thorstad *et al*., 2020). There are several reasons why poorly audited catch returns could be unreliable, including accidental or

deliberate under- or over-catch declaration by recreational and commercial fishers (Potter, 2001); a study by Small (1991) suggested that this possible bias could be corrected to give estimates of catches similar to those derived using capture-mark-recapture studies (Potter, 2001). Variations in stock sizes may be due to natural variability or be the result of human actions to manage their size. Aside from the practical issues, there are also issues relating to the quantitative modelling of exploitation rates. River flow is thought to affect the catchability and availability of fish (Gee and Milner, 1980; Gillson *et al*., 2020), but also the anglers' perceptions of those factors (Aprahamian and Ball, 1995; Milner *et al*., 2001). Angling effort should have a strong and positive relationship with catch (e.g., Gee and Milner, 1980; Gargan *et al*., 2001; Davidson *et al*., 2017), but some studies have found no such relationship (e.g., Crozier and Kennedy, 2001), or even a negative relationship (e.g., Beaumont *et al*., 1991). Relationships among variables related to angling records are frequently highly noisy and this could be due to the omission of important sources of variation, such as differences within and between rivers (Milner *et al*., 2001). Nevertheless, catches have been found to be consistent with expectations at larger spatial and temporal scales (Milner *et al*., 2001).

Our study aims to derive annual salmon stock estimates (with uncertainties) from RER for all PSRs across E&W using a single, consistent, transparent and statistically robust method that transfers strength from the "data-rich" rivers with fishery-independent data to "data-poor" rivers with fishery-dependent data. There were three main objectives to: (1) develop a statistical model describing RER measured on a subset of salmon rivers in E&W equipped with automated fish counting and/or trapping facilities (hereafter fish counter or counter) using an *a priori* defined set of expert-agreed potentially influential explanatory variables; (2) transfer that statistical model to other salmon rivers in E&W that are not equipped with fish counting facilities and for which RER cannot therefore be calculated directly; and, (3) use the estimated RERs to derive salmon stock estimates from rod catches for all major salmon-producing rivers across E&W. We developed a special case of the model proposed by Lebot *et al*. (2022) in which fishery-independent available stock estimates are treated as constant data, rather than latent unobserved quantities, and in which we attempt to describe more of the variation in the RER with additional measured covariates, negating the need for the year-within-river random terms. In other respects, our approach generalises that of Lebot *et al*. (2022) by allowing for overdispersion in catches given the stock, i.e., we use a Beta-Binomial regression as used by Mäntyniemi *et al*. (2015) and allowing non-linear effects of our covariates on catches from the available stock. We opt to use a Bayesian framework to allow uncertainty in the model parameter estimates to propagate through to the derived stock estimates.

#### 5.3.2.2 Methods

Salmon stock size estimates are derived from adjusted catch data raised by an estimate of RER on the stock (Solomon and Potter, 1992; Shelton, 2001b). In essence, the exploitation rate of a stock is the proportion of the available salmon in the stock that were caught by anglers. Currently, the best measures of available stocks come from the 12 rivers where a fishery-independent RSE is reported and estimates of RER for these rivers are transported to rivers without a fishery-independent stock estimate. This process is akin to using “data-rich” stocks to inform “data-poor” stocks in marine fisheries (Prevost *et al*., 2003; Punt *et al*., 2011; Bentley, 2015). A variety of methods have been proposed and used in E&W (and elsewhere) to estimate RER. Early methods included a power function given by catch / effort ∝ abundance^b (or equivalently, catch ∝ effort × abundance^b), where b has been estimated to be various values around 0.3-0.7 (Small, 1991; Gardiner, 2001). However, this technique is known to predict unrealistically high values of rod exploitation that suggest catches greater than abundances (Gardiner, 2001). An alternative to this model included an effect allowing for saturation of fishing effort at high abundance (Richards and Schnute, 1986). Recently, however, there has been a move towards the use of hierarchical Bayesian modelling, frequently built upon standard generalised linear models, often adapted to fit better highly variable data, such as Beta-Binomial regression (Mäntyniemi *et al*., 2015).

##### 5.3.2.2.1 Principal salmon river data and returning stock estimates

There are 64 PSRs with monitored salmon stocks in E&W (Figure 5.5), and our analysis was designed to estimate exploitation rates on them all. We collated data characterising each of these PSR.

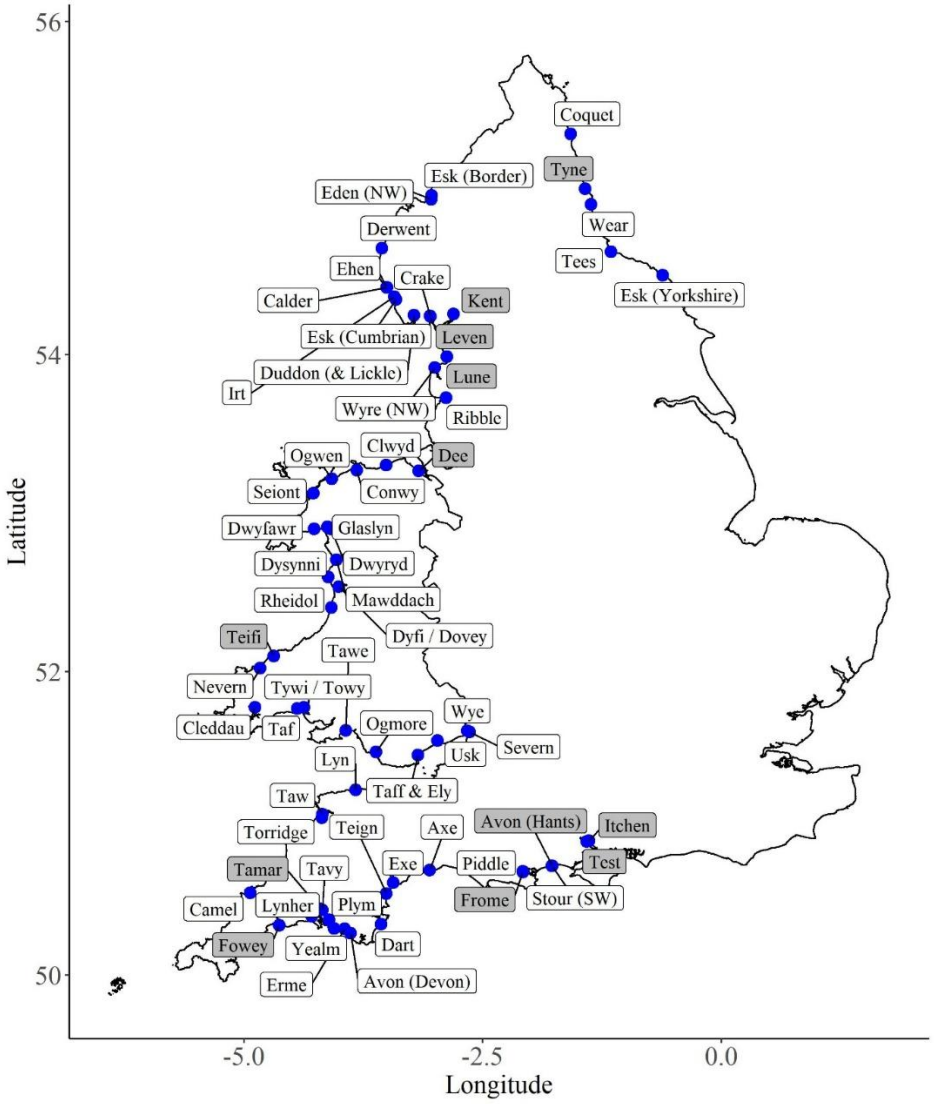



*Figure 5.5. Locations of the 64 principal salmon rivers in England and Wales. Only 12 of these PSR (indicated by grey boxes) has a fish counter or trap to derive a returning stock estimate that is needed to calculate a rod exploitation rate.*

*Table 5.2. Details of the 12 principal salmon rivers (PSR) in England and Wales that derive a fishery-independent returning stock estimate (RSE). Latitude and Longitude are for the river mouth; River type is 'Chalk' or 'Spate' as classified by their Base Flow Index; Years is the total number of annual RSEs available; Gaps are years for which a RSE was absent; Method denotes how the RSE is estimated; Months shows period to which the annual RSE corresponds; and Validation denotes the RSE validation method.*

| River | Location | Latitude | Longitude | River type | Fishery area (HA) | Period | Years | Gaps | Method | Months | Validation |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Avon (Hants) | England | 50.730 | -1.770 | Chalk | 369 | 2006-2020 | 10 | 2013, 2014, 2016, 2018, 2019 | Resistivity counter | Jan - Dec | Wave form and periodic video review |
| Dee | Wales | 53.277 | -3.169 | Spate | 617 | 1994-2020 | 27 | | Mark/recapture | Jan - Dec | NA |
| Fowey | England | 50.334 | -4.632 | Spate | 42 | 1995-2020 | 26 | | Resistivity counter | Mar – Feb | Wave form and periodic video review |
| Frome | England | 50.689 | -2.081 | Chalk | 88 | 1994-2020 | 24 | 2012, 2013, 2014 | Resistivity counter | Mar – Feb | Wave form and periodic video review |
| Itchen | England | 50.896 | -1.385 | Chalk | 69 | 1994-2020 | 26 | 2011 | Resistivity counter | Jan - Dec | Wave form and periodic video review |
| Kent | England | 54.250 | -2.805 | Spate | 68 | 1994-2010 | 17 | | Resistivity counter | Jan - Dec | Wave form and periodic video review |
| Leven | England | 54.234 | -3.049 | Spate | 46 | 2000-2013 | 10 | 2001, 2004, 2005, 2006 | Resistivity counter | Jan - Dec | Wave form and periodic video review |
| Lune | England | 53.988 | -2.874 | Spate | 423 | 1994-2014 | 21 | | Resistivity counter and trap | Jan - Dec | Wave form, trap speciation and periodic video review |

| River | Location | Latitude | Longitude | River type | Fishery area (HA) | Period | Years | Gaps | Method | Months | Validation |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Tamar | England | 50.443 | -4.200 | Spate | 293 | 1994-2020 | 27 | | Resistivity counter and trap | Jan - Dec | Wave form, trap speciation and periodic video review |
| Teifi | Wales | 52.102 | -4.688 | Spate | 326 | 2010-2020 | 11 | | ARIS multibeam sonar | Jan - Dec | Periodic video review |
| Test | England | 50.890 | -1.411 | Chalk | 138 | 1994-2020 | 25 | 2011, 2012 | Resistivity counter | Jan - Dec | Wave form and periodic video review |
| Tyne | England | 55.010 | -1.427 | Spate | 542 | 2004-2020 | 17 | | Resistivity counter | Jan - Dec | Wave form and periodic video review |

Only 12 of these 64 PSR have a fish counter that could be used to calculate a fishery-independent RSE, namely the rivers Avon (Hants; short for Hampshire), Dee, Fowey, Frome, Itchen, Kent, Leven, Lune, Tamar, Teifi, Test and Tyne (Table 5.2; and Cefas, EA and NRW, 2020). Ideally, these rivers would have been purposely selected to capture the range of conditions experienced by salmon stocks across all the E&W PSRs, i.e., they would be a representative sample of salmon rivers (Prevost *et al*., 2003).

Unfortunately, rivers are rarely selected for their representativeness, but rather for other, often historical or opportunistic, reasons (e.g., Lebot *et al*., 2022). Among these rivers, for example, fish counting/trapping facilities were installed in the chalk rivers (Table 5.2) and the rivers Fowey and Tamar primarily to monitor migratory fish populations with respect to water resource management (S. Toms, pers. comm.*).* In contrast, the rivers in Wales and northern England were largely selected for interest in the fish stocks per se and methods to monitor them (B. Shields, pers. comm*).* Representativeness is important if we are to generalise findings from these RSE rivers to the other non-RSE PSRs; if they are not representative, then their generalisation will be limited. With this in mind, we designed our model to account for potential non-representativeness by including river random effects in fitting and extrapolating.

#### *5.3.2.2.2 Angler catch effort and associated data*

A national (statutory) catch return-reminder system was introduced in E&W in 1994, replacing various previously operated regional systems (Cefas, EA and NRW, 2020). The current system requires that all anglers wishing to catch migratory salmonids purchase a rod licence and thereby are legally bound to report details of their angling catches and fishing effort to the EA (and its predecessors) by the end of the angling year (Solomon and Potter, 1992). Angling for salmon without a licence/or/and failing to provide a catch-return are offences and can incur a financial penalty (Solomon and Potter, 1992). Rod licence details and the catch-return data reported against them are kept by the EA in the National Rod Licence Catch Database (RCdb). A completely anonymised version of the RCdb provided the following data for each salmon caught: licence number, date, river and method of capture (fly, bait, spin), the weight of the fish (lbs/kg), and whether it was released or retained (fate). Aside from these individual fish records, the total number of fish caught/released (including nil returns) and fishing effort (angler-days for both salmon and sea trout combined) are requested from each licence holder for each river fished in each year.

There are three notable issues with rod licence and catch-return data (Potter, 2001). First, catch-return data are not submitted against all licences, despite repeated reminders and the associated risk of a fine (Small and Downham, 1985). Small (1991) analysed licence catch-returns and derived probable reporting rates and details of how they could be used to correct declared catch. On the basis of their

work, a national rod catch declaration rate of 0.91 was derived for salmon in E&W and has been (for most rivers and in most years, except where catches from fisheries owners are judged to be more accurate and used) the sole correction applied to declared catches since 1994 to estimate total catches (Davidson *et al*., 2017). Second, effort spent fishing for salmon is not currently distinguished from effort spent fishing for other migratory fish, notably sea trout. While the effects of this composite fishing effort data might be limited given that salmon and sea trout co-occur in many of the PSRs (Milner *et al*., 2007) and anglers targeting one species regularly catch the other (Shields *et al*., 2007), questionnaires were sent to licence holders in 1992 and 2006 asking them to estimate the amount of effort they spent on each species. The results of these surveys have been used to calculate a river-specific mean (of 1992 and 2006) salmon angling effort rate ($\xi$) that has been applied to declared effort since 1994 (Davidson *et al*., 2017). Third, effort is sometimes omitted when catch-return data are submitted against a licence. To adjust for this, an effort declaration rate is calculated as the ratio between the declared catch and the declared catch with effort. For this study, both declared catch and declared effort were adjusted to account for these rates, thus: (1) declared catches were adjusted by the national rod catch declaration rate $\lambda$, which is taken to be 0.91 in most rivers in most years (Small and Downham, 1985), to account for incomplete declarations, and (2) declared effort for salmon was calculated as $effort\ salmon = declared\ effort \times \chi \times \xi \times \lambda$ where $\chi$ is the effort declaration rate, $\xi$ is the salmon angling effort rate, and $\lambda$ is the national licence declaration rate.

Given the adjusted declared effort for salmon, we calculated two measures of effort to include as explanatory variables in our statistical models of RER. First, we followed the approach taken by Davidson *et al*. (2017) and scaled it to the river size so that it measured fishing days on salmon per hectare, i.e., Angler effort (Figure S1). Because Davidson *et al*. (2017) found support for a non-linear (convex) relationship between exploitation rate and rod effort for sea trout, we explored a non-linear (convex) functional form in our statistical models of RER. Second, there are some suggestions that anglers can exert a disproportionate influence on exploitation rate if their effort yields a good return, perhaps due to their skill or persistence (Beaumont *et al*., 1991; Solomon and Potter, 1992). To account for this, we calculated the proportion of declared effort for salmon that yielded a minimum of one salmon caught in that river and year, i.e., Successful effort. Both variables were z-standardised (subtracted mean and divided by the standard deviation) across rivers and years before including them in models as explanatory variables.

Aside from declared catch and effort data, the additional data on individual catches (e.g., capture method and fate) can be used to calculate additional and possibly river- and year-specific explanatory variables for inclusion in our statistical models of RER. Different capture methods, including the use of barbless hooks, are likely to influence exploitation rates: for salmon (Grilli *et al*., 2021) and for sea trout (Shields *et al*., 2007). Calculation of an explanatory variable to represent capture method from the catch-return data is, however, challenging for two reasons: (1) capture method is infrequently reported, and (2) river-specific byelaws and club restrictions

are not always well documented and can censor the variable, i.e., making it appear as though certain methods are less effective when they are actually banned. Given these potential issues, we did not consider ‘capture method’ as an explanatory variable, but rather we explore in the Discussion the possible implications of that our decision, including proposals to include it as a subsequent extension to this work.

In contrast, the fate of individual fish was well-documented and could be used to calculate an explanatory variable: Release proportion. This explanatory variable was calculated to represent river- and year-specific changes in catch-and-release practices, in particular an increase in the practice of voluntary catch-and-release, and the influence it might have on RER through released fish eventually becoming re-available for capture. There are, however, two reasons why this approach could be improved: (1) catch-and-release has become mandatory on salmon rivers in Wales since 2020 (Cefas, EA and NRW, 2020) which introduces the possibility that estimates since then might not be directly comparable with the years preceding them, if there is a greater likelihood that catch returns will be falsified under a mandatory regime, and (2) returning salmon back to the river should influence RER indirectly by changing the stock available to be captured within a year, rather than influencing RER directly. To account for changes in catch-and-release practices, such variability could be better explored by treating the available stock as a dynamic rather than static state.

#### *5.3.2.2.3 Salmon rod exploitation rate explanatory variables*

We researched and agreed a set of explanatory variables that were expected to describe variation in RER on the PSRs (Table 5.3).

*Table 5.3. A set of a priori expert-agreed explanatory variables expected to describe mean and variation in Atlantic salmon rod exploitation rate (RER) across the 64 principal salmon rivers in England and Wales. Columns are the explanatory variable Name and Description, the expert-agreed Hypothesis of its effect on either mean or variation in RER, and the main Reference informing the hypothesis.*

| Model part | Name | Description | Hypothesis | References |
|---|---|---|---|---|
| Mean | Angler effort | Number of declared days fished for salmon in each river in each year (salmon and sea trout effort is split based on 1992 and 2006 questionnaires to licence holders) divided by accessible wetted area (hectares) - see below | positive becoming negative | Davidson *et al.* (2017) |
| | Successful effort | Proportion of declared days fished for which a salmonid was caught in each river in each year | positive | Beaumont *et al.* (1991) |
| | Release proportion | Percent of salmon that are returned to the river after capture in each year in each river | positive | |
| | Mean flow | Mean river water flow from the beginning to the end of the river-specific fishing season in each year in each river[1] | positive | Milner *et al.* (2001) |
| | Base Flow Index | A measure that characterises differences in exploitation rate by base flow index that separates spate and chalk stream rivers | positive | |
| Variance | Area (hectares) | Wetted area accessible to salmon spawners | negative | Milner *et al.* (2001) |

Through its influence on fish behaviour and availability, and on angler behaviour, river flow is expected to explain variation in salmon catchability and thus RER within and between rivers (reviewed in Milner *et al*., 2001). To account for river flow, we calculated a river- and year-specific measure of within-angling-season Mean flow for inclusion in our statistical models of RER. River flow data were obtained from the E&W river flow gauging station network, queried via the UK Centre for Ecology and Hydrology (CEH) National River Flow Archive (https://nrfa.ceh.ac.uk/), and individual flow gauging stations, as required. For each river, gauging stations were selected in the lower main river (where possible) to best represent flow conditions on the

[1] Various ways to summarise in-season flow conditions were considered (e.g., hydrological indices proposed by Richter *et al*., 1996), including single and multiple variables to quantify high and low flow conditions and events, but they were complicated by issues, such as collinearity with other explanatory variable and unintuitive or weak relationships with the response variable, compared to mean flow.

catchment as a whole and over the period covered by the RSEs. Where suitable gauging stations/flow data were absent from a catchment, flow data from an appropriate neighbouring catchment were used. In all cases, the gauged daily mean flow data extracted to calculate the flow variables were limited to the period of the salmon angling season from the Salmonid and Freshwater Fisheries Statistics (https://www.gov.uk/government/publications/salmonid-and-freshwater-fisheries-statistics-2020). The resulting measures of mean flow were z-standardised within each river across years before they were included in models as explanatory variables.

To promote generalisation, we calculated variables representing river type and river size for inclusion as explanatory variables in our statistical models of RER. Chalk streams have a higher Base Flow Index than spate rivers because they are largely aquifer-fed and thereby produce a more consistent and higher mean flow (see Figure S6 in Gregory *et al*., 2023). We extracted the Base Flow Index for each of the 64 PSRs from the CEH National River Flow Archive and z-standardised them across rivers before including them in models as an explanatory variable. The RER on smaller rivers might be expected to demonstrate higher inter-annual variability as they are likely to accommodate smaller stocks that could thereby be disproportionately affected by processes acting upon them, such as angler behaviour (Milner *et al*., 2001). To account for this possibility, we extracted fishery Area (hectares) from Table 26 in Cefas, EA and NRW (2020) and z-standardised it across rivers before including it in models as an explanatory variable.

The RSE and explanatory variables were calculated for each of the 12 PSRs where a RSE is reported and for which a RER can therefore be calculated (Figure 5.6).

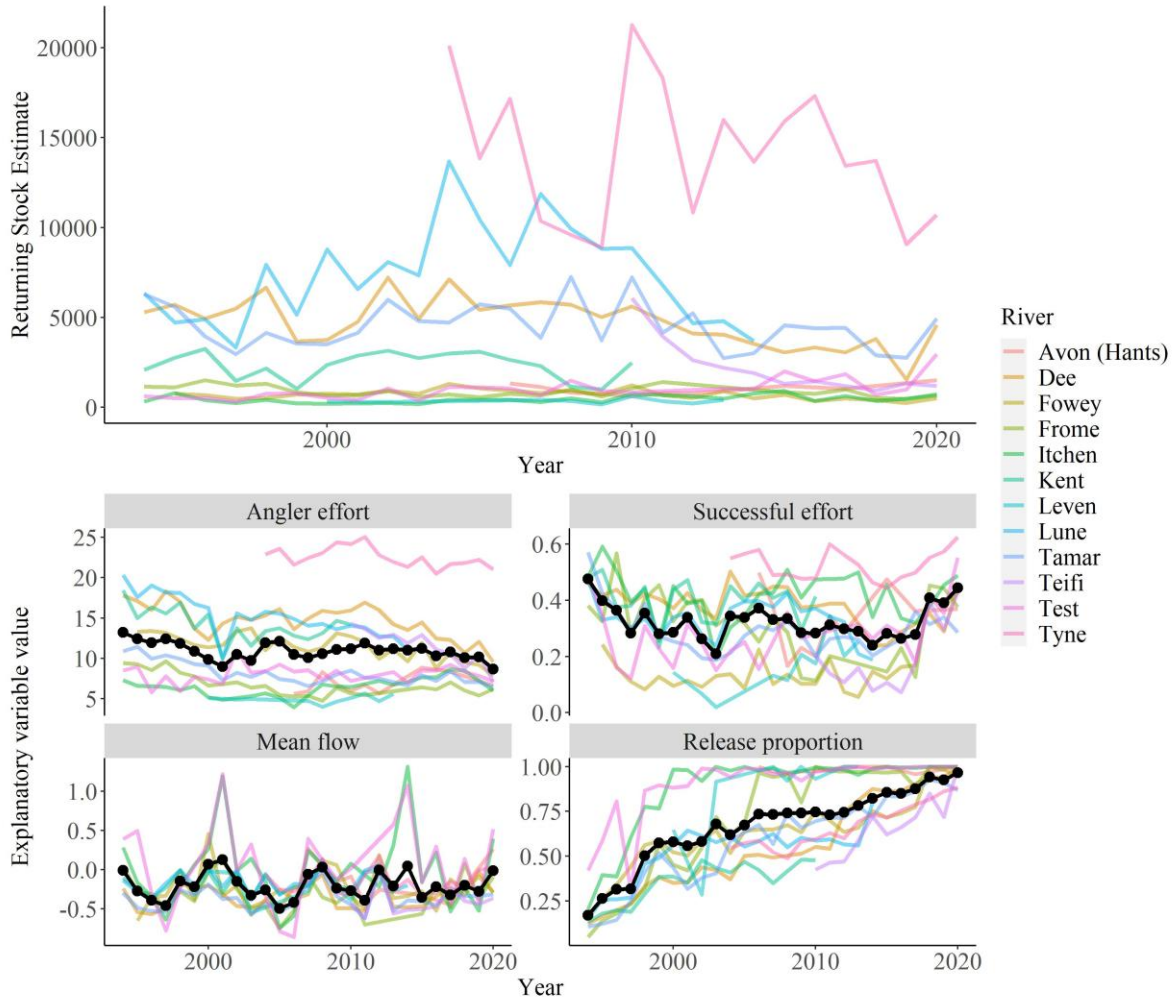



*Figure 5.6. Plots showing returning stock estimates (RSE) and explanatory variables expected to describe variation in Atlantic salmon rod exploitation rate for each RSE river. Black lines represent the mean explanatory variable values across all rivers.*

#### *5.3.2.2.4 Rod exploitation rate model*

To address the first objective of our study, we developed a Beta-Binomial model, using the aforementioned *a priori* defined set of expert-agreed potentially influential explanatory variables, to describe the exploitation rate for RSE rivers as a linear combination of the explanatory variables. This is given by Equation 5.5 below:

$$C_{r,y} \sim \text{Binomial}(N_{r,y}, p_{r,y})$$
$$p_{r,y} \sim \text{Beta}(\alpha_{r,y}, \beta_{r,y})$$
$$\alpha_{r,y} = \mu_{r,y}\phi_{r,y}$$
$$\beta_{r,y} = (1 - \mu_{r,y})\phi_{r,y}$$
$$\text{logit}(\mu_{r,y}) = \delta X_{r,y} + \nu_r + \zeta_y$$
$$\log(\phi_{r,y}) = \gamma Z_{r,y}$$

Equation 5.5

where

$$\nu_r \sim \text{Normal}(0, \sigma_r)$$
$$\zeta_y \sim \text{Normal}(0, \sigma_y)$$

and

$$C_{r,y} = c_{r,y}/\lambda$$

where $c_{r,y}$ is the declared rod catch in river $r$ in year $y$ and $\lambda$ is the licence declaration rate, taken to be 0.91 in most rivers in most years (Small and Downham, 1985; Cefas, EA and NRW, 2021a), $N_{r,y}$ is the RSE of river $r$ in year $y$, $p_{r,y}$ is the exploitation rate of river $r$ in year $y$, $\alpha$ and $\beta$ are the shape parameters of a Beta distribution, $\delta$ is a vector of coefficients representing the effects of the explanatory variables $X_{r,y}$ on the mean river- and year-specific expected exploitation rate $\mu_{r,y}$, and $\gamma$ is a vector of coefficients representing the effects of the explanatory variables $Z_{y,r}$ on the river- and year-specific variation in exploitation rates $\phi_{r,y}$. Parameters $\nu_r$ and $\zeta_y$ are random effects allowing the expected mean exploitation rate to vary by $\sigma_r$ among rivers, representing differences between rivers not captured by covariates, and by $\sigma_y$ among years, representing a temporal synchrony between rivers not captured by covariates, respectively. We used weakly informative priors: Gaussian (mean = 0, Standard Deviation (sd) = 1000) for coefficients representing explanatory variable effects on exploitation rate, Student-t (mean = 0, sd = 100, degrees of freedom (df) = 3) for the random effect variance, and Gamma (location = 0.001, scale = 0.001) for the model errors.

The model parameter posterior distributions were estimated from 16000 Markov Chain Monte Carlo (MCMC) iterations (8 parallel chains run for 2000 iterations and no thinning) using Hamiltonian Monte Carlo implemented in Stan (http://mc-stan.org) and fitted using package `brms` (Bürkner, 2017) in R (https://www.r-project.org). Convergence was assessed by visual examination of MCMC trace plots, the Gelman-Rubin statistic (Brooks and Gelman, 1998) and the bulk effective sample

size, and were considered stable if the chains were mixing, non-convergent and well represented by the samples, i.e., < 1.05 and > 200 (per chain) for all parameters, respectively. Bayesian $R^2$ values were calculated according to Gelman *et al*. (2019).

Given that this model was to be extrapolated to data from rivers not used to parameterise it, it was deemed worthwhile simplifying it to those *a priori* expert-agreed explanatory variables (Table 5.3) that explained a non-negligible amount of the variation in RER. To do this, we started with the saturated model including all variables (Table 5.3) and then removed iteratively those whose estimated effect was weakest or most uncertain, i.e., those whose 95% credible intervals intercepted 0 or were widest. We repeated this process until the estimated effects of all remaining variables were considered non-negligible, i.e., their credible intervals did not intercept 0 and were not too wide. The final "best" model was therefore the one explaining the highest variance with the fewest parameters, i.e., the most parsimonious. We confirmed that this was the "best" model according to Information Criterion as the one with the fewest parameters (or explanatory variables) that was also within < 2 change in leave-one-out cross-validation Information Criterion (looIC), known as δlooIC, of the model with the lowest δlooIC (0.00) (Vehtari *et al*., 2017).

#### *5.3.2.2.5 Model validation, inference and extrapolation*

To achieve the second objective of our study, the transfer of salmon-counting data from data-rich rivers to data-poor rivers without counters, we had to have confidence that our "best" statistical model for the 12 PSRs with a RSE had some predictive ability. To test this, we did a k = 10-fold stratified cross-validation experiment whereby we trained the model on nine data folds, each stratified to ensure that all rivers were represented, and used that trained model to predict the total catch on the one omitted fold. We chose to use stratified rather than random samples of the data because there was considerable variation between RER calculated for the 12 PSRs, with a RSE that our model accounted for with a river random effect, the variance of which would not be representative if whole rivers were omitted from the training data. Once satisfied that our model was generalisable, we used it for inference by plotting the partial effects of the retained explanatory variables and comparing their coefficient estimates with the hypothesised relationships (Table 5.4).

To achieve our third objective, i.e., to extrapolate our generalisable model to estimate salmon stocks in all 64 PSRs in E&W, we took 2000 draws from the model parameter posteriors and used them to predict an annual RSE ($\widehat{N}_{r,y} = C_{r,y}/\widehat{p_{r,y}}$, and 95% credible intervals) for each of the other 52 salmon rivers in E&W where an RSE is not reported. This prediction assumed that each river was well represented by the 12 PSRs where an RSE is reported and set the random terms to their means (zero). Resulting estimates included uncertainties, represented by 95% credible intervals.

#### 5.3.2.3 Results

Overall, there was substantial between-year variation in calculated RERs for the 12 PSRs where an RSE is reported (both between and within-river) and exploratory analysis suggested that the relationships with the *a priori* chosen explanatory variables were in the directions hypothesised.

##### 5.3.2.3.1 Explanatory variable effects and inference

Posterior estimates of explanatory variable effects from the Beta-Binomial model fits suggested that all *a priori* hypothesised variables, except for Base Flow Index (BaseFlowIdx) and Area (Hectares), explained a non-negligible amount of the variation in the mean of, or variation in, RER for the 12 PSRs where an RSE is reported (Table 5.4, Figure 5.7). Specifically, the 95% credible intervals of Angler effort (but not its second order term), Successful effort, and Mean flow effects were narrow and did not overlap 0, suggesting that their effects were non-negligible. The 95% credible intervals of Base Flow Index and Area (Hectares) effects meanwhile, were wide and although they did not overlap 0, their contribution to explaining variation in RER could be considered negligible owing to the high uncertainty in the estimates. Model selection confirmed that the most parsimonious model, taken to be the “best” model taken forward for inference and extrapolation, omitted the Base Flow Index and Area (Hectares) effects, suggesting that they were negligible (Table 5.4). MCMC chains for this model were well-mixing according to the convergence statistics and the random effect estimates were judged to be approximately Gaussian.

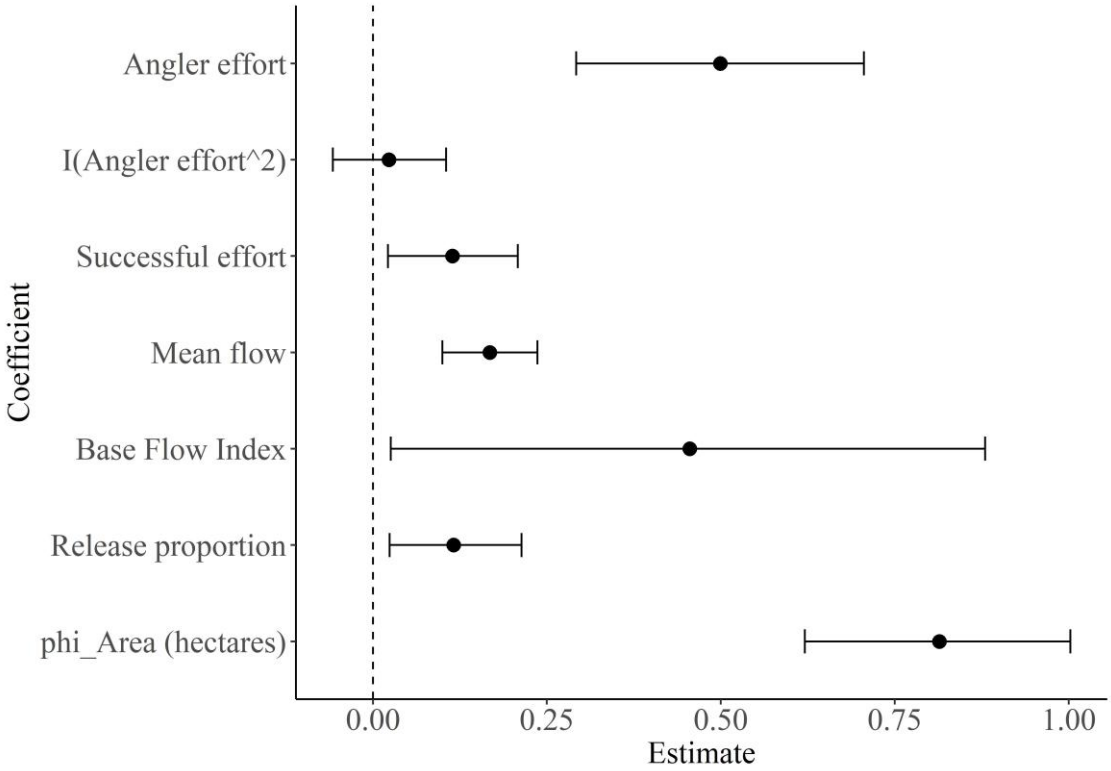



*Figure 5.7. A plot of the posterior coefficient estimate means and their 95% credible intervals for explanatory variables retained in the model describing Atlantic salmon rod exploitation rates on the 12 principal salmon rivers in England and Wales where a returning stock estimate (RSE) is reported. The effect of Base Flow Index whose credible intervals overlap the dashed line at 0 was considered negligible, whereas the effects of the other variables were considered non-negligible using Information Criteria.*

*Table 5.4. Model comparison table showing the variables tested in the μ and ϕ parts of the Beta-Binomial models, the leave-one-out cross-validation Information Criteria (looIC) and its difference from the saturated model (δlooIC) and the variation explained by the model ($R^2$). The random effect formulation (1 | x) expresses that they were included as random intercepts.*

| **Name** | **$\mu$ formula** | **$\phi$ formula** | **looIC** | **$\delta$looIC** | **$R^2$** | **Best** |
|---|---|---|---|---|---|---|
| saturated | SalCatch \| trials(RSE) ~ DeclSalEffHa_std + SuccessEff_std + mnflow_std + BaseFlowIdx_std + pRelease_std + (1 \| RiverName) + (1 \| Year) | phi ~ 1 + AreaHA_std | 2947.58 | 0.00 | 0.96 | 0 |
| no BaseFlowIdx | SalCatch \| trials(RSE) ~ DeclSalEffHa_std + SuccessEff_std + mnflow_std + pRelease_std + (1 \| RiverName) + (1 \| Year) | phi ~ 1 + AreaHA_std | 2947.90 | 0.31 | 0.95 | 1 |
| no BaseFlowIdx or AreaHA | SalCatch \| trials(RSE) ~ DeclSalEffHa_std + SuccessEff_std + mnflow_std + pRelease_std + (1 \| RiverName) + (1 \| Year) | phi ~ 1 | 3011.17 | 63.58 | 0.94 | 0 |
| no AreaHA | SalCatch \| trials(RSE) ~ DeclSalEffHa_std + SuccessEff_std + mnflow_std + BaseFlowIdx_std + pRelease_std + (1 \| RiverName) + (1 \| Year) | phi ~ 1 | 3011.92 | 64.33 | 0.94 | 0 |
| no BaseFlowIdx or AreaHA or mnflow | SalCatch \| trials(RSE) ~ DeclSalEffHa_std + SuccessEff_std + pRelease_std + (1 \| RiverName) + (1 \| Year) | phi ~ 1 | 3027.18 | 79.60 | 0.93 | 0 |

Plots of the explanatory variable partial effects confirm that the direction of the effects were as hypothesised (Table 5.3), including a quasi-linear effect of Angler effort (Figure 5.8). Specifically, the effects of Angler effort, Successful effort, Mean flow and Release proportion on RER were all positive, albeit sometimes weak.

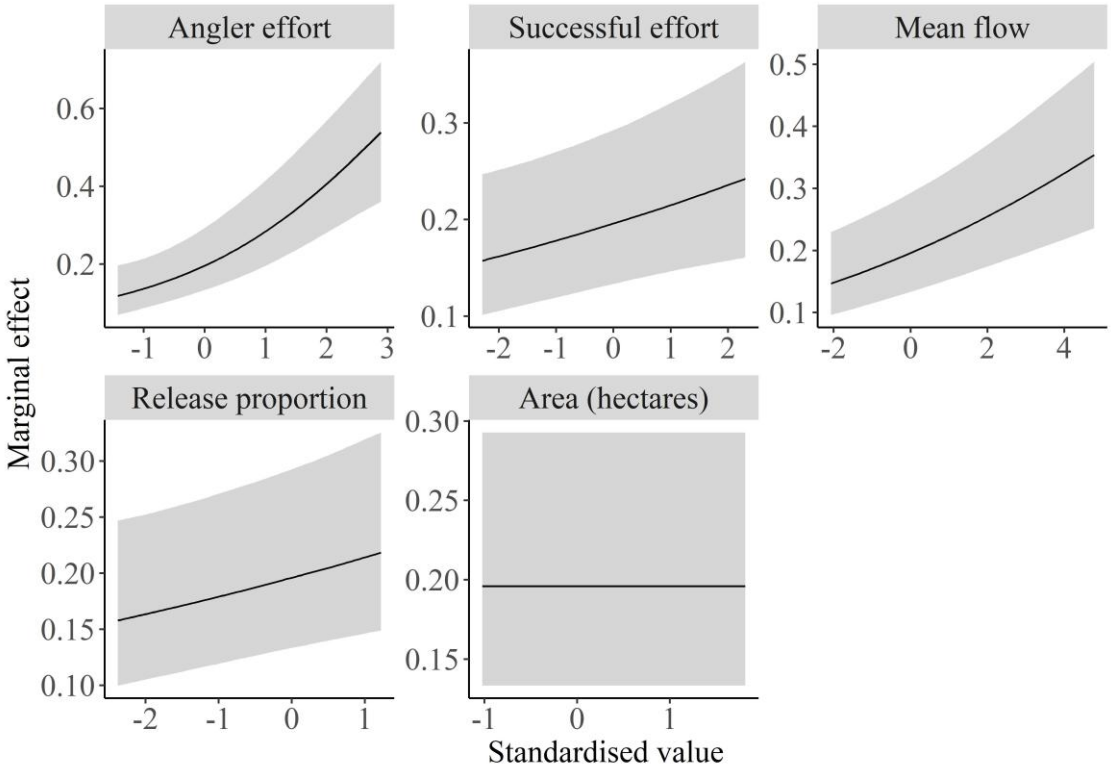



*Figure 5.8. Partial-effect plots showing the direction, shape and strength of explanatory variable effects on Atlantic salmon rod exploitation rate on the 12 principal salmon rivers in England and Wales where a returning stock estimate (RSE) is reported. Grey bands represent the 95% credible intervals of the partial effects.*

Line plots of the observed and estimated RER suggest that the model was able to describe the main patterns in RER inter-annual variations for each of the 12 PSRs with a RSE (Figure 5.9), albeit with many annual discrepancies, some of which were outside the estimated 95% credible intervals. Specifically, there were large discrepancies between observed and estimated RER on the rivers Avon (Hants), Fowey, Itchen, Kent and Leven, for which the 95% credible intervals of the estimated RER did not always include the observed value. Some of the correspondence

between observed and estimated RER was likely helped by the year random effect that allowed for a degree of synchronicity between rivers.

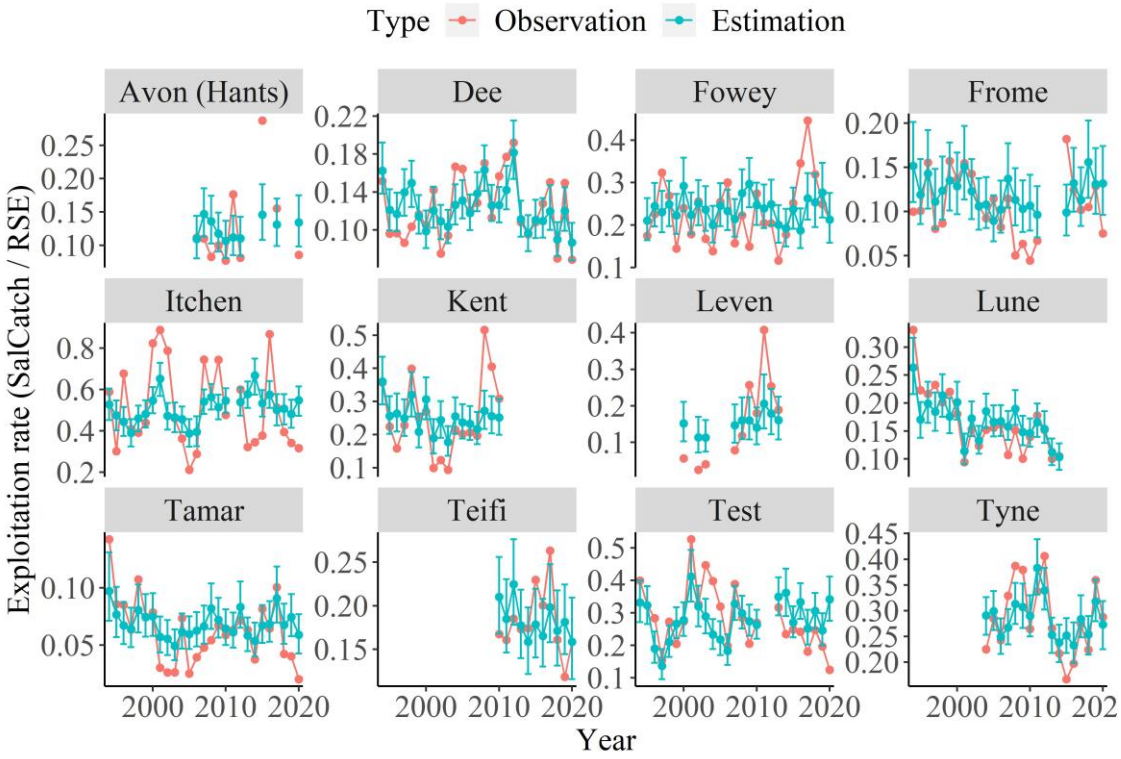



*Figure 5.9. Plots of the fitted Atlantic salmon rod exploitation rate on the 12 principal salmon rivers in England and Wales where a returning stock estimate (RSE) is reported. Points are the calculated observed RER values (Observation), or the posterior estimate means with error bars represent their 95% credible intervals (Estimation).*

#### *5.3.2.3.2 Model validation and extrapolation*

Visual inspection of the results from a (k = 10) fold stratified cross-validation experiment suggested that the “best” statistical model was able to predict annual catches for each of the 12 PSRs where a RSE is reported with reasonable certainty (Figure 5.10). Furthermore, posterior predictive checks suggested that the model was able to reproduce replicate response variables with comparable characteristics.

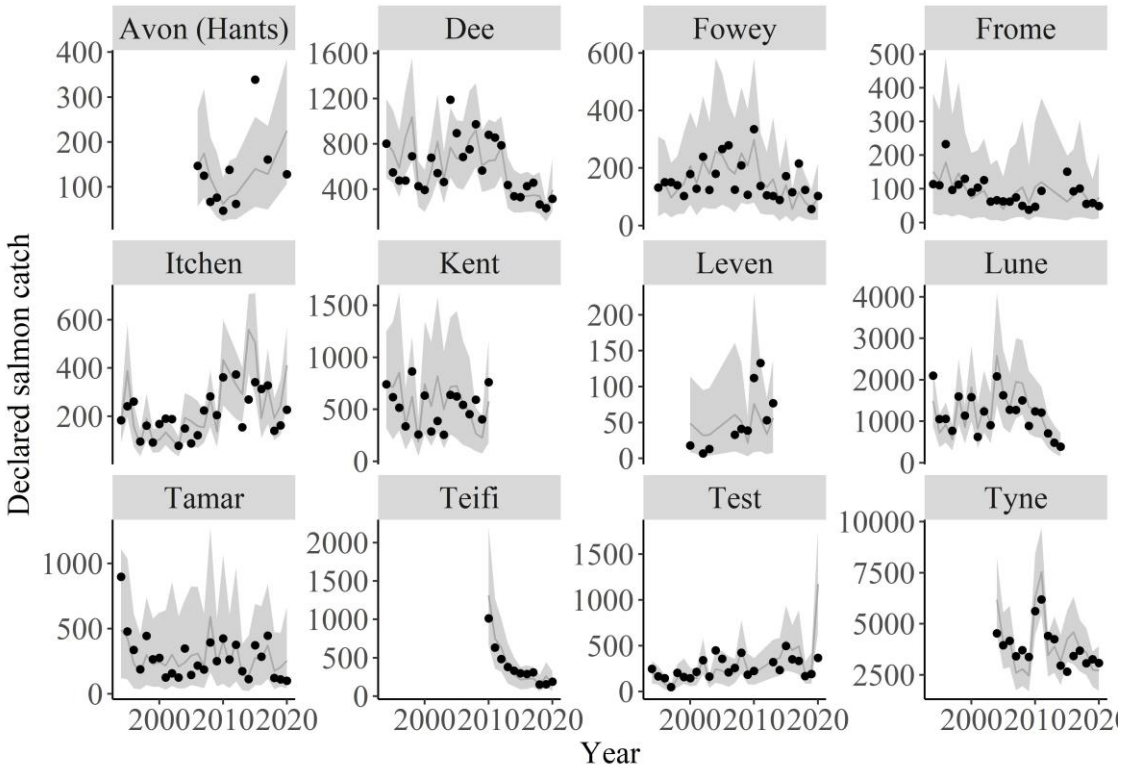



*Figure 5.10. A plot of the predicted k = 10-fold stratified cross-validation Atlantic salmon catches on the 12 principal salmon rivers in England and Wales where a returning stock estimate (RSE) is reported. Points are the observations, and the error bands represent the 95% credible intervals of their predicted values from the cross-validation.*

Having confirmed its predictive ability, the model was then extrapolated to the 52 PSRs where a RSE is not reported, as well as those years in the 12 PSRs where RSEs were missing (Figure 5.11). The resulting extrapolations seemed reasonable and a potentially useful baseline from which local experts and managers could make carefully audited changes.

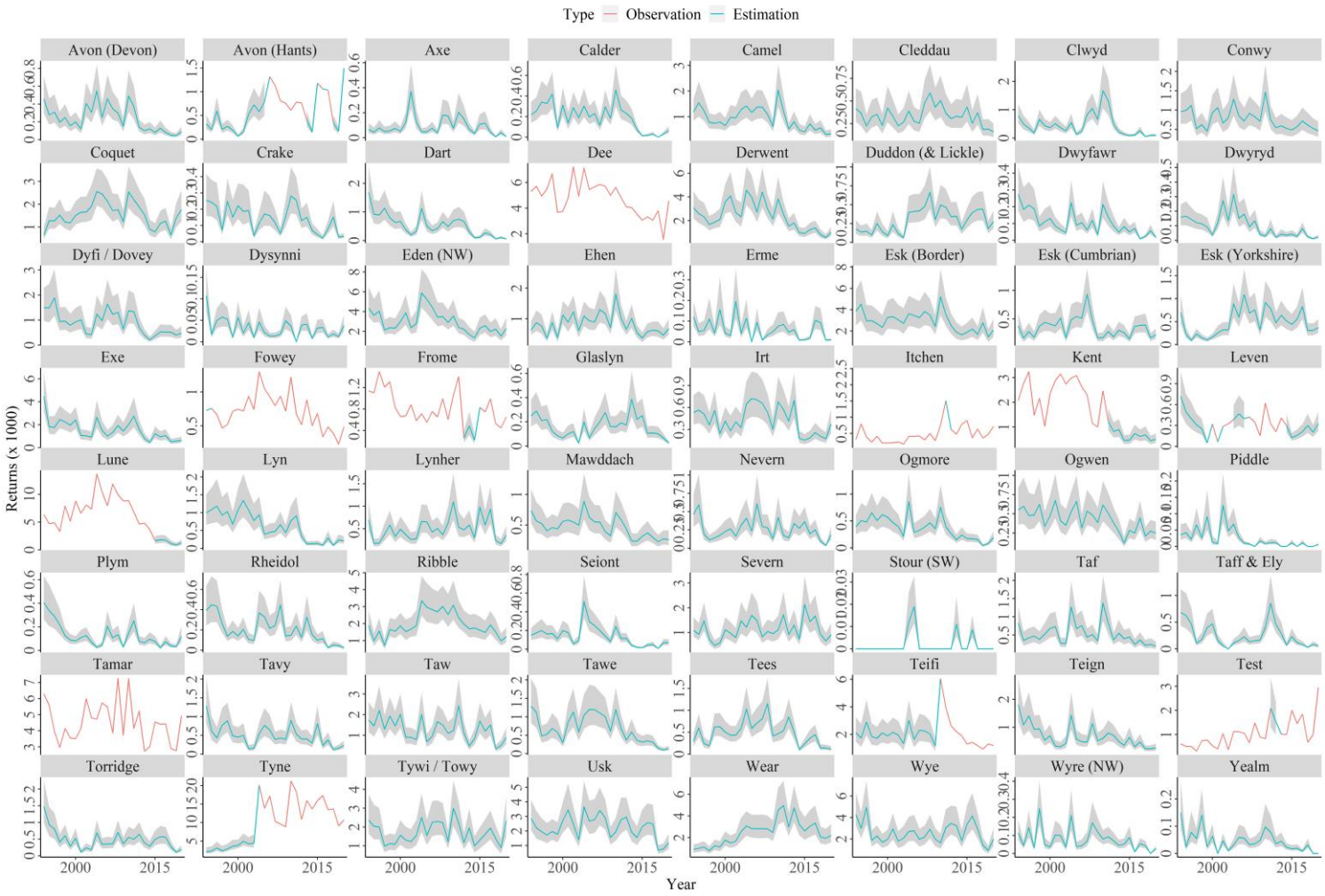



*Figure 5.11. A plot of the observed and estimated number of returning Atlantic salmon on the 64 principal salmon rivers in England and Wales. Lines link the annual posterior estimate means and confidence bands represent their 95% credible intervals.*

#### 5.3.2.4 Discussion

We present a consistent, transparent, and statistically robust method to derive annual salmon stock estimates from RER for all major salmon-producing rivers across E&W. This method shares similarities with a number of recently published methods, for example Lebot *et al*. (2022) and Mäntyniemi *et al*. (2015), but it extends them to make use of the comparatively rich data on angler catch and effort available for E&W, and to include consideration of non-linear effects of some of these explanatory variables. Our results suggest that many of these angling data can be included in the model to improve estimates of RER in ways predicted from our expectations. For example, Angling effort was positively related to RER (Davidson *et al*., 2017), as was Successful effort, suggesting that patterns in RER could be attributable to a few skilled or persistent anglers, which could see RER increase despite decreasing effort, as has been reported elsewhere (e.g., Beaumont *et al*., 1991). Using these additional data can help avoid the need for additional complexities and assumptions (assuming that the data are representative and complete) and might therefore better resonate with fisheries managers and anglers. However, our results also leave space for future and ongoing improvements to the model and its inputs to reduce discrepancies between observed and estimated RER in rivers with a RSE.

To explore whether the model was generalisable, we used a robust and stringent stratified cross-validation procedure. The successful validation of our model suggests that it can be extrapolated to data from rivers that were not used to parameterise it, thereby enabling us to use data from "data-rich" rivers to inform "data-poor" rivers (Bentley, 2015). Furthermore, the model appeared to be robust to rivers with highly contrasting declared salmon catches, deriving plausible predictions for rivers with low declared salmon catches, such as the rivers Stour (SW), Piddle and Yealm, each of which reported no declared catches in at least one year, to rivers with high declared salmon catches, such as the rivers Test and Itchen, perhaps due to more targeted effort on individual fish. There are only six (<10 %) chalk stream rivers among the 64 PSRs and yet four (30 %) of those were among the 12 for which an RSE is reported and were used to train this RER model. Angler behaviours, and perhaps fish behaviours, might differ for chalk stream rivers compared to non-chalk stream rivers (Beaumont *et al*., 1991). Nevertheless, we proposed and tested models including a base flow index as a measure of river type, but this index explained negligible variance in actual RER for the 12 rivers used to train the model. This suggests that any difference in RER between chalk stream and spate rivers is negligible, or at least a less important source of variation than those other explanatory variables that were retained in the final model.

The model outputs provide point estimates of salmon stocks returning to all 64 PSRs in E&W, together with an estimate of their uncertainty. The point estimates are an integral part of the E&W salmon stock assessment procedure, forming the basis for the calculation of spawner and egg numbers used to assess compliance with CLs and (thereafter) evaluate the need for management intervention to protect stock

status (Davidson *et al*., 2017; Cefas, EA and NRW, 2020). A logical extension of this process could be to allow uncertainties in the salmon stock estimates to propagate through to the assessment stage, thereby accounting for some additional uncertainty due to the salmon stock estimation process. For example, egg deposition estimates could be derived from spawning stock estimates including their uncertainties. Allowing for the propagation of such uncertainties through the stock assessment process would align with the precautionary approach recommended by NASCO (NASCO, 1998) and with the approaches appearing in neighbouring jurisdictions, such as the Republic of Ireland (White *et al*., 2016, 2023). In addition to the results for individual rivers, aggregating the salmon stock estimates to the whole E&W spatial scale within the model, thereby allowing for proper propagation of uncertainties, could provide an important input to the international salmon stock assessment process undertaken by the ICES Working Group on North Atlantic Salmon (ICES, 2023). Specifically, the stock estimates and their uncertainties could be conditioned on sea age splits and provided as estimates of adult returns for E&W, obviating the need for run-reconstruction and ensuring the national and international stock abundance estimates are closely aligned.

The Beta-Binomial approach taken here was chosen as a trade-off between ease of understanding and necessary complexity. As a trade-off, it is accepted and indeed encouraged that the outputs from the RER model are subject to review by regional experts before they are used in any stock assessment process. Changes to the outputs could be achieved in a variety of ways, including (but not limited to) (1) modifying the characteristics of the priors given to the model to better represent, for example, mean river-specific RERs, or (2) modifying the outputs directly, especially where there are unique events, such as the introduction of a local byelaw or the effects of the coronavirus pandemic on angling effort (Cefas, EA and NRW, 2021a), that might affect annual estimates in ways that the core RER model may not account for fully. In the former case, without additional information, the salmon stock estimates for rivers where an RSE is not reported will be derived from an overall mean RER (albeit with a river-specific deviation), which might need to be altered to ensure salmon stock estimates are, on average, lower / higher or less / more variable than estimated. In the latter case, it will be imperative that such changes to the output are carefully recorded to ensure that these can be fully accounted for during any audits and future assessments. Aside from the model outputs, the model and its input data should use the best available information and as such are subject to future and ongoing improvements, and we encourage the reader to visit the model codes (released at https://github.com/CefasRepRes/salmon-rod-exploitation) to check for updates.

If we can move away from the need for ease of understanding and incorporate additional complexities that might make the estimate of salmon stocks even more realistic, then there are a few clear ways that our model could be improved. Although we included Release proportion as an explanatory variable of RER in our model, we know that releasing a fish back into the river – although it won't change the annual run of fish to that river (or RSE) – will, in general terms, change the number of fish

available to be caught when compared, for example, to past practices where it was usual for most rod-caught fish to be killed. However, while more fish may be available to capture (in relative terms, because they are being released rather than killed) than in former times, the true rate at which they are caught (i.e., the vulnerability to capture of the average fish) may not change greatly. If this was an issue, we could address it by modelling the number of available fish explicitly. This could be done by, for example, using a separate sub-model to estimate the number of fish available, such as a coupled Poisson-Binomial approach (e.g., Marsh *et al*., 2021; Lebot *et al*., 2022), or by using state-space models that model the ecological and observation processes separately (Buoro *et al*., 2019; Gregory *et al*., 2019). Either of these approaches would allow other available data representing factors affecting catches or stocks to be incorporated directly, rather than by proxy. Whether this type of alternative approach is needed would require further investigation into this issue.

Another extension of our model would be to modify it to estimate different salmon stock components separately – namely 1SW and MSW fish – rather than combined, as is done here. Salmon stock assessments frequently account for these two sea-age groups separately, principally for fisheries management purposes because they have different reproductive potentials, but also to help maintain the biological diversity of returning stocks. This has been the case, for example, in the high seas mixed-stock fisheries off Greenland and the Faroes, where these two stock components have faced different levels of exploitation by virtue of different migratory patterns (ICES, 2021). Similarly, management of homewater fisheries in the UK and elsewhere accounts for 1SW and MSW fish separately, although the CLs set for individual river stocks in E&W do not distinguish between these stock components. Salmon that have spent longer at sea tend to be larger and enter rivers earlier than those staying out for shorter periods. Larger salmon produce more eggs but can also be subjected to different (higher) RERs as anglers seek bigger quarry, but also, in the case of early run MSW fish, because of differences in catchability and the length of time fish are exposed to the fisheries (Davidson *et al*., 2000; Shelton, 2001a). These points could have important implications for salmon stock assessment (Thorley *et al*., 2007; Lebot *et al*., 2022). Sea-age-specific RERs could be dealt with separately by extending this Binomial sampling to multinomial sampling with Dirichlet priors informed by sea-age specific explanatory variables (Douma and Weedon, 2019).

Aside from modifications to the approach taken here, the outputs could also be improved by enhancements to the inputs. For example, we could include additional explanatory variables to explain more of the high inter-annual variability in RER. These might include angling method/gear (Shields *et al*., 2007; Grilli *et al*., 2021), which could also extend to angling restrictions, such as bait bans and barbless hooks. Data on the method of capture are submitted as part of routine catch returns, but they refer to captured fish only and so may not reflect method selection generally. Ideally, to include ‘capture method’, we would want to ensure that the sample of rivers used to parameterise the model included some that prohibited

certain angling methods alongside others that did not. Another area for possible model improvement relates to variation in migration or run timing of returning adult salmon. Evidence suggests, sometimes from fish counters and traps, that run timings have changed and might continue to change, perhaps in response to changing conditions at sea (de Eyto *et al*., 2022). Although this could be considered as an additional explanatory variable, as suggested above it could be better represented in state-space models.

Notwithstanding additional explanatory variables, we could also improve the variables already included. For example, Angler effort is currently adjusted to separate effort for salmon vs. sea trout; however, this adjustment is made based on only two angler surveys several years apart. Instead, rod licence returns could be adjusted to ask anglers to specify their effort split as part of routine rod licence reporting. Similarly, Angler effort is currently recorded only in 'days' (effectively the number of daily fishing sessions per river per year), whereas actual time spent fishing would be more nuanced and, if this were better recorded, then it could be used to produce a more realistic weighting of angler effort. After investigations into a variety of flow metrics, such as numbers of seasonal spate events, we used river discharge as Mean flow. There are, however, many other ways that this could be defined (see Gillson *et al*. (2020)) that could better explain variation in RER while also capturing our understanding of the complex relationships between river discharge, fish and angler behaviours. Notwithstanding changes to the inputs, we could also include additional random terms that could allow for between-year variation within rivers, for example.

Salmon stock sizes have declined dramatically over the last 70 years (Limburg and Waldman, 2009; Chaput, 2012; ICES, 2021). Commercial salmon fishing was cited as the main driver of these declines during the 20$^{th}$ century (Limburg and Waldman, 2009; Chaput, 2012), particularly large commercial catches off West Greenland, where salmon are thought to aggregate on feeding grounds (Dadswell *et al*., 2010; Olmos *et al*., 2019). Yet, salmon stock sizes have continued to decline despite the closure of those commercial fisheries in 1998, leading to widespread closures of local and small-scale mixed stock fisheries along national coastlines and in estuaries (Chase, 2003). While there is no doubt that these closures have been beneficial to salmon stock numbers, they represent the loss of a data stream that could have been used in national and international salmon stock assessments (Youngson *et al*., 2003).

Given the state of salmon stocks and the subsequent loss of stock assessment data, there is a need to use available data to the best effect possible. To this end, the approach to estimating salmon stocks for all 64 PSRs in E&W presented here represents a consistent, transparent, and statistically robust method that uses information from "data-rich" rivers to inform estimates for "data-poor" rivers. This approach could be extended relatively simply to include newly available data, such as may derive from to technological advances or exploiting publicly available data (Lennox *et al*., 2022) and could form the basis of a more comprehensive approach

that separates the ecological and observation processes, should that be needed. It does, however, still require angler-reported catch and effort data and some fishery-independent stock estimates without which we will need to seek an alternative approach to stock estimation.

**Recommendation 3**

*Estimation of annual salmon rod exploitation rates (RER) for each Principal Salmon River should ideally be derived using a single, consistent, transparent and statistically robust method such as that presented in Section 5.3.2. Where model outputs conflict with empirical evidence, the annual RER may be adjusted by local Area Fisheries Technical Specialists in discussion with local stakeholders, providing a sound and justifiable case is clearly documented and agreed with Agency National Specialists Group. The new national methodology for estimating exploitation rates should be reviewed and updated periodically to ensure that the most appropriate data and statistical procedures are being utilised.*

**Recommendation 4**

*Fishery-independent returning stock estimates, such as those derived by resistivity counters and fish traps, and fishery-dependent data on angler catches and effort, are the backbone of the current salmon stock assessment, and every effort should be made to safeguard their continued supply, including investment in infrastructure to collect, validate, and store their underlying data.*

**Proposal 10**

*If the method to estimate annual salmon rod exploitation rates presented in this review is used, as recommended (Recommendation 3), then it should be extended to provide one-sea-winter (1SW)- and multi-sea-winter (MSW)-specific exploitation rates (and associated uncertainties) directly as model outputs, rather than deriving them from post-treatment of the combined (posterior) estimate.*

#### *5.3.2.5 Supplementary information*

Supplementary information for this section, i.e., Figures and the R session info and model summary, can be downloaded from the journal website for the published peer-reviewed paper at https://academic.oup.com/icesjms/article/80/10/2504/7335584#supplementary-data.

### 5.3.3 Updates to the Rod Exploitation Rate (RER) model

In this section, we present updated results due to updating the data from 2021 to 2023 and introducing a change to the model, specifically including catchment area in the mean part of the Beta-Binomial regression.

#### *5.3.3.1 Updated data*

All data were updated to include data for 2021 to 2023 for the revised analysis.

There was no change in the 64 salmon rivers considered to be PSRs in 2021 or 2022.

Principal Salmon Rivers that report a RSE are the Avon (Hants), Dee, Fowey, Frome, Itchen, Kent, Leven, Lune, Tamar, Teifi, Test, and Tyne. For a variety of reasons, the Lune, Kent, and Leven did not report a RSE in 2021 to 2023; all the other rivers reported a RSE in 2021 to 2023 (Figure 5.12).

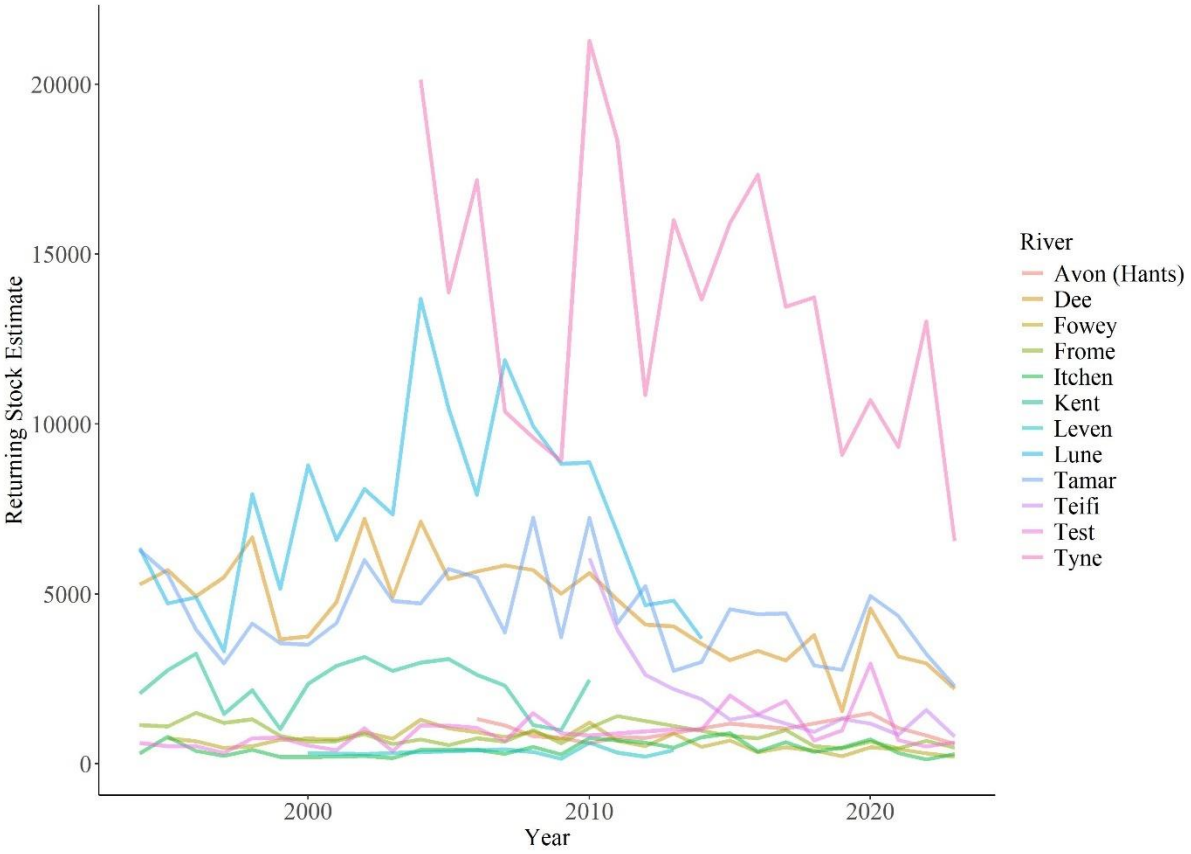



*Figure 5.12. An updated (using data to 2023) plot showing returning stock estimates (RSE) for each RSE river.*

The EA RCdb was updated annually in 2021 to 2023, as is customary. Using the updated RCdb data, effort declaration rate was calculated for 2021 to 2023. It is noted that there was no declared effort on the River Yealm in 2021, a situation unprecedented in this or any other PSR since 1994. To allow for this possibility in other rivers and years in the future, the scripts were adjusted to enter a zero in the declared catch. This also required a few other changes to the scripts, including in-filling other missing fields in those rivers and years. Using the updated RCdb data, the variables Angler catch, Angler effort, Successful effort, and Release proportion were all updated to include data from 2021 to 2023. The script was simplified to use the “last observation carried forward” for missing proportion released values, rather than the mean of the two preceding non-missing values.

Licence declaration rates were updated for 2021 to 2023 using owners’ returns, where applicable.

There were no changes to the salmon angling effort rate, which was based upon angler surveys done in 1992 and 2006.

The RER explanatory variable Mean flow was updated for 2021 to 2023, with some notable changes and additions. The daily river flow data for Gregory *et al*. (2023) was collated from the CEH National River Flow Archive (NRFA). A renewed interface to the Hydrology Data Explorer (HDE), including more spatial and temporal coverage and more functionality, was released in March 2023. For most rivers, the daily river flow gauging station used in Gregory *et al*. (2023) could be updated to include data for 2021 to 2023, from the NRFA or the HDE. For a few gauging stations, however, the HDE held more complete and consistent river flow data than the NRFA, and the decision was taken to draw data from the HDE rather than the NRFA. Missing data in the resulting daily river flow data were imputed using NRFA and/or HDE data using the "epipercentile" method, recommended by Harvey *et al*. (2012), and the resulting time series was used to calculate the mean flow variable.

The Base Flow Index and Area (hectares) for each river did not change and were the same as for Gregory *et al*. (2023).

The updated explanatory variables are shown in Figure 5.13.

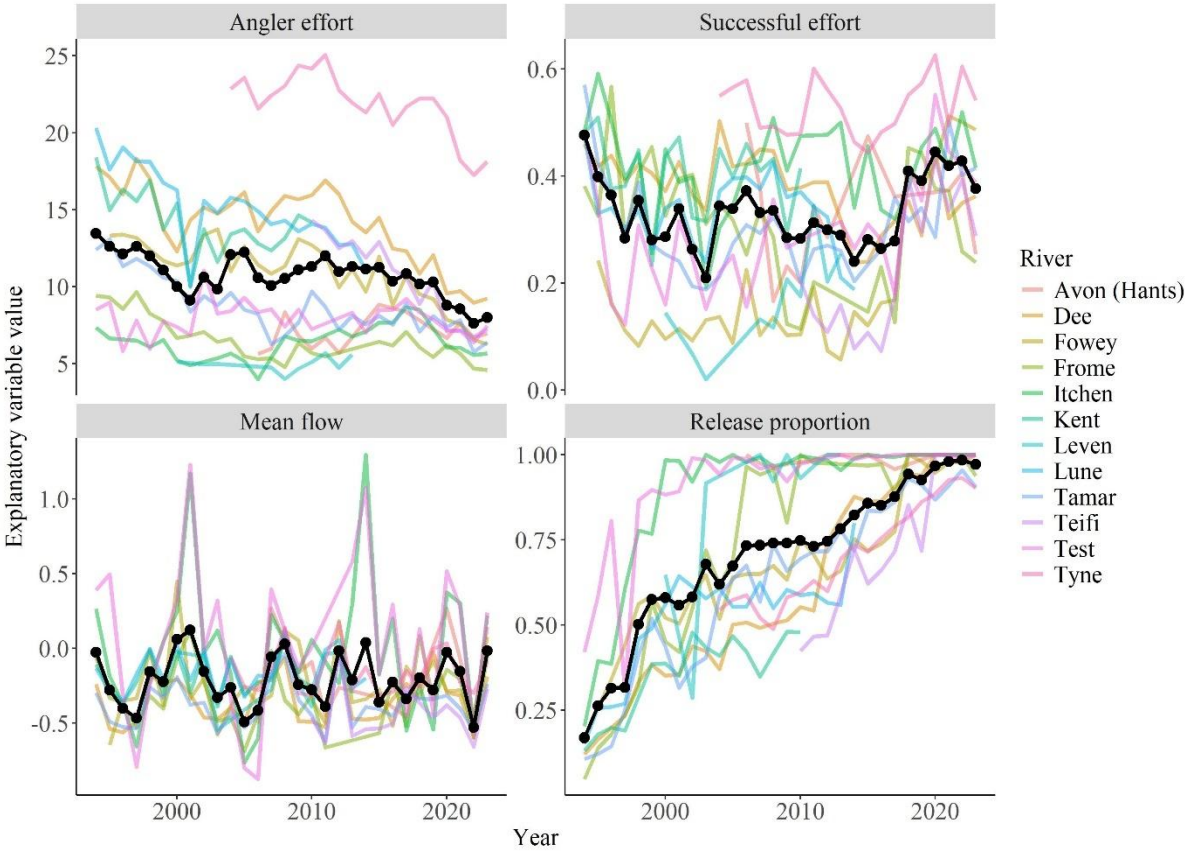



*Figure 5.13. Updated (using data to 2023) plots showing explanatory variables expected to describe variation in Atlantic salmon rod exploitation rate for each RSE river. Black lines represent the mean explanatory variable values across all rivers.*

#### 5.3.3.2 Updated rod exploitation rate model

Following the publication of Gregory *et al*. (2023), discussion among its co-authors identified a possible explanatory variable – log area (hectares), also known as lnAreaHA – that could be included in the model to account for apparent differences in the expected mean exploitation rate between rivers of different sizes. A more detailed investigation of the proposal to include it as an explanatory variable of expected mean exploitation rate is provided in a document "areas-model-exploitation-comparisons.html" that is available on request. Here, we took the decision to include lnAreaHA in the models including 2021 to 2023 updated data. So, the symbolic formula (written in R syntax) for the saturated model was (note the line tagged "# NEW"):

```
# R code for the saturated model fit using brms

saturated_model <- bf(SalCatch | trials(RSE) ~ 1 +

   poly(DeclSalEffHa_std, 2, raw = TRUE) +

   SuccessEff_std +

   mnflow_std +

   BaseFlowIdx_std +

   pRelease_std +

   lnAreaHA_std + # NEW

   (1|RiverName) + (1|Year),

 phi ~ 1 +

   AreaHA_std +

   (1|RiverName))
```

#### 5.3.3.3 Updated results

There is no qualitative difference between the results published in Gregory *et al*. (2023) using data up until 2020 and the results presented here that include: (1) updated data from 2021 to 2023, (2) some changes to the sources of river flow data, (3) some changes to the licence declaration rate data, and (4) inclusion of log area (hectares) as an additional explanatory variable of the expected mean exploitation rate of each river.

The “best model” was still the model omitting the base flow index variable (Table 5.5), albeit that its credible intervals did not intercept zero (Figure 5.14).

*Table 5.5. An updated (using data to 2023) model comparison table showing the variables tested in the μ and ϕ parts of the Beta-Binomial models, the leave-one-out cross-validation Information Criteria (looIC) and its difference from the saturated model (δlooIC) and the variation explained by the model (R2). The random effect formulation (1 | x) expresses that they were included as random intercepts.*

| Name | μ formula | ϕ formula | looIC | δlooIC | $R^2$ | Best |
|---|---|---|---|---|---|---|
| no BaseFlowIdx | Catch \| RSE, mu ~ DeclSalEffHa_std + SuccessEff_std + mnflow_std + pRelease_std + lnAreaHA_std + (1 \| RiverName) + (1 \| Year) | phi ~ 1 + AreaHA_std | 3241.43 | 0.00 | 0.96 | 1 |
| saturated | Catch \| RSE, mu ~ DeclSalEffHa_std + SuccessEff_std + mnflow_std + BaseFlowIdx_std + pRelease_std + lnAreaHA_std + (1 \| RiverName) + (1 \| Year) | phi ~ 1 + AreaHA_std | 3241.51 | 0.08 | 0.96 | 0 |
| no BaseFlowIdx or AreaHA | Catch \| RSE, mu ~ DeclSalEffHa_std + SuccessEff_std + mnflow_std + pRelease_std + lnAreaHA_std + (1 \| RiverName) + (1 \| Year) | phi ~ 1 | 3311.69 | 70.26 | 0.94 | 0 |
| no AreaHA | Catch \| RSE, mu ~ DeclSalEffHa_std + SuccessEff_std + mnflow_std + BaseFlowIdx_std + pRelease_std + lnAreaHA_std + (1 \| RiverName) + (1 \| Year) | phi ~ 1 | 3312.43 | 71.00 | 0.94 | 0 |
| no BaseFlowIdx or AreaHA or mnflow | Catch \| RSE, mu ~ DeclSalEffHa_std + SuccessEff_std + pRelease_std + lnAreaHA_std + (1 \| RiverName) + (1 \| Year) | phi ~ 1 | 3326.09 | 84.66 | 0.94 | 0 |

Presented below are the updated results plots in Gregory *et al*. (2023), in the order that they are presented in Gregory *et al*. (2023).

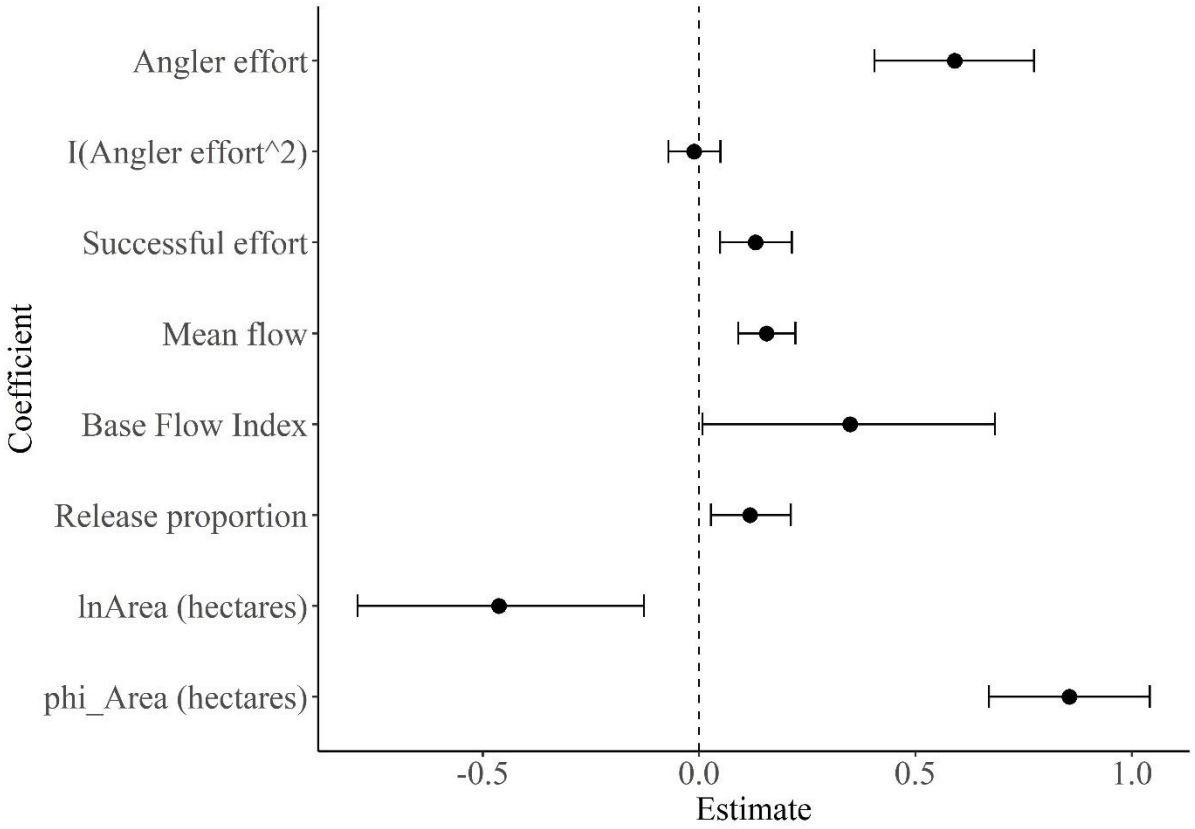



*Figure 5.14. An updated (using data to 2023) plot of the posterior coefficient estimate means and their 95% credible intervals for explanatory variables retained in the model describing Atlantic salmon RERs on the 12 PSR in E&W where a RSE is reported. The effect of BaseFlowIdx whose credible intervals overlap the dashed line at 0 was considered negligible, whereas the effects of the other variables were considered non-negligible using Information Criteria.*

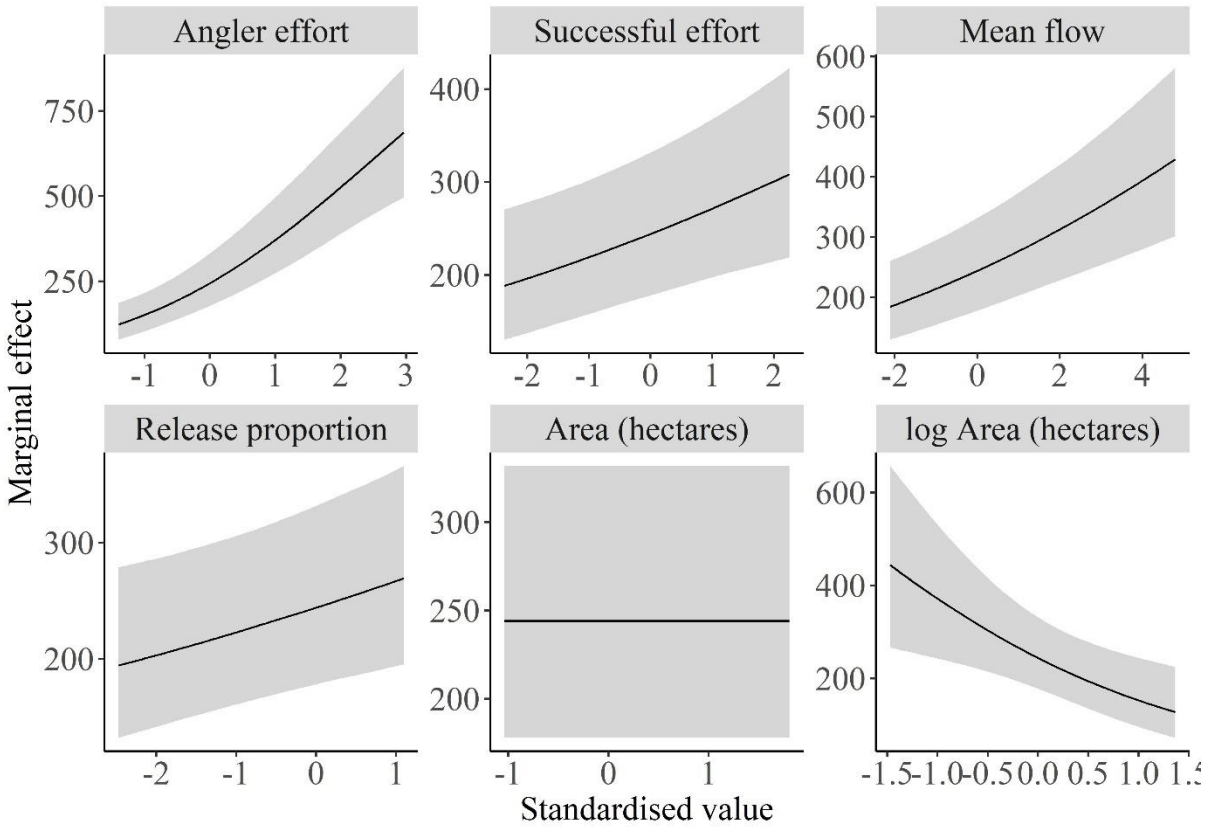



*Figure 5.15. Updated (using data to 2023) partial-effect plots showing the direction, shape, and strength of explanatory variable effects on Atlantic salmon RER on the 12 PSR in E&W where a RSE is reported. Grey bands represent the 95% credible intervals of the partial effects.*

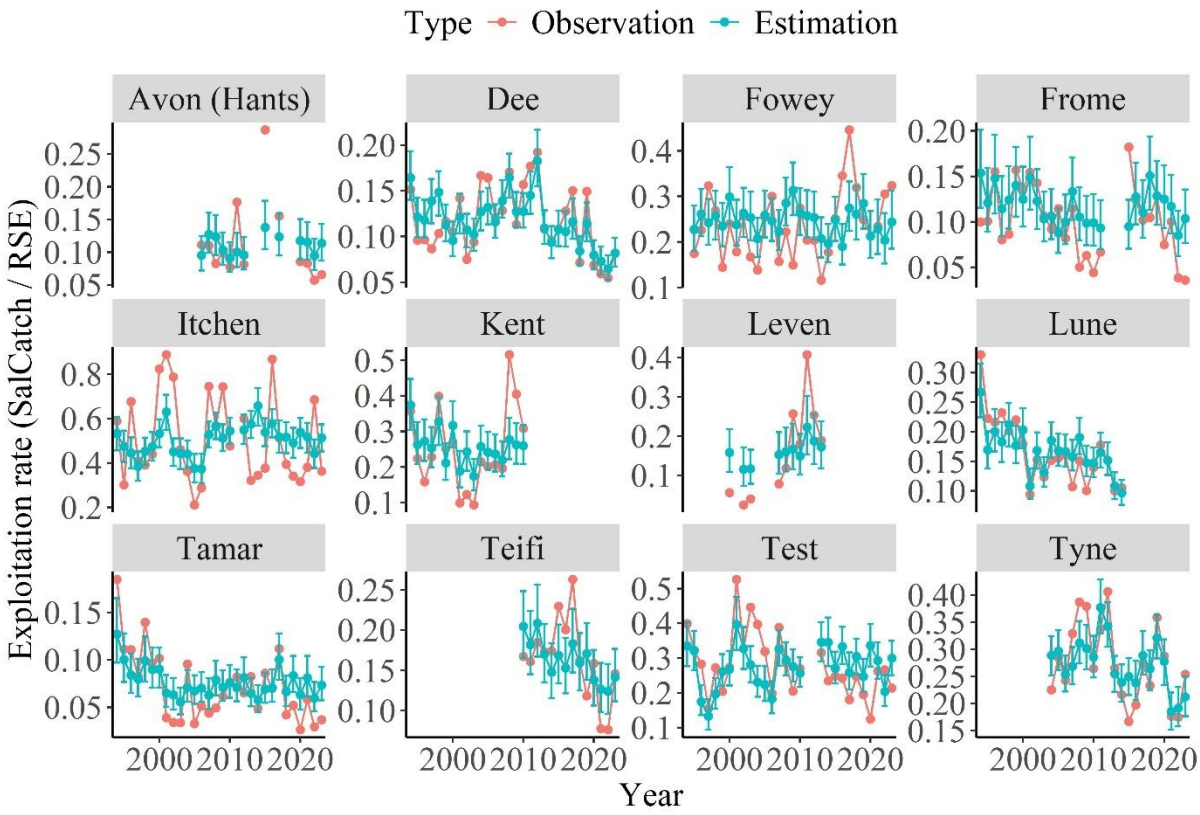



*Figure 5.16. Updated (using data to 2023) plots of the fitted Atlantic salmon RER on the 12 PSR in E&W where a RSE is reported. Points are the calculated observed RER values (Observation), or the posterior estimate means with error bars represent their 95% credible intervals (Estimation).*

The validation and extrapolation to returning stock estimates on the other 52 PSRs (and missing years in the 12 PSRs reporting an RSE) are shown.

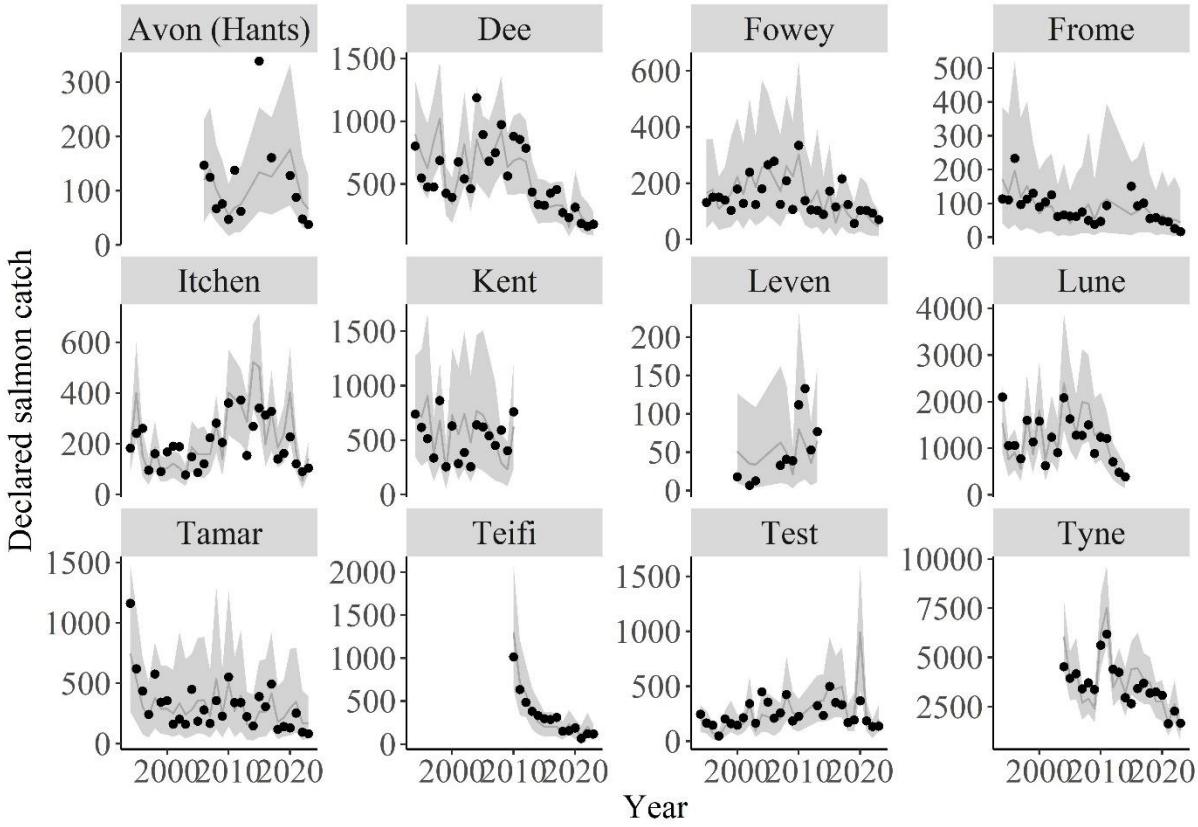



*Figure 5.17. An updated (using data to 2023) plot of the predicted k = 10-fold stratified cross-validation Atlantic salmon catches on the 12 PSR in E&W where a RSE is reported. Points are the observations, and the error bands represent the 95% credible intervals of their predicted values from the cross-validation.*

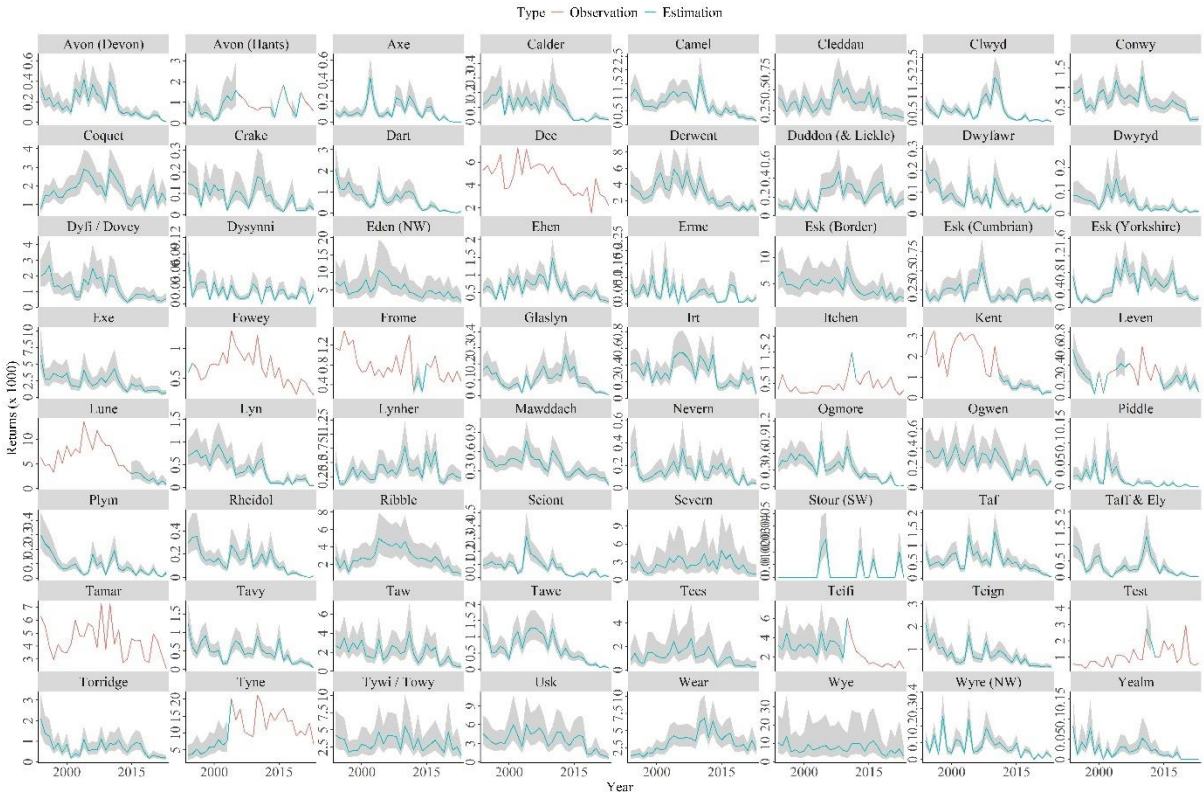



*Figure 5.18. An updated (using data to 2023) plot of the observed and estimated number of returning Atlantic salmon on the 64 PSR in E&W. Lines link the annual posterior estimate means and confidence bands represent their 95% credible intervals.*

### *5.3.3.4 Discussion about updates to data since Gregory et al., 2023*

There is no qualitative difference between the updated results presented here and those presented in Gregory *et al*. (2023), despite a few changes to the methods. However, there is every reason to expect there to be future differences as new data are introduced to the model, as those new data might uncover or strengthen formerly weak relationships. For example, the estimated effect of the base flow index explanatory variable was more certain with these updated data, albeit that the “best model” judged using our methodology still omitted it.

Following consultation with Hydrology experts from the EA, the network of gauging stations used to obtain river flow data for each principal salmon river in England will be revised to incorporate the most reliable gauge within each catchment, thereby ensuring a continuous and accurate time series with minimal data gaps. Where gaps exist in any given year, the data are infilled using a standardised methodology, or a known relationship with a nearby gauging station. Flow data for English principal salmon rivers are obtained from the EA Hydrology Data Explorer (https://environment.data.gov.uk/hydrology/landing) each year to update the time

series used to calculate the mean flow variable. For Welsh principal salmon rivers flow data will be provided directly by the NRW Hydrology team each year.

## 5.4 Post-Release Survival and Recaptures

The estimate of catch and release (C&R) survival that we apply within the stock assessment method is 80%. This value was primarily based on the results of a radiotracking study of 208 salmon caught by rod-and-line from the River Eden between 1999 and 2002 (Gowans, 2004). In that study, from 63.9% to 93.0% of rod-caught salmon that were radio-tagged were tracked to spawning (representing 'worst' to 'best case' survival scenarios, respectively). Overall, based on these 208 rod-caught salmon that were caught using fly and spinning methods and accounting for the effect of the study, it was estimated that at least 85% of released rod-caught salmon would be expected to survive to spawn. For the purposes of applying a C&R survival rate to all river stock assessments, this estimate was rounded down to 80% to account for likely higher mortalities associated with bait (specifically worm) fishing methods that were avoided in this study. This value is effectively a combination of natural mortality plus the mortality associated with C&R and is consistent with values used by other countries. A default natural mortality rate of 9% between river entry and spawning is applied to the fish that are not caught (Milner *et al., 2000)*.

This overall survival rate could potentially be refined in the future to reflect the differing proportions of the rod catch that are taken on different fishing methods. Strictly that would require more definitive evidence than is currently available on the survival of fish caught by different methods. That should not detract from the imperative to adopt C&R best practice to maximise post release survival.

Reviews by Cowx *et al*. (2017) and Lennox *et al*. (2017) recognise a pattern of highest survival amongst fish caught on fly, intermediate survival amongst fish caught on spinner/lure and lowest survival amongst fish caught on bait that are more commonly, although not exclusively, deep-hooked. While the Lennox *et al*. (2017) review estimates survival rates associated with the different fishing methods, it should be recognised that a particularly low number of salmon were caught on bait, potentially associated with the nature of the tracking studies reviewed if researchers avoided the tracking of bait-caught salmon.

Water temperature is also recognised as an important factor influencing post-release survival, with higher water temperature at the time of capture tending to cause lower survival. As freshwater potentially warms up in future climate change scenarios, this could make C&R mortality more common or require at least the temporary closure of fisheries at higher temperatures (van Leeuwen *et al*., 2020).

While most studies on C&R survival focus on the rate of survival prior to spawning, Bouchard *et al*. (2022) identified a potential impact of C&R on subsequent reproductive success. They found that the reproductive success of salmon subject to

C&R (measured as the number of assigned offspring) was reduced by 26% (CI:14%–37%) compared to non-caught fish. So, while a high proportion of the C&R salmon survived to spawn (~83%), their actual success in producing viable offspring was reduced when compared to non-caught salmon.

At the time of writing, net and fixed engine fisheries that are licensed to operate in E&W are required to release all salmon caught. We currently do not have a reliable assessment of the degree of C&R survival associated with netting methods. Evaluation of the effect of C&R survival by different nets should be examined when considering remedial measures including balancing net and rod fishery impacts when considering regulatory changes.

The overall percentage of rod caught fish released by anglers has increased progressively since such data were first recorded in 1993 (10%) to exceed 90% in recent years (Cefas, Environment Agency, and Natural Resources Wales, 2023). The use of C&R is intended to increase the number of fish surviving to spawn and thus help rivers to meet their CLs and achieve long-term sustainability of the stocks. However, the extent to which C&R may directly affect catches within the fishing season is unclear. Several published studies have reported recapture rates ranging between 0 and 13% (Gargan *et al*., 2015; Gowans, 2004; Gowans *et al*., 1999; Lennox *et al*., 2015; Thorley *et al*., 2007; Thorstad *et al*., 2003; Thorstad *et al*., 2019; Whoriskey *et al*., 2000). Over the range of studies reported, the average recapture rate was approximately 7%.

Results from unpublished data from the Welsh Dee (2007-2013) have also provided some information on the recapture rates for rod-released salmon. In this tagging study, the rates of recapture for rod-released salmon were highly variable between years, ranging from 0 to 18%, but averaged close to 7%, which equates to around a third of the initial capture rate of 21%.

To illustrate the possible effects of multiple C&R of individual fish on declared catches, in a scenario where:

i. fish experienced an initial rod capture rate of 15% (in line with the general average exploitation rate for rivers in England and Wales);
ii. the C&R rate was 100%;
iii. the rod capture rate for released fish was half the initial or subsequent capture rate; and
iv. no fish were caught more than three times;

then, for every 1,000 fish entering the rod fishery, 150 would be caught at first capture, ~11 at second capture and ~1 fish at third capture. Thus, the total catch of ~162 fish would be ‘inflated’ by recaptures of released fish by only around 8%. This is a relatively small amount and so may be of little concern, for example, as a source of error in estimating spawning escapement from rod catches.

Time of capture within the fishing season has been shown to be an important factor in influencing the likelihood of a fish being caught more than once. The study by Thorley *et al*., (2007) on the River Spey reported that recapture rates were markedly higher for fish entering rivers and initially captured early in the year (January to March), than for fish that were initially captured later in the season (May to July). The implication of this observation is that it will be the multi-sea-winter component of the stock that will be at greatest risk of being captured more than once and therefore be over-represented in catch data and egg deposition calculations. Having said that, the seasonal pattern of low early season catches, and high late season catches on English and Welsh rivers means that the likely effect of over-representation of the MSW component will be small.

Further consideration should be given to perceptions of potentially high rates of recapture on chalk streams and some small West Country rivers, where fish lies are predictable and individual fish are very visible, so may be directly targeted repeatedly by anglers. Understanding likely recapture rates in these scenarios would be particularly valuable.

Incorporating the likelihood of recapture into the current egg deposition calculations would not be a straightforward process, given the way that calculations are currently structured around weight and sea-age categories. While a correction factor-type approach could be applied to the declared rod catch, based on the average recaptures form reported studies, this might seem overly crude in this context in applying a fixed adjustment to all rivers where more variability in rates of recapture might be justified. Also, such an approach could easily over-estimate potential recaptures, given the high proportion of the catch that is taken at the end of the fishing season, when the likelihood of recapture is likely to be low.

Further assessment of scenarios such as the above is required to incorporate the likely impact that the recapture of released fish will have on total stock estimates across the full range of rivers and considering the increasing emphasis on the use of C&R.

**Proposal 11**

*Research studies are required to better inform the derivation and application of recapture rates based on season, sea-age and river types. The method of calculating the annual egg deposition of the salmon stock should be re-structured to more accurately reflect and account for the frequency of recaptures.*

## 5.5 In-river survival

The estimate of in-river survival applied in the stock assessment method is 91%, which corresponds to a 9% rate of mortality (Environment Agency, 2003*)*, as noted above. This estimate represents fish lost due to factors other than licensed rod

catch, so mainly natural mortality and illegal catch. Estimates for in-river survival are difficult to obtain, but radio-tracking studies give some insight into the proportion of fish that suffer mortality during their upstream freshwater spawning migration. Data from the Twyi (Clarke *et al*., 1994) indicate total losses of 10%, comprising 5% illegal catch and 5% natural mortality. On the Welsh Dee, provisional data (1991-1993) show similar losses of 8%, comprising 2% illegal catch and 6% natural mortality. There may be good reasons why losses should vary on different rivers, but the recommended start value is 9%. Note that this value is incorporated in the post-release mortality rate for those fish caught-and-released, as they could still be subject to other in-river impacts.

Observations in recent years have identified a variety of emerging natural stressors on salmon that could potentially affect the natural mortality rate, such as Red Vent Syndrome, Red Skin Disease and increased incidence of fungal infections with associated mortalities. Such stressors, combined with rising water temperatures, mediated through climate change, could potentially decrease the in-river survival rate. There are no / insufficient data from which to develop corrections for such mortalities, but these remain under surveillance.

**Proposal 12**

*In addition to assessing the percentage of repeat rod and line captures, there is a need to evaluate whether levels of natural mortality have also varied over time as a consequence of environmental change, disease risk and changes in predator distribution, all of which may have significant consequences for egg deposition and future smolt output.*

## 5.6 Angler reporting of catch weights

While the age-weight keys for the rivers Dee and Tamar are based on the controlled sampling (including weighing) of adult fish, the origin of weights submitted in the catch returns of anglers, i.e. whether from weighed fish or estimated, is unknown. Furthermore, the opportunities to compare the weights of individual fish from these two sources are limited.

On the Welsh Dee, Floy tagging of trap-sampled salmon has been carried out since the early 1990s to estimate run size by mark-recapture. This relies on angler reported tag returns. In the case of several recaptures, fish have been weighed at the point of tagging and the weight of the same fish recorded by the angler reporting the catch.

The weights of these fish are compared in Figure 5.19 and indicate – from the regression line fitted to these data sets - that, on average, trap and angler recorded weights are close to parity across the full range of fish sizes, but with a tendency for

angler reported weights to exceed trap recorded weights for salmon below ~8 lbs and to underestimate trap recorded weights above ~8 lbs (Table 5.6).

**Proposal 13**

*Given that the Dee and Tamar trap length to weight keys are based upon fork length and not total length of measured salmon, it is necessary to increase awareness within the angling community of the need to assess captured fish weights based upon the fork length rather than total length, so as to maximise use of these data.*

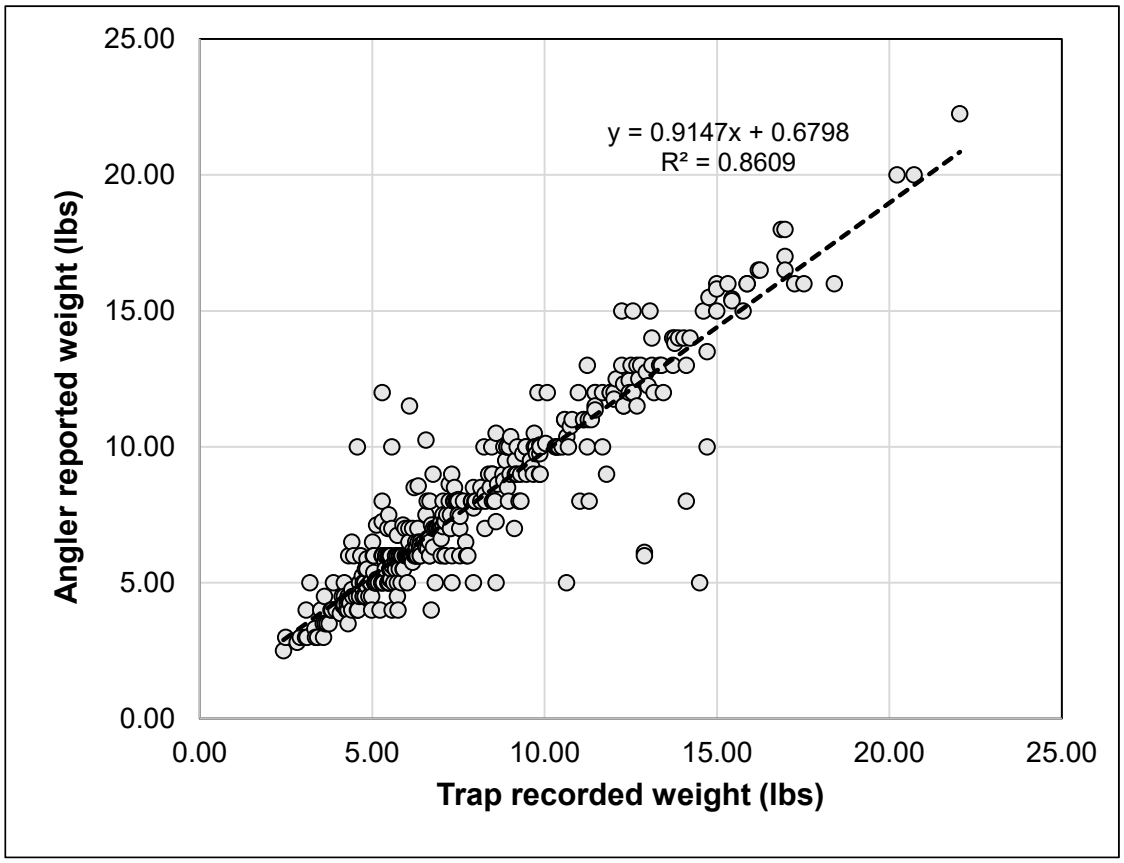



*Figure 5.19. Comparison of individual weights of Floy tagged salmon on the Welsh Dee (i) as recorded at Chester Weir fish trap and (ii) as reported by logbook anglers at the point of recapture, 1992-2022.*

*Table 5.6. Average angler reported weights compared to trap recorded weights of salmon in the Welsh Dee, the former predicted from the regression relationship shown in Figure 5.19.*

| **Trap recorded weights (lbs):** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2.00 | 4.00 | 6.00 | 8.00 | 10.00 | 12.00 | 14.00 | 16.00 | 18.00 | 20.00 | 22.00 | 24.00 |
| **Angler reported weights (lbs):** | | | | | | | | | | | |
| 2.51 | 4.34 | 6.17 | 8.00 | 9.83 | 11.66 | 13.49 | 15.32 | 17.14 | 18.97 | 20.80 | 22.63 |

## 5.7 Estimating 1SW and MSW fish in declared catches and returns

### 5.7.1 Review and proposals

Age-weight keys derived from sampling of adult salmon at Chester Weir fish trap on the Welsh Dee have been a component of the stock assessment process for several years. Each year, an updated age-weight key has been applied to all PSR stocks of salmon to estimate proportions of 1SW and MSW fish in declared angling catches and adult returns. This approach replaced a number of methods for estimating sea age composition described in Environment Agency (2003).

Since 2017, age-weight keys have also been developed from an equivalent adult trapping programme on the River Tamar and, for reasons of geography, have been applied in preference to the Dee age-weight key to river stocks in southern and south-west England.

In both cases, age-weight keys define the proportions of 1SW salmon sampled in 1 lb weight categories by month (January to December). Weight categories range from >0 to ≤1 lb (mid-point 0.5 lbs) to >19 to ≤20 lbs (mid-point 19.5 lbs). A final category of >20 lbs is centred on the mean weight (by river and year) of all rod-caught fish with declared weights above 20 lbs.

For each assessment year, the Dee and Tamar age-weight keys are revised to include only sampled fish from the latest 10-year period up to and including the assessment year. On both the Dee and Tamar, sampling of fish takes place at head-of-tide trapping facilities and the age-weight keys that result relate to the months in which fish were caught at these locations (i.e. no adjustment has been made to

reflect any lag between the month of river entry and the month of capture in the rod fishery). Examples of age-weight keys produced for both the Dee and Tamar for the 2020 assessment are shown in Table 5.7a and b (1SW proportions highlighted).

Each age-weight key is used to assign a probability (likelihood) that a rod caught salmon within a particular weight category and caught in a particular month is a 1SW fish (as opposed to a MSW fish). The summation of these probabilities for individual fish provides an estimate of the total number of 1SW salmon in the rod catch (with the numbers of MSW salmon in the rod catch comprising the remainder). Except on the counted rivers where RSEs are calculated from validated counter data, rod catches are raised to RSEs for 1SW, and MSW, fish by applying sea-age-specific angling exploitation rates.

While both Dee and Tamar age-weight keys have been used in the stock assessment process for several years, there has been no examination of the two age-weight keys applied to the same river stocks or comparison of resulting outputs.

*Table 5.7. Age-weight keys for (a) the Dee and (b) the Tamar: 2020 assessment year. NB, highlighted cells reflect 1SW proportions based on scale analysis of trap caught salmon, unhighlighted cells reflect an assumed MSW salmon where no trap data exists.*

*a. Dee age-weight key 2011-2020: proportion of 1SW salmon by month by 1lb weight category*

| **Weight lbs** | | | **Month** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Range** | **Midpoint** | **Category** | **Jan** | **Feb** | **Mar** | **Apr** | **May** | **Jun** | **Jul** | **Aug** | **Sep** | **Oct** | **Nov** | **Dec** |
| <1 | 0.5 | 1 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| 1-2 | 1.5 | 2 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| 2-3 | 2.5 | 3 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 1.000 | 0.917 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| 3-4 | 3.5 | 4 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| 4-5 | 4.5 | 5 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 0.500 | 0.980 | 0.994 | 1.000 | 0.895 | 1.000 | 1.000 |
| 5-6 | 5.5 | 6 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.964 | 0.978 | 0.980 | 1.000 | 1.000 | 1.000 |
| 6-7 | 6.5 | 7 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.714 | 0.899 | 0.956 | 0.923 | 0.833 | 1.000 |
| 7-8 | 7.5 | 8 | 0.000 | 0.000 | 0.000 | 0.000 | 0.091 | 0.000 | 0.226 | 0.436 | 0.781 | 0.909 | 1.000 | 0.666 |
| 8-9 | 8.5 | 9 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.053 | 0.121 | 0.560 | 1.000 | 0.200 | 0.000 |

| Weight lbs | | | Month | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Range** | **Midpoint** | **Category** | **Jan** | **Feb** | **Mar** | **Apr** | **May** | **Jun** | **Jul** | **Aug** | **Sep** | **Oct** | **Nov** | **Dec** |
| 9-10 | 9.5 | 10 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.250 | 0.000 | 0.000 |
| 10-11 | 10.5 | 11 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.125 | 0.200 | 0.000 |
| 11-12 | 11.5 | 12 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 12-13 | 12.5 | 13 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 13-14 | 13.5 | 14 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 14-15 | 14.5 | 15 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 15-16 | 15.5 | 16 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 16-17 | 16.5 | 17 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 17-18 | 17.5 | 18 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 18-19 | 18.5 | 19 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 19-≤20 | 19.5 | 20 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| >20 | 20.5 | 21 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

*b. Tamar age-weight key 2011-2020: proportion of 1SW salmon by month by 1lb weight category*

| Weight lbs | | | Month | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Range** | **Midpoint** | **Category** | **Jan** | **Feb** | **Mar** | **Apr** | **May** | **Jun** | **Jul** | **Aug** | **Sep** | **Oct** | **Nov** | **Dec** |
| <1 | 0.5 | 1 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| 1-2 | 1.5 | 2 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| 2-3 | 2.5 | 3 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| 3-4 | 3.5 | 4 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| 4-5 | 4.5 | 5 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 | 0.979 | 1.000 | 1.000 | 1.000 | 0.969 | 1.000 | 1.000 |
| 5-6 | 5.5 | 6 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.929 | 0.989 | 0.989 | 1.000 | 0.973 | 0.833 | 1.000 |
| 6-7 | 6.5 | 7 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.357 | 0.957 | 0.981 | 0.905 | 0.950 | 1.000 | 1.000 |
| 7-8 | 7.5 | 8 | 0.000 | 0.000 | 0.000 | 0.000 | 0.091 | 0.149 | 0.471 | 0.583 | 0.692 | 0.625 | 0.666 | 0.666 |
| 8-9 | 8.5 | 9 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.051 | 0.081 | 0.286 | 0.833 | 0.375 | 0.333 | 0.333 |

| Weight lbs | | | Month | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Range | Midpoint | Category | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| 9-10 | 9.5 | 10 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.023 | 0.000 | 0.000 | 0.250 | 0.167 | 0.143 |
| 10-11 | 10.5 | 11 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 11-12 | 11.5 | 12 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 12-13 | 12.5 | 13 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 13-14 | 13.5 | 14 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 14-15 | 14.5 | 15 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 15-16 | 15.5 | 16 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 16-17 | 16.5 | 17 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 17-18 | 17.5 | 18 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 18-19 | 18.5 | 19 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 19-≤20 | 19.5 | 20 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| >20 | 20.5 | 21 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

### 5.7.2 Implementation and outcomes

Both the Dee and Tamar age-weight keys were applied to 20 rivers in E&W for five assessment years (2017-2021) to examine the outcome in terms of estimates of the proportions of 1SW salmon in the rod catch and numbers of eggs deposited by fish of all sea ages.

Figure 5.20 shows that estimates of the proportions of 1SW salmon resulting from application of the two age-weight keys were very similar in most cases, with the great majority of values within the +/- 0.10 (or 10%) bands. The occasional values outside this range were usually associated with years where the declared catch/RSE was particularly small.

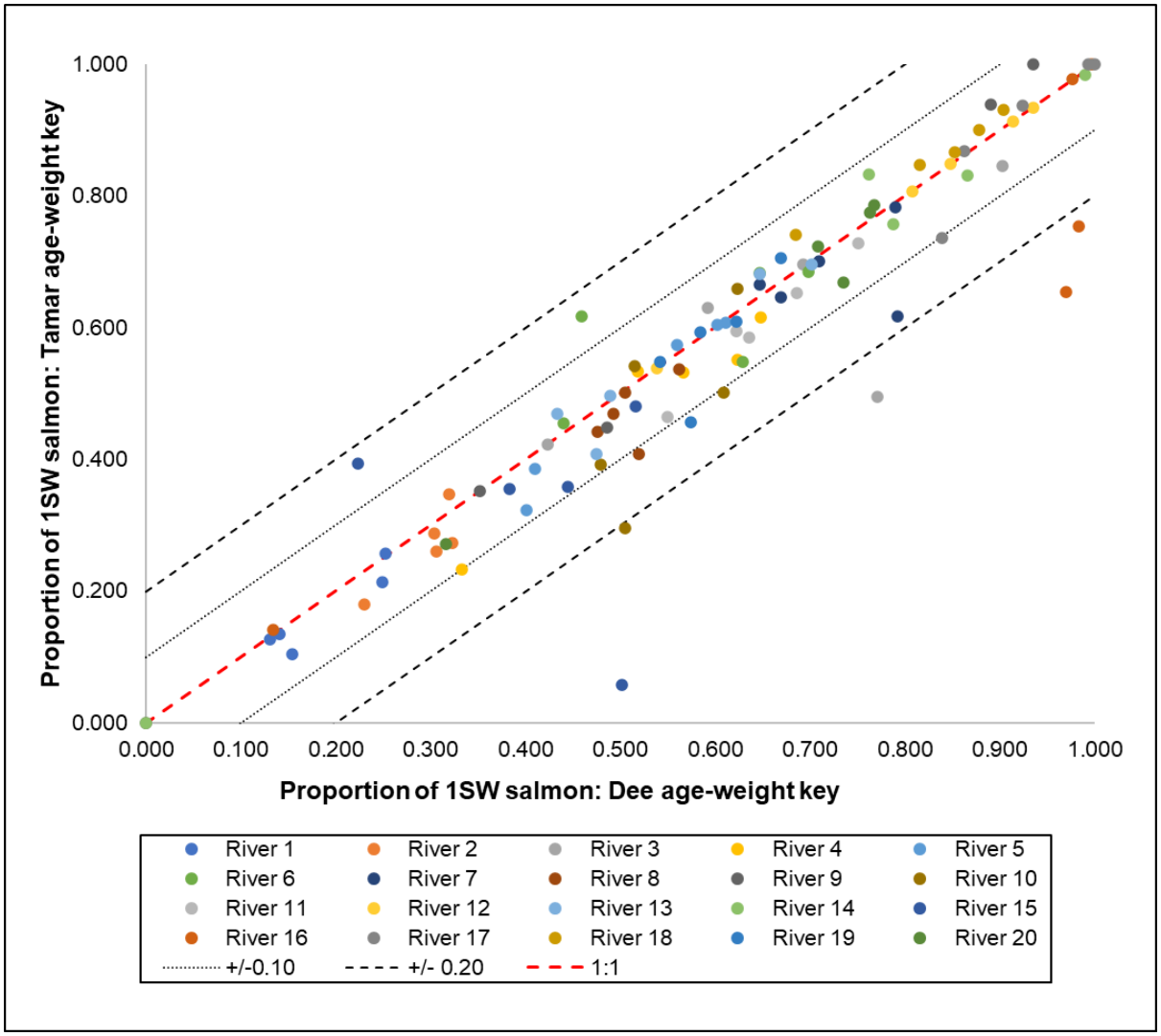



*Figure 5.20. Comparison of estimates of the proportion of 1SW salmon resulting from application of the Dee and Tamar age-weight keys on 20 rivers, 2017-2021. The dotted and dashed lines delimit a +/-10% and +/-20% difference from the 1:1 ratio (red dashed line).*

Similarly, egg deposition estimates arising from application of the two age-weight keys were also closely aligned (Figure 5.21), with virtually all 'Test' (Tamar age-weight key) estimates within +/-10% of the 'Control' (Dee age-weight key) estimates.

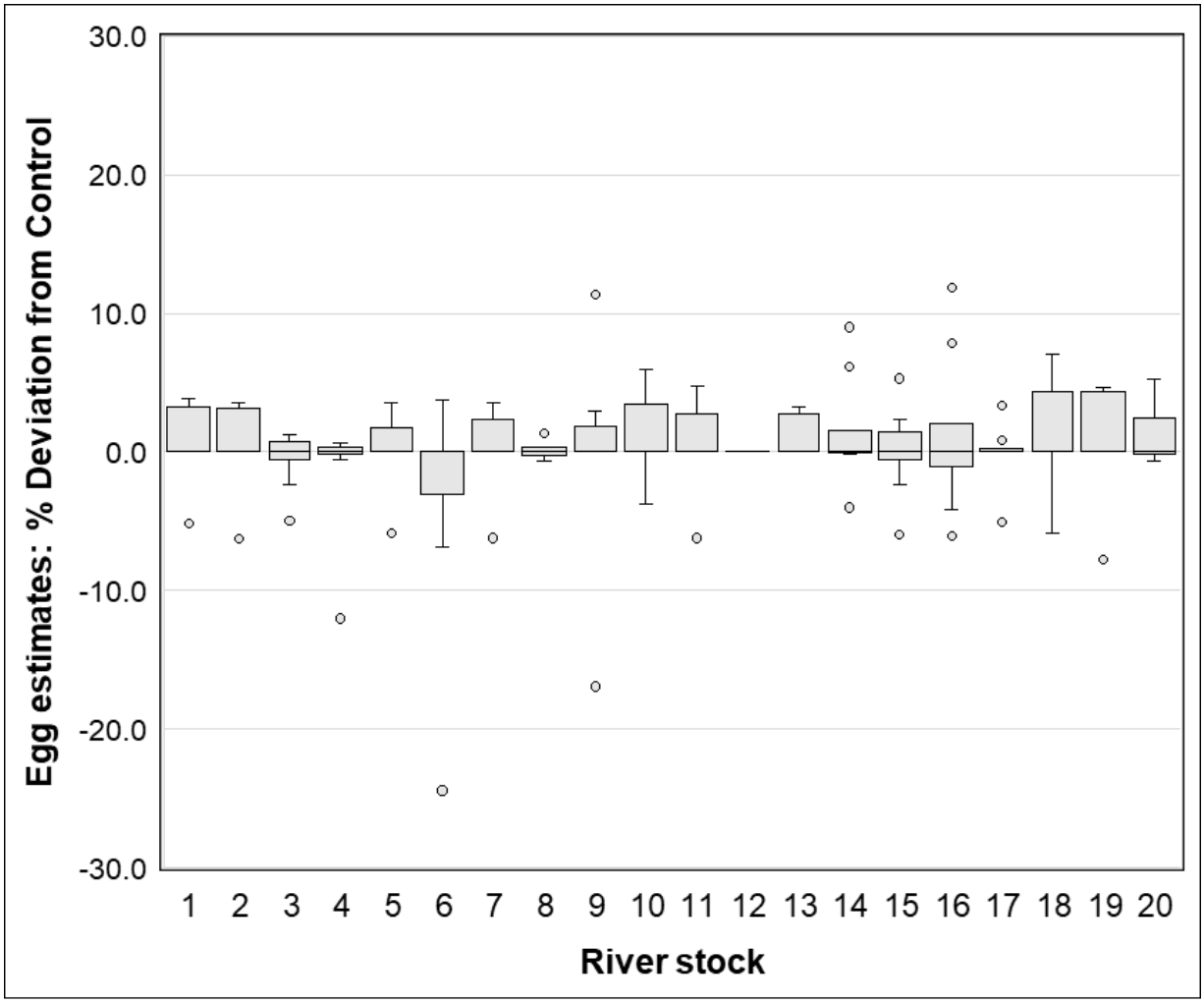



*Figure 5.21. Comparison of egg estimates resulting from application of the Dee (Control) and Tamar (Test) age-weight keys to 20 rivers, 2017 to 2021. Boxes delimit the 25%–75% interquartile range (IQR) for the percentage change in annual egg deposition estimates, the horizontal bar represents the median, whiskers delimit the 1.5 x IQR range, the black dots represent extreme values ± 1.5 x the IQR.*

**Proposal 14**

*Future work should seek to identify a more objective basis, such as geographical or other grounds, for the application of separate age-weight keys and/or consider the merits/demerits of combining data from the rivers Dee and Tamar into one age-weight key. Consider developing an age-weight key using data from the River Frome index river, to apply to chalk stream salmon populations, subject to the availability of suitable data.*

## 5.8 Application of sex ratios to identify the proportion of female spawners

### 5.8.1 One-sea winter Salmon

Our review of the current process identified the requirement to evaluate whether the relationship between the percentage of females and catchment area is still appropriate using more recent information and including additional rivers (e.g. the Tamar) to estimate the proportion of female 1SW fish and testing the resultant change in egg deposition estimates.

Current default procedures in E&W use different approaches to identify the proportion of female 1SW and MSW salmon in the returning stock (see Environment Agency, 2003).

In the absence of local information, a regression relationship between the percentage of female 1SW salmon and catchment area (various rivers) has been used to predict the former on most PSRs in E&W (Environment Agency, 2003). This relationship $(r^2 = 0.65;\ p = 0.05)$ is shown in Equation 5.6 below and was based on the 1990s dataset given in Table 5.8:

$$Log10\ Percent\ female\ 1SW\ salmon = 2.03 - 0.126\ Log10\ Catchment\ area \quad \text{Equation 5.6}$$

These data are represented by the open circles in Figure 5.22 with the corresponding regression relationship represented by the black trend line.

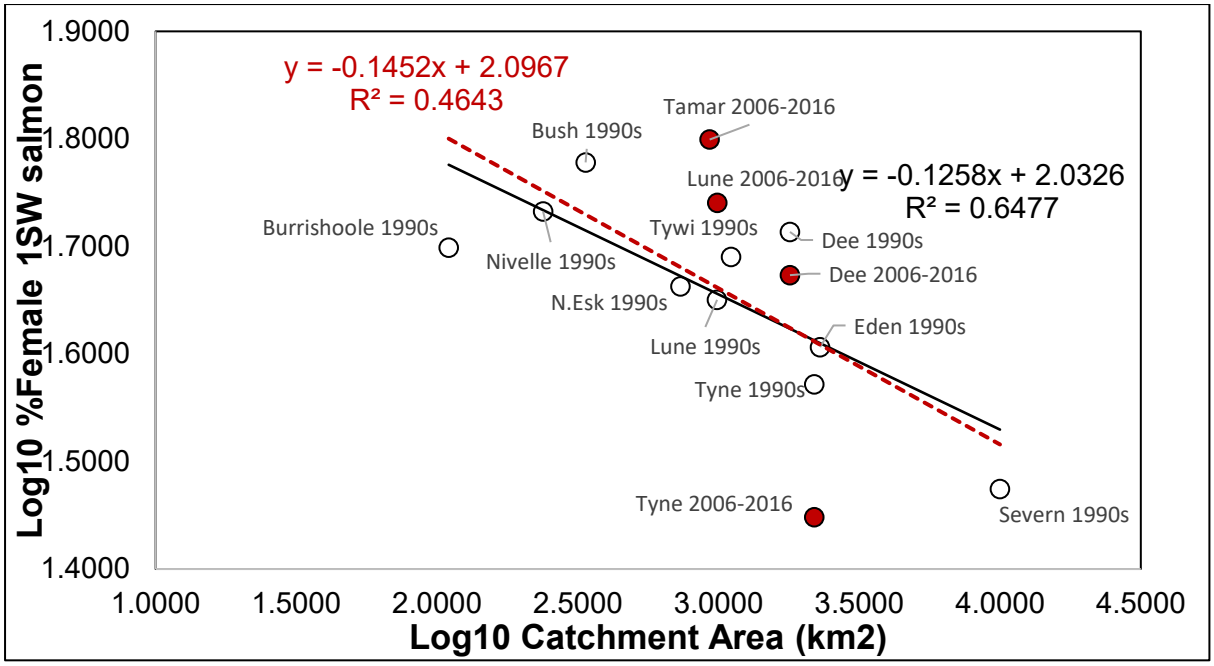



*Figure 5.22. Relationship between Log10 percentage female 1SW salmon and catchment area (km$^2$) for various rivers. The solid black trend line is the linear regression fitted to historic data (black open circles) from the 1990s (Adapted from Environment Agency, 2003). The dashed red trend line is the linear regression fitted to a combination of historic (black open circles) and more contemporary sampling data obtained for the rivers Tyne, Tamar, Dee and Lune from 2006-2016 (red closed circles).*

More contemporary data – obtained from sampling on the E&W index rivers Tyne, Tamar, Dee and Lune from 2006-2016, have been added as red circles to Figure 5.22. A red trend line (and associated regression relationship) fitted to a combination of these and historic (1990s) datasets (the latter excluding the Tyne, Dee and Lune) are also shown in Figure 5.22. There appears little difference between this relationship and the relationship based solely on the historic (1990s) data, although individual data points from the same river stock may differ markedly between the two time periods.

### 5.8.2 Multi-sea winter salmon

No similar relationship, in terms of trend or statistical significance (as presented in Figure 5.22), between sex ratio and geographical catchment area, were evident for MSW salmon. For this sea age group, a single default value for the proportion of females of 0.687 was derived from the mean of the 1990s observations shown in Table 5.8 (Environment Agency, 2003). This default value has been used from the

outset on most rivers in E&W in procedures to derive annual egg deposition estimates.

*Table 5.8. Percentage of female salmon by sea age in various rivers (Based on Environment Agency, 2003).*

| Period | Source | Catchment Area ($km^2$) | $Log_{10}$ Catchment Area ($km^2$) | 1SW Salmon % Females | $Log_{10}$ 1SW Salmon % Females | MSW Salmon % Females | $Log_{10}$ MSW Salmon % Females |
|---|---|---|---|---|---|---|---|
| 1990s | SAP Guidelines | 110 | 2.041 | 50.0 | 1.699 | | |
| 1990s | SAP Guidelines | 337 | 2.528 | 60.0 | 1.778 | | |
| 1990s | SAP Guidelines | 988 | 2.995 | 44.7 | 1.650 | | |
| 1990s | SAP Guidelines | 2294 | 3.361 | 40.4 | 1.606 | | |
| 1990s | SAP Guidelines | 1108 | 3.045 | 49.0 | 1.690 | 45.7 | 1.660 |
| 1990s | SAP Guidelines | 732 | 2.865 | 46.0 | 1.663 | 62.2 | 1.794 |
| 1990s | SAP Guidelines | 1793 | 3.254 | 51.7 | 1.713 | 66.3 | 1.822 |
| 1990s | SAP Guidelines | 238 | 2.377 | 54.0 | 1.732 | 77.0 | 1.886 |
| 1990s | SAP Guidelines | 2185 | 3.339 | 37.3 | 1.572 | 79.4 | 1.900 |
| 1990s | SAP Guidelines | 9991 | 4.000 | 29.8 | 1.474 | 81.6 | 1.912 |
| 2006-2016 | E&W Index river | 2185 | 3.339 | 28.1 | 1.449 | 58.5 | 1.767 |

| Period | Source | Catchment Area ($km^2$) | $Log_{10}$ Catchment Area ($km^2$) | 1SW Salmon % Females | $Log_{10}$ 1SW Salmon % Females | MSW Salmon % Females | $Log_{10}$ MSW Salmon % Females |
|---|---|---|---|---|---|---|---|
| 2006-2016 | E&W Index river | 930 | 2.968 | 63.0 | 1.799 | 62.6 | 1.797 |
| 2006-2016 | E&W Index river | 1793 | 3.254 | 47.1 | 1.673 | 75.5 | 1.878 |
| 2006-2016 | E&W Index river | 988 | 2.995 | 55.0 | 1.740 | 74.3 | 1.871 |

### 5.8.3 New data based on genetic screening

On the index rivers Tamar and Dee, where year-round trapping programmes collect biological data from returning salmon, the sex of fish has been judged from external ('phenotypic') characteristics, but with some uncertainty (e.g. dependent on the degree of maturation and the development of more pronounced differences in the appearance of fish of different sex).

More recently, the development of genetic screening methods has allowed the sex of fish to be determined definitively (and non-destructively) from scale samples or other biological material. This has been the case on the Tamar – as reported by King *et al.* (2022). The study was part of a larger project conducted by the EA and the University of Exeter which also included application of the same genetic methods to scale samples collected from salmon on the River Dee. On both the Tamar (King *et al.,* 2022) and Dee, the probability of identifying the correct sex from external characteristics (judged against the genetic assignment of sex) tended to increase through the year.

On the Tamar a total of 2 838 samples were obtained from trap caught fish to determine sex using genetic screening. From these samples, the proportion of females from genetic screening (*Pf Genetic)* for 1SW and 2SW fish (mean for the years 2015-2020) were 0.447 and 0.795, respectively (King *et al.,* 2022).

On the Dee, genetic analysis by the University of Exeter of scale material obtained from a representative 2016-2020 sub-sample of fish resulted in assignment of sex in 910 individuals, with mean *Pf Genetic* estimates for 1SW and MSW fish of 0.367 and 0.813, respectively.

Using the mean sex ratios by sea age from genetic analysis, a correction factor (CF) can be calculated for the rivers Dee and Tamar. This is achieved by the following simple equation:

$$pF\ CF = pF\ Genetic / pF\ Original$$

Where:

pF CF = the sea age specific correction factor

pF Genetic = the mean sex ratio for the river obtained from genetic analysis

pF Original = the original sex ratio set out in the SAP

These sea-age-specific CFs can be applied to the original river specific sex ratios set out in the SAP (Environment Agency, 2003), on a geographical basis, with CFs from

the Tamar being applied to southwest and southern rivers and Dee CFs applied elsewhere.

### 5.8.4 Implementation and outcomes

Figure 5.23 below compares 10-year time-series of egg estimates (2011-2020) generated for 20 principal river stocks using both current procedures ('Control') and the same ('Test') procedures except for inclusion of the modified approaches described above for deriving sex (pFemales) in 1SW and MSW salmon.

From the boxplot in Figure 5.23, it is evident that introducing the revised ('Test') procedures for deriving sex (pFemales) results in decreased egg deposition estimates in most cases, but generally within -10% of the egg estimates obtained using the current ('Control') procedure. The middle 50% of observations for any one river lie within the shaded box with the mean % deviation from the Control indicated by the 'X' symbol.

This comparison is extended to examination of compliance with Conservation Limits in Table 5.9, applying the current statistical trend-based method to assign a 'risk' status to each river stock in 2020 and 2025.

On this basis, and as might be expected from the differences in egg deposition estimates (Figure 5.23), Control and Test procedures result in very similar or slightly worse outcomes in terms of Conservation Limit compliance ('risk status') and trends in egg deposition estimates.

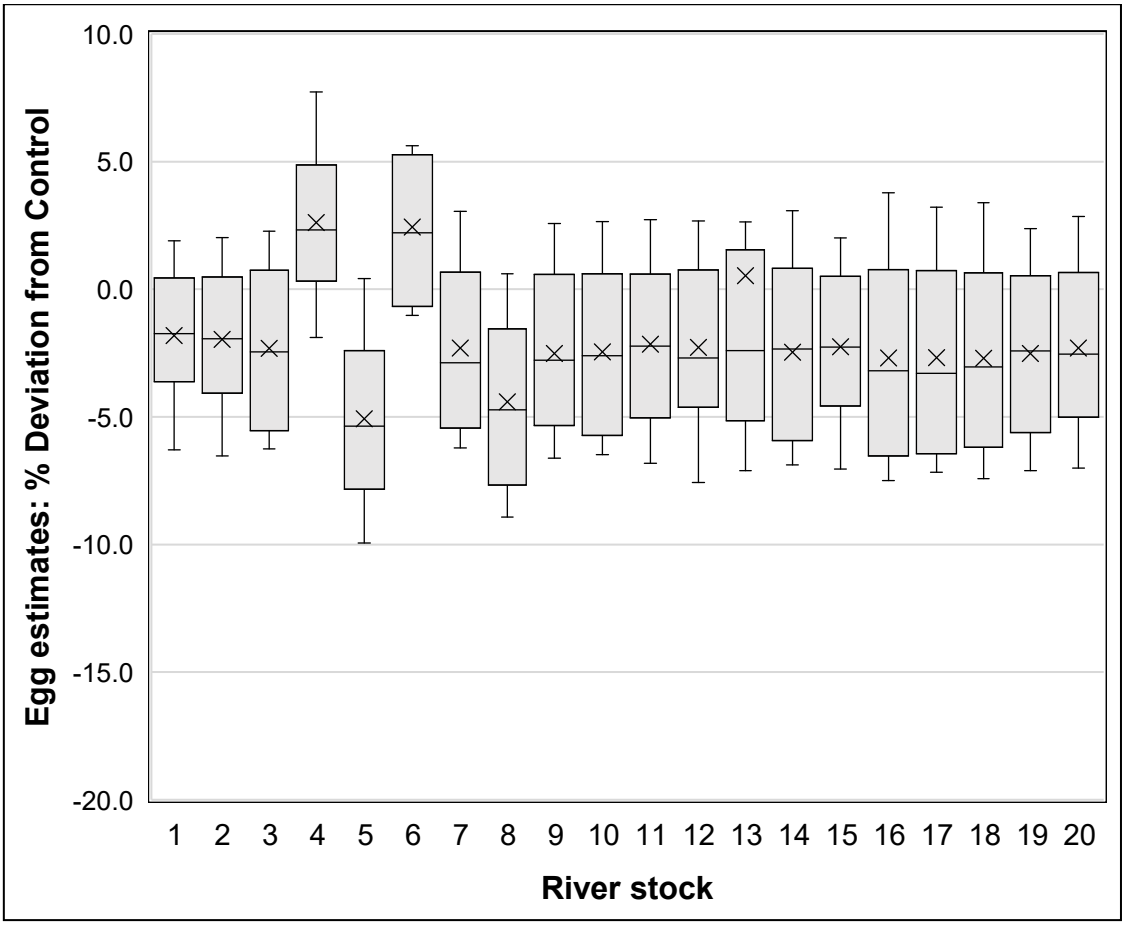



*Figure 5.23. Comparison of egg estimates (10 years x 20 principal river stocks) resulting from current ('Control') procedures and the same ('Test') procedures except for inclusion of modified approaches (above) to deriving sex (pFemales) in 1SW and MSW salmon ('Test'). The boxplots illustrate the minimum, first quartile, median, third quartile, and maximum value for the percentage change in annual egg deposition estimates. The 'X' denotes the mean deviation from the control.*

*Table 5.9. Sex determination (pFemales) for 1SW and MSW salmon: Comparison of CL compliance outcomes resulting from application of Control and Test procedures (above) to generate annual egg estimates on 20 principal salmon rivers for the 10-year period: 2011-2020.*

**'Control': Current procedure**

| | | | 10-year trend in egg estimates: | | |
|---|---|---|---|---|---|
| | Risk' status: | | Prob. (p) of upward trend (see key below) | | |
| River stock | Current year: 2020 | Projected: 2025 | p | Direction | Certainty |
| 1 | At risk | Prob at risk | 0.315 | - | Uncertain |
| 2 | Prob at risk | Prob at risk | 0.146 | - - | Uncertain |
| 3 | At risk | At risk | 0.182 | - - | Uncertain |
| 4 | At risk | At risk | 0.002 | - - - | Down |
| 5 | At risk | Prob at risk | 0.319 | - | Uncertain |
| 6 | At risk | At risk | 0.017 | - - - | Down |
| 7 | At risk | At risk | 0.025 | - - - | Down |
| 8 | At risk | At risk | 0.002 | - - - | Down |
| 9 | At risk | At risk | 0.005 | - - - | Down |
| 10 | At risk | Prob at risk | 0.287 | - - | Uncertain |
| 11 | At risk | At risk | 0.219 | - - | Uncertain |
| 12 | At risk | Prob at risk | 0.795 | ++ | Uncertain |
| 13 | Prob at risk | Prob at risk | 0.263 | - - | Uncertain |
| 14 | Prob at risk | Prob at risk | 0.383 | - | Uncertain |
| 15 | At risk | At risk | 0.006 | - - - | Down |

**'Control': Current procedure**

| | Risk' status: | | 10-year trend in egg estimates: Prob. (p) of upward trend (see key below) | | |
|---|---|---|---|---|---|
| River stock | Current year: 2020 | Projected: 2025 | p | Direction | Certainty |
| 16 | At risk | At risk | 0.117 | - - | Uncertain |
| 17 | At risk | At risk | 0.217 | - - | Uncertain |
| 18 | Prob at risk | Prob at risk | 0.402 | - | Uncertain |
| 19 | Prob at risk | Prob at risk | 0.398 | - | Uncertain |
| 20 | At risk | At risk | 0.032 | - - - | Down |

**'Test': Inclusion of modified approach to deriving sex in 1SW and MSW salmon:**

| | Risk' status: | | 10-year trend in egg estimates: Prob. (p) of upward trend (see key below) | | |
|---|---|---|---|---|---|
| River stock | Current year: 2020 | Projected: 2025 | p | Direction | Certainty |
| 1 | At risk | Prob at risk | 0.288 | - - | Uncertain |
| 2 | Prob at risk | Prob at risk | 0.140 | - - | Uncertain |
| 3 | At risk | At risk | 0.185 | - - | Uncertain |
| 4 | At risk | At risk | 0.003 | - - - | Down |
| 5 | Prob at risk | Prob at risk | 0.418 | - | Uncertain |
| 6 | At risk | At risk | 0.028 | - - - | Down |
| 7 | At risk | At risk | 0.020 | - - - | Down |

**'Test': Inclusion of modified approach to deriving sex in 1SW and MSW salmon:**

| | Risk' status: | | 10-year trend in egg estimates: Prob. (p) of upward trend (see key below) | | |
|---|---|---|---|---|---|
| River stock | Current year: 2020 | Projected: 2025 | p | Direction | Certainty |
| 8 | At risk | At risk | 0.006 | - - - | Down |
| 9 | At risk | At risk | 0.006 | - - - | Down |
| 10 | At risk | Prob at risk | 0.279 | - - | Uncertain |
| 11 | At risk | At risk | 0.258 | - - | Uncertain |
| 12 | At risk | Prob at risk | 0.761 | ++ | Uncertain |
| 13 | Prob at risk | Prob at risk | 0.339 | - | Uncertain |
| 14 | At risk | Prob at risk | 0.379 | - | Uncertain |
| 15 | At risk | At risk | 0.008 | - - - | Down |
| 16 | At risk | At risk | 0.098 | - - - | Uncertain |
| 17 | At risk | At risk | 0.215 | - - | Uncertain |
| 18 | Prob at risk | Prob at risk | 0.451 | - | Uncertain |
| 19 | Prob not at risk | Prob not at risk | 0.571 | + | Uncertain |
| 20 | At risk | At risk | 0.042 | - - - | Down |

| Probability (p) of uptrend: | |
|---|---|
| p<=0.05 | --- |
| 0.05<p<=0.10 | --- |
| 0.10<p<=0.30 | -- |
| 0.30<p<=0.50 | - |
| 0.50<p<0.70 | + |
| 0.70<=p<0.90 | ++ |
| 0.90<=p<0.95 | +++ |
| p=>0.95 | +++ |

**Recommendation 5**

*Use genetically derived sex determination data obtained from studies undertaken on the rivers Tamar and Dee to update the estimated proportion of females for one-sea-winter (1SW) and multi-sea-winter (MSW) salmon in all other principal salmon rivers.*

**Proposal 15**

*Undertake further genetic analysis to determine sex ratios by sea-age for the rivers Dee and Tamar to periodically update sex ratio estimates for all Principal Salmon Rivers. Consider including genetic samples from the River Frome Index River to update sex ratios for the chalk streams, subject to the availability and suitability of data.*

## 5.9 Selection of size-fecundity relationships to estimate egg deposition

The purpose of this section was to test whether the fecundity estimates for Atlantic salmon based on Pope *et al*. (1961) remain appropriate by comparing them against more recent fecundity estimates from E&W and elsewhere and examining the resultant scale of change in egg deposition.

Current procedures in E&W adopt the size (length)-fecundity relationship of Pope *et al.* (1961) (shown in Equation 5.7 below) as the default means of estimating salmon egg numbers (eggs per female) by weight class:

$$Log10\ Eggs\ =\ -0.582\ +\ 2.3345\ \times\ Log10\ (Length\ (cm)) \qquad \text{Equation 5.7}$$

This relationship is a composite of length-fecundity relationships produced for six Scottish rivers. To apply this to weighed fish (only fish weights are submitted in E&W angler catch returns), weights (lb) were converted to length (cm; measured as fork length) using Equation 5.8 below (see Salmon Action Plan Guidelines: Environment Agency, 2003):

$$Length\ (cm)\ =\ (Weight\ (lbs)/0.0000244)\text{^}(1/3)$$ Equation 5.8

As part of this review, size-fecundity data were sought for salmon from rivers in E&W. Two data sets were obtained, both from wild salmon stripped in hatcheries in Wales run by the EA, NRW and predecessor organisations from 1998 to 2014. Namely:

- Dee and Clwyd: 1998 to 2012
- Wye and Taff: 2011 to 2014

Comparison of these two data sets indicated that the respective length-fecundity relationships were not significantly different from each other; hence both data sets were combined to produce a composite length-fecundity relationship. This relationship is compared with that of Pope *et al.* (1961) in Figure 5.24, where it is evident that both relationships are closely aligned, with the relationship of Pope *et al.* (1961) falling within the 95% Confidence limits and Prediction limits of the relationship for the Dee, Clwyd, Wye and Taff. A third length-fecundity relationship derived from wild salmon broodstock collected on the River Tamar (King *et al.*, 2022), is also shown in Figure 5.24.

In addition to the development and potential implementation of a length-fecundity relationship based on E&W data, this relationship could be further refined by replacement of the current default weight-length relationships (as part of the length-fecundity calculation) with more contemporary relationships based on size and sea age data collected from adult salmon sampled on the index rivers Dee and Tamar.

Figure 5.25 shows $Log_{10}$ weight (lbs) v $Log_{10}$ length (cm) relationships for the Dee and Tamar derived from data sets collected over the common 10-year period: 2011-2020. These relationships are closely aligned for the two rivers, although they exhibit some statistical differences between rivers and sea ages (1SW and MSW salmon).

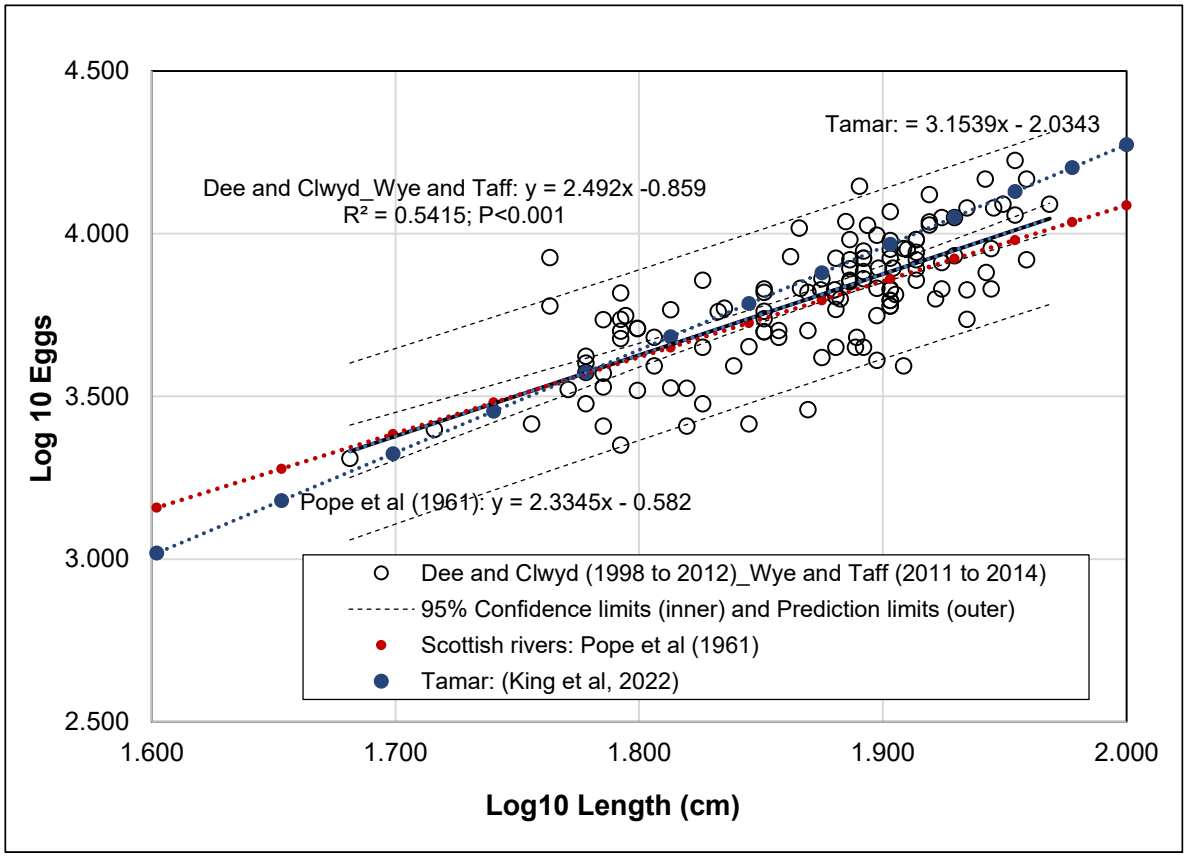



*Figure 5.24. Length-fecundity relationship for salmon from the rivers Dee, Clwyd, Wye and Taff compared to the relationship of Pope et al. (1961).*

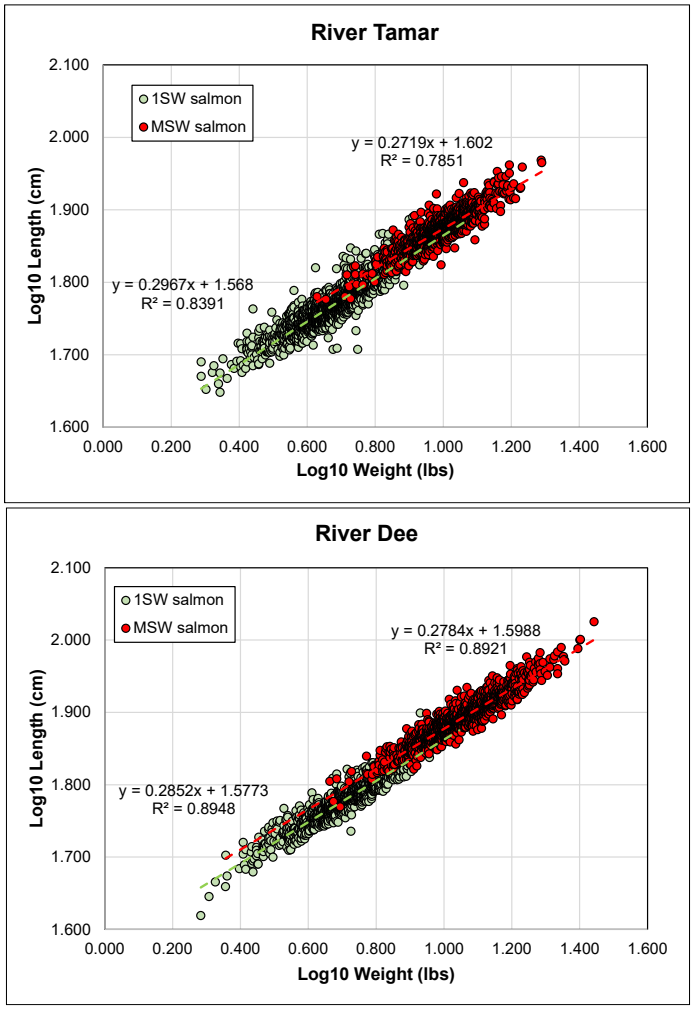



*Figure 5.25. Weight-length relationships for 1SW and MSW salmon sampled on the Dee and Tamar, 2011-2020.*

## Recommendation 6

*Apply the length-fecundity relationship obtained from data collected on the rivers Dee, Clwyd, Wye and Taff to inform the default relationship in procedures to derive annual egg deposition estimates for England and Wales. In addition, and in the absence of river-specific alternatives, weight-length relationships for one-sea-winter (1SW) and multi-sea-winter (MSW) salmon on the rivers Dee and Tamar should be renewed and applied annually (based on the latest 10-year datasets) to convert rod catch weight data into length data as part of these procedures.*

As discussed above, the length-fecundity relationship of Pope *et al.* (1961) has been applied, from the outset, as the default relationship in procedures to derive egg deposition estimates on most of the 64 PSRs in E&W.

Several studies undertaken by jurisdictions in the UK, the Republic of Ireland and elsewhere have reviewed size-fecundity relationships and their application (e.g. O'Connell, Dempson and Reddin, 2008; Bacon *et al.,* 2012; de Eyto *et al.*, 2015; Hanson *et al.*, 2020).

Bacon *et al*. (2012) found that, 50 years on, the size-fecundity relationships of Pope *et al.* (1961) remained accurate for salmon in upland Scottish rivers.

Other comparisons between size-fecundity relationships have been made, including with the relationship of Pope *et al.* (1961). These are summarised in Table 5.10 - where fecundity values for a standard sized 70 cm (~3.4 kg) salmon have been estimated from various sources (after de Eyto *et al.*, 2015).

In general terms, most of the estimates in Table 5.10 are similar to that of Pope *et al.* (1961) only deviating within a few hundred eggs despite the wide geographical spread of studies which contribute to this comparison.

While this simple comparison of size and fecundity suggests a good degree of consistency among rivers, other factors influencing the number and size of eggs carried by returning fish have been identified. For example, Bacon *et al.* (2012) found differences in length-fecundity relationships between lowland and upland stocks from the same river system (including differences in egg size). Similarly, Hanson *et al.* (2020) identified a number of covariates, in addition to body size, that influenced fecundity estimates, including developmental characteristics of age-at-smolting and years spent at sea.

**Proposal 16**

*Other sources of salmon size-fecundity data for England and Wales should be explored – including the possibility of obtaining contemporary data from the Kielder hatchery on the Tyne. Similarly, more sophisticated options for estimating fecundity (and its uncertainty) in English and Welsh rivers should be examined to incorporate influential (but widely available) covariates in addition to body size.*

*Table 5.10. Predicted fecundity of a salmon of fork length 70 cm (or ~3.4 kg) from various studies (after de Eyto et al., 2015).*

| | | Eggs per Female | | |
|---|---|---|---|---|
| **Source** | **Predictor** | **Median** | **Lower** | **Upper** |
| England and Wales (E&W): Dee, Clwyd, Wye and Taff (1998-2014) | Length: 70cm | 5482 | 3006 | 9998 |
| E&W: Dee, Clwyd, Wye, Taff (1998-2014) - Dee 1SW weight- length conversion | Weight: 3.4kg | 4936 | | |
| E&W: Dee, Clwyd, Wye, Taff (1998-2014) - Dee MSW weight- length conversion | Weight: 3.4kg | 5397 | | |
| England and Wales (E&W): Tamar (King *et al.*, 2022) | Length: 70cm | 6095 | | |
| E&W: Tamar (King *et al.*, 2022) - Tamar 1SW weight-length conversion | Weight: 3.4kg | 5366 | | |
| E&W: Tamar (King *et al.*, 2022) - Tamar MSW weight-length conversion | Weight: 3.4kg | 5867 | | |
| Scotland (Pope *et al.*, 1961) | Length: 70cm | 5314 | | |
| Scotland (Pope *et al.*, 1961) - SAP Guidelines: All SW weight-length conversion | Weight: 3.4kg | 4877 | | |
| Scotland (Pope *et al.*, 1961) - SAP Guidelines: Dee 1SW weight- length conversion | Weight: 3.4kg | 4816 | | |
| Scotland (Pope *et al.*, 1961) - SAP Guidelines: Dee MSW weight- length conversion | Weight: 3.4kg | 5236 | | |

| | | Eggs per Female | | |
|---|---|---|---|---|
| **Source** | **Predictor** | **Median** | **Lower** | **Upper** |
| Scotland (Pope *et al.*, 1961) - SAP Guidelines: Tamar 1SW weight-length conversion | Weight: 3.4kg | 4835 | | |
| Scotland (Pope *et al.*, 1961) - SAP Guidelines: Tamar MSW weight-length conversion | Weight: 3.4kg | 5166 | | |
| Ireland (de Eyto *et al.,* 2015) | Weight: 3.4kg | 4398 | 3689 | 5202 |
| Scotland and Norway (Fleming, 1996) | Length: 70cm | | 4600 | 6067 |
| N Spain (Cabellero, 2013) | Weight: 3.4kg | 5355 | | |
| NW France (Prevost and Porcher, 1996) | Weight: 3.4kg | 5488 | | |
| R Nivelle, France (Dumas and Prouzet, 2003) | Weight: ~3.4kg | 5647 | | |

### 5.9.1 Implementation and outcomes

Figure 5.26 below compares 10-year time-series of egg estimates (2011-2020) generated for 22 PSR stocks using both current procedures ('Control') and the same ('Test') procedures except for (1) replacing the length-fecundity relationship of Pope *et al*. (1961) with the equivalent relationship derived using data from rivers in E&W: Dee, Clwyd, Wye and Taff and (2) applying the weight to length conversion for the Welsh Dee based on salmon sampled in the decade 2011-2020.

From the boxplot in Figure 5.26, it is evident that introducing the revised ('Test') size-fecundity relationship results in increased egg deposition estimates in the majority of cases, but within +10% of the egg estimates obtained using the current ('Control') procedure. As previously, the middle 50% of observations for any one river lie within the shaded box with the mean % deviation from the Control indicated by the 'X' symbol and connecting line.

This comparison is extended to examination of compliance with CL in Table 5.11, applying the current statistical trend-based method to assign a 'risk' status to each river stock in 2020 and 2025.

On this basis, and as might be expected from the differences in egg deposition estimates (Figure 5.26), Control and Test procedures result in very similar outcomes in terms of CL compliance ('risk status') and trends in egg deposition estimates. The notable exceptions are slight improvements in risk status on the rivers 17 and 19.

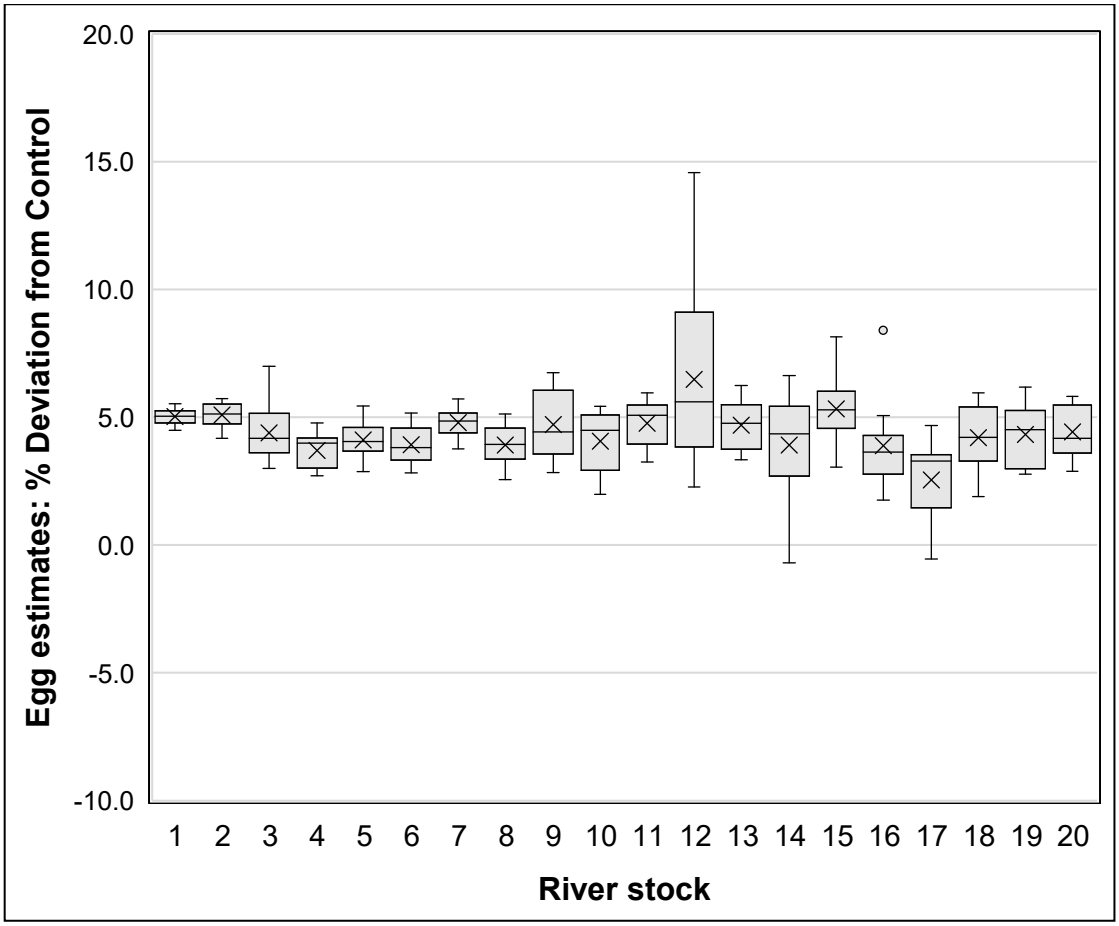



*Figure 5.26. A boxplot comparing egg estimates (10 years x 20 principal river stocks) resulting from current ('Control') procedures and the same ('Test') procedures except for (i) replacing the default length-fecundity relationship of Pope et al. (1961) with the relationship for E&W data from the Dee, Clwyd, Wye and Taff (Test) and (ii) applying the weight to length conversion for the Welsh Dee based on salmon sampled in the decade 2011-2020. Boxes delimit the 25%–75% interquartile range (IQR), the horizontal bar represents the median, whiskers delimit the 1.5 x IQR range, the black dots represent extreme values ± 1.5 x the IQR, and the 'X' indicates the mean percentage deviation from the control.*

*Table 5.11. Size-Fecundity relationships: Comparison of CL compliance outcomes resulting from application of Control and Test procedures (above) to generate annual egg estimates on 22 principal salmon rivers for the 10-year period: 2011-2020.*

**'Control': Current procedure**

| | Risk' status: | | 10-year trend in egg estimates: Prob. (p) of upward trend (see key below) | | |
|---|---|---|---|---|---|
| **River stock** | **Current year: 2020** | **Projected: 2025** | **p** | **Direction** | **Certainty** |
| 1 | At risk | Prob at risk | 0.315 | - | Uncertain |
| 2 | Prob at risk | Prob at risk | 0.146 | - - | Uncertain |
| 3 | At risk | At risk | 0.182 | - - | Uncertain |
| 4 | At risk | At risk | 0.002 | - - - | Down |
| 5 | At risk | Prob at risk | 0.319 | - | Uncertain |
| 6 | At risk | At risk | 0.017 | - - - | Down |
| 7 | At risk | At risk | 0.025 | - - - | Down |
| 8 | At risk | At risk | 0.002 | - - - | Down |
| 9 | At risk | At risk | 0.005 | - - - | Down |
| 10 | At risk | Prob at risk | 0.287 | - - | Uncertain |
| 11 | At risk | At risk | 0.219 | - - | Uncertain |
| 12 | At risk | Prob at risk | 0.795 | ++ | Uncertain |
| 13 | Prob at risk | Prob at risk | 0.263 | - - | Uncertain |
| 14 | Prob at risk | Prob at risk | 0.383 | - | Uncertain |

**'Control': Current procedure**

| River stock | Risk' status: Current year: 2020 | Risk' status: Projected: 2025 | 10-year trend in egg estimates: Prob. (p) of upward trend (see key below) p | Direction | Certainty |
|---|---|---|---|---|---|
| 15 | At risk | At risk | 0.006 | - - - | Down |
| 16 | At risk | At risk | 0.117 | - - | Uncertain |
| 17 | At risk | At risk | 0.217 | - - | Uncertain |
| 18 | Prob at risk | Prob at risk | 0.402 | - | Uncertain |
| 19 | Prob at risk | Prob at risk | 0.398 | - | Uncertain |
| 20 | At risk | At risk | 0.032 | - - - | Down |

**'Test': Revised (E&W) Size-Fecundity relationships**

| River stock | Risk' status: Current year: 2020 | Risk' status: Projected: 2025 | 10-year trend in egg estimates: Prob. (p) of upward trend (see key below) p | Direction | Certainty |
|---|---|---|---|---|---|
| 1 | At risk | Prob at risk | 0.317 | - | Uncertain |
| 2 | Prob at risk | Prob at risk | 0.150 | - - | Uncertain |
| 3 | At risk | At risk | 0.190 | - - | Uncertain |

**'Test': Revised (E&W) Size-Fecundity relationships**

| | Risk' status: | | 10-year trend in egg estimates: Prob. (p) of upward trend (see key below) | | |
|---|---|---|---|---|---|
| River stock | Current year: 2020 | Projected: 2025 | p | Direction | Certainty |
| 4 | At risk | At risk | 0.002 | - - - | Down |
| 5 | At risk | Prob at risk | 0.334 | - | Uncertain |
| 6 | At risk | At risk | 0.018 | - - - | Down |
| 7 | At risk | At risk | 0.029 | - - - | Down |
| 8 | At risk | At risk | 0.002 | - - - | Down |
| 9 | At risk | At risk | 0.006 | - - - | Down |
| 10 | At risk | Prob at risk | 0.302 | - | Uncertain |
| 11 | At risk | At risk | 0.221 | - - | Uncertain |
| 12 | At risk | Prob at risk | 0.803 | ++ | Uncertain |
| 13 | Prob at risk | Prob at risk | 0.283 | - - | Uncertain |
| 14 | Prob at risk | Prob at risk | 0.390 | - | Uncertain |
| 15 | At risk | At risk | 0.007 | - - - | Down |
| 16 | At risk | At risk | 0.118 | - - | Uncertain |
| 17 | At risk | Prob at risk | 0.229 | - - | Uncertain |
| 18 | Prob at risk | Prob at risk | 0.415 | - | Uncertain |

**'Test': Revised (E&W) Size-Fecundity relationships**

| | Risk' status: | | 10-year trend in egg estimates: Prob. (p) of upward trend (see key below) | | |
|---|---|---|---|---|---|
| **River stock** | **Current year: 2020** | **Projected: 2025** | **p** | **Direction** | **Certainty** |
| 19 | Prob not at risk | Prob not at risk | 0.424 | - | Uncertain |
| 20 | At risk | At risk | 0.035 | - - - | Down |

| Probability (p) of uptrend: | |
|---|---|
| p<=0.05 | --- |
| 0.05<p<=0.10 | --- |
| 0.10<p<=0.30 | -- |
| 0.30<p<=0.50 | - |
| 0.50<p<0.70 | + |
| 0.70<=p<0.90 | ++ |
| 0.90<=p<0.95 | +++ |
| p=>0.95 | +++ |

# 6 The compliance assessment method

## 6.1 Introduction

The objective of this section was to review and evaluate the formal statistical method currently used to assess the status of salmon stocks (or more precisely, the number of eggs produced by spawning fish) in England and Wales (E&W) against Biological Reference Points (BRPs) (hereafter termed 'compliance assessment') and potential changes to those methods. This primarily reflects the requirements of the Ministerial Direction (1998, see Annex 1) and the outcome of the National Salmon Stock Assessment workshop (Atlantic Salmon Trust, 2017), as well as additional feedback received from a range of salmon fishery stakeholders and interested parties following the implementation of salmon rod and net fishery regulatory reviews in both E&W. This section summarises the findings of the review into the current compliance assessment that has been undertaken taking account of the compliance assessment methods that are being applied within other salmon management jurisdictions (see sections 3.2 and 3.3). There follows a summary of our recommended new compliance assessment method that is based upon a two-tiered assessment. It also provides proposals for how compliance assessment could be conducted in the future. We conclude with comparisons of the assessment classes achieved with the current approach versus those using the new compliance assessment approach.

## 6.2 Principles to guide the review of compliance assessment approaches

In evaluating the current compliance assessment method, and potentially drawing up new ones, we should bear the following five principles in mind, as summarised below:

**(1) NASCO guidelines:** Parties to NASCO adopted salmon management guidelines, which lay out the precautionary approach and the setting of CLs (CNL9846 Agreement on Adoption of a Precautionary Approach.PDF (nasco.int). The CL is defined as the spawning stock level that will achieve Maximum Sustainable Yield (MSY). The use of CLs and Management Targets (MTs) follows from NASCO guidelines (NASCO, 2009), wherein Section 2.4e states that: "*Management targets should also be established at a level above the CL to assist fishery managers in ensuring that there is a high probability of stocks exceeding their CLs".* Management decisions should prioritise protecting salmon stocks rather than allowing over-exploitation of those stocks through fishing (NASCO, 1998) and other human impacts.

**(2) Simplicity and communicability:** The methods should be clearly described so that the basic principles (if not all the technical details) can be understood by regulators, policy makers and stakeholders.

**(3) Transparency:** It should be possible for all people concerned to see how the compliance assessment is carried out and for the relevant documents and software to be publicly available.

**(4) Consistency in approach and decision making:** In examining current statistical compliance methods, the default position at the outset is to retain, as far as possible, existing approaches and/or the principles that underpin them if they are shown to be appropriate. This is considered important because maintaining consistency in management decision making over time facilitates easier understanding. Accordingly, no recommendations for change will be made unless there are good reasons to do so.

**(5) Statistical best practice:** The statistical analyses applied should be valid according to the best available statistical understanding and practices.

## 6.3 Review of the current compliance assessment approach

This section provides an overview of how the statistical compliance assessment for the 64 Principal Salmon Rivers (PSRs) in E&W is currently conducted (hereafter *current compliance assessment approach*). The method was originally developed by the EA (Environment Agency, 2012).

Note that, in the sections that follow, we define E to be a random variable representing the log to the base 10 ($\log_{10}$) of egg deposition numbers, where egg deposition is in millions of eggs (see Figure 6.1).

### 6.3.1 Summary of the current compliance assessment approach

For the current year's assessment, the estimates of egg deposition E for that year and the previous nine years, i.e., 1 + 9 = 10 years, are used. A Bayesian 20$^{th}$ percentile linear regression including a possibly positive effect of a preceding spawning year on the current year is fitted to these data points using WinBugs software, and graphical and tabular outputs produced in an Excel spreadsheet.

A simple linear trend is also estimated, the parameters of which are used to project the 20$^{th}$ percentile of E ($E_{20}$) five years into the future, i.e., 10 + 5 = 15$^{th}$ year of the data, written as $E_{20}^{(15)}$. Using a Bayesian method, the probability that this $E_{20}^{(15)}$

value exceeds the CL is estimated. The river's stock status classification is assigned according to this probability, as described more comprehensively below.

We do not comment here on whether this is the correct thing to do, we are simply stating what is currently done. We also note that aspects of the current approach are difficult to understand.

### 6.3.2 Components of the current compliance assessment approach

#### *6.3.2.1 Management Objective*

The Management Objective (MO), as defined in the original Salmon Action Plan (SAP) Guidelines for England and Wales, is that a stock should be meeting or exceeding its CL (see Section 2.1) in at least four years out of five on average (i.e. >80% of the time; Figure 6.1). This led to the use of 20$^{th}$ percentile regression modelling in the compliance assessment approach to estimate the probability of $E_{20}^{(15)}$ meeting or exceeding its CL. It is important to note, however, that the MO only defines the use of the 20$^{th}$ percentile regression – it does not mean that if a river's estimate of E exceeds its compliance limit in at least 4 years out of 5 then the river 'passes'. As is explained below, the current method also uses the uncertainty in the estimation of E for the final classification of the stock status.

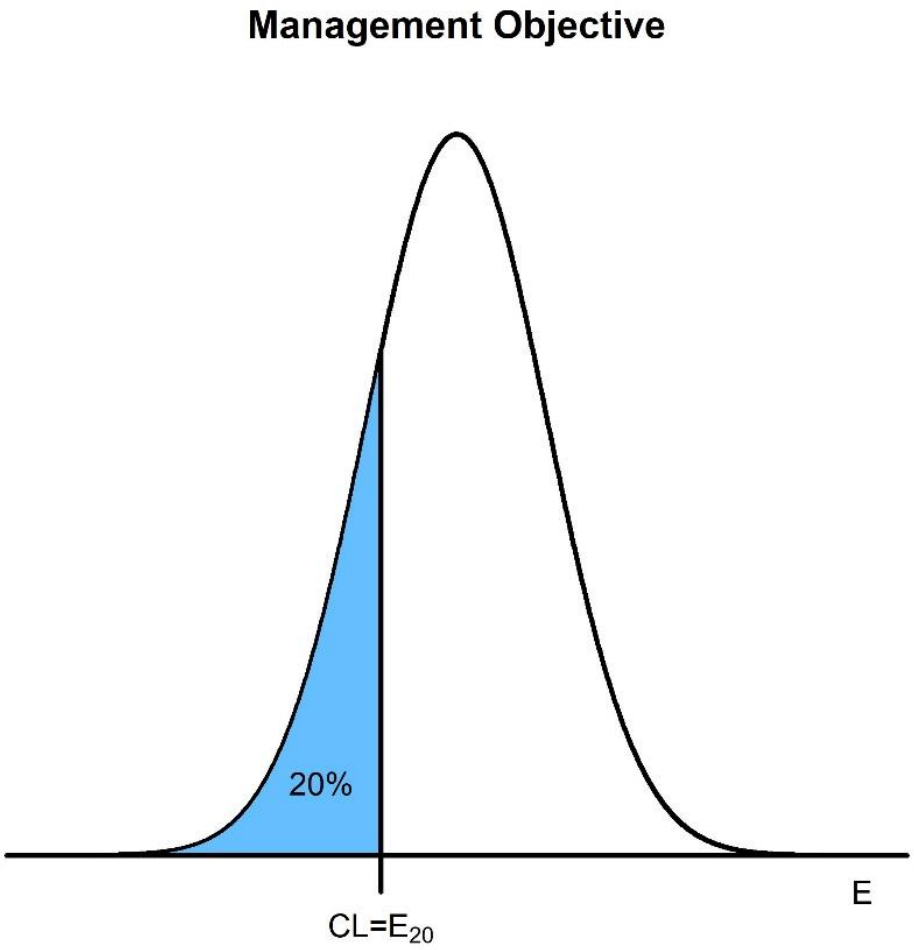



*Figure 6.1. Illustration of the concept behind the Management Objective (MO). The plot shows the distribution of E - measured in log10(eggs in millions). The MO states that a river's egg deposition should be meeting or exceeding its CL in 4 out of 5 years on average, or 80% of the time. Equivalently, if the twentieth percentile of E (E20) is at the CL, then there is an 80% probability that E will exceed the CL.*

#### *6.3.2.2 Management Target*

As defined by NASCO, "Management targets should also be established at a level above the CL to assist fishery managers in ensuring that there is a high probability of stocks exceeding their CLs" (Section 2.4e of NASCO guidelines (2009)). In England and Wales, the MT is a spawning stock level for managers to aim at for each river to ensure the MO is met and is not used in the quantitative assessment. Currently, the England and Wales MTs (Figure 6.2) are calculated as shown in Equation 6.1 below:

$$MT = CL + 0.842 * SD(E^{(10)})$$ Equation 6.1

where SD($E^{(10)}$) is the standard deviation of egg deposition from the current year and the previous 9 years. Assuming a Gaussian distribution for E, the constant, 0.842, is used to ensure that the MT equates to the mean or median of E (see Figure 6.2), with the 20th percentile of E equal to the CL

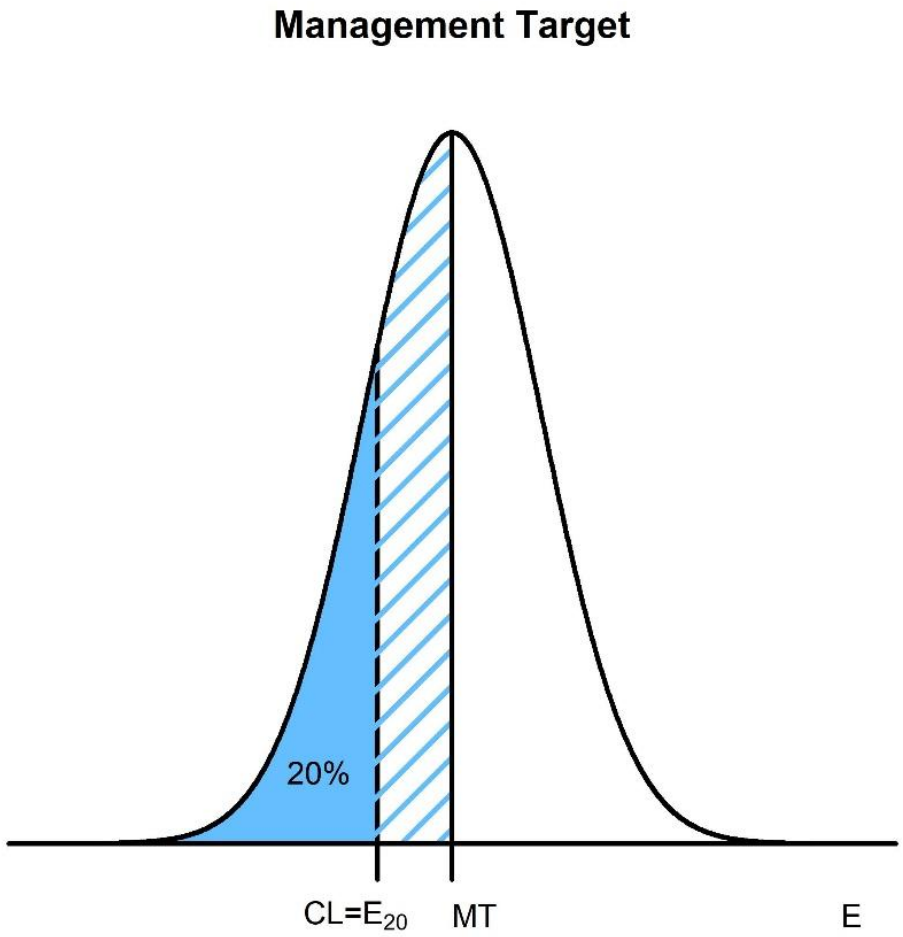



*Figure 6.2. Illustration of the Management Target (MT). This is calculated by the formula: MT = CL + 0.842*SD(E(10)), where SD(E(10)) denotes the standard deviation of the observed values of E from the current year and the previous 9 years' egg deposition estimates. Assuming that E has a Gaussian distribution with E20 equal to the CL, the MT is the mean or median of E.*

#### 6.3.2.3 Projection into the future

The NASCO Guidelines recommend using an element of future projection:

"With respect to the achievement of the reference points or other measures of abundance and diversity: …… Ideally, stock levels should also be forecast for one or more years ahead to provide some predictions of future expected achievement of management objectives under current (or modified) management measures …".

Currently in the E&W method, egg deposition is projected five years ahead using the regression line based on data for the last ten years. This projection was intended to give early warning of potential declines or poor state in the near future. Conversely, if egg deposition is low but the trend is upwards, then any resultant management decision may be less restrictive than if there was no trend or a negative trend. One characteristic of this projection is that the associated uncertainty inevitably increases as one projects further into the future. Because of this increased uncertainty, the risk classification of the stock is more likely to be allocated as one of the two middle 'Probably' classes (see section 6.3.2.5).

#### 6.3.2.4 Modelling dependence

The current method includes a possible positive effect of a preceding spawning year on the current year, specifically a parameter which models dependence between an egg deposition estimate and the egg deposition in the preceding year. This parameter is constant across all rivers. This treatment is different to the linear regression parameters, which are all estimated uniquely for each river.

#### 6.3.2.5 Stock status classes

Assigning a final stock status incorporates uncertainty in the estimation of E. Specifically, this uncertainty is used to estimate the probabilities of the $E_{20}^{(15)}$ being above the CL. These probabilities are set at 95%, 50% and 5%. The probabilities are used to define the four classes of stock status:

- Not At Risk (NAR): $p > 95\%$ probability that $E_{20}$ is above CL
- Probably Not At Risk (PNAR): $50\% < p \leq 95\%$
- Probably At Risk (PAR): $5\% < p \leq 50\%$
- At Risk (AR): $p \leq 5\%$

### 6.3.3 Statistical details of the current compliance assessment approach

The current compliance assessment approach is based on a linear regression model of the form shown in Equation 6.3 below:

$$E_{i,t} = \alpha_i + \beta_i \left( t - \frac{T}{2} \right) + \varepsilon_{i,t} \qquad \text{Equation 6.3}$$

where $E_{\{i,t\}}$ is the log10 egg deposition in river $i$ in year $t \in$ 1,…,T, year is centred through the term $\frac{T}{2}$ , where $T = 10$ is the total number of years with egg deposition, and $\varepsilon_{i,t}$ is an error term that is an autoregressive function of time (see section 6.3.3.1). A Bayesian method is used to estimate the intercept and slope parameters $\alpha_i$ and $\beta_i$. Both parameters are assigned uninformative priors. The credible interval for the 5-year projection is obtained from setting $t = 15$ in Equation 6.3 and using posterior distribution simulations of $\alpha_i$ and $\beta_i$.

#### *6.3.3.1 Statistical theory behind projection and dependency in time*

In summary:

- The underlying model assumes that E changes linearly in time
- Prediction of E projected into the future assumes dependence in time estimated through a correlation parameter $\rho$
- All estimation and calculation of credible intervals for projection is done using a Bayesian approach.

The code for the current approach assumes that the annual egg deposition estimates for each river are not independent of those values for the same river in different years. An observation depends on some underlying mean μ (modelled by a linear trend) and on the previous observation (except for year 1 in the data). This dependence on the previous observation is governed by a dependence parameter ρ. The biological basis for dependence is discussed further in Section 6.4.3.

Note that in the modelling treatment below, we assume standard mean regression modelling. However, the general concepts are the same for both types of regression – the 20$^{th}$ percentile component is a minor modification.

Define $E_{i,t}$ to be the log egg deposition for river *i* in year *t*. The model assumes that:

$$\mathrm{f}\left(E_{i,t}\middle|E_{i,t-1}\right) \sim Normal\left(\rho E_{i,t-1} + \mu_{i,t}(1-\rho),\ {\sigma_i}^2(1-\rho^2)\right) \quad \text{Equation 6.4}$$

where the first term in the bracket *Normal*( , ) is the conditional mean and the second term is the conditional variance. The term $\mu_{i,t}$ represents the linear trend for river *i* in year *t*. Note that for small $\rho$, the conditional mean is approximately $\mu_{i,t}$.

Our view is that the conditional mean and variance components in Equation 6.4 are not correct. Assume that:

$$E_{i,t}|E_{i,t-1} = \mu_{i,t} + \epsilon_{i,t} \quad \text{Equation 6.5}$$

where the error term $\epsilon_{i,t}$ is correlated with the previous error term $\epsilon_{i,t-1}$. Specifically, we assume that $\epsilon_{i,t}$ has an autoregressive AR(1) process such that:

$$\epsilon_{i,t} = \rho\epsilon_{i,t-1} + z_{i,t} \quad \text{Equation 6.6}$$

where $z_{i,t} \sim N(0, {\sigma_i}^2)$. Thus, the autoregressive AR(1) process means that the residual at time *t* depends on the residual at time *t-1* (but does not depend on any earlier values) plus some independent error. The dependency is governed by the correlation parameter $\rho$ such that $|\rho| < 1$.

We model the mean function by:

$$\mu_{i,t} = \alpha_i + \beta_i\left(t - \frac{T}{2}\right) \quad \text{Equation 6.7}$$

Centring *t* through the term $\frac{T}{2}$, where $T$ is the total number of years with egg deposition, ensures that the intercept ($\alpha_i$) and trend ($\beta_i$) parameters are independent of each other but serves no other purpose. For the egg deposition models, $T = 10$.

Using Equation 6.6, we can write Equation 6.5 as:

$$E_{i,t}|E_{i,t-1} = \mu_{i,t} + \rho\epsilon_{i,t-1} + z_{i,t}$$

Then, substituting in the value for the residual $\epsilon_{i,t-1}$, we obtain

$$E_{i,t}|E_{i,t-1} = \mu_{i,t} + \rho(E_{i,t-1} - \mu_{i,t-1}) + z_{i,t} \qquad \text{Equation 6.8}$$

Thus, the conditional distribution is:

$$\mathrm{f}\left(E_{i,t}\middle|E_{i,t-1}\right) \sim Normal\left(\mu_{i,t} + \rho\left(E_{i,t-1} - \mu_{i,t-1}\right),\ {\sigma_i}^2\right) \qquad \text{Equation 6.9}$$

This differs in terms of both the conditional mean and variance from that used in Equation 6.4. For Equation 6.9, the mean has a term $\rho\mu_{i,t-1}$ instead of $\rho\mu_{i,t}$ in Equation 6.4. The variance in Equation 6.4 is reduced by a factor $(1-\rho^2)$ compared to that in Equation 6.9. Of course, if $\rho$ is small, then this factor will be close to 1 and there will be little difference between Equations 6.4 and 6.9. However, as $\rho$ increases, the difference becomes more important.

#### *6.3.3.2 Consideration of future projection time periods*

The NASCO Guidelines recommend using an element of future projection but do not specify the time period. The current approach focusses on the projected compliance state five years into the future. However, because uncertainty around the projection gets larger with every additional year of projection, the projected stock status classification at five years in the future is more likely to be either of the two Probably classes (in the current system).

The rationale for using a projection in the compliance assessment process is that the trend in egg deposition estimates over the most recent 10 years, if it were to continue, is used to indicate the possible status of returning adult stocks - including those arising from the current spawning year (i.e., year 0). The spawning age timing of fish arising from eggs deposited in the current year will depend on the life-history characteristics of individual fish and these vary between rivers, with generations typically varying between 3-5 years. By opting for a 5-year projection, the current approach enables early management intervention under moderate future projection uncertainty, compared with higher uncertainty associated with longer time periods.

### 6.3.3.3 *Illustrations of theoretical concepts*

Figure 6.3 illustrates some example realisations of the model defined by equations 6.5 to 6.7. The first row illustrates the situation in which the residuals are strongly dependent (ρ = 0.8), leading to runs of successive years with positive or negative residuals. The bottom row gives two realisations where the residuals are independent, so that residuals are randomly scattered around the regression line.

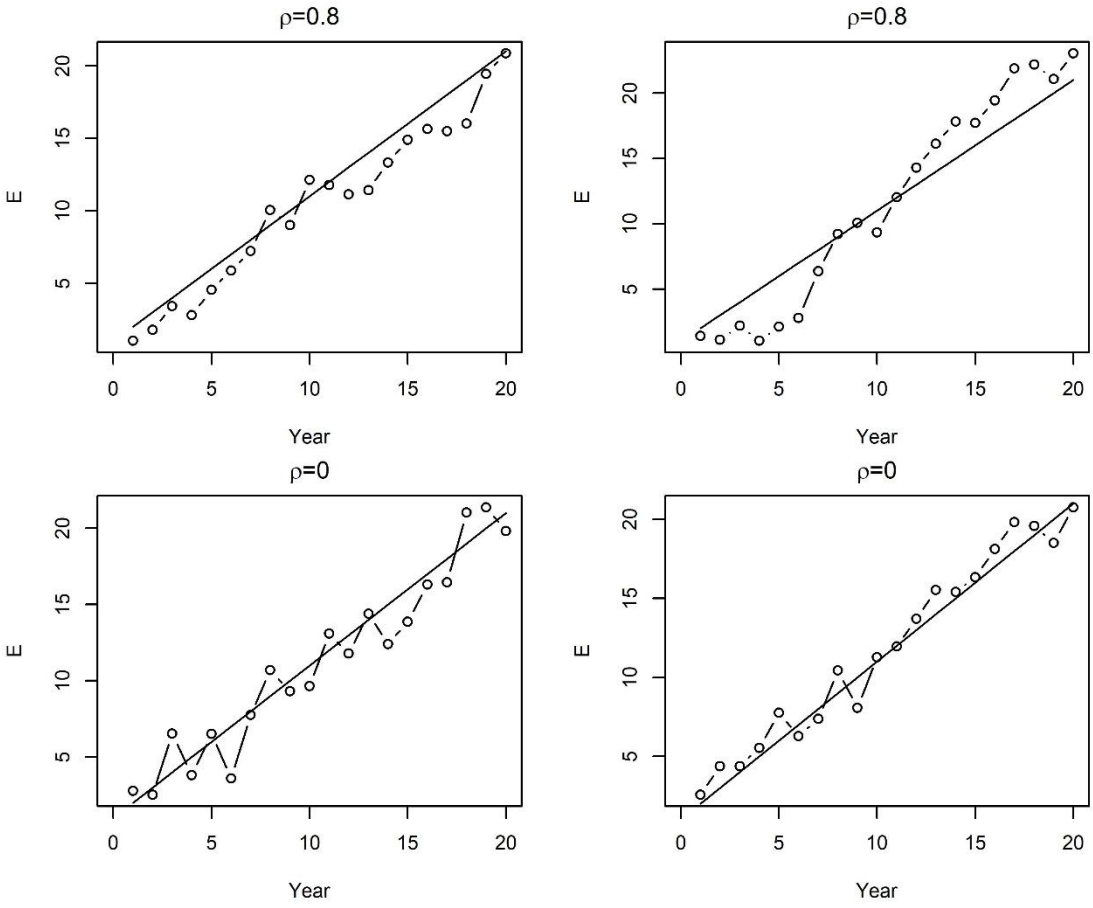



*Figure 6.3. Each of the graphs shows a simulation, for T = 20 years, of the process defined by equations 6.5 to 6.7. The plots on the top row are with ρ = 0.8. As a consequence of the high correlation between residuals, there are runs of positive or negative residuals. The plots on the second row are for ρ = 0. For these plots, the residuals are independent of each other.*

#### 6.3.3.3.1 *Projecting values when successive egg depositions are correlated*

Currently, the five-year projection is based on the $E_{20}$ linear trend. However, this is not how projections would normally be done under the time series model that is being used here. In this section, we describe how the parameter ρ would normally be

used to make projections when the series is correlated. This approach echoes one of the recommendations made by HR Wallingford when they reviewed the current approach. On page 27 of their report, HR Wallingford said:

“The current formula is centred on the linear trend although it may be more appropriate to use the predictive distribution of future egg counts”.

For a particular realisation of the joint distribution of the parameters (α, β, σ, ρ) from the WinBUGS output to project the level of future E, we can use the mean of the conditional distribution to predict the value at time t. This comes from Equation 6.9 so that:

$$\hat{E}_{i,t} = \mu_{i,t} + \rho\left(E_{i,t-1} - \mu_{i,t-1}\right) \quad t = 2, \ldots, 11$$

In words, the predicted value at time t is the value of the mean at time *t* plus *ρ* times the previous residual. At time *t = 1*, we take the predicted value to be $\hat{E}_{i,1} = \mu_{i,1}$. At time *t = 11*, the effect of ρ propagates information from *t = 10*. When *t = 12,…,15* (i.e., when projecting beyond the time scale of the data and its lagged effect), we do not have any *E* values. We thus replace $E_{i,t-1}$ by the previous prediction $\hat{E}_{i,t-1}$. Thus, the prediction becomes:

$$\hat{E}_{i,t} = \mu_{i,t} + \rho\left(\hat{E}_{i,t-1} - \mu_{i,t-1}\right) \quad t = 12, \ldots, 15 \qquad \text{Equation 6.10}$$

This prediction procedure is shown graphically in Figure 6.4. This gives the prediction for the medians of each of the parameter values from the joint distribution. We can see that this projection tends to the linear trend as we project further into the future. Thus, for five-year projection, using the trend as a predictor (which is currently done) will give very similar results to that in Equation 6.10. However, for a projection of fewer years ahead or for large values of $\rho$, the results will become increasingly different as the high dependence (due to large $\rho$) on the preceding value propagates the difference forwards in time.

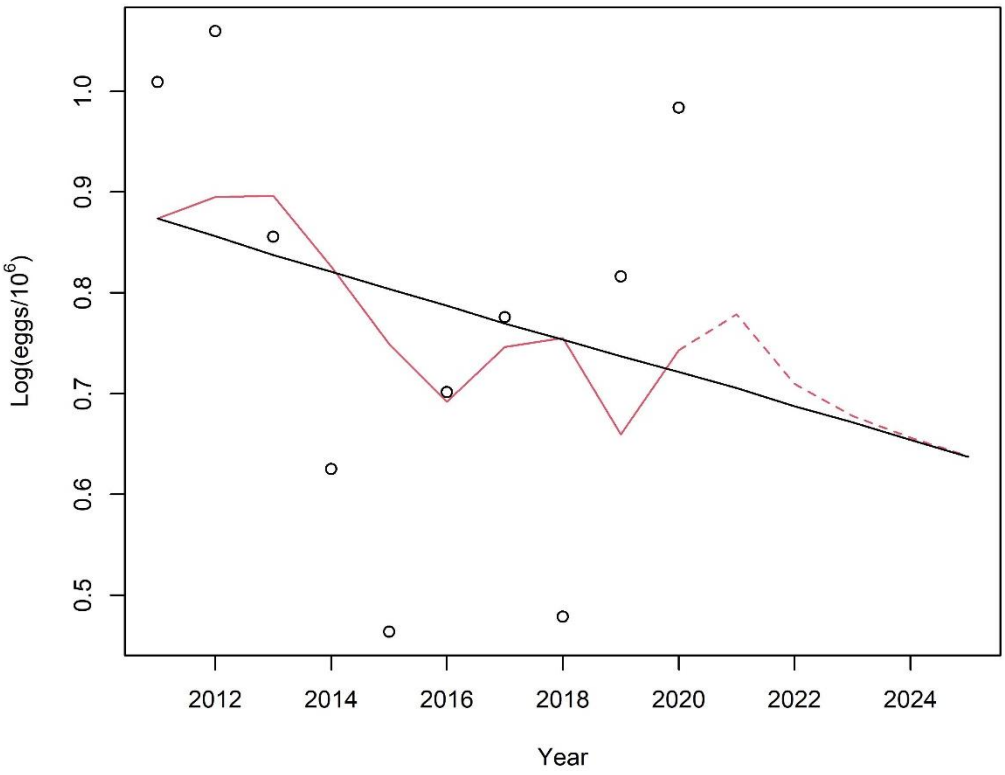



*Figure 6.4. Projection for one realisation of the joint distribution for an anonymous river. The black line is the linear trend in the mean. The red line is the projection. The dashed red line is where the projection is based on the previous year's projection rather than on an actual egg deposition estimate (open circle). The value of the dependence parameters ρ is 0.28.*

## 6.4 Our critique of the current compliance assessment approach

In this section, we consider the five principles outlined in Section 6.2 and note where the current compliance assessment approach does or does not satisfy these principles. We also develop an additional reason in support of change, associated with the low levels of egg deposition in some rivers in recent years.

**(1) NASCO guidance:** The use of CLs and MTs follows from guidelines produced by NASCO (NASCO, 2009). However, there are some features or unintended consequences of the statistical methods adopted that are less than ideal, as discussed below. The current approach follows NASCO guidance and so satisfies this principle to prioritise protecting salmon stocks over fisheries and other exploitation.

**(2) Simplicity and communicability:** The methods should be described clearly enough for the basic principles (if not all the technical details) to be understood by regulators, policy makers and stakeholders. It was recognised at the National Salmon Stock Assessment workshop (Atlantic Salmon Trust, 2017) that the 20$^{th}$ percentile regression is not used commonly and is difficult to explain and interpret - making it harder for people to understand. Based on our review of approaches of other jurisdictions, our current compliance assessment approach, which uses a single reference point and four probability rules to define four possible stock classifications ($\leq$ 0.05, 0.06–0.50, 0.51–0.95, and > 0.95) seems complicated – other jurisdictions use two probability bounds to define three possible stock classifications, much like a traffic light system, such as Critical, Cautious, and Healthy.

**(3) Transparency:** It should be possible for all people concerned to see how the assessment is carried out and for the relevant documents and software to be publicly available. Public documents describe the current approach in general, but the technical details of the stock assessment exist in fragmented form and there is not enough information for external stakeholders to properly evaluate and/or check the assessments themselves. Potential solutions include putting all the relevant documents online, including simple guides such as infographics, an interactive web application, and publishing the core principles in an open access, academic publication and code in a publicly accessible version-controlled repository, e.g., GitHub.

**(4) Consistency:** This consideration is not applicable at this stage.

**(5) Statistical best practice:** The underlying Bayesian approach of the current method is statistically sound and allows probability statements relating to thresholds to be made in a correct manner. Similarly, the precautionary concept of projection into the future is a good one, and one which we would wish to retain as part of a new compliance assessment method.

The underlying theory behind the current compliance assessment (by this, we mean the core mathematical details and statistical processes) was not written down formally in an academic publication or official report that we could trace. However, there are two sources of information that we can use to infer this theory. One is a review of the approach by HR Wallingford in 2012 (Environment Agency, 2012). The other is the WinBUGS code used to run the Bayesian model. The latter is probably the more appropriate to consider as the Wallingford review was based on this code.

A detailed review of the statistical theory and practice revealed four elements that could be improved:

- unintended consequences of uncertainty around estimating the 20$^{th}$ percentile relative to the MT
- the assumptions around the statistical distribution of E
- whether or not modelling dependence between years is required

We examine these each in turn below.

### 6.4.1 Unintended consequences of uncertainty

There are unintended consequences of uncertainty with respect to achieving the MT and the CL. The MT in the current compliance assessment approach is set above the CL. However, because there is uncertainty in the estimation of the 20$^{th}$ percentile, rivers having egg deposition levels at or above the MT will not necessarily achieve the desired NAR or PNAR classification (see Figure 6.5).

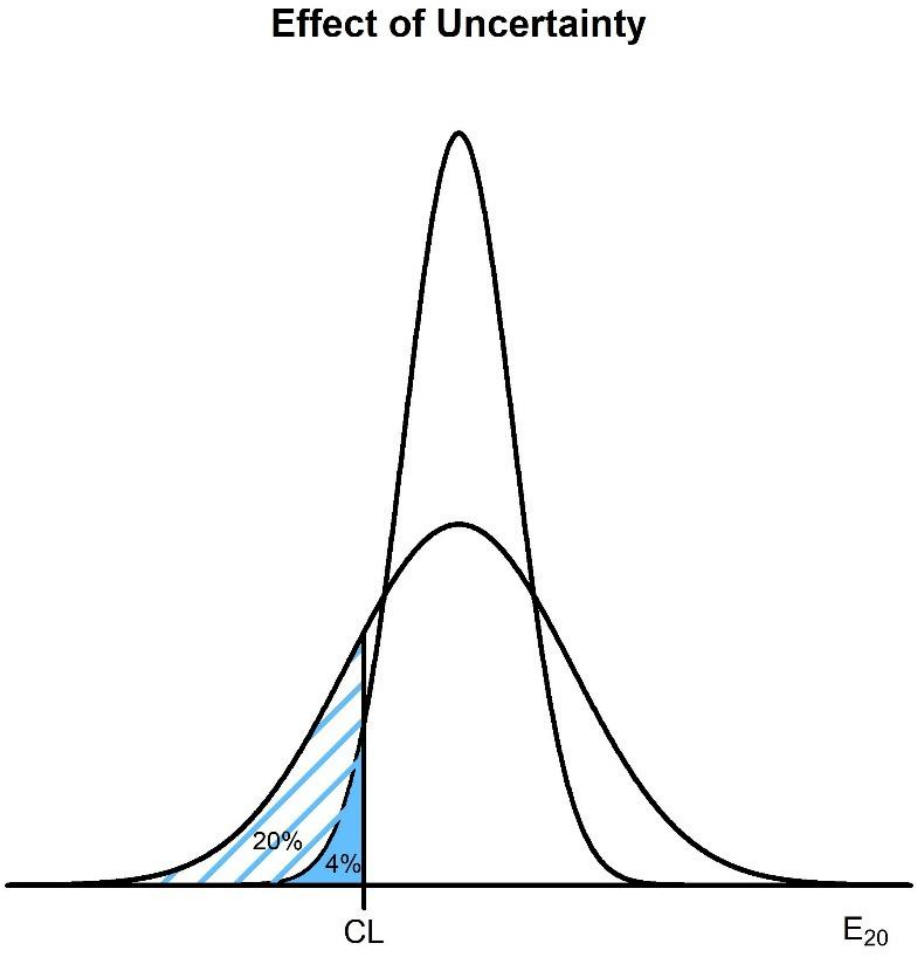



*Figure 6.5. Illustration of the effect of uncertainty in estimating the 20th percentile E20. The figure shows two potential distributions of E20. They both have the same mean but one has a higher variance than the other. For the high variance distribution, the probability of the E20 being above the CL is 80% = 0.8, putting it in the PNAR category. For the low variance distribution, the probability of the E20 being above the CL is 96% = 0.96, putting it in the NAR category.*

For example, consider results from the 2011 and 2020 assessments based on the current 20$^{th}$ percentile regression approach (Table 6.1). In 2011, there were 22 rivers where the previous 10-year mean (2002-2011) was above the MT. Of these, 20 had classifications of either PNAR or NAR, but one river was classified as PAR and one as AR. In 2020, only eight rivers had a 10-year mean (2011-2020) above the MT. Of these, five were PAR, three were PNAR and none of them were NAR. A major contributing factor to these 'anomalies' is that there is inevitable uncertainty in the projection that can make it difficult for a river to achieve either of the top two classifications.

*Table 6.1. Classifications from 20th percentile 5-year ahead projection of the 22 rivers whose 10-year mean E from 2002-2011 was above the MT (2011 assessment) and the eight rivers whose 10-year mean from 2011-2020 was above the MT (2020 assessment).*

| Assessment | AR | PAR | PNAR | NAR |
|---|---|---|---|---|
| 2011 | 1 | 1 | 10 | 10 |
| 2020 | 0 | 5 | 3 | 0 |

The 20$^{th}$ percentile regression can lead to anomalies where all egg deposition estimates in a river's time series are above the CL, but where the river is not classified as NAR. For example, see the egg depositions and $\log_{10}$CL for the four rivers in Figure 6.6. Rivers 1 and 3 have PAR classifications (though there is a downward trend for river 3 and so the 5-year projection will be lower than the egg deposition points), whereas rivers 2 and 4 have PNAR classifications. The main reason for this is because of the uncertainty in the projection of the 20$^{th}$ percentile, but this is an anomaly that can be difficult to communicate to stakeholders. River 2 has a downward trajectory and river 4 has high variation. These effects both contribute to NAR not being assigned to either river.

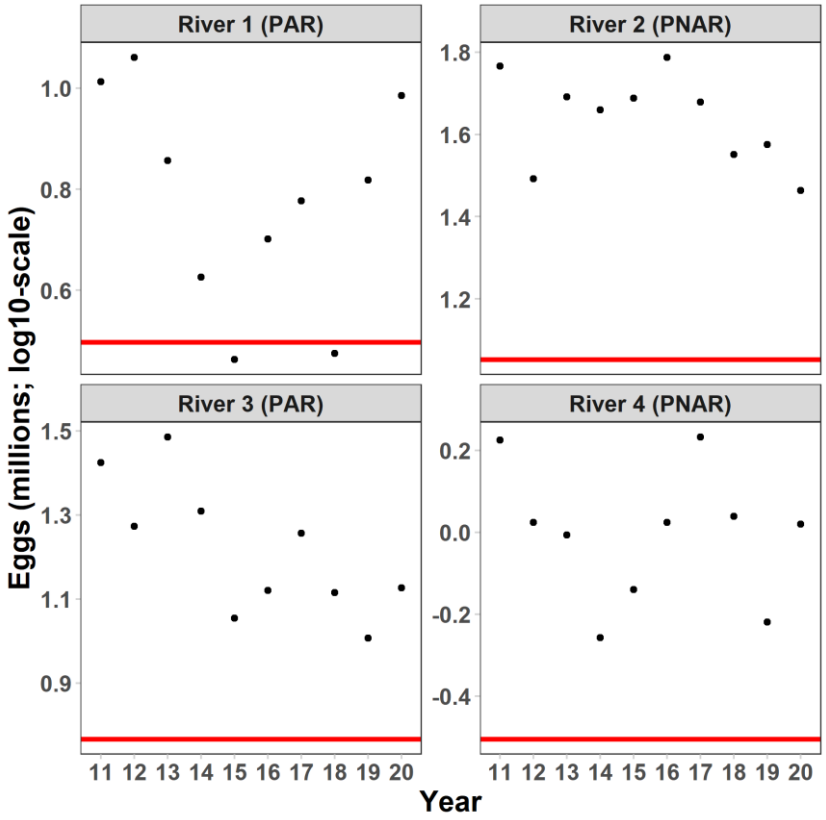



*Figure 6.6. Examples where egg depositions are above the CL for at least four out of the last five years, but where the assessment is not NAR using the current method based on 20th percentile regression. The value of the assessment is shown in the title of each plot. The red horizontal line is the log10CL.*

It is not widely understood that the 20$^{th}$ percentile is used as a direct implication of the MO, that "a stock should be meeting or exceeding its CL in at least four years out of five on average". However, uncertainty in estimating the $E_{20}$ means that the classification method may not satisfy the spirit of the MO because uncertainty in estimating the $E_{20}$ affects the final classification. We can see this in Figure 6.5. Both distributions of $E_{20}$ have the same mean, above the CL. However, the higher variation distribution would be allocated PNAR whereas the lower variation distribution would be allocated NAR.

### 6.4.2 The assumptions around the statistical distribution of E

With 20$^{th}$ percentile regression, one would expect around 80% of the estimated annual egg deposition points to fall above the 20$^{th}$ percentile regression line. This was the case in the earlier years of implementation of the current compliance assessment. However, in recent years, the percentage of points above the line has been rising. For example, 81.7% of the observed points across all rivers were above

the line in 2010, whereas 93.9% of the points were above the line in 2019. Our investigation of this issue revealed that there was a minor error in the code for the Bayesian model. When corrected, and when a separate value of the dependence parameter ρ was used for each river (see below), this reduced the 2019 figure to 83.9% (though, conversely, the 2010 figure was increased to 83.9%). One possibility is that because egg deposition for most of the 64 PSRs in England and Wales rivers has declined to very low levels in recent years, the normality assumption for E in standard mean regression, and the $E_{20}$ distribution in the 20$^{th}$ percentile regression, is starting to break down.

### 6.4.3 Is it necessary to model dependence between years?

The current compliance assessment approach includes a dependence parameter ρ. There is a biological reasoning for assuming some dependence between annual egg deposition estimates over time. The eggs deposited in one year will become the adult spawners several years later, so a strong year for egg deposition might, in the absence of strong density-dependent forces, be expected to result in strong adult returns and egg deposition. Similarly, as the 1SW salmon in one year and the 2SW salmon in the next year derive from the same egg deposition year (and smolt year), all other things being equal, one might expect a strong 1SW return in year t, to be reflected in a strong 2SW return in year t+1. However, salmon biology is much more complicated than this. The eggs deposited in a river in England or Wales in a specific year may give rise to smolts after one, two or even three years in freshwater, and those smolts may return as 1SW, 2SW or older adults, and even return as repeat spawners. Hence, the returns from a single year's eggs may occur after two to six or more years. A data-rich cohort analysis would be required to fully assess dependence over time. For the reasons above, the assumption of dependence between returns in one year and the next is simplistic for a single stock. Further biological issues are briefly considered later in this section.

The current compliance assessment approach assumes a constant value of ρ for all rivers, which is a likely an oversimplification and overlooks river-specific differences due to stock sea-age compositions and local conditions. An alternative would be to estimate a separate ρ for each river, on the basis that there could be local reasons pertaining to each river, but these reasons could differ between rivers. Thus, an alternative to Equation 6.4 is to fit a different $\rho$ dependence parameter to each river. However, using the principle of simplicity, we should first investigate whether there is evidence from the data that any dependence parameter is needed.

A standard tool for assessing dependency in data is the autocorrelation function (ACF). Essentially, the ACF measures the correlation between observations and those at one, two, three, etc., time points (known as lags) before them. If observations are independent, then these correlations will be low. The autocorrelation plots give some dashed, horizontal confidence interval lines. These

provide a guide as to whether any observed autocorrelation is real or could be attributed to chance. Thus, when evaluating the autocorrelation plots, we are looking at lagged autocorrelations that cross these dashed lines.

We investigated autocorrelations for each river for the 2010 assessment (egg depositions from 2001 to 2010) and the 2020 assessment (egg depositions from 2011 to 2020). The autocorrelation was evaluated using the residual values after fitting a standard linear regression model.

Figure 6.7 shows five rivers where the lag autocorrelation estimates fall below the lower confidence band for the 2001 to 2010 data. For these rivers, the significant autocorrelation is negative. For the 2011 to 2020 data, only two rivers had autocorrelations that exceeded either of the correlation bands (both negative).

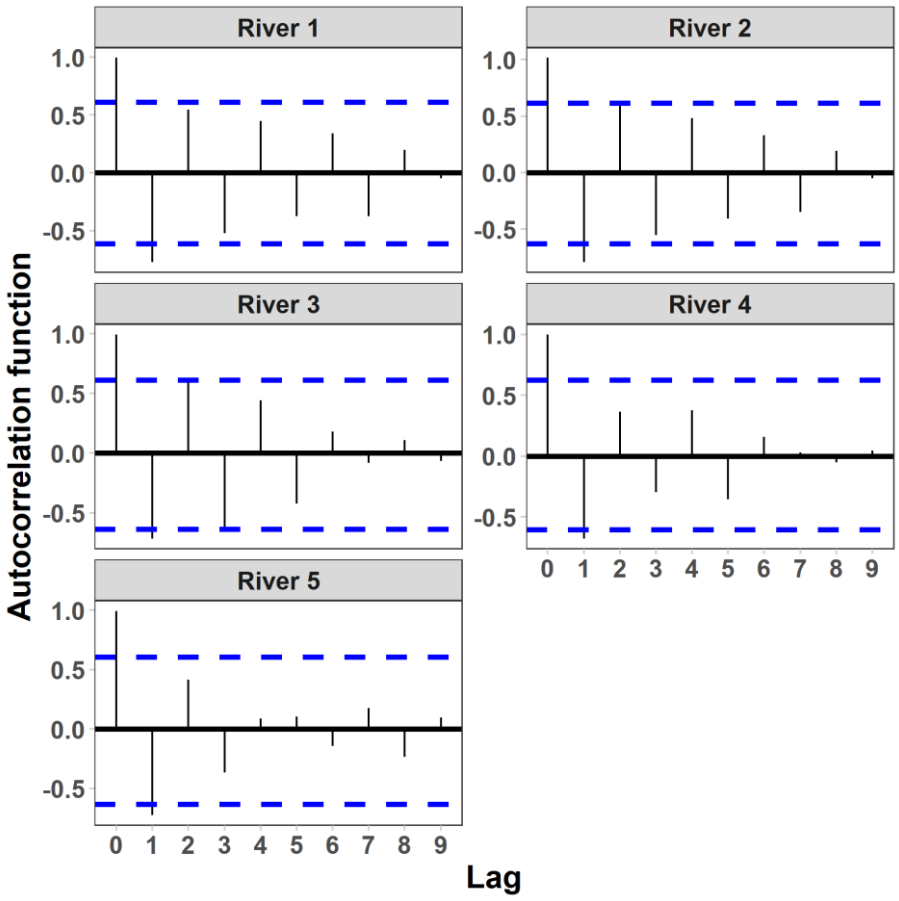



*Figure 6.7. Five rivers for the 2001-2010 data where the autocorrelation of residuals from a linear regression model exceeded the lower confidence band. All these exceedances are for negative autocorrelations.*

Thus, out of the 64 PSRs, very few had statistically significant temporal autocorrelations, and there were fewer (two) for the more recent 2011-2020 data than for the 2001-2010 data (five). This suggests that any autocorrelation effect is reducing but that, if present, it is negative for some rivers.

A negative correlation suggests that if you have a better than average egg production year then you are likely to have worse than average egg production in the following year (or, conversely, if you have a worse than average year, this will probably result in a better than average one next year). One explanation for the negative correlation could be density dependence among cohorts.

As a result of the potential for a negative dependence parameter, the prior distribution for the dependence parameters in the WinBUGS programme for the simulations was changed to be Uniform(-0.7, 0.7), rather than Uniform(0, 0.7). This allowed the potential for negative value of ρ *a priori*.

Overall, this investigation suggests there is little evidence in the data (especially the more recent data) to support the use of a dependence parameter. However, we can further test this assertion in a simulation study that measures the precision of the projection of future values with and without the dependence parameter.

We examined the ability of five approaches to predict E:

1) Different dependence parameter ρ for each river, use trend line for projection
2) Different dependence parameter ρ for each river, use Equation 6.10 for projection but with $\rho_i$ instead of ρ
3) Single value of ρ for all rivers, use trend line for projection
4) Single value of ρ for all rivers, use Equation 6.10 for projection
5) Trend from linear regression with no dependence

The five approaches consider different forms of the dependence parameter (i.e. constant across all rivers, different for each river, no dependence) and whether projection derived directly from the linear regression line or used the potentially better approach defined by Equation 6.10. For simplicity and because of the distributional problem with 20$^{th}$ percentile regression outlined above, all five approaches use standard linear regression for the projection. However, the importance or not of the dependence parameter should not be affected by the form of linear regression used.

We used the six assessments from 2010 to 2015 to evaluate the five approaches. This allowed us to compare the projected value five years ahead with the actual value, between these scenarios. Thus, for example, for the 2015 assessment we compared the projected and subsequent actual values for 2020.

In each of the assessments we projected the value of E five years ahead for each of the 64 PSRs. As a measure of projection performance, we used the mean absolute error (MAE) of the differences between the projected E and the observed data (i.e., $\log_{10}$ egg deposition) over the 64 PSRs. Thus, our measure is shown in Equation 6.11 below:

$$MAE = \frac{1}{64}\sum_{j=1}^{64}|obs_j - pred_j| \qquad \text{Equation 6.11}$$

The results are shown in Table 6.2 below. By year, there are very little differences between each of the methods. The last column of Table 6.2 shows that the overall means of the five methods are identical. If we had used shorter projection time spans (e.g. 1 or 3 years), then we might have seen differences between methods that used

the trend line vs Equation 6.10 for projection. As was illustrated for an anonymous river in Figure 6.9, the projection using Equation 6.10 and the trend line get closer as the number of projected years increases.

*Table 6.2. Mean absolute error (MAE, Equation 6.2) in five-year ahead projections for the five methods for assessment years 2010 to 2015. Also shown is the overall mean for each method over all the assessment years.*

| | **Assessment year** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **2010** | **2011** | **2012** | **2013** | **2014** | **2015** | **Mean** |
| Method 1 | 0.41 | 0.46 | 0.33 | 0.32 | 0.30 | 0.32 | 0.36 |
| Method 2 | 0.40 | 0.47 | 0.33 | 0.32 | 0.30 | 0.32 | 0.36 |
| Method 3 | 0.41 | 0.46 | 0.33 | 0.32 | 0.30 | 0.32 | 0.36 |
| Method 4 | 0.40 | 0.42 | 0.33 | 0.32 | 0.30 | 0.31 | 0.36 |
| Method 5 | 0.41 | 0.46 | 0.33 | 0.33 | 0.30 | 0.32 | 0.36 |

Our conclusion from this simulation study is that the simplest approach, Method 5 (the trend from linear regression with no dependence), is the one that we recommend using for projection.

## 6.5 New Assessment

To help with clarity, we note that the approach described in this section refers to all the 64 PSRs. Thus, each river will have its own estimates and probability distributions for the model parameters. Note also that all egg deposition data is transformed by a $\log_{10}$ transformation. Thus, in the modelling context, when we refer to egg deposition data we are referring to the transformed data. The reason for the transformation is to ensure that the modelling assumptions of normality and constant variance of residuals are better satisfied.

There are two parts to the new assessment: the past five-year mean and a five-year forward projection. Both are estimated within a Bayesian framework so that probability statements can be made about the metrics generated.

### 6.5.1 Past five-year mean

The mean $\mu$ of the past five-years of egg deposition data is calculated. Thus, for the assessment in year $t$ we have the model

$$E^{(t,5)} = \mu^{(t)} + \delta \qquad \text{Equation 6.12}$$

where $E^{(t,5)}$ is the egg deposition from years $(t-4), (t-3) \cdots t$, $\mu^{(t)}$ is the past five-year mean and $\delta$ is an error term such that $\delta \sim N(0, \tau^2)$. In our Bayesian computations, we use uninformative priors for $\mu^{(t)}$ and $\tau^2$.

The past 5-year mean (for brevity, *past mean*) represents the performance of the river in the most recent time-period available.

### 6.5.2 Five-year forward projection

Firstly, a standard linear regression model is fitted to the last ten years of egg deposition data for each river:

$$E_t = \alpha + \beta\left(t - \frac{T}{2}\right) + \varepsilon_t \qquad (t = 1 \cdots 10) \qquad \text{Equation 6.13}$$

where $t$ represents year, which is centred through the term $\frac{T}{2}$, where $T = 10$ is the total number of years with egg deposition, and $\varepsilon_t$ is an error term that is assumed to have a normal distribution with mean 0 and variance $\sigma_i^2$. We use a Bayesian method to estimate the intercept and slope parameters $\alpha$ and $\beta$. Both parameters are assigned uninformative priors. The posterior distribution for the 5-year projection is obtained from setting $t = 15$ in Equation 6.11 and using posterior distribution simulations of $\alpha$ and $\beta$.

**Recommendation 7**

*Apply standard linear regression with no temporal dependence (autocorrelation) to evaluate the trend in annual egg deposition estimates as part of the compliance assessment.*

### 6.5.3 Metric classifications

Both the past mean and the forward projection metrics are classified into one of three classes: Healthy, Cautious or Critical. These are based on the probability that the metric being measured (the mean or the forward projection) is above each of the upper and lower reference points (see next section for how these are derived). Specifically, a metric is:

- *Critical* if the probability that it is above the LRP is less than 0.75
- *Cautious* if the probability it is above the LRP is greater than or equal to 0.75 and the probability it is above the URP is less than 0.75
- *Healthy* if the probability it is above the URP is greater than or equal to 0.75.

Recall that these probabilities are calculated from the posterior distribution of each metric. The 0.75 probability is used because it was adopted by ICES for the simultaneous attainment of seven management objectives (ICES, 2003) as part of an agreed management plan for the West Greenland fishery. The same probability has also been used as a level of risk aversion applied for catch advice for homewater fisheries on the North American stock complex, and in national assessment procedures elsewhere.

The final classification for a river is determined by the lowest class of the past mean and forward projection metrics. This is a precautionary approach designed to protect stocks. Consider the two scenarios that might happen: (i) past mean lower than forward projection. In this situation, we use the recent past mean data to determine class because the forward projection is modelled and might not happen in practice; (ii) forward projection lower than past mean. Here, we use forward projection to determine class as the linear regression model predicts what will happen in the future if past trends continue.

Another way to define and visualise the classification process is through credible intervals. If we calculate a 50% credible interval for a metric, then the lower credible interval bound is equivalent to the $25^{th}$ percentile of the metric. Thus, if the lower bound is at a lower or upper reference point, there is a 0.75 probability that the metric is above the reference point. If we define the lower credible interval bound for a metric to be LB. Then, the metric is:

- *Critical* if LB < LRP
- *Cautious* if LB ≥ LRP and LB < URP
- *Healthy* if LB ≥ URP

Figure 6.8 illustrates the classification with some stylised examples, using the 50% credible interval approach.

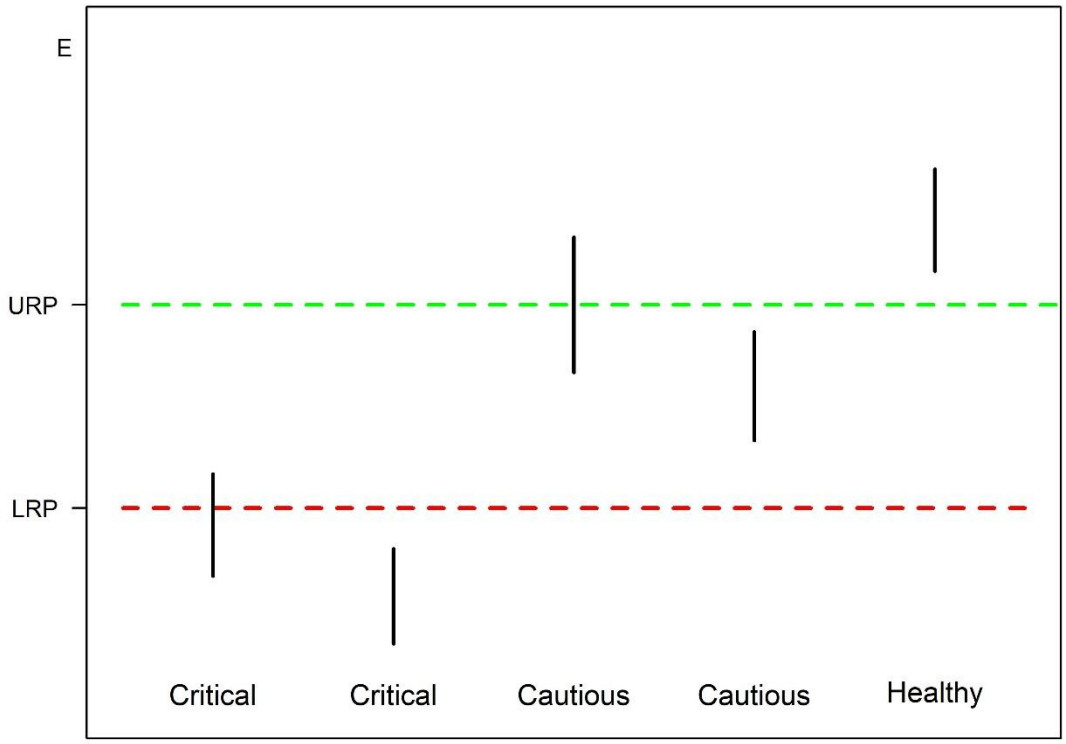



*Figure 6.8. Five scenarios of 50% credible intervals for an assessment metrics (past five-year mean or five-year forward projection). Each scenario shows the class that it is allocated to, depending on the lower bound (LB) of the credible interval. For example, the first scenario is in the Critical class because the LB is not greater than the LRP; the third scenario is Cautious because the LB is above the LRP but below the URP; the fifth scenario is Healthy because the LB is greater than the URP.*

### 6.5.4 Deriving the Upper and Lower Reference Points

Our new approach requires the use of upper and lower reference points. The selection of these reference points has a biological basis but also depends on how managers will use them in their decision-making process. This is particularly the case for the Upper Reference Point (URP), since this sets the manager-defined desired status condition of a healthy stock, i.e. one capable of withstanding an acceptable level of harvest (akin to sustainable exploitation) and other pressures without risk to future generations of the stock.

The Limit Reference Points and Upper Stock Reference (equivalent to URP) have been devised for assessment and management of Canadian fisheries (including Atlantic salmon) as part of their Precautionary Approach (PA) framework (Fisheries and Oceans Canada, 2006 and 2009). Within the Canadian PA framework, these reference points define Critical, Cautious and Healthy zones with respect to stock status – see Figure 6.9.

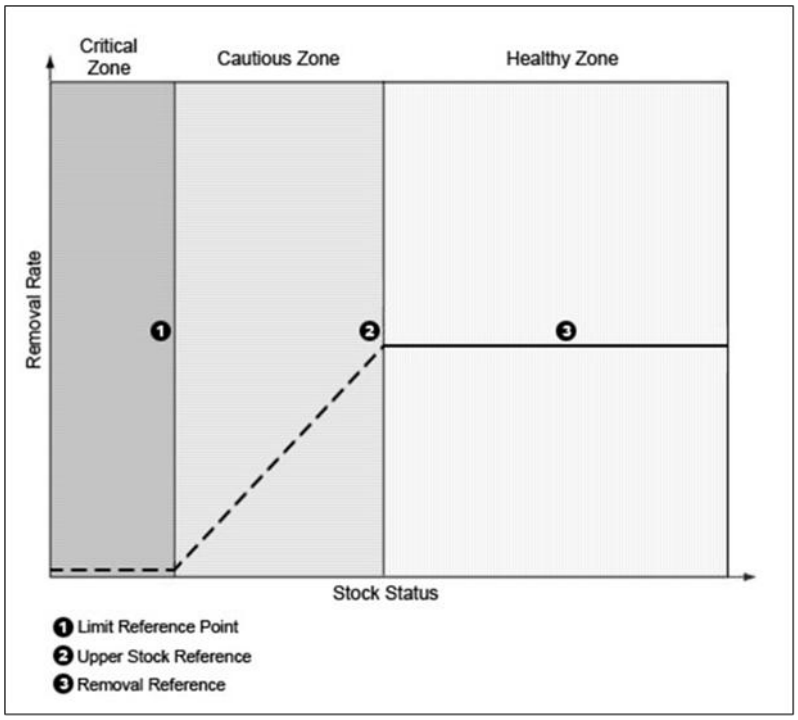



*Figure 6.9. Precautionary Approach (PA) framework to inform decision making on catch controls (Fisheries and Oceans Canada, 2009).*

For E&W, it is proposed that:

- The LRP is the CL, adopted as a limit reference point below which there is an increased risk of stock collapse as abundance levels fall toward zero
- The URP is defined as the level of egg deposition required to maximise freshwater production, i.e., to attain the theoretical maximum smolt (Max Smolt) output, for each catchment. This new approach breaks the association in the current system between the MT and the MO, establishing a new (and more explicit) link between the MT and the freshwater production potential of the river system (and, indirectly, the need to provide high-quality riverine environments to support that potential)

Given the pressures on salmon production in both the freshwater and marine environments, alongside the reality that most of the actions to reduce pressures are likely to occur in the freshwater and estuarine environments, a fundamental strategy to improve the status of salmon stocks is to maximise freshwater productivity by ensuring that the highest number of smolts enter the ocean in the best condition (Thorstad *et al*., 2021). Hence the proposed URP is set at the theoretical Maximum Smolt (MS) for each catchment.

Both the LRP and URP are defined in terms of egg numbers (but retaining the flexibility to convert egg numbers to adult spawners as the need arises). This is consistent with the application of the CL and MT in the current process. Thus, the value of Maximum Smolt on the stock-recruitment curve is equivalent to the number of eggs (strictly, the $\log_{10}$ of eggs) that a river would need to produce to maximise the number of smolts produced. The MS for each of the 64 PSRs will be derived from parameter estimates from the non-linear Ricker stock-recruitment curve (Wyatt and Barnard 1997a, b), as illustrated in Figure 6.10.

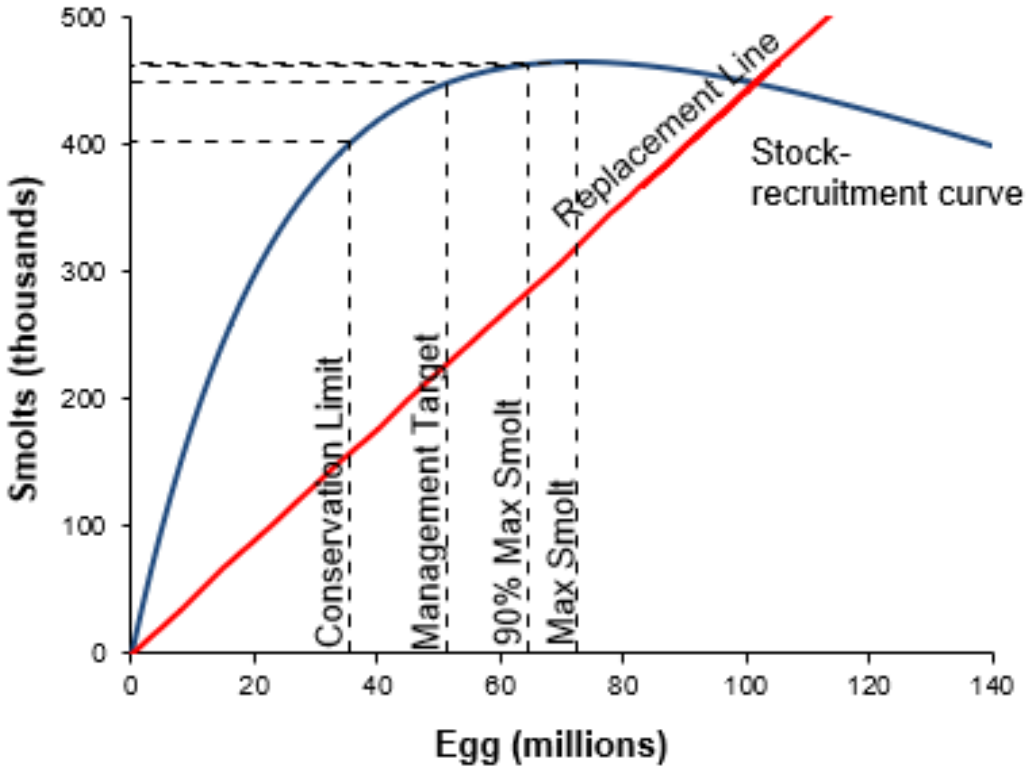



*Figure 6.10. Location of various Biological Reference Points on a generalised egg-to-smolt (Ricker) stock-recruitment relationship.*

We considered setting the URP as 1.5*CL, as the resultant egg deposition would be close to that of the MT on most rivers under the current compliance process, and had been trialled in the Gulf of St Lawrence region of Canada (although it was replaced with 3.5*CL reference). However, given that the 1.5*CL does not have an immediate biological/stock management basis, and in ten E&W stocks it is higher than the MS, we propose to use MS as the URP.

The consequences of introducing the LRP and URP, as proposed above, are examined in Section 8 of this report in terms of compliance outcomes. This includes the incorporation of other changes to the statistical procedure used to assess compliance.

## 6.6 Reasons for Changing the Current Compliance Assessment Approach

Given the findings of our review and reflecting the recommendations from the National Salmon Stock Assessment Workshop (Atlantic Salmon Trust, 2017), we provide reasoning for making changes to the current compliance assessment approach. We present these changes in relation to each of the guiding principles from section 6.2 and then provide corresponding recommendations.

**NASCO guidelines:** The revised approach continues to follow NASCO guidelines, such that management decisions are based on annual review of compliance with BRPs, a lower reference point based on the CL and a higher reference point based on maximum smolt output. One of the two metrics in the new system is a future projection to provide some early warning.

Proposed revisions to the basis of the URP and to the statistical approach to determine compliance with reference points in the current year and projections are consistent with NASCO guidelines. The new approach deals with many of the criticisms levelled at the current method, whilst maintaining a strong precautionary approach, as required by NASCO guidelines, to protecting salmon stock sustainability.

**Simplicity and communicability:** Changing to a standard linear regression for the projection component is both statistically justified and simplifies the description of the statistical approach. The new approach also reduces the number of classes from four to three. These new classes are easy to communicate and understand.

The new approach retains many aspects of the current approach and remains similarly protective and informative about current or projected stock status but should be easier for all to understand. This change will involve a change in terminology, with the assessment process built around the LRP and the URP.

**Transparency:** All relevant documents and software will be peer-reviewed and made publicly available, as soon as possible. Ultimately, it is hoped that a web-based interactive reporting process, akin to the approach adopted in Scotland, will provide annual updates on the assessment results and underlying data.

**Consistency:** Although some changes to the statistical approach are proposed, the underlying Bayesian approach of the current method remains the same because it allows probability statements relating to thresholds to be made in an appropriate manner, albeit requiring some specialist knowledge to implement. Similarly, the precautionary concept of projection into the future is a good one and one which we would wish to retain as part of a new compliance assessment method.

**Statistical best practice:** A projection is retained, but the regression is changed from a 20th percentile regression to standard mean regression as this is both statistically robust and more understandable to stakeholders.

**Recommendation 8**

*Undertake the annual salmon stock status assessment based on:*

- *stock performance against two catchment-specific biological reference points (BRPs) defined in terms of egg numbers (the Lower Reference Point = a minimum salmon stock Conservation Limit, and the Upper Reference Point = the catchment Maximum Smolt potential);*
- *replacing the current projected egg deposition compliance assessment with a two-tiered scheme using, first, the arithmetic mean of estimated annual egg deposition from the past five years and, second, a five year forward projection based on standard mean regression of the last 10 years of annual egg deposition estimates;*
- *both the past mean and the forward projection metrics are classified into one of three classes: Healthy, Cautious or Critical. These are based on the probability that the metric being measured (the mean or the forward projection) is above each of the upper and lower reference points (see next section for how these are derived). Specifically, a metric is:*
  *Critical if the probability that it is above the LRP is less than 0.75;*
  *Cautious if the probability it is above the LRP is greater than or equal to 0.75 and the probability it is above the URP is less than 0.75;*
  *Healthy if the probability it is above the URP is greater than or equal to 0.75.*
- *The final classification for a river is determined by the lowest class of the past mean and forward projection metrics. This is a precautionary approach designed to protect stocks.*

## 6.7 Illustrations of the proposed new compliance assessment approach

The past mean and forward projection metrics are shown as part of the new compliance assessment approach in Figure 6.11. This illustrates the results from the current 20th percentile method versus the past five-year mean and five-year projection two-stage approach for 2011 to 2020 compliance assessments.

The current 20th percentile method is more conservative in that the 20th percentile regression line (blue) is mostly below the standard regression line (black).

Because the lower bound of the 90% credible intervals, based on current 20th percentile regression (blue vertical line) lower value, extends below the CL (red, dashed horizontal line) the river does not qualify as NAR but sits in the PNAR category.

However, for the new compliance assessment approach both metrics would be Healthy because both the lower limit of the past five-year mean (black, 2018) and the projection 50% credible intervals (black, 2025) are above the URP (green dashed line).

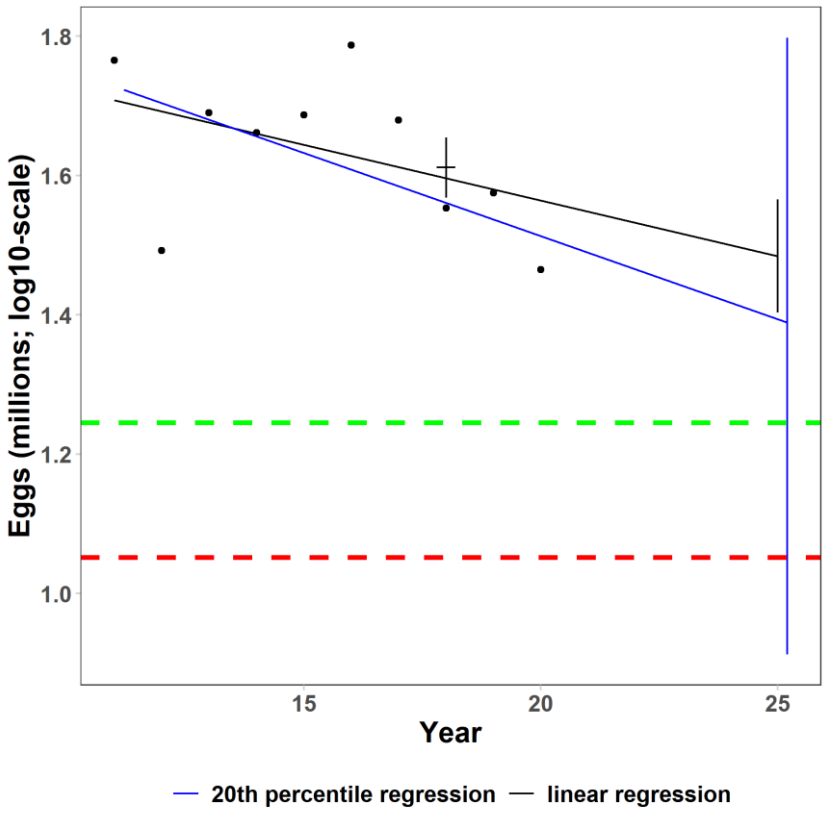



*Figure 6.11. An example assessment showing comparisons of the current 20th percentile forward projection method (blue) versus the past 5-year mean and 5-year projection methods (black). The diagonal blue line is the 20th percentile regression line, and the vertical blue line is the 90% credible interval for the 20th percentile five-year projection. The black diagonal line is the standard linear regression line, and the black vertical line in 2018 is the 50% credible interval for the most recent 5-year mean; the black vertical line in 2025 is the 50% credible interval for the 5-year projection. The horizontal dashed green line is the Upper Reference Point (URP, i.e.*

*the Maximum Smolt, MS), and the horizontal dashed red line is the Lower Reference Point (LRP, i.e. the Conservation Limit, CL) for the new approach and also the single reference point for the current 20th percentile approach (both are the CL).*

Figure 6.12 illustrates the proposed method using assessment data from a river above the URP from 2011-2020. The teal and blue vertical lines give 50% credible intervals for the past five-year mean and the projection, respectively.

From observation of the plots in Figure 6.12, Healthy classifications in all years seems sensible given that all observed data points are well above the URP. Using the current compliance assessment gives Cautious (i.e. Probably not at Risk or Probably at Risk in current-method terminology) classifications between 2013 and 2020 (not shown) because of the high variability in the five-year projection 20$^{th}$ percentile credible intervals and the high probability of 95% needed for achieving the Healthy (NAR) classification.

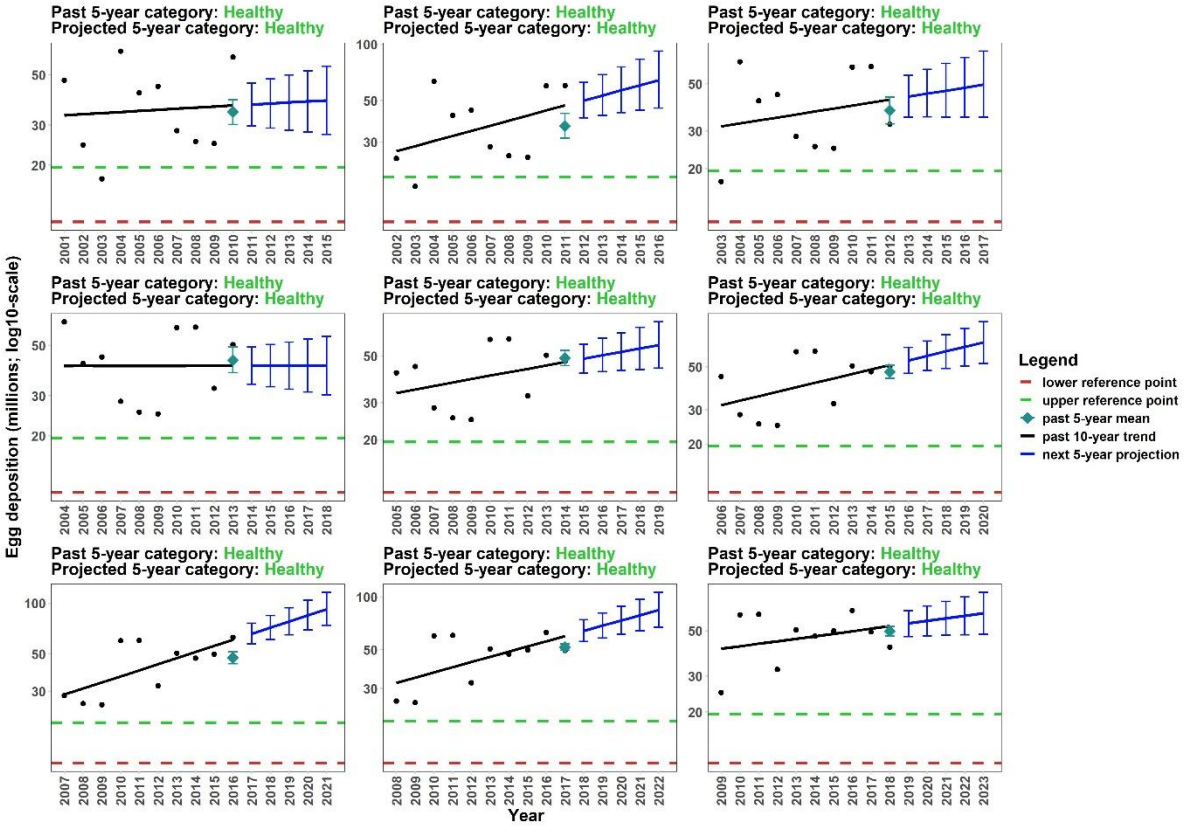



*Figure 6.12. Illustrations of the new compliance assessment approach for assessment years between 2011 and 2019 (each using data up to the preceding year) for a river with healthy status. The classifications of the two assessments (past five-year mean and five-year projection) are shown in the title of each plot. The*

*green dashed line represents the Upper Reference Point (URP, i.e. the Maximum Smolt, MS), whereas the red dashed line represents the Lower Reference Point (LRP, i.e. the Conservation Limit, CL). The teal and blue vertical lines give 50% credibility intervals for the five-year mean and projection, respectively.*

Figure 6.13 and Figure 6.14 give illustrations for assessment date for two rivers with statuses that change through time based on the past five-year mean and the projection methods. These years have been chosen to show a period of decline in the classification levels. For example, in 2010 the river in Figure 6.13 achieved Healthy for both tiers of assessment; but both tiers were Critical in 2018. Similarly, the river in Figure 6.14 went from two Healthy scores in 2012 to Cautious for the past five-year mean method and Critical for forward projection in 2018.

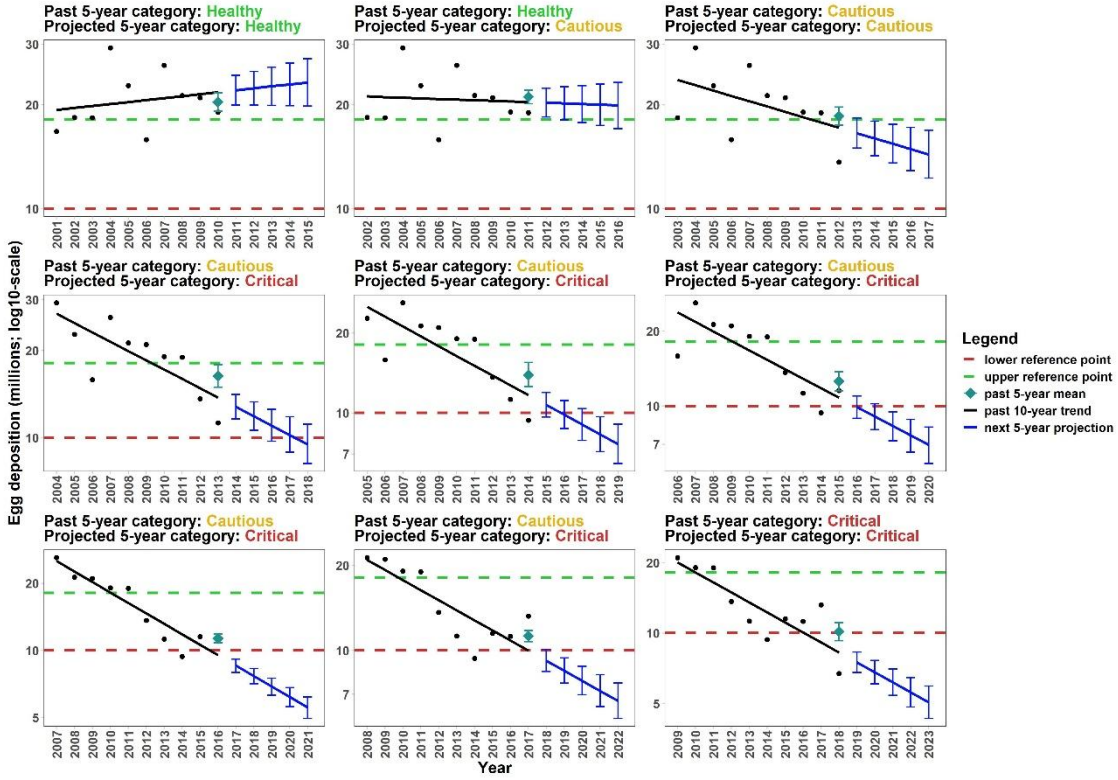



*Figure 6.13. Illustrations of the new compliance assessment approach for assessment years between 2011 and 2019 (each using data up to the preceding year) for a river with changing status. The classifications of the two assessments (past five-year mean followed by five-year projection) are shown in the title of each plot. The green dashed line represents the Upper Reference Point (URP, i.e. the Maximum Smolt, MS), whereas the red dashed line represents the Lower Reference Point (LRP, i.e. the Conservation Limit, CL). The teal and blue vertical lines give 50% credible intervals for the five-year mean and the projection, respectively.*

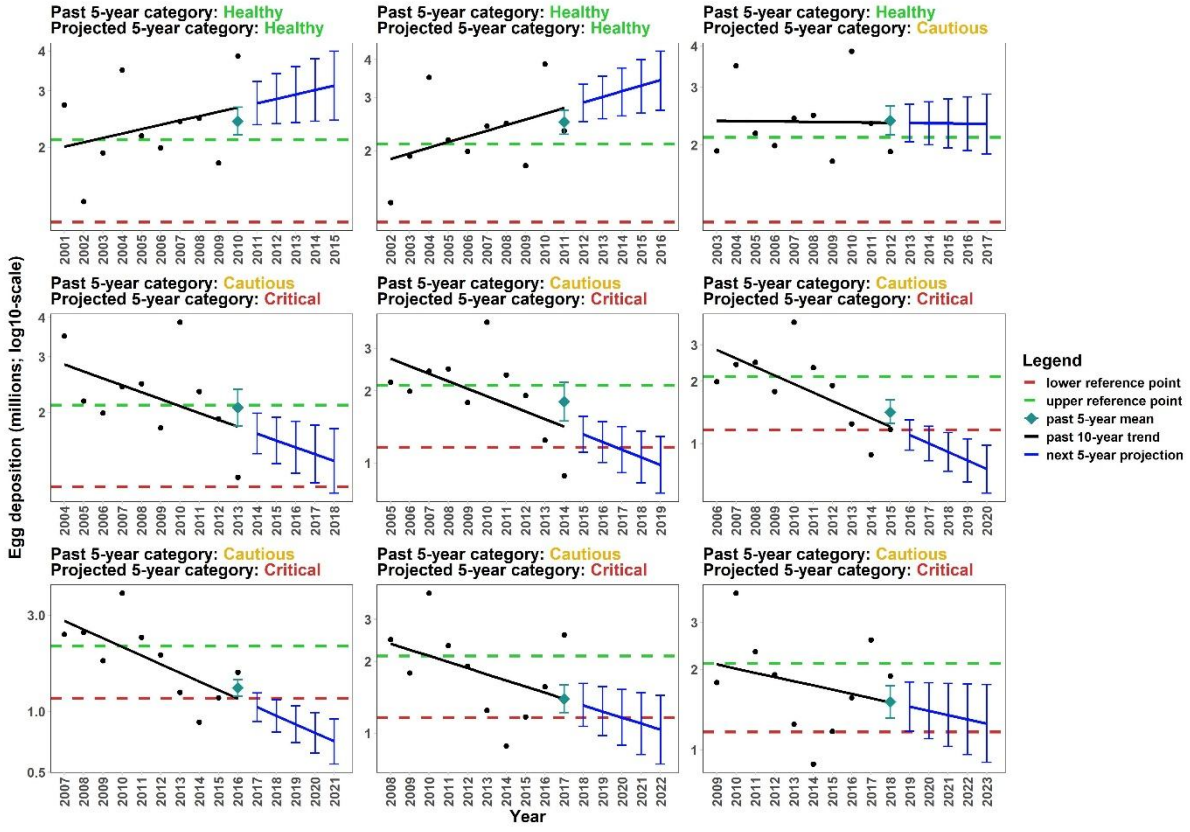



*Figure 6.14. Illustrations of the ne compliance assessment approach for assessment years between 2011 and 2019 (each using data up to the preceding year) for a river with changing status. The classifications of the two assessments (past five-year mean and five-year projection) are shown in the title of each plot. The green dashed line represents the Upper Reference Point (URP, i.e. the Maximum Smolt, MS), whereas the red dashed line represents the Lower Reference Point (LRP, i.e. the Conservation Limit, CL). The teal and blue vertical lines give 50% credible intervals for the five-year mean and projection, respectively.*

# 7 Salmon fishery management decision structure for England and Wales

## 7.1 Introduction

The overarching objective of salmon fishery management is to secure the long-term sustainability and resilience of salmon populations by maintaining stocks above safe biological limits, ensuring that the environmental, social and economic benefits associated with salmon are safeguarded and enhanced for current and future generations. In the context of the current declines in salmon stocks, driven by a range of factors that are principally influenced by environmental conditions in freshwater and poor marine survival, it is widely acknowledged that there should be no exploitation when stocks are below these limits.

This section describes the salmon management Decision Structure (DS) currently applied in England and Wales to support a consistent approach to the management of salmon exploitation by rod and net fisheries. It goes on to consider the need and options for updating the DS to reflect changes to the stock assessment process, as well as various recommendations that we are proposing to improve the clarity, consistency and efficacy of actions.

A new DS is recommended along with proposals for how additional data may be used to support management decisions and how changes to the regulatory mechanisms could improve the process further in the future

## 7.2 The current salmon management Decision Structure

The current salmon management DS in England and Wales was established by the Environment Agency in 2007 and follows principles laid out in NASCO's guidance on Decision Structures (NASCO, 2002), that states:

"In applying the Decision Structure, management decisions should be taken in accordance with an assessment of risk, such that, in the face of uncertainty, there is a low risk to abundance and diversity of the stock(s). The probability of achieving the management goals should be high. The results of using the Decision Structure should be monitored and evaluated to ensure that the actions taken in managing salmon fisheries are consistent with the Precautionary Approach."

Although not mandatory, as a contracted party to NASCO, the UK Government is obliged to implement this best practice guidance in managing salmon stocks and their dependent rod and net fisheries.

The aim of the DS applied in E&W is to provide fishery managers with guidance to allow them to consistently apply exploitation controls in response to the status of the stock. The guidance is based on the precautionary principle and is driven by the outcome of the annual salmon stock assessment process. Consideration is also given to the socio-economic impacts and benefits of the fishery in question.

Fishing exploitation controls are only ever part of a package of measures to sustain and restore salmon stocks, and as such the DS also recognises the need for wider measures to address the pressures that affect salmon.

The present salmon management DS sets out the actions to be taken in response to annual Management Objective (MO) compliance assessments for each salmon stock (Cefas, Environment Agency, and Natural Resources Wales, 2024b). As described in Section 2, the compliance categories are currently based on the probability of the stock meeting the Management Objective (MO) of exceeding the CL in, on average, 4 of every 5 years.

The projected probability (or equivalent percentage) estimate of a stock meeting the MO in five years' time is used to assign each salmon stock into one of four categories, these being:

- Not At Risk (NAR) > 95%
- Probably Not at Risk (PNAR) 51-95%
- Probably at Risk (PAR) 5-50%
- At Risk (AR) < 5%

It should be noted that whilst the CL compliance categories are based on the probability of achieving the MO, the DS refers to the probability of *failing* the MO. Although this has no direct impact on the decisions *per se*, its use may have created additional confusion for managers and stakeholders.

The use of projected stock performance as the primary guide for decisions is recommended in the NASCO guidance. The main benefit of this approach is that it provides an early warning when the stock has a high probability of falling below its CL and prompts managers to initiate control measures in a timely manner. However, due to the inevitable uncertainty around projections, stock compliance frequently tends towards either of the "probable" categories. Hence, the actions required in the 'At Risk' category may not be applied with sufficient urgency to prevent stocks declining from 'Probably at Risk' to 'At Risk'.

The current DS has also been described as lacking specificity with regards to:

- The required management actions

- The deadlines / timeline for implementation of measures, or
- The threshold level at which management actions are triggered or relaxed

For example, the DS currently provides an intended direction of travel for exploitation, e.g. for ‘At Risk’ rivers the proposed action is to *reduce exploitation to zero,* without describing exactly how that reduction is to be achieved. This introduces a risk of either failing to implement measures consistently on a national basis or failing to do so in a timely and effective manner. This lack of clarity applies equally to when and how restrictions are to be relaxed when stocks are recovering.

## 7.3 Review of the current Decision Structure process

The original intention was for the DS to be considered annually following the annual stock assessments. The EA and NRW local managers are advised of these assessments, and they then begin the process of deciding what changes are appropriate, as guided by the DS outputs. Recovering salmon rivers that do not yet have CLs established are deemed to be ‘At Risk’.

The current DS is a 4-stage process (Cefas, Environment Agency, and Natural Resources Wales, 2024b), comprising:

1) Stock assessment
2) Screening of potential options
3) Evaluation of options
4) Implementation of options

In practice, these options predominately comprise measures to either tighten or relax controls on fishing, including provisions for method control, seasonal restrictions or the need for catch and release. These controls may be voluntary or mandatory, depending on the level of risk the stock is under.

Where voluntary measures have been promoted, these are typically sought through engagement with local fishing stakeholders. The voluntary approach has the benefit of ensuring that fisheries are involved in the decision making and do not feel subject to “top-down control”. Voluntary measures can potentially be implemented more quickly than statutory measures, given the extensive legal and statutory consultation processes that are required to implement byelaws. Ideally, voluntary restrictions would be adopted as clearly defined fishery rules across a whole catchment to ensure consistent application. In practice, however, voluntary measures are often adopted inconsistently. The lack of consistency between river fisheries and individual riparian owners can be a hindrance to full and effective implementation of voluntary salmon stock protective measures. It should be noted however that some fisheries adopt measures that are more protective than those required / advised by the agencies.  Voluntary measures may also be recommended and adopted by net fisheries.

Mandatory controls have the benefit of being clearly and consistently applicable to all and are legally enforceable. For example, mandatory controls can lead to a more rapid and consistent adoption of 100% catch and release, once they are introduced. Overall, licensed rod and net fishers tend to accept and abide to byelaws once implemented. Mandatory controls are currently implemented through Net Limitation Orders (NLOs) which set the number of net licenses, and byelaws which can impose season, method and catch restrictions on rod and net fisheries, or closure of net fisheries. These processes however are resource heavy and can be time consuming, typically taking up to two years to conclude (Environment Agency, 2010) but can take substantially longer.

The current DS is not explicit about whether and when mandatory measures are required in addition to, or instead of, voluntary ones. Management decisions recommended by the DS are formally scrutinised and approved via the relevant EA or NRW governance routes. Where regulatory measures are required, approval will be required at the appropriate level of delegated authority and, for byelaws and NLOs, will require statutory formal consultation and Ministerial approval.

## 7.4 Key requirements for a revised salmon management Decision Structure

The adoption of the revised stock assessment methods proposed in previous sections will necessitate a revision to the DS, if only to reflect the proposed three new stock categorisations. However, this also presents an opportunity for improving the DS process to address some of the issues raised both internally and by external stakeholders, e.g. from an internal salmon stock assessment workshop, through the National Salmon Stock Assessment Workshop (Atlantic Salmon Trust, 2017), and from recent salmon fishery byelaw and NLO consultation responses. These areas for improvement can be summarised as follows:

- The decision-making process should be clearer and more transparent for the benefit of all interested parties
- Ensure that only salmon stocks at sustainable population levels are subject to exploitation, with management focused on protecting and restoring stocks where this is not achieved.
- Implement control measures in a timely and responsive manner so that emerging declines are addressed before stocks deteriorate further.
- There should be consistency in how controls are applied. This is an important requirement for both fishery managers and stakeholders, and a necessary pre-requisite to ensure the fisheries regulations are applied consistently on cross-border rivers

- Ideally, fisheries management control measures should be predefined and applied responsively once a stock is determined to be within a specific category. This too would facilitate more timely management interventions
- The DS should *ideally* also consider other available and relevant salmon stock assessment data, such as juvenile population assessments, which on some rivers have proven to be crucial in the early identification of imminent stock decline. The interrogation and use of these data have subsequently led to the implementation of salmon fishery protection measures at an earlier stage than would normally have been the case if relying on the formal adult salmon stock assessment alone
- The current DS management process focuses on fishery exploitation controls. Whilst this remains a key component of stock protection and rebuilding, the revised DS should also recognise the need for additional action(s) to address other pressures limiting the salmon stock

## 7.5 Recommendations for a new salmon management Decision Structure

The basic requirement for a new DS is that appropriate management actions align with the three stock gradings proposed. It is recommended that each stock will receive an overall grade (numbered from 1 to 3) derived from the lower of the current and projected salmon stock categories. These stock Grades are as follows:

1. Healthy: Stock is above the URP
2. Cautious: Stock is above the LRP but on or below the URP
3. Critical: Stock is on or below the LRP

For each PSR, the current and projected stock categorisations will be considered in combination to determine an overall river grading. The lowest outcome category derived from either the current or projected salmon stock assessment processes will be used to determine the final river grading. Hence, the management classification of each PSR will be precautionary. Importantly, this approach will provide transparency for external stakeholders who will be able to see what aspect of stock assessment performance is driving the final annual river grading for any given PSR. The potential combinations of stock assessment categorisations derived from both the current and projected salmon stock assessments and the resultant final PSR gradings are set out in Table 7.1.

Only river stocks that are currently and projected to be above the URP are deemed to be in River Grade 1. These stocks are considered capable of supporting

sustainable exploitation whilst maintaining stock resilience and long-term productivity.

Here managers can seek to optimise sustainable exploitation and the socio-economic benefits that arise from exploitation. However, should the current or projected status of the stock fall into either of the two lower stock compliance classes, the lowest will be used to set the River Grade.

*Table 7.1. Derivation of management classifications from a two-tiered compliance assessment process. Stock Compliance Categories are Healthy = Egg Deposition Estimates above URP (Maximum Smolt), Cautious = Egg Deposition Estimates Between the Upper and Lower Reference Points, and Critical = Egg Deposition Estimates equal to or Below LRP (Conservation Limit). River Grades (1-3) reflect the lower of the two Stock Compliance classes. A 'traffic light' colour scheme is applied to the River Grade for illustrative purposes.*

| Stock Compliance Categories | | Final River Grade |
|---|---|---|
| Stage 1<br>Current Assessment<br>*Past five-year mean* | Stage 2<br>Projected Assessment<br>*Next 5-year projection* | |
| Healthy | Healthy | 1 |
| | Cautious | 2 |
| | Critical | 3 |
| Cautious | Healthy | 2 |
| | Cautious | 2 |
| | Critical | 3 |
| Critical | Healthy | 3 |
| | Cautious | 3 |
| | Critical | 3 |

Having established the River Grade for the stock on each PSR, the DS then needs to describe the fishery objectives and management actions that are required in

response to each of these three management gradings. These are set out in the table below (Table 7.2).

*Table 7.2. Recommended DS Objectives and Actions according to River Grade*

| River Grade | Objectives | Default Actions |
|---|---|---|
| 1 | Maintain healthy salmon stocks and maximise sustainable socio-economic benefits through appropriate exploitation, whilst protecting populations from current and emerging pressures. | 1.1 No additional exploitation control management is required, whilst maintaining core statutory and voluntary management interventions<br><br>1.2 Additional mandatory fishing controls introduced for stock recovery may be reviewed and, where no longer necessary, removed.<br><br>1.3 Continue to promote voluntary catch and release and best-practice angling methods to support stock resilience.<br><br>1.4 Continue to support measures that maintain ecosystem resilience and contribute to long-term salmon population recovery and nature recovery objectives.<br><br>1.5 Support measures that maximise the socio-economic value of the fishery |
| 2 | | 2.1 Maintain existing exploitation controls as a precautionary measure to support stock recovery and prevent further decline.<br><br>2.2 Where a river has improved from Grade 3 to Grade 2, mandatory recovery measures should initially be retained as a precaution and reviewed annually. Relaxation can be considered where evidence indicates continued improvement towards Grade 1 status.<br><br>2.3 Where a river has deteriorated from Grade 1 to Grade 2, voluntary management action should be taken promptly to minimise further decline and promote stock recovery. Measures may include: |

| | | |
|---|---|---|
| | Apply a precautionary approach to halt decline and promote stock recovery towards healthy population levels, whilst maintaining appropriate socio-economic benefits where this can be achieved without compromising recovery. | **For rod fisheries**: Implement voluntary measures, with best practice promoted by clubs, fisheries and NGOs, and ideally reflected in fishery rules, this would include method restrictions such as:<br><br>o Fly and spin only<br>o Barbless hooks only<br>o No use of certain baits either for full or part of the season<br>o No use of treble hooks with spinner and lures.<br><br>**For salmon and sea trout net fisheries**: Consider measures to reduce exploitation fisheries, including voluntary effort reduction, reducing licences availability via NLO process, net buy-outs or catch restrictions.<br><br>2.4 Review annually whether additional *mandatory* controls are required, taking account of stock status, uptake of voluntary measures, juvenile abundance and other relevant evidence. Indicators for considering additional mandatory controls might include::<br><br>• Marked reduction in abundance of a stock component (e.g. MSW fish).<br>• Marked and unexpected decline in juvenile abundance or distribution.<br>• Other evidence indicating increased risk to stock recovery.<br><br>2.5 Develop and implement a Stock Recovery Plan to address current and emerging pressures limiting stock recovery. |
| *3* | Prioritise stock recovery and protection from further decline through measures that minimise exploitation and address pressures limiting population recovery. | 3.1 Statutory measures to eliminate harvest and minimise fishery-related impacts should be developed and implemented without delay. Measures should include:<br><br>For rod fisheries:<br><br>o Byelaws to require 100% mandatory catch and release. |

| | | |
|---|---|---|
| | | ○ Byelaws to mandate method controls to maximise post-release survival, such as<br>○ Restrictions on the use of specified baits.<br>○ Mandatory use of barbless or de-barbed hooks.<br>○ Restrictions on hook size and hook type where appropriate.<br>○ Season amendments or reductions to protect salmon and vulnerable stock components.<br><br>**For salmon and sea trout net fisheries**: The default management response should be to eliminate salmon harvest and substantially reduce fishery-related mortality through measures including:<br><br>○ Byelaws to require full catch and release of salmon (no harvest)<br>○ Byelaws to reduce or amend the season to avoid salmon and/or vulnerable stock components<br>○ Apply a Zero or reducing Net Limitation Order (NLO) to reduce fishing effort and participation.<br><br>○ Implement byelaws to close fisheries where necessary to protect critically depleted stocks.<br><br>3.2 Whilst statutory controls are being developed and implemented, protective voluntary measures should be adopted urgently as interim controls. For example, fisheries, clubs and associations should be encouraged to implement voluntary catch-and-release measures and other actions that minimise fishery-related mortality.<br><br>3.3 Urgently develop and implement measures identified within the Catchment Salmon Stock Rebuilding Plan to address current and emerging pressures limiting stock recovery. |

## 7.6 Implementation of the new Decision Structure

The Decision Structure (DS) as set out in Table 7.2 should be applied annually following completion of the national salmon stock assessment.

Following classification each year, managers should review stock trends, monitoring data, existing management measures and progress against any recovery actions to determine whether current measures remain appropriate.

Where a river changes grade, a management review should be undertaken. This review should consider the magnitude and persistence of the change, supporting evidence from other monitoring programmes, the effectiveness of existing measures and the feasibility, proportionality and timing of further interventions. The review should also recognise that implementation of statutory measures, including byelaws and NLOs, requires evidence gathering, stakeholder engagement and formal regulatory processes, and may therefore take longer than the annual assessment cycle.

Measures can be strengthened, maintained or relaxed in response to changes in stock status, with any departure from the default management response clearly justified and documented.

## 7.7 Criteria for relaxing protective measures within the Decision Structure

When a stock improves its River Grade, the need for additional controls should be reviewed. The relaxation of measures should be informed by evidence of sustained stock recovery and should proceed in a precautionary manner to avoid renewed decline.

River Grade 1: Any *additional* mandatory catch and release and method restrictions still in place can be relaxed as soon as practicable. Fishing Associations may consider relaxation of voluntary measures. It would be expected that a core group of regulatory measures would remain in place, such as long-term method restrictions, season lengths.

River Grade 2: Where a stock moves from Grade 3 to Grade 2 any *additional* mandatory C&R and method restrictions may be relaxed, either by repealing the existing byelaw or when the current byelaw expires. Additional information, i.e. the status of juvenile stocks, would need to be considered.

## 7.8 Implementation of salmon stock rebuilding plans

All Principal Salmon Rivers should have catchment-specific management plans to identify and prioritise specific actions to maintain, restore and improve the status of salmon stocks. Where the salmon stock within a river has been assessed to be in Grade 1, the objective of the plan is to ensure continued achievement of both the URP and LRP to optimise the long-term productivity and resilience of the stock.

Where a salmon stock has been classified as Grade 2 or Grade 3, actions should focus on preventing further decline, improving ecosystem resilience and restoring the stock towards the URP by addressing the factors limiting recovery.

Attention should be focussed on maximising future juvenile recruitment success and maximising future smolt output.

Stock rebuilding programmes, designed to bring a stock back into sustainability, should ideally be co-developed between Government Organisations, NGOs and local fishery stakeholder groups following the NASCO salmon stock rebuilding guidance https://nasco.int/conservation/stock-rebuilding/. Actions should be prioritised to ensure that those with the greatest potential to enable stock recovery are implemented as quickly as possible.

The nature and extent of the plan will depend upon the status of the stock and the pressures that it is facing.  Plans should ideally follow the NASCO guidance on Stock Rebuilding Programmes, and include:

- An evaluation of the status of stock
- An evaluation of the causes of stock decline and threats to stock
- Identifying and involving stakeholders
- Planning and prioritising management actions
- Assesses social and economic factors
- Monitoring and evaluations of progress

Actions to address the issues impacting upon salmon should be addressed in addition to the implementation of rod and net fishery exploitation controls. Whilst the responsibility for co-ordinating these actions sits primarily with the EA and NRW, delivery will require all interested parties to work collaboratively together for the benefit of the salmon stock.

**Proposal 17**

*Salmon stock rebuilding plans, based upon the North Atlantic Salmon Conservation Organisation (NASCO) guidance, should be developed for all rivers which fall into*

*river grades 2 and 3 recognising the value and strength of existing and developing catchment partnership approaches.*

## 7.9 The Byelaw and NLO consultation process

Where mandatory C&R and other measures are prescribed, these will need to be implemented through the existing Byelaw making processes.

This is a structured statutory process led by the Environment Agency (England) and Natural Resources Wales, typically taking 12–24 months from initiation to confirmation. The process begins with evidence gathering (including stock assessments and risk designation), followed by the development of draft measures and informal stakeholder engagement. This is followed by a formal public consultation period (usually 6–12 weeks) on the proposed byelaws or NLOs. After considering responses, regulators may revise the proposals before submitting them to the Secretary of State (England) or Welsh Ministers (Wales) for approval. This stage can involve further scrutiny or inquiry if objections are unresolved. Once confirmed, there is a statutory notice and implementation period, with measures typically coming into force the following season. Overall, while urgent measures can sometimes be expedited, the process is inherently deliberative to ensure legal robustness, transparency, and stakeholder input.

Looking to the future, ideally these measures would be implemented in a more timely fashion in response to changing stock status.

## 7.10 Timetable for publishing the annual findings

The annual salmon stock assessment timetable broadly follows a fixed yearly cycle aligned to data availability and reporting deadlines. Initial data collation (rod catch returns, counter data, and biological inputs) occurs January–March following the previous fishing season, alongside validation and processing of returns. The national stock assessment analysis is then undertaken during spring (March–May), generating updated estimates of returns, spawning escapement and egg deposition, and compliance with Conservation Limits and Management Targets. Provisional assessments are provided to ICES WGNAS in March, to allow ICES to advise NASCO ahead of its annual Council and Commissions meeting in June. The annual 'Assessment of Salmon Stocks in England and Wales' reports (e.g., Status and Background, Cefas, EA and NRW 2024a, b) are published later in the year, which provides an opportunity to include additional data if necessary.

Once annual stock assessments have been produced, the Decision Structure is used to determine whether additional controls are required, or existing measures can be relaxed. The EA and NRW then inform stakeholders via the England Fisheries Group (EFG) and Wales Fisheries Forum (WFF), respectively, of their annual assessments of stock status (Compliance Classes) and management approach according to the DS.

Where the DS review indicates that additional measures are required, or can be relaxed, the relevant Operational Teams will be informed to initiate local engagement and begin any required regulatory procedures.

## 7.11 Conclusions

A new DS is set out in response to the revised stock assessment methodology and categories.

**Recommendation 9**

*A new salmon fishery management Decision Structure should be implemented across England and Wales. This would be based on river grades determined by the annual performance of the stock as tested against both the current (past five-year mean) and projected (future five-year projection) stock compliance categories. These categories will be considered in combination to determine a single overall river grading ranging from 1 to 3. The lower of the two assessment categories will be used to determine the placement into a final annual river grade.*

The revised DS has also been designed to address feedback from staff and stakeholders. We believe that it satisfies the need for increased clarity and transparency for all interested parties. The two-stage compliance assessment based on two biological reference points, with the establishment of an overall River Grade, clearly conveys the status of the stock and provides precautionary triggers on which to base management decisions.

Using these river grades, Fishery managers should be able to implement measures to protect the most vulnerable stocks in a timely manner based on the actions recommended in the DS.

The revised DS is clear that stocks that are currently or projected to be at or below the LRP (the CL; River Grade 3) should not be subject to a harvestable take of salmon.  Stocks above the LRP but at or below the URP (River Grade 2) require a precautionary recovery-focused approach. Where some exploitation can be

maintained without compromising recovery, this may continue, but restoring the stock towards the URP should remain the primary objective.

The need to protect stocks in a more timely manner is also addressed, with timelines for stock assessment and DS reviews to support implementation of measures.

The DS provides precautionary and clear guidance on what additional measures are required when a stock declines to a lower River Grade, and how measures can be relaxed as stocks improve. However, it still requires measure to be delivered by existing regulatory mechanisms, e.g., byelaw/NLO, and that these can take time.

**Proposal 18**

*Recognising that assessments of stock abundance based on fishery-dependent data sources (e.g. catches), have an inherent uncertainty (which may be increasing as an unintended consequence of catch-and-release), other information sources, especially fishery-independent, e.g., juvenile surveys, counter and trap data, should be used to support stock status assessments and management decision-making.*

**Proposal 19**

*The means of communicating the process and results of annual stock status categories and river gradings needs to be reviewed and updated to reflect today's audiences and their methods of being informed.*

**Proposal 20**

*Regulatory mechanisms should be developed to implement management actions more quickly than at present.*

At the current time, neither the EA nor NRW have legal vires to automatically link the publication of the annual salmon stock assessment for principal salmon rivers in England and Wales to the implementation of management measures without applying current byelaw making processes. This would require a byelaw to be sought annually and would require formal advertisement and consultation followed by Ministerial approval. This would be both time consuming and costly to apply following the publication of the annual stock assessment with an expected implementation within the following year.

Our preference would be to seek new legislation that would automatically link the strengthening or relaxation of fishery management measures to the annual publication of the stock assessment outcome allowing for a short period of external consultation with implementation within the following year similar to the approach used within other management jurisdictions.

# 8 Stock performance from current versus proposed assessments

The purpose of this section of the report is to compare the outcomes of the current ('old') and proposed ('new') procedures for: (1) estimating spawner and egg numbers, and (2) assessing compliance with Conservation Limits (CLs) and associated reference points.

Comparisons were undertaken on data collected on all 64 Principal Salmon Rivers (PSRs) in England and Wales in the 10-year period 2013-2022.

## 8.1 Egg deposition estimates

On the majority of PSRs in England and Wales, Returning Stock Estimates (RSEs), numbers of spawners, and egg deposition estimates have been derived from rod catches using the current and revised methods described in Section 5.

For the comparison of annual egg deposition estimates described here (illustrated in Figure 8.1), the proposed method incorporates all changes proposed as part of this review, including changes in the way exploitation rates have been modelled; the application of those rates to 1SW and MSW salmon; and modified procedures for estimating sex composition and fecundity, etc. Earlier in this report, these changes were examined as separate components of the overall process (see Section 5).

On the rivers Tyne, Test, Itchen, Hants Avon, Frome, Tamar, Fowey, Taff, Teifi and Dee, run estimates over all or part of the 10-year time-series have been enumerated directly from counters and/or traps rather than derived from rod catches. For these rivers exploitation rates are known, and therefore only changes to the other input metrics have been applied in the revised methodology.

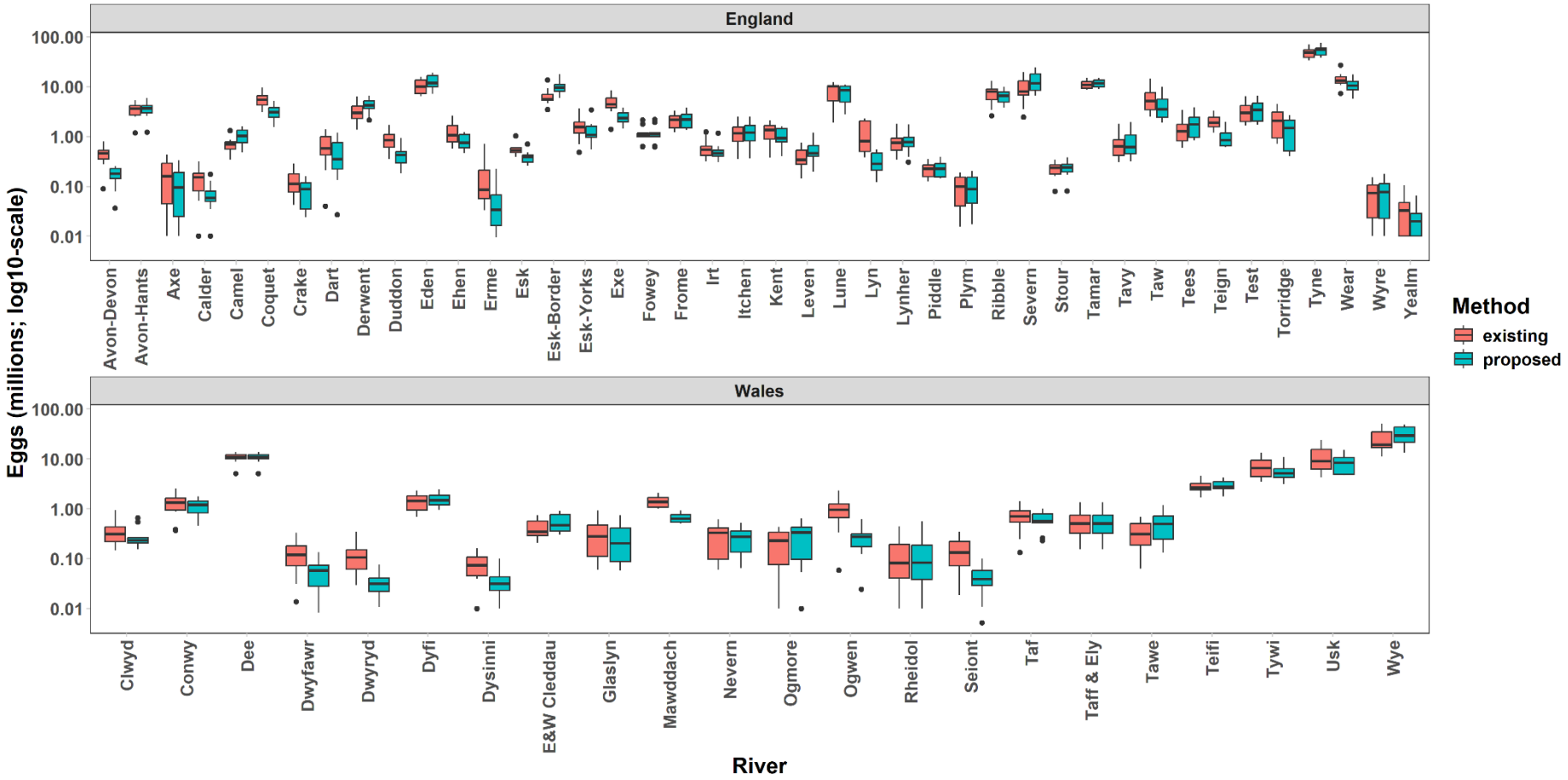



*Figure 8.1. Box plots comparing annual egg deposition estimates between the existing and proposed methods in the Principal Salmon Rivers in England (top) and Wales (bottom), 2013-2022. Boxes delimit the 25%–75% interquartile range (IQR), the horizontal bar represents the median, whiskers delimit the 1.5 x IQR range, and the black dots represent extreme values ± 1.5 x the IQR.*

From Figure 8.1, it is evident that the proposed method can generate annual egg deposition estimates that are quantitatively similar to the existing method, although for some rivers the difference is considerable. However, it is important to note that the compliance assessment approach does not finish with egg deposition but rather uses the recent time series of those estimates within a framework to assess overall compliance relative to the reference points (existing: CL; proposed: CL and MSO). Thus, from a practical management application point of view, the most important comparison is that of the Compliance Assessment, which is presented and discussed below.

## 8.2 Conservation Limit compliance from existing and proposed methods

The current and revised compliance methods share some similarities. For example, both refer to the CL as a biological reference point (BRP) and both project compliance status five years into the future based on linear trends fitted to the latest 10-year series of egg data. However, there are differences, in that the revised compliance methodology refers to the Upper Reference Point (URP: Maximum Smolt), as well as the CL, and is a two-tier assessment accounting for mean egg deposition levels in the latest 5-year period, as well as the projected status five years into the future based upon CL compliance over the last 10-year period. Furthermore, even where there are general similarities, the details of underlying statistical methods differ (see Section 6).

Because of this change in the number of reference points and the accompanying risk categorisation, it is not possible to make direct like-for-like comparisons between compliance outcomes arising from the current and proposed approaches. Rather, these outcomes can only be compared in broad terms referring to the general conservation status of stocks. For illustrative purposes, therefore, we have applied an equivalency rule that the two lowest stock categories, At Risk and Probably At Risk, of the existing method equate to the Critical class in the proposed approach.

It is evident from the comparisons shown in Table 8.1 below, that the compliance outcomes from the existing and proposed approaches are broadly aligned, resulting in similar conclusions about the status of these stocks and the need for remedial measures (the latter directed via the Decision Structure – see Section 7).

By applying this rule, most of the rivers have no change in Compliance Status between the two procedures. Five rivers have a change only in their 2022 status - two show an improvement in status while three show a deterioration in status, and three rivers have a change only in their projected 2027 state, with all three showing a deterioration in status; the same three rivers show the same deterioration in status in both 2022 and 2027.

*Table 8.1. Comparison of compliance outcomes resulting from existing and proposed procedures for all 64 Principal Salmon Rivers in England and Wales, 2013-2022. Red cells indicate a deterioration in stock status and green cells denote an improvement in stock status when applying the proposed methodology.*

| River | 2022 Risk Status | | 2027 Projected Risk Status | |
|---|---|---|---|---|
| | **Existing** | **Proposed** | **Existing** | **Proposed** |
| Coquet | Probably Not At Risk | Critical | Probably Not At Risk | Critical |
| Tyne | Not At Risk | Healthy | Not At Risk | Healthy |
| Wear | Probably Not At Risk | Cautious | Probably At Risk | Critical |
| Tees | At Risk | Critical | At Risk | Critical |
| Esk-Yorks | At Risk | Critical | At Risk | Critical |
| Test | At Risk | Critical | At Risk | Critical |
| Itchen | At Risk | Critical | At Risk | Critical |
| Avon-Hants | At Risk | Critical | At Risk | Critical |
| Stour | At Risk | Critical | At Risk | Critical |
| Piddle | At Risk | Critical | Probably At Risk | Critical |
| Frome | Probably Not At Risk | Cautious | Probably Not At Risk | Cautious |
| Axe | At Risk | Critical | At Risk | Critical |
| Exe | At Risk | Critical | At Risk | Critical |
| Teign | At Risk | Critical | At Risk | Critical |
| Dart | At Risk | Critical | At Risk | Critical |
| Avon-Devon | At Risk | Critical | At Risk | Critical |
| Erme | At Risk | Critical | At Risk | Critical |

| River | 2022 Risk Status | | 2027 Projected Risk Status | |
|---|---|---|---|---|
| | Existing | Proposed | Existing | Proposed |
| Yealm | At Risk | Critical | Probably At Risk | Critical |
| Plym | At Risk | Critical | At Risk | Critical |
| Tavy | At Risk | Critical | At Risk | Critical |
| Tamar | Probably At Risk | Critical | Probably not At Risk | Cautious |
| Lynher | Probably At Risk | Critical | Probably At Risk | Critical |
| Fowey | Probably At Risk | Cautious | Probably At Risk | Critical |
| Camel | At Risk | Critical | At Risk | Critical |
| Taw | At Risk | Critical | Probably At Risk | Critical |
| Torridge | At Risk | Critical | At Risk | Critical |
| Lyn | Probably At Risk | Critical | Probably At Risk | Critical |
| Severn | At Risk | Critical | At Risk | Critical |
| Ribble | At Risk | Critical | At Risk | Critical |
| Wyre | At Risk | Critical | At Risk | Critical |
| Lune | At Risk | Critical | At Risk | Critical |
| Kent | At Risk | Critical | At Risk | Critical |
| Leven | At Risk | Critical | At Risk | Critical |
| Crake | At Risk | Critical | At Risk | Critical |
| Duddon | Probably Not At Risk | Critical | Probably Not At Risk | Critical |
| Esk | Probably Not At Risk | Critical | Probably Not At Risk | Critical |

| River | 2022 Risk Status | | 2027 Projected Risk Status | |
|---|---|---|---|---|
| | Existing | Proposed | Existing | Proposed |
| Irt | Probably At Risk | Critical | Probably At Risk | Critical |
| Ehen | At Risk | Critical | At Risk | Critical |
| Calder | At Risk | Critical | Probably At Risk | Critical |
| Derwent | At Risk | Critical | At Risk | Critical |
| Eden | At Risk | Critical | At Risk | Critical |
| Esk-Border | At Risk | Cautious | Probably At Risk | Critical |
| Wye | At Risk | Critical | At Risk | Critical |
| Usk | At Risk | Critical | At Risk | Critical |
| Taff & Ely | At Risk | Critical | At Risk | Critical |
| Ogmore | At Risk | Critical | At Risk | Critical |
| Tawe | At Risk | Critical | At Risk | Critical |
| Tywi | At Risk | Critical | At Risk | Critical |
| Taf | At Risk | Critical | At Risk | Critical |
| E&W Cleddau | At Risk | Critical | At Risk | Critical |
| Teifi | At Risk | Critical | At Risk | Critical |
| Rheidol | At Risk | Critical | At Risk | Critical |
| Nevern | At Risk | Critical | At Risk | Critical |
| Dyfi | At Risk | Critical | At Risk | Critical |
| Dysinni | At Risk | Critical | At Risk | Critical |

| River | 2022 Risk Status | | 2027 Projected Risk Status | |
|---|---|---|---|---|
| | Existing | Proposed | Existing | Proposed |
| Mawddach | Probably At Risk | Critical | Probably At Risk | Critical |
| Dwyryd | At Risk | Critical | At Risk | Critical |
| Glaslyn | At Risk | Critical | At Risk | Critical |
| Dwyfawr | At Risk | Critical | At Risk | Critical |
| Seiont | At Risk | Critical | At Risk | Critical |
| Ogwen | At Risk | Critical | At Risk | Critical |
| Conwy | At Risk | Critical | At Risk | Critical |
| Clwyd | At Risk | Critical | At Risk | Critical |
| Dee | At Risk | Critical | At Risk | Critical |

# 9 Proposals for future developments

## 9.1 Assessment data and implementation

### 9.1.1 Gathering data to assess the status of salmon stocks

Although the best available data has been used at the time of compiling this review, it has been acknowledged throughout that there could be updated, alternative, or additional data which could improve on those currently used (e.g., more accurate, precise, complete, relevant, etc.).

Some data are judged to be irreplaceable and for these data it is important to protect the resilience and operational capability of the monitoring programmes ensuring that validated data is accessible and adequately retained in suitable databases. Examples of such data are those produced from adult migratory salmonid fish traps, automated acoustic and resistivity counters, and Artificial Intelligence based camera systems that are used to collect fishery-independent data on salmon populations. These data are used to derive fishery-independent estimates of stock size, biological characteristics, and genetic data, which are used together with fishery-dependent data to inform estimates of abundance, sea-age composition, rod exploitation rates, fecundity, and sex ratio.

Similarly, it is equally important to compile statutory rod fishery catch return data to provide information on angling catches, fishing effort, methods and the numbers of fish captured and their individual weights. These data are vital in underpinning both current and future salmon stock assessment processes and their continued maintenance, collection, management, and storage is essential. Moreover, we recommend that these data are organised in such a way that they are publicly accessible.

Other data could be replaced by alternatives in future developments. Examples of such data could be those derived from maps, such as measurements of wetted area, that could use more contemporary maps assumed to be more accurate (e.g., see section 3.4). Any decision to replace an existing data source with an alternative would need to be explored exhaustively to understand how it can be accommodated by existing methods or whether new methods would be required, and how any changes might affect the stock assessment methods, outputs, or outcomes. In addition, environmental data, such as river discharge and water temperature, in-river vegetation, and macroinvertebrate quantities and compositions, and water quality metrics, including pollutants and algae, could all be considered as additional information that might be explored and tested for their ability to describe stock

estimates or the process used to derive them (e.g., see section 3.11.2 where river discharge data are used to describe rod exploitation rates).

Finally, additional data could be used to inform wider aspects of the current stock assessment that are based on historical or inaccessible data or informed judgments or opinions. Examples of such data might include:

- Environmental DNA (eDNA) data that could supplement existing knowledge on the presence or absence of salmon, their predators, competitors, or parasites, in waterbodies inhabited at different stages of their life history, and/or infectious diseases
- Telemetry data that have been used in the past to understand the implications of catch-and-release angling on individual fish captures and to understand the sampling efficiency of in-river structures, such as fish traps and resistivity counters

### 9.1.2 Options for automating implementation

Advances in computation resources, including processors, storage, and facilities to maximise their use (e.g., more efficient and extensible programming languages), have created options for automating many aspects of computer work, including data collection, storage, and analysis. Some of these options could be used to automate implementation of parts of the salmon stock assessment. For example, computer resource-intensive methods, such as object detection and classification from images and videos using convolutional neural networks, have become widespread and accessible (e.g., Li *et al*., 2023) and have already been used in the detection and classification of fish species from videos, such as those used on fishery-independent fish counters in some PSRs. Continuous improvements to computer programming languages that are used to manipulate, visualise, and analyse data, could also be used to automate the implementation of parts of the salmon stock assessment. As open-source initiatives, these resources should be somewhat future-proof and regularly updated with cutting-edge advancements. An immediate improvement towards automating the salmon SAM implementation is therefore to move away from proprietary software, such as workbooks, to use scripted workflows written in open-source computer programming languages. Once these scripted workflows are written, it is increasingly common to use them together with other open-source tools to (semi-) automate reporting using parameterised documents.

(Although initially included as Proposal 21, this task has since been escalated to a recommendation to improve the efficiency, reproducibility, and resilience of some parts of the stock assessment, for example the egg deposition calculations.)

**Recommendation 10**

*Replace manual data preparation and analysis using proprietary software, such as workbooks, with scripted workflows written in open-source computer programming languages which can be made available to the Public.*

Initiatives are already underway to develop capacity around these options across UK government departments, including the use of Artificial Intelligence (AI) in the Department for Environment, Food & Rural Affairs AI Incubator scheme (https://defra.sharepoint.com/sites/Community448/SitePages/AI-Incubator.aspx). Indeed, the use of AI to detect and classify salmon from video-verified resistivity counter records is an existing AI Incubators project sponsored by Defra and the Environment Agency (https://defra.sharepoint.com/sites/Community448/SitePages/Salmon-Index.aspx).

**Proposal 21**

*Continue supporting efforts to explore the use of advanced computing to automate the collection, storage, analysis and reporting of data for salmon stock assessment.*

## 9.2 Other indicators of stock status

Other fishery-independent metrics of stock status should be considered to help guide management decisions and future proof the assessment.

Fishery-independent metrics of stock status are likely to become increasingly important for fisheries managers to assess salmon population performance in the future. As rod catches decline, there is likely to be an increasing need to rely upon adult return data obtained from validated fish counters or traps as well as juvenile abundance data derived from electric fishing surveys.

**Proposal 22**

*Examine whether juvenile (fry and parr) density estimates from electric fishing surveys could be used as surrogates of smolt output in rivers where the annual numbers of downstream migrating smolts are not monitored. This would require exploratory analysis of the use of fry and parr density estimates from electric fishing surveys at the site scale to provide indices of juvenile production averaged across the catchment relative to benchmarked levels (carrying capacity) from a habitat model (e.g. HABSCORE).*

## 9.3 Supporting decision making by managers

### 9.3.1 Annual implementation of DS control measures

A weakness of the current DS implementation process is the time taken for control measures to be formally adopted or relaxed via local or national byelaws.

As set out in section 1, one of the key aspirations for a revised salmon stock assessment and DS process in England and Wales is to establish regulatory mechanisms that will allow for fishing control measures to be applied automatically, based on the publication of the annual national salmon stock assessment compliance outcomes. This approach would require annual salmon stock assessments to be finalised and formally published to inform the management measures that would be applied in the following fishing season. This approach could potentially be designed to enable a period of consultation with external stakeholders increasing the opportunity for openness and transparency but would clearly have additional staff resource implications.

This approach is currently used in Scotland and the Republic of Ireland and has several key benefits in terms of quickly and efficiently applying necessary stock exploitation measures when required by the national salmon stock assessment.

To refine the publication of the final stock assessments consideration should also be given to the possible appointment of an independent scientific panel to work with the EA, NRW and Cefas to review the provisional annual national salmon stock assessments.

**Proposal 23**

*Consideration should be given to the appointment of an independent scientific panel to work with the Environment Agency, Natural Resources Wales, and the Centre of Environment, Fisheries and Aquaculture (Cefas) to review the provisional annual national salmon stock assessments.*

This panel would provide further independent scrutiny and increase the level of transparency within the process to ensure that all relevant data and evidence is fully considered in the signing off of the annual salmon stock classifications for each PSR. This would implement a similar approach to that adopted in the Republic of Ireland by Inland Fisheries Ireland and would be particularly beneficial if there was an

opportunity to link the implementation of management measures to the annual publication of the salmon stock assessment.

The EA and NRW seek Defra and Welsh Government support for new legal processes that enables the implementation of appropriate fishery management measures, as set out in the national salmon management decision structure, to be directly linked to the annual publication of salmon stock assessments for all PSRs. This would remove the need for longer term fishery management byelaws, increase transparency in the process and provide a more agile approach that can react faster to changes in salmon stock performance.

### 9.3.2 Inclusion of juvenile salmon stock assessment and performance

The current salmon fishery management DS considers annual salmon stock classifications based upon estimated adult salmon egg deposition within each river catchment. There is an assumption that the estimated number of spawning salmon consequently results in successful egg deposition and subsequent juvenile production to sustain the population into the future. However, spawning and juvenile recruitment failures have now been observed within several river catchments in recent years. These declines are believed to be linked primarily to unusually warm winter water temperatures that have impacted upon either adult salmon survival and spawning success or egg survival and hatching. In such instances, despite the annual salmon stock egg deposition estimate levels exceeding the catchment CL, poor salmon fry recruitment has been observed throughout the catchment in the following year. Whilst density dependent effects can potentially help to compensate for poor juvenile salmon recruitment, if the spawning failure has been extensive or occurs in successive years this will almost certainly result in poor numbers of returning adults in future years creating a longer-term recruitment crisis and the eventual collapse of the fishery. From a stock and fishery management perspective, it is clearly vital to be aware of this potential risk as soon as possible and to implement management actions that seek to maximise spawning escapement to help recover juvenile stocks and smolt output as quickly as possible.

At present, salmon monitoring in England and Wales is broadly based upon a core salmon monitoring programme that combines bi-annual temporal monitoring survey sites with a more extensive spatial programme that is undertaken every six years with rivers surveyed on a rolling programme. This level of frequency and survey site coverage is not adequate to detect changes in annual recruitment unless the decline exists in a year when the full spatial programme is being conducted. There is therefore currently a high risk that spawning failures in any given year will go undetected and unmanaged consequently resulting in a sudden collapse in returning adult salmon in future years.

**Proposal 24**

*Improve the level of annual juvenile salmon monitoring on all Principal Salmon Rivers that are subject to annual salmon stock assessments. A juvenile salmon monitoring programme should be established on each principal salmon river based on best practice salmon monitoring guidelines to provide an annual index of juvenile salmon fry and parr abundance. In addition, existing juvenile salmon electric fishing survey data collected by the Environment Agency and Natural Resources Wales should be combined, where possible, with comparable data obtained from third parties, e.g., Rivers Trust fisheries monitoring programmes, to ensure that the availability of data is maximised.*

If such a programme were to become established, the annual juvenile salmon population assessments could be included within the formal salmon management DS to provide an early warning of likely failures in salmon stock status.

## 9.4 Overarching considerations

### 9.4.1 Consideration of uncertainties

The term “uncertainties” covers a range of issues, from decisions about what processes to include in an assessment and what to do when data representing processes are incomplete or inadequate, through to those related to the quality and reliability of input data, and accuracy and precision of model-estimated parameters. A stock assessment for any species in any jurisdiction will require the stock assessors to consider how to deal with these inevitable uncertainties. For the national salmon stock assessment, most of these uncertainties are dealt with using pragmatic decisions, e.g., to maximise information from the best available data, and simplifying assumptions, e.g., using best available science from published and expert information. These decisions and assumptions allow us to do a stock assessment and adopt the precautionary approach recommended by NASCO.

A future research idea would be to explore the sensitivity of the national stock assessment, including all its pragmatic decisions and simplifying assumptions, to changes in salmon numbers and the management actions that are consequently triggered. For example, what management actions would the national stock assessment trigger if all the underlying numbers of salmon spawners were reduced to half their 2015-2025 mean? Such a sensitivity analysis could be undertaken using simulation testing.

**Proposal 25**

*Explore the sensitivity of the national salmon stock assessment, including all its pragmatic decisions and simplifying assumptions, to trigger suitable management actions in response to changes in the underlying numbers of salmon.*

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# 12 Glossary of terms

Abstraction – Taking water, either permanently or temporarily, from a water source (river, stream, spring, pond, lake, or groundwater).

Acoustic tag – An electronic transmitter which emits acoustic frequencies and is attached to (or inserted into) a fish to enable its position to be determined in fresh water or the sea.

Adult – Salmon after the middle of the first winter spent at sea, after which the main categorisation is by sea-age, measured in sea-winters (e.g., grilse, or 1SW; two sea winter, or 2SW).

Anadromous fish – Fish, born in freshwater, that migrates to sea, to grow and mature, and then returns to freshwater as an adult to spawn (e.g., salmon and sea trout).

Autocorrelation function (ACF) - measures the correlation between observations in a time series and earlier observations of the same series at different time lags.

Bayesian inference - A statistical method that uses Bayes' Theorem to update the probability of a hypothesis as new evidence becomes available. It continuously refines predictions by combining initial beliefs (priors) with new, observed data (likelihoods) to generate updated beliefs (posteriors).

Beta-Binomial regression – A type of regression used to estimate the probability of success from >1 trials, where the probability of success, here analogous to exploitation rate, can be more variable than expected under the assumptions of a simpler Binomial regression and optionally explained by explanatory variables.

Biological Reference Point (BRP) - is a benchmark or threshold derived from scientific data and population models used to evaluate the status of a fish stock and guide management decisions.

Bycatch – The incidental capture of non-targeted fish.

Byelaw – A law established by the Environment Agency and/or Natural Resources Wales that applies within their jurisdiction.

Catchment – The area of land drained by a river (e.g., River Tyne catchment).

Catch-and-release (C&R) – A stock conservation measure applied in commercial and recreational fisheries where salmon are released alive back into the wild at the place of capture.

Catch per unit effort (CPUE) – Catch data standardised by fishing effort to estimate catch rates.

Catch returns – The submission of catch data by licenced fishers to the Environment

Agency and Natural Resources Wales. All migratory salmonid rod and net licence holders in England, Wales, and the Border Esk are legally required to submit a catch return, even if a nil return. This includes details of their catch of salmon and sea trout (numbers and weights), fishing dates, and information on fishing effort (e.g., the number of days fished in the case of anglers).

Conservation Limit (CL) – The minimum spawning stock levels below which stocks should not be allowed to fall. The CL for each river is set at a stock size (defined in terms of eggs deposited) below which further reductions in spawner numbers are likely to result in significant reductions in the number of juvenile fish produced in future generations.

Correction Factors (CF) - Numerical adjustments applied to fisheries data or estimates to account for known biases, incomplete observations, or differences between measured and true values.

Decision Structure – A framework used to translate salmon stock assessment results into consistent and precautionary fisheries management actions, including controls on exploitation and measures to support stock recovery.

Dependent variable – see Response variable.

Dependence parameter – A unknown quantity that describes a dependency (temporal or spatial) among observations in a response variable, often referred to as $\rho$, usually bounded between [-1, +1], and the value of which is estimated from a statistical model.

Diadromous - is an adjective that describes fish that migrate between salt water and fresh water during their life cycle.

Dissolved oxygen – The amount of oxygen dissolved in water; one of the features that is used to classify water quality.

Distant-water fisheries – Fisheries in areas outside the jurisdiction of the country of origin of the exploited stock. With respect to the NASCO convention, this specifically refers to the fisheries under the jurisdiction of the Faroe Islands and Greenland.

Electric fishing - a scientific and management technique that applies a controlled electrical current (AC or DC) through water between an anode and a cathode to stimulate the nervous system of fish allowing researchers to scoop them up safely with nets.

Escapement – Fish that survive to spawn after exploitation of the stock.

EU Directive – A European Union legal instruction, binding on Member States, but which must be implemented through national legislation within a prescribed timescale.

Explanatory variable – A (usually) measured variable, such as air temperature, that is

used to explain variations in a response (or dependent) variable in a statistical model.

Exploitation – Removal of fish from a stock by fishing.

Extant exploitation rate – Catch of fish from a particular stock divided by the number of fish from that stock estimated to be alive at the time of the fishery.

Favourable condition – A term used in relation to the EU's Habitats Directive (92/43/EEC) where a designated feature and its associated environment is in good ecological condition.

Favourable conservation status – A term used in relation to the EU Habitats Directive (92/43/EEC), as retained in UK law, where a habitat or species is in a state where its distribution, abundance, structure, or function is sustained throughout the biogeographic region over the long term.

Fecundity - The reproductive capacity of an individual fish, typically expressed as the number of eggs produced by a female.

Fishery – There is no descriptive definition of 'fishery' in English law and its meaning has to be determined from the context of the legislation or other text where it is applied (MAFF, 2000). Uses include (i) for ecologists, the ecosystem including its fish, whether or not these are fished for, (ii) for fisheries managers, the enterprise managed, (iii) for fishers, the place where they fish, (iv) for bureaucrats, the sphere of activity covered by the relevant law.

Fixed engine (FE) – The term fixed engine is an ancient one used in the UK as a general descriptor of stationary fishing gears.

Focus Area Reports (FARs) – Reports prepared by each relevant jurisdiction within NASCO providing an in-depth assessment of measures being taken or planned to implement NASCO Agreements, Resolutions, and Guidelines in relation to Fishery Management, Protection, Restoration and Enhancement of Salmon Habitat, and Aquaculture and associated activities.

Fry – Young salmon that have hatched out in the current year, normally in May at the stage from independence of the yolk sac as the primary source of nutrition up to dispersal from spawning areas (redds).

Good ecological status – A key target under the EU's Water Framework Directive (WFD). Water bodies of 'good ecological status' should have the biological and chemical characteristics expected under sustainable conditions. Practicality and the cost to society must be considered in achieving this and this principle is also inherent in the WFD as retained under UK law.

Good ecological potential – An alternative key target under the EU's Water Framework Directive (WFD). Water bodies that have been artificial or physically altered to fulfil important uses such as flood and coastal risk management are designated as Heavily

Modified Waterbodies (HMWBs) under the WFD as retained under UK law. These water bodies are set the alternative target of Good Ecological Potential (GEP), which is the maximum ecological quality they could achieve given the constraints imposed upon them.

Grilse – An adult salmon that has spent only one winter feeding at sea (1SW salmon) before returning to freshwater to spawn; normally only applied to salmon in homewaters.

HABSCORE - A system for measuring and evaluating the quality of salmonid stream habitats. Habscore uses a combination of in-stream habitat and catchment features to predict salmon and trout, fry and parr populations as Habitat Quality Scores, and to compare those expected densities against electrofishing data to produce Habitat Utilisation Indices.

Homewater fisheries – Fisheries within the jurisdiction of the countries of origin of the exploited stocks (within 12 miles of the shore).

Hydrology Data Explorer (HDE) - An online tool for England for exploring and accessing hydrological data, such as river flows and water levels, to support analysis and assessment of river conditions.

IBIS (Integrated Aquatic Resources Management between Ireland, Northern Ireland and Scotland) – A partnership between the Loughs Agency, Queen's University Belfast, and the University of Glasgow, supported by the EU's INTERREG IVA Programme.

Implementation Plan – Reports prepared by each relevant jurisdiction within NASCO describing proposed approaches for meeting the objectives of NASCO’s Agreements, Resolutions, and Guidelines.

Index river – Rivers where comprehensive monitoring programmes are undertaken to collect long-term datasets on salmon stock abundance and biology to better understand population processes. Examples include the rivers Dee, Frome, and Tamar.

International Council for the Exploration of the Sea (ICES) – An international organisation, established in 1902, that develops science and advice to evaluate the status of various fish stocks (including Atlantic salmon) and support their sustainable exploitation. The United Kingdom is a member country. ICES consists of a network of more than 4000 scientists from over 350 institutes in 20 member countries.

Juvenile carrying capacity - The maximum number or density of juvenile fish that a habitat can sustainably support given the available habitat and resources.

Lowess smoothing - (Locally Weighted Scatterplot Smoothing) is a non-parametric smoothing method that estimates an underlying trend by fitting locally weighted regressions to successive subsets of the data.

Management Objective (MO) – The 'Management Objective' used for each river in England and Wales is that the stock should be meeting or exceeding its CL in at least four years out of five (i.e., at least 80% of the time).

Management Target (MT) – A spawning stock level for managers to aim at in order to meet the management objective.

Markov Chain Monte Carlo (MCMC) – An algorithm used to sample randomly from a probability distribution to approximate a target distribution. For example, an MCMC draw from a standard Normal distribution is taken to be an approximation of the mean of a standard Normal distribution. Generally, the more samples that are drawn, the more accurate (and precise) the approximation. MCMC is widely used in Bayesian inference to approximate complex and high-dimensional distributions that would be hard to derive analytically.

Maximum Smolt - The maximum number of smolts that a river or habitat is estimated to be capable of producing under specified conditions.

Maximum Sustainable Yield - The largest long-term average catch that can be taken from a fish stock while maintaining its productive capacity.

Microtag – A coded wire tag 1.1 mm long and 0.25 mm diameter, typically inserted into the nasal cartilage (snout) of juvenile salmonids and detectable in live fish, but only readable after removal from the fish. Commonly abbreviated to CWT (coded wire tag).

Migratory fish - Fish that move between different habitats or areas, often at particular stages of their life cycle, for purposes such as spawning, feeding or growth.

Mixed stock fishery (MSF) – A fishery that predominantly exploits mixed river stocks of salmon. The policy in England and Wales is to move to close coastal net fisheries that exploit predominantly mixed stocks where the capacity to manage individual stocks is compromised. Fisheries, including MSFs, operating within estuary limits are assumed to exploit predominantly fish that originated from waters upstream of the fishery; these fisheries are carefully managed to protect the weakest of the exploited stocks, guided by the decision structure, and taking into account socio-economic factors and European Conservation status where applicable.

Multi-Sea-Winter (MSW) salmon – An adult salmon that has spent two or more winters at sea.

National Fish Population Database (NFPD) - The Environment Agency's main database for storing and processing information collected from freshwater, estuarine and coastal fisheries surveys, including fish population and habitat data.

National River Flow Archive (NRFA) - he UK's official archive of river flow data, collating and providing access to hydrometric records from gauging stations across the UK.

National Rod Licence Catch Database (RCdb) - A database containing catch-return information reported by recreational salmon and sea trout anglers, including details of declared catches and fishing effort.

Net Limitation Order (NLO) – Mechanism within the Salmon and Freshwater Fisheries Act, 1975 whereby the competent authority may apply to limit the number of nets or traps fishing a public fishery.

Nominal catch – The nominal catch of a fishery is defined as the round, fresh weight of fish that are caught and retained.

North Atlantic Salmon Conservation Organisation (NASCO) – An international organisation established in 1984 following calls for international co-operation on the management of salmon stocks. Its objective is to conserve, restore, enhance, and rationally manage salmon through international co-operation taking account of the best available scientific information. The Contracting Parties to the NASCO Convention are currently: Canada, Denmark (in respect of the Faroe Islands and Greenland), EU, Iceland, Norway, the Russian Federation, United Kingdom, and the USA.

Online (on-line) lakes - Lakes situated directly on a river or stream, such that the watercourse flows into, through and out of the lake.

One-Sea-Winter (1SW) salmon – An adult salmon that has spent one winter at sea (see also grilse).

Parr – Juvenile salmon in the stage following fry until its migration as a smolt, salmon parr are typically <16 cm long and have parr-marks (dark vertical bars) on the sides of the body.

Post-smolt – Young salmon, at the stage from leaving the river (as smolts) until the middle of its first winter in the sea.

Precautionary approach – A concept enshrined in Principle 15 of the Rio Declaration of the UN Conference on Environment and Development, which states: "In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation".

Pre-fishery abundance (PFA) – The PFA of salmon from England and Wales is defined

as the number of fish alive in the sea on January 1 in their first sea winter. This is split between maturing (potential 1SW) and non-maturing (potential MSW) fish.

Principal Salmon River – A major salmon river with the prospect of annual rod catches of at least 50 salmon around the time (~1996) of the development of Salmon Action Plans (SAPs). In total, there are 64 Principal Salmon Rivers in England and Wales.

Production – The assimilation of nutrients to produce growth in a population over a given period.

Radio tag – An electronic transmitter which emits radio frequencies and is attached to (or inserted into) a fish to enable its position to be determined in fresh water.

Ranching – The production of salmon through smolt releases with the intent of harvesting the total population that returns to fresh water (harvesting can include fish collected for broodstock).

Recruits / Recruitment – The abundance of fish measured at a particular point in the life cycle, e.g., at the juvenile stages, the smolt stage, prior to the first fishery (recruitment to the fishery), or as returning spawners.

Reference point – An estimated value derived from an agreed scientific procedure and/or model which corresponds to a state of the resource and/or of the fishery and can be used to assess stock status or inform management decisions.

Replacement Line - A line on a stock–recruitment plot representing where each level of spawning stock produces sufficient recruits to replace itself in the next generation.

Response variable – A (usually) measured variable, such as numbers of returning adult salmon, whose variations are explained by explanatory variable(s) in a statistical model. Sometimes called a Dependent variable.

Returning Stock Estimate (RSE) – An estimate of the number of adult salmon returning to the mouth of a river.

River Basin District (RBD) – A river basin or several river basins, together with associated coastal waters. For each River Basin District, the Water Framework Directive requires a River Basin Management Plan to be published. These are plans that set out the environmental objectives for all the water bodies within the River Basin District and how they will be achieved. The plans are based upon a detailed analysis of the pressures on the water bodies and an assessment of their impacts. The plans must be reviewed and updated every six years.

Rod exploitation rates - The proportion of a returning salmon stock that is caught by the recreational rod fishery over a specified period.

Run – The number of adult salmon ascending, or smolts descending, a river in a given year. The main smolt run takes place in spring, whereas adult salmon runs may occur

in spring, summer, autumn, or winter.

Special Areas of Conservation (SACs) – An area designated under the EU Habitats Directive (92/43/EEC) giving added protection to identified species and habitats. Where salmon is a “qualifying species”, additional protection measures are required specifically for salmon.

Salmon Action Plans (SAPs) – Bespoke plans that set out the stock conservation objectives for each Principal Salmon River and how they will be achieved. Following a Ministerial Directive in 1998, Salmon Action Plans reviewed the status of individual river stocks and their fisheries (including evaluation of stocks against Conservation Limits), identified the main factors limiting stock and fishery performance, and drew up a costed list of remedial options.

Salmonid – A fish belonging to the family *Salmonidae*, which includes the Atlantic salmon (*Salmo salar*), brown trout / sea trout (*Salmo trutta*), charr (*Salvelinus alpinus*) and rainbow trout (*Oncorhynchus mykiss*).

Sea age – The number of winters that a salmon has remained at sea.

Sea trout – Anadromous form of the trout (*Salmo trutta*) from the post-smolt stage; the brown trout remains in fresh water throughout its life.

Site of Special Scientific Interest (SSSI) – An area of land notified under the Wildlife and Countryside Act 1981 by the appropriate nature conservation body as being of special interest by virtue of its flora and fauna, geological or physio-geographical features.

Smolt – The stage in the life cycle of a salmon when the parr undergo physiological changes, become silver in appearance and migrate to sea. Salmon smolts are typically 12–16 cm long and migrate to sea in spring.

Smolt age – The number of winters, after hatching, that a juvenile salmon remains in freshwater prior to emigration as a smolt (this does not, therefore, include the winter in which the egg was laid).

Smoltification - The physiological, behavioural and physical changes that prepare juvenile salmonids for migration from freshwater to the marine environment.

Socio-economic factors - Social and economic considerations that may influence fisheries management decisions, such as the benefits, costs and impacts of fisheries on people, communities and local economies.

Spawning Target - The level of spawning stock, often expressed as egg deposition, considered sufficient to support the long-term sustainable production of a salmon stock.

Spring salmon – Multi-sea-winter salmon which return to freshwater early in the year,

usually before the end of May.

Special Area of Conservation (SAC) – Protected Areas established for the protection of habitats or species under the EU Habitats Directive (92/43/EEC) (Special Areas of Conservation).

Stock – A management unit comprising one or more salmon populations, which may be used to describe those salmon either originating from or occurring in a particular area. Thus, salmon from separate rivers are referred to as “river stocks”. (N.B. Very large management units, such as the salmon exploited at West Greenland, which originate from many rivers, are often referred to as ‘stock complexes’).

Stocking – The intentional release of fish into an ecosystem.

Stock-recruitment - The relationship between the size of the spawning stock and the number of offspring (recruits) it subsequently produces.

Stream Order - Stream order is a classification system used in hydrology to define the relative size and hierarchical position of streams within a catchment. The Strahler method of defining stream order, as used in HABSCORE and conservation limit setting, defines the uppermost tributary as a first order stream. Where two first order streams meet, they create a second order stream. A third order stream is only created by the confluence of two second order streams. Importantly stream order may change depending on the scale of map being used.

Sustainable use – The use of a biological resource in a way and at a rate that does not lead to the long-term decline of its potential to meet the needs and aspirations of present and future generations. Sustainable use does not imply that abundance is constant.

Total Allowable Catch (TAC) – A catch limit (or quota) that prescribes the maximum amount (weight or number) of salmon a fishery is permitted to harvest.

Transitional waters - Bodies of surface water, such as estuaries, where freshwater and coastal waters mix and conditions are partly saline.

Transportation Model - A salmon stock assessment model used to derive egg-to-smolt stock–recruitment curves and replacement lines, which are used to establish conservation limits for individual salmon rivers.

Upper Stock Reference Point – used in the Canadian approach

Water Framework Directive (WFD) – An EU directive that commits European Union Member States to achieve good status for all water bodies (including marine waters up to one nautical mile from shore) by 2015. Transposed into The Water Environment (Water Framework Directive) (England and Wales) Regulations 2017, following the UK departure from the EU.

WinBugs – A discontinued but historically significant statistical software package used for Bayesian analysis using Markov chain Monte Carlo (MCMC) methods. Replacement software packages include Just Another Gibbs Sampler (JAGS) and Numerical Inference for statistical Models using Bayesian and Likelihood Estimation (NIMBLE).

Working Group on North Atlantic Salmon (WGNAS) – An ICES Working Group responsible for the annual assessment of the status of salmon stocks across the North Atlantic and for supporting ICES in generating catch advice to NASCO for the West Greenland and Faroes fisheries. This Working Group also supports ICES in developing advice on a wide range of other issues to support NASCO in exercising its responsibilities for the conservation, restoration, enhancement, and rational management of wild salmon in the North Atlantic.

# 13 Glossary of acronyms

1SW – One Sea Winter

2SW – Two Sea Winter

3SW – Three Sea Winter

AC - Alternating Current

ACF - Autocorrelation Function

ACOM - Advisory Committee

AGOL – Arc GIS Online

AI - Artificial Intelligence

AR - At Risk

ARIS - Adaptive Resolution Imaging Sonar

BRP - Biological Reference Point

C&R - Catch and Release

Cefas / CEFAS - The Centre for Environment, Fisheries and Aquaculture Science

CEH - The Centre for Ecology and Hydrology

CF - Condition Factor

CI - Credible Interval

CL - Conservation Limit

CM - Centimetre

CoGePoMi - comité de gestion des poissons migrateurs

COSEWIC - Committee on the Status of Endangered Wildlife in Canada

CPUE - Catch per unit effort

CWT - Coded wire tag

DAERA - Department of Agriculture, Environment and Rural Affairs

DC - Direct current

Defra - Department for Environment, Food and Rural Affairs.

Df - Degrees of freedom

DFO - Department of Fisheries and Oceans

DIM - Density-independent mortality

DNA - Deoxyribonucleic acid

DPS - District Population segment

DS - Decision Structure

E&W / EW - England and Wales

EA - Environment Agency

eDNA - Environmental DNA

EEC - European Economic Community

EFG - England Fisheries Group

ESA - Endangered Species Act

EU - European Union

FARs - Focus Area Reports

FE - Fixed engine

GEP – Good Ecological Potential

GES - Good Ecological Status

GIS - Geographical Information System

GWCT - Game and Wildlife Conservation Trust

HDE - Hydrology Data Explorer

HMWBs - Heavily Modified Waterbodies

ICES - International Council for the Exploration of the Sea

IFI - Inland Fisheries Ireland

IP - Implementation Plan

IQR – Interquartile Range

JAGS - Just Another Gibbs Sampler

LB - Lower bound

LooIC - Leave-one-out cross-validation Information Criteria

LOWESS - Locally Weighted Scatterplot Smoothing

LRP - Lower Reference Point

MAE - Mean absolute error

MAFF - Ministry of Agriculture, Fisheries and Food

MCMC - Markov Chain Monte Carlo

MO - Management Objective

MS - Maximum Smolt

MSF - Mixed stock fishery

MSO - Maximum Smolt Output

MSW - Multi-sea winter

MSY - Maximum Sustainable Yield

MT - Management Target

NAC - North American Commission

NAR - Not At Risk

NASCO - North Atlantic Salmon Conservation Organisation

NEAC - North East Atlantic Commission

NFCS - National Fisheries Classification Scheme

NFPD - National Fish Population Database

NGOs - Non-Government Organisations

NIMBLE - Numerical Inference for statistical Models using Bayesian and Likelihood Estimation

NLO - Net Limitation Order

NRA - National Rivers Authority

NRFA - National River Flow Archive

NRW - Natural Resources Wales

OS - Ordnance Survey

OSMM - Ordnance Survey Master Map

PA - Precautionary Approach

PAR - Probably At Risk

PFA - Pre-fishery abundance

PNAR - Probably Not At Risk

PSR - Principal Salmon River

R&D - Research and Development

RBD - River Basin District

RCdb - National Rod Licence Catch Database

RER - Rod exploitation rate

RFERACs - Regional Fisheries, Ecology and Recreation Committees

RP - Replacement Point

RSE - Returning stock estimate

S-R / SR - Stock-recruitment

SAC - Special Area of Conservation

SAM - Stock Assessment Model

SAMARCH - SAlmonid Management Round the Channel

SAP - Salmon Action Plan

SD - Standard Deviation

SHRU - Salmon habitat recovery unit

SMNR - Sustainable Management of Natural Resources

SMSY - Spawning stock size at maximum sustainable yield

SSB - Spawning stock biomass

SSCS - Standing Scientific Committee on Salmon

SSSI - Site of Special Scientific Interest

TAC - Total Allowable Catch

TEGOS - Technical Expert Group on Salmon

UK - United Kingdom

UN - United Nations

URP - Upper Reference Point

USA - United States of America

USR - Upper stock reference

WFD - Water Framework Directive

WFF - Wales Fisheries Forum

WGNAS - Working Group on North Atlantic Salmon

WWA - Welsh Water Authority

# 14 Annexes

## 14.1 Annex 1: Full text of the 1998 Ministerial Direction

Environment Act 1995

Section 40 (1)

Directions given to the Environment Agency by the Minister of Agriculture, Fisheries and Food and Secretary of State for Wales

Reference: 98/1

The Minister of Agriculture, Fisheries and Food and Secretary of State for Wales (hereinafter referred to as “the Ministers”), in exercise of the powers conferred on them by virtue of Section 40(1) of the Environment Act 1995(a) and of all other powers enabling them in that behalf, and after consultation with the Environment Agency (hereinafter referred to as “the Agency”) in accordance with section 40 (6) of the said Act, hereby make the following directions:

With respect to the carrying out of its duty to maintain, improve and develop salmon fisheries, trout fisheries, freshwater fisheries and eel fisheries under section 6(6) of the said Act, the Agency shall comply with the obligations contained in the attached schedule.

These directions shall apply from 1 September 1998 and may be amended or revoked by the Ministers.

| Authorised by the Minister of Agriculture, Fisheries and Food to sign in that behalf | Authorised by the Secretary of State for Wales to sign in that behalf |
|---|---|
| 31 July 1998 | 12 August 1998 |

C I LLEWELYN

An Assistant Secretary in the Ministry of Agriculture, Fisheries and Food

ALISON M JACKSON

An Assistant Secretary in the Welsh Office

**(a)** 1995 c.25.

SCHEDULE

In accordance with the adoption of a precautionary approach for the management of salmon, the Agency shall:

a. Prepare salmon action plans by 2002 for the rivers listed in the attached table.

b. In preparing these plans develop and set spawning targets1 for each river.

c. Once set, review compliance of stock levels with these targets annually giving due regard to stock characteristics such as age composition and run-timing, and take appropriate action.

d. Ensure that target setting and compliance assessment procedures are regularly revised to take account of improvements in methodologies and new data.

e. Take account of the compliance stock levels with spawning targets when initiating and conducting reviews of Net Limitation Orders and byelaws for salmon fisheries; and

f. Maintain a comprehensive and complete data archive of catches and other assessment data for English and Welsh rivers, reporting definitive annual stock and fishery assessments annually.

Also, in conjunction with the Centre for Environment, Fisheries and Aquaculture Science (CEFAS) and by the end of March each year, the Agency shall:

g. Prepare a joint report describing the status of salmon stocks and fisheries in the preceding year, including providing provisional assessments of compliance of salmon stock abundance estimates with the spawning targets in preceding years, for use in assessments

prepared by the International Council for the Exploration of the Sea and negotiations undertaken in the North Atlantic Salmon Conservation Organisation.

NOTE

1. Spawning targets in this context equate to conservation limits as defined by NASCO.

TABLE OF RIVERS

| REGION | |
|---|---|
| Midlands | Severn, Severn Estuary |
| North East | Coquet, Esk, Tees, Tyne, Wear |
| North West | Border Esk, Cumbrian Esk, Derwent, Duddon, Eden, Ehen, Irt, Kent, Leven, Lune, Ribble, Wyre |
| Southern | Itchen, Test |
| South West | Avon (Devon), Avon (Hants), Axe, Camel, Dart, Erme, Exe, Fowey,<br>Frome, Lyn, Lynher, Piddle, Plym, Stour, Tamar, Tavy, Taw, Teign, Torridge, Yealm |
| Thames | Thames |

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| Welsh | Cleddau, Clwyd, Conwy, Dee, Dwyfawr, Dyfi, Dysynni, Glaslyn/Dwryrd, Mawddach, Nevern, Ogmore, Ogwen, Rheidol, Seiont, Taf, Taff, Tawe, Teifi, Twyi, Usk, Wye |

## 14.2 Annex 2: Assessment and management of salmon across NASCO jurisdictions

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| **North American Commission (NAC)** | Canada – Newfoundland and Labrador Region | The Wild Atlantic Salmon Conservation Policy (2009) is the keystone of the management of wild Atlantic salmon stocks and fisheries. Commercial fisheries for Atlantic salmon have been prohibited in Newfoundland since 1992 and in Labrador since 1998. Only indigenous, recreational, and resident subsistence fisheries are permitted. A range of management measures have been implemented to restore and maintain populations including fishery closures, seasonal fishing restrictions and catch retention limits, a prohibition on the retention of large salmon (≥ 63 cm) in recreational fisheries, and daily limits | Stocks that exceed 150% of their conservation limit in a given year are considered to be in the 'healthy zone' and available for exploitation. | • Stock status is assessed based on compliance with river-specific egg deposition and spawner requirements. Temporal trends in indices of abundance (e.g. smolt production and marine survival rates) are also used as an indicator of stock status. Annual comparisons are made to the previous five-year mean in Newfoundland and six-year mean in Labrador, which correspond to the average generation time for Atlantic salmon in each respective area.<br>• Catches are reported in two size classes (small: < 63 cm and large: ≥ 63 cm) that represent 1SW and repeat spawning fish.<br>• Numbers of adult returns are estimated using count data from fish counters/traps for home-water fisheries, or derived from catches raised | 1) A stock that has met more than 150% of its conservation limit in a given year was considered to be in the 'healthy zone' and therefore available for exploitation.<br>2) A stock that has met 100–150% of its conservation limit in a given year was situated in the 'cautious zone'. Management actions are required to improve stock status to reach the level of the 'healthy zone'.<br>3) A stock that has met less than 100% of its conservation limit in a given year was in the 'critical zone'. Management actions are required to promote stock growth and reduce fisheries- |

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| | | on catch-and-release fishing. | | by exploitation rates to aggregate data to the regional level for mixed-stock fisheries.<br>• Egg deposition estimates are derived from the number of adult returns and the biological characteristics of the population (e.g. fecundity, sex ratio and size data).<br>• In Newfoundland, the lower limit reference point (LRP) for egg deposition is 2.4 eggs per $m^2$ of river rearing habitat and 368 eggs per hectare of lake habitat. The LRP egg deposition rate for Labrador is 1.9 eggs per $m^2$ of river rearing habitat and for the Straits Area of Labrador is 2.4 eggs per $m^2$ of river rearing habitat and 105 eggs per hectare of lake habitat.<br>• Annual egg deposition estimates are compared to the LRP and an upper stock reference (USR) point that is set at 150% of the LRP. | related mortality to the lowest level possible. |
| | Canada – Gulf of St Lawrence Region | The Wild Atlantic Salmon Conservation Policy (2009) provides the main regulatory framework for the management of wild Atlantic salmon stocks | Stocks that exceed 150% of their conservation limit in a given year are considered to be in the ‘healthy zone’ | • Stock status is assessed based on estimated adult returns compared to river-specific egg deposition and spawner requirements. Temporal trends in indices of | 1) A stock that has met more than 150% of its conservation limit in a given year is considered to be in the ‘healthy zone’ and |

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| | | and fisheries. Commercial fisheries for Atlantic salmon have been closed since 1984. All directed fisheries have been prohibited in southeast New Brunswick since 1998. Only indigenous, recreational, and resident subsistence fisheries are permitted elsewhere. Numerous management measures have been implemented to restore and maintain populations including fishery closures, daily and seasonal fishing restrictions and catch retention limits, the mandatory catch-and-release of large salmon (≥ 63 cm) and the carcass tagging of small salmon (< 63 cm) retained in recreational fisheries. | and available for exploitation. | abundance (e.g. juvenile densities, catch per unit effort and smolt production) are also used as indicators of stock status. Annual comparisons are made to the previous five-year mean, which corresponds to the average generation time for Atlantic salmon in the region.<br>• Catches are reported in two length classes (small: < 63 cm and large: ≥ 63 cm) considered to represent the sizes of 1SW and MSW fish.<br>• Numbers of adult returns are estimated using count data from fish counters/traps, end of season snorkelling surveys of spawning females, redd surveys, and mark-recapture experiments for home-water fisheries, or derived from catches raised by exploitation rates to aggregate data to the regional level for mixed-stock fisheries.<br>• Egg deposition requirements are estimated from freshwater production dynamics translated to adult returns to estimate the spawning stock at MSY. Stock-recruitment relationships for data-rich | therefore available for exploitation.<br>2) A stock that has met 100–150% of its conservation limit in a given year is situated in the 'cautious zone'. Management actions are required to improve stock status to reach the level of the 'healthy zone'.<br>3) A stock that has met less than 100% of its conservation limit in a given year is in the 'critical zone'. Management actions are urgently required to promote stock growth and reduce fisheries-related mortality to the lowest level possible. |

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| | | | | stocks are transported to data-poor stocks based on habitat area and spawner age composition using a hierarchical Bayesian modelling framework.<br>• A lower limit reference point (LRP) for egg deposition rates has been set at 2.4 eggs per $m^2$ of juvenile rearing habitat for all rivers in the Gulf region, except the Restigouche River where a value of 1.68 eggs per $m^2$ of juvenile rearing habitat is used. The value for the Restigouche River is based on a stock and recruitment analysis of index rivers in the province of Quebec and a reference spawning escapement value resulting in the maximum surplus of fish.<br>• Annual egg deposition estimates are compared to the LRP, which is set at a 0.75 probability that the resultant recruitment will be at least 50% of maximum recruitment. | |
| | Canada – Maritimes Region | The Wild Atlantic Salmon Conservation Policy (2009) is the main | Stocks that meet less than 100% of their conservation | • Stock status is assessed based on estimated egg deposition compared to river- | 1) A stock that has met less than 100% of its conservation limit in a given year is in the |

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| | | regulatory framework for the management of wild Atlantic salmon stocks and fisheries. Populations in many rivers are extirpated and the designatable unit in the Inner Bay of Fundy has been listed as endangered under the Species at Risk Act (2003). The other three designatable units (Southern Upland, eastern Cape Breton and outer Bay of Fundy) have been assessed by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) as endangered, and are undergoing a review process for a federal listing decision. Commercial fisheries for Atlantic salmon have been prohibited since 1984. Only indigenous and recreational fisheries are permitted on the Middle, Baddeck and North rivers in eastern Cape Breton. Indigenous fishers report zero harvest on these rivers and catch- | limit in a given year are considered to be in the 'critical zone'. An upper stock reference point defining the cautious–healthy zone boundary has not been developed due to the depressed status of stocks in the region. | specific conservation egg requirements. Juvenile densities, smolt production estimates, and catch and effort data are also used as indicators of stock status. Approaches are river- and area-specific, depending on data availability.<br>• Catches of adult salmon are reported in two length classes (small: < 63 cm and large: ≥ 63 cm) that represent the sizes of 1SW and MSW fish.<br>• Returns of wild and hatchery-reared adult salmon are estimated using count data from fish traps in fishways and fences, dive surveys, mark-recapture experiments for index rivers, or derived from catches raised by catch rates for non-index rivers.<br>• Egg deposition estimates are derived from the number of adult spawners and the biological characteristics of the population (e.g. fecundity, sex ratio and size data).<br>• Conservation limits are estimated based on an egg deposition rate of 2.4 eggs per $m^2$ multiplied by the amount of accessible fluvial | critical zone. Management actions are required to promote stock growth and reduce fisheries-related mortality to the lowest level possible. |

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| | | and-release fishing is permitted during cold-water periods with a daily catch-and-release limit of two fish. Limited hatchery intervention programs exist to offset potential catch-and-release mortalities and preserve the genetic diversity/prevent extirpation of some critically low priority populations. | | rearing habitat with a suitable gradient.<br>• Annual egg deposition estimates are compared to a lower limit reference point (LRP) for egg deposition rates, set at 2.4 eggs per $m^2$ of juvenile rearing habitat. A 4% catch-and-release mortality rate is applied to estimate spawning escapement for rivers with recreational fisheries.<br>• Juvenile abundance estimates from electric fishing surveys are compared to Elson's norm values of 29 fry per 100 $m^2$ and 38 parr per 100 $m^2$. A smolt production estimate of 3.8 smolts per 100 $m^2$ is used as a general reference value for rivers at or near the egg deposition requirement. | |
| | Canada – Québec Region | The Wild Atlantic Salmon Conservation Policy (2009) is the main regulatory framework for the management of wild Atlantic salmon stocks and fisheries. Accompanying legislation includes the Quebec | Stocks that meet or exceed their optimal conservation threshold over a five-year period are considered to be in the 'healthy stock' status zone | • Stock status is assessed based on compliance with river-specific egg deposition and spawner requirements. Temporal trends in indices of abundance (e.g. juvenile densities, survival rates and smolt production) are also used as indicators of stock | 1) A stock that has met or exceeded its optimal conservation threshold over a five-year period is considered to be in the healthy stock status zone and therefore available for exploitation. |

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| | | Fishery Regulations (1990) and the Act Respecting the Conservation and Development of Wildlife (2002). The latter prioritises the allocation of halieutic resources based on the reproductive stock, fishing for food purposes, recreational fishing and commercial fishing. Commercial fisheries for Atlantic salmon have been prohibited since 2000. Only indigenous, recreational, and resident subsistence fisheries are permitted. A range of measures have been implemented to restore and maintain populations including fishery closures, daily and seasonal fishing restrictions and catch retention limits, mandatory catch reporting, catch-and-release fishing, habitat improvement works and stock enhancement programmes. Management modalities | and available for exploitation. | status. Annual comparisons are made to the previous five-year mean, which corresponds to the average generation time for Atlantic salmon in the region. Approaches are river-specific.<br>• Catches are reported in two size classes (small: < 63 cm and large: ≥ 63 cm) that represent 1SW and MSW fish.<br>• Returns of wild and hatchery-reared adult salmon are estimated using count data from fish counters/traps and snorkelling/canoeing surveys, or derived from catches raised by exploitation rates.<br>• Rivers are classified into one of six categories based on the data available to estimate adult returns: (C1) count data from fish counters/traps or snorkel/canoe surveys exist to estimate numbers of returning small and large salmon; (C2) count data from fish counters/traps or snorkel/canoe surveys are available to estimate returns but numbers of returning small and large salmon are derived from recreational | 2) A stock that has been below its optimal conservation threshold but above its demographic and genetic conservation thresholds over a five-year period is situated in the cautious stock status zone. Management actions are required to reduce exploitation and increase stock size above the optimal conservation threshold. Mandatory catch-and-release of large salmon (≥ 63 cm) is required.<br>3) A stock that has met less than 100% of its demographic or genetic conservation thresholds over a five-year period is in the critical stock status zone. Management actions are urgently required to promote stock growth and reduce fisheries-related mortality to the lowest level possible. |

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| | | are established on a “river by river” basis. | | catches; (C3) multiple factors including catch numbers, fishing effort, season duration and river accessibility distance are used to estimate returns; (C4) inter-annual variation in returns is assumed to be similar to that observed in other rivers; (C5) catches raised by the mean regional exploitation rate are used to estimate returns; and (C6) returns are derived from other rivers in the same area based on available habitat area.<br>• Egg deposition estimates are derived from the number of adult returns and the biological characteristics of the population (e.g. fecundity, sex ratio and size data).<br>• Egg deposition requirements are estimated from freshwater production dynamics translated to adult returns to estimate the spawning stock at MSY. Stock-recruitment relationships for data-rich stocks are transported to data-poor stocks based on habitat area and spawner age composition using a | |

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| | | | | hierarchical Bayesian modelling framework.<br>• Annual egg deposition estimates are compared to a lower limit reference point (LRP) and an upper stock reference (USR) point for egg deposition rates. The LRP (known as the demographic conservation threshold) is set at the egg deposition rate that corresponds to a 0.75 probability that the resultant recruitment will be ≥ 50% of maximum recruitment. The USR (the optimal conservation threshold) represents a > 0.95 probability that the spawning stock will be at the level required to achieve MSY. Another LRP (the genetic conservation threshold) based on genetic parameters is set at the abundance level providing 90% of the population's genetic diversity that will be preserved for next 100 years. | |
| | The United States of America | Possession of Atlantic salmon is prohibited in the U.S. Exclusive Economic Zone under the | No catch advice is provided given that fishing is prohibited and | • Stock status is assessed based on estimated adult returns compared to spawner requirements. Temporal | A series of criteria focused on abundance, productivity, and habitat accessibility |

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| | | Magnuson-Stevens Act (1987). Remnant populations of Atlantic salmon from the Gulf of Maine district population segment (DPS) were first listed as endangered under the Endangered Species Act (ESA) in 2000. In 2009, the listing was updated to include additional watersheds across a broader geographic range and the designation of critical habitat. Numerous management measures have been established to conserve and restore populations including the closure of commercial and recreational fisheries, and a wide variety of river restoration efforts and stock enhancement programmes. | populations are critically imperilled with spawning stock levels well below conservation limits. | trends in juvenile abundance metrics are also used as indicators of stock status.<br>• Returns of naturally-reared and hatchery origin adult salmon are estimated using count data from fish traps or redd surveys.<br>• Conservation limits are calculated by estimating the required number of spawning adults based on a target egg deposition rate of 2.4 eggs per $m^2$ of fluvial rearing habitat and a mean fecundity of 7200 eggs, multiplied by a factor of 2 assuming a 1:1 female-to-male spawning ratio.<br>• Juvenile abundance metrics (e.g. densities, survival rates and smolt production) are estimated from electric fishing surveys and mark-recapture data from rotary screw traps. | metrics must be met to reclassify or delist the Gulf of Maine DPS under the ESA.<br>1) Reclassifying the Gulf of Maine DPS from endangered to threatened will be considered when all the following criteria are met: Annual returns ≥ 1500 wild-origin adults, or hatchery stocked eggs, fry or parr spawning in the wild, with an annual escapement ≥ 500 naturally-reared adults in ≥ 2 out of 3 salmon habitat recovery units (SHRU's). A positive mean growth rate > 1 over a 10-year period. In each SHRU, ≥ 7500 accessible and suitable spawning and rearing habitat units capable of supporting the offspring of 1500 naturally-reared adults.<br>2) Delisting the Gulf of Maine DPS will be considered when all the following criteria |

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| | | | | | are met: Annual escapement ≥ 2000 wild adults in each SHRU, and a total of ≥ 6000 wild adults in the DPS. Each SHRU has a positive mean growth rate of > 1 over a 10-year period, with a < 0.50 probability that the DPS will fall below 500 adult wild spawners in the next 15 years. Sufficient suitable spawning and rearing habitat for the offspring of 6000 wild adults is accessible and distributed throughout their critical habitat, with ≥ 30,000 accessible and suitable habitat units in each SHRU. |
| **North East Atlantic Commission (NEAC) – Northern NEAC** | Finland | Bilateral agreements between Finland and Norway are the keystone of the management of Atlantic salmon stocks in transboundary rivers flowing into the Northeast Atlantic. These bilateral agreements were | A 0.75 average probability of each population meeting its conservation limit over a four-year period. | • Stock status is assessed based on compliance with egg and spawner requirements.<br>• Annual catches are reported by weight group representing the sizes of 1SW, 2SW and 3SW salmon. | 1) At least a 0.75 average probability of meeting the conservation limit over a four-year period. Harvested sustainably. The management target is achieved and no additional restrictions |

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| | | established for the River Näätämöjoki (or Neidenelva) in 1984 and for the largest salmon producing river, the River Teno (or Tana), in 2017. The Finnish Fishing Act (2015) and the Norwegian Salmon and Inland Fisheries Act (2009) also provide regulatory frameworks for fishing controls. A range of management measures have been implemented to conserve and restore salmon populations including daily, weekly and seasonal fishing closures, fishing gear restrictions, and temporal and spatial quotas for recreational angling permits. | | • Numbers of adult returns are estimated using count data from fish traps, sonar and snorkelling surveys of spawning females, or derived from catches and exploitation rate estimates.<br>• Female spawning biomass is estimated as the product of catch weight divided by the exploitation rate minus catch weight multiplied by proportion of females for all weight groups.<br>• Egg deposition estimates are derived from the average maximum number of recruits at the peak of the stock-recruit relationship.<br>• The egg deposition requirement is estimated by transporting stock-recruitment relationships from data-rich to data-poor rivers with a similar egg deposition capacity. Populations are assigned into four egg deposition categories (0.5–1.5, 1.5–3, 3–5 and > 5 eggs per $m^2$) and the egg deposition requirement is estimated from wetted area using GIS.<br>• Female spawning stock biomass requirements are | on exploitation are required.<br>2) Less than a 0.75 average probability of meeting the conservation limit over a four-year period. Harvested unsustainably. The management target may not have been achieved and exploitation should be reduced. |

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| | | | | calculated by converting the required egg deposition into the required female spawning biomass using two approaches: (1) a biomass-based target assuming a fixed fecundity of 1800 eggs $kg^{-1}$ per female; and (2) a stock-specific relative fecundity ratio based on sea-age composition. Stock-specific sea-age compositions are estimated from genetic stock identification and tributary-specific catch samples.<br>• Uncertainties in estimates of adult returns, exploitation rates, the proportion of females, and female spawning biomass are considered in the calculation of compliance estimates and the categorisation of stock status. | |
| | Norway | The Salmon and Inland Fisheries Act (2009) and the Nature Diversity Act (2009) provide the main regulatory frameworks for the management of wild Atlantic salmon stocks and fisheries. Bilateral agreements between | A 0.75 average probability of the population meeting its conservation limit over a four-year period, and greater than 140% average attainment (non- | • Catch statistics form the foundation of the assessment. Annual catches are reported by weight group considered to represent the sizes of 1SW, 2SW and 3SW salmon.<br>• Numbers of adult returns are estimated from catches and exploitation rates, derived | 1) More than a 0.75 average probability of the stock meeting its conservation limit over a four-year period, and greater than 140% average attainment (non-truncated) during the same period. If marine survival |

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| | | Norway and Finland have also been established to manage Atlantic salmon stocks in transboundary rivers flowing into the Northeast Atlantic. These bilateral agreements were established for the River Neidenelva (or Näätämöjoki) in 1984 and for the largest salmon producing river, the River Tana (or Teno), in 2017. A number of management measures have been implemented to conserve and restore salmon stocks including fishery closures, daily and seasonal fishing restrictions and catch retention limits, and prohibitions on fishing gear. In principle, fishing is only permitted in areas where salmon populations have an identifiable surplus above the conservation limit, however, socioeconomic implications and cultural traditions are also considered. | truncated) during the same period. | from local estimates (different counting methods) or knowledge on fishing pressure.<br>• Female spawning biomass is estimated as the product of catch weight divided by the exploitation rate minus catch weight multiplied by proportion of females for all weight groups.<br>• Conservation limits in terms of egg deposition are derived from the average maximum number of recruits at the asymptote of the stock-recruitment relationship.<br>• The egg deposition requirement is estimated by transporting stock-recruitment relationships from 9 rivers to the remaining 430 populations. Populations are grouped into four egg deposition categories (0.5–1.5, 1.5–3, 3–5 and 5–7 eggs per $m^2$) and the egg deposition requirement is estimated using GIS-derived measurements of wetted area.<br>• Uncertainties in estimates of adult returns, exploitation rates, the proportion of | remains at current levels, the stock can probably be more heavily exploited.<br>2) A 0.75 average probability of the stock meeting its conservation limit over a four-year period. The management target is achieved and no additional restrictions on exploitation are required.<br>3) A 0.4–0.74 average probability of the stock meeting its conservation limit over a four-year period. The management target may not have been achieved and exploitation should be moderately reduced.<br>4) A 0.2–0.39 average probability of the stock meeting its conservation limit over a four-year period. The management target is likely not achieved and exploitation should be significantly reduced.<br>5) Less than a 0.2 average probability of |

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| | | | | females, and female spawning biomass are considered in the calculation of compliance estimates and the categorisation of stock status.<br>• A quality norm is an instrument of the Nature Diversity Act (2009) that has been developed for Norwegian salmon populations to classify stock status in 2 dimensions: (1) the compliance estimate and harvest potential for the stock; and (2) genetic integrity of the stock. | the stock meeting its conservation limit over a four-year period. The management target is not achieved and exploitation should be substantially reduced.<br>6) If the quality of a stock according to the quality norm is moderate or poorer, measures should be implemented by the relevant authorities responsible for the management of the identified anthropogenic impact factors to improve the quality of the stock to reach the level of 'good'. |
| | Russia | The Federal Law on Fisheries and Conservation of Aquatic Biological Resources (2004) is the keystone of the management of wild Atlantic salmon stocks and fisheries. Accompanying legislation includes Federal Laws on the Animal World (1995), | A 1.0 probability that the stock will meet its conservation limit in a given year.<br><br>For rivers without conservation limits, a stable or | • Stock status is assessed using four approaches: (1) estimated adult returns are compared to egg deposition and spawner requirements; (2) temporal trends in annual catch numbers are used to infer changes in stock size; (3) annual parr (> 0+) densities are compared to pre-smolt abundance | Rivers with conservation limits:<br><br>1) More than a 1.0 probability of the river meeting its conservation limit in a given year. The stock is considered to be at full reproductive capacity. No additional |

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| | | the Water Code (1995), Environmental protection (2000), and Environmental Impact Assessment (1995). Regional fisheries regulations have also been established in Murmansk, Archangelsk, the Republic of Karelia, the Komi Republic and Nenets Autonomous Okrug. Wild Atlantic salmon are exploited by commercial, recreational, and indigenous subsistence fisheries. Mixed-stock fisheries are prohibited in estuaries, 0.5 km inside and outside river mouths. Several management measures have been implemented to conserve and restore stocks including fishery closures, fishing effort controls, the setting of annual TACs and the allocation of quotas, daily and seasonal fishing restrictions, catch-and-release fishing, habitat improvement works and | increasing temporal trend in annual catch numbers or a pre-smolt abundance requirement of 10 parr (> 0+) per 100 $m^2$ in a given year. | requirements; and (4) smolt counts are used as indices of smolt production. Approaches are river-specific.<br>• Returns of wild and hatchery-reared adult salmon are estimated using count data from fish counters/traps and mark-recapture experiments, or derived from catches raised by exploitation rates.<br>• Conservation limits have been developed for all salmon producing rivers in the Murmansk region and for several rivers in the Archangelsk region. River-specific conservation limits are under development.<br>• Genetic stock identification estimates the proportion of wild and hatchery-reared Atlantic salmon in the catches. | management actions required.<br>2) An 0.8-1.0 probability of the river meeting its conservation limit in a given year. The stock is at risk of reduced reproductive capacity. Management actions required to improve stock status and reduce exploitation.<br>3) Less than an 0.8 probability of the river meeting its conservation limit in a given year. The stock is suffering reduced reproductive capacity. Management actions urgently required to promote stock growth and reduce exploitation to the lowest level possible.<br><br>Rivers without conservation limits:<br><br>1) An increasing temporal trend in annual catch numbers is indicative of stock growth. Rivers with a mean parr |

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| | | stock enhancement programmes. | | | abundance above 10 per 100 $m^2$ are at full reproductive capacity. No additional management actions required.<br>2) The lack of a temporal trend in annual catch numbers denotes relative stability in stock size. Rivers with a mean parr abundance above 10 per 100 $m^2$ are at full reproductive capacity. No additional management actions required.<br>3) A decreasing temporal trend in annual catch numbers indicates a reduction in stock size. Rivers with a mean parr abundance below 10 per 100 $m^2$ are suffering reduced reproductive capacity. Management actions urgently required to promote stock growth and reduce exploitation to the lowest level possible. |

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| | Sweden | The Swedish Fisheries Act (1993) provides the main regulatory framework for the management of wild Atlantic salmon stocks and fisheries. Accompanying legislation includes the fishing, aquaculture and fisheries ordinance (1994) and a compendium of regulations (Havs- och Vattenmyndighetens författningssamling) issued by the Swedish Agency for Marine and Water management. Local byelaws have also been established for privately owned fisheries by fishing associations. Commercial fisheries for Atlantic salmon have been prohibited since 2014. Recreational fisheries are permitted in rivers and coastal waters, but mixed-stock fisheries are closed in estuaries and along the coast. All fishing rights in rivers are privately owned, whereas coastal fishing is a | A ≤ 0.1 probability that the index river Högvadsån has fallen below its conservation limit in a given year, and a pre-smolt abundance requirement of 10 parr (> 0+) per 100 $m^2$ in a given year for non-index rivers. | • Stock status is assessed using two approaches: (1) estimated adult returns are compared to egg deposition and spawner requirements for the index river Högvadsån; and (2) parr abundance estimates from electric fishing surveys are compared to pre-smolt abundance requirements for non-index rivers. A lack of data on the numbers of adult returns in most rivers has necessitated the use of parr abundance estimates to evaluate compliance with conservation limits two years after the spawning run.<br>• Numbers of adult returns are estimated using count data from a fish trap for the index river Högvadsån.<br>• Parr densities from electric fishing surveys are used to estimate pre-smolt abundance as a proxy for smolt production.<br>• Egg deposition for the index river Högvadsån is calculated by multiplying the number of adult returns with mean weight (1SW: 2.7 kg and | Index river:<br>1) A ≤ 0.1 probability that the stock has fallen below its conservation limit in a given year. The stock is at full reproductive capacity. No further management actions required.<br>2) A 0.11–0.5 probability that the stock has fallen below its conservation limit in a given year. The stock is at risk of reduced reproductive capacity. Management actions required to improve stock status. Local river management units are responsible for implementing actions focusing on restoring juvenile rearing habitat, reducing hydropower-related mortality, and decreasing exploitation rates.<br>3) More than a 0.5 probability that the |

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| | | common resource. Numerous management measures have been implemented to maintain and enhance stocks including fishery closures, seasonal fishing restrictions and catch retention limits, the liming of acidified rivers, river restoration works and stock enhancement programmes to compensate for lost freshwater production due to hydropower schemes. | | MSW: 5.5 kg) and fecundity (1300 eggs per kg) estimates assuming a sex ratio of 50:50 males/females.<br>• An egg deposition requirement for the index river Högvadsån has been set at 4.5 eggs per $m^2$ of juvenile rearing habitat based on non-parametric bootstrapping of a Ricker stock-recruitment relationship to establish probability density functions.<br>• A pre-smolt abundance requirement for non-index rivers has been set at 10 parr per 100 $m^2$ based on Ricker stock-recruitment relationships between pre-smolt densities (1+ parr) for 8 undisturbed rivers and spawning biomass for the index river Högvadsån. | stock has fallen below its conservation limit in a given year. The stock is suffering reduced reproductive capacity. Management actions urgently required to promote stock growth. If local actions to restore juvenile rearing habitat, reduce hydropower-related mortality and decrease exploitation rates are insufficient to promote stock growth, new fishing rules are implemented in the compendium of regulations.<br><br>Non-index rivers:<br><br>1) Rivers with a mean parr abundance above 10 per 100 $m^2$ and the lower 5% of the 90% confidence interval around the mean above 10 in a given year are at full reproductive capacity. No further |

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| | Iceland – north/east regions | The Icelandic Salmonid Fisheries Act (2006) is the main regulatory framework for the management of wild Atlantic salmon stocks and fisheries. No biological reference points for Atlantic salmon have been stipulated in the Act. Directed fisheries for wild Atlantic salmon have been prohibited at sea since 1932 and in coastal waters since 1997. Commercial and recreational fisheries are only permitted in freshwater lakes and rivers. Fishery associations are responsible for the implementation of harvest plans for privately owned fisheries in rivers. | Temporal trends in annual catch numbers are used to infer stock status because fishing effort has remained relatively stable over the last 40 years. | • Stock status is assessed based on temporal trends in annual catch numbers. Juvenile abundance metrics (e.g. densities, survival rates, and smolt production) from electric fishing surveys and mark-recapture experiments are also used as indicators of stock status.<br>• Returns of wild and hatchery-reared adult salmon are estimated using count data from a fish counter for the index river Vesturdalsa or derived from rod catches raised by exploitation rates for non-index rivers.<br>• River-specific conservation limits are under development. Progress has been hindered by a lack of field-based measurements of wetted area. Conservation limits for all salmon producing rivers | None specified because there is no formal requirement to estimate compliance with conservation limits under the Icelandic Salmonid Fisheries Act (2006).<br><br>Temporal trends in annual catch numbers are evaluated and fishery associations subsequently implement harvest plans to ensure that spawning stock size is at the level required for sustainable exploitation. If harvests are deemed to be above safe biological limits, the Directorate of Fisheries can undertake management actions to improve stock status. |

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| | | Management measures to conserve and restore stocks have focused on fishing effort controls, daily and seasonal fishing restrictions and catch retention limits, catch-and-release of large MSW salmon (69 cm length or 4 kg weight), river restoration efforts and stock enhancement programmes. | | will be developed in the future by transferring stock-recruitment relationships from data-rich to data-poor rivers based on carrying capacity.<br>• Genetic stock identification estimates the proportion of wild and hatchery-reared salmon in the catches. | |
| **Southern NEAC** | Republic of Ireland | The Wild Salmon and Sea Trout Tagging Scheme Regulations are the main framework for the management of Atlantic salmon stocks and fisheries. They stipulate catchment-specific annual harvest restrictions in rivers exceeding their conservation limit. Accompanying legislation includes the Conservation of Salmon & Sea Trout Bye-laws, which specify the rivers closed to salmon fishing and restricted to catch-and-release-only fishing with further limits on | A 0.75 probability that the stock will meet its conservation limit in the following year. | • Stock status is assessed based on estimated adult returns for the forthcoming season compared to spawner requirements.<br>• Wetted area and accessible fluvial area are estimated using a predictive model including field-based measurements of river widths and GIS derived values for upstream catchment area and the Shreve river network drainage index.<br>• Catch weights are split into two size classes (< 4 kg and ≥ 4 kg) that represent 1SW and MSW fish or based on known run-timing (before and after 31st May). | 1) A 0.75 probability of meeting the conservation limit in the following year. Only rivers with a harvestable surplus above the conservation limit are open for exploitation. Harvests must not exceed the surplus above the conservation limit. Estuarine fisheries are only permitted if all rivers in the embayment have at least a 75% average probability of meeting their conservation limits simultaneously. |

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| | | permissible gears. Salmon fishing is only permitted in rivers and estuaries meeting their conservation limits. Mixed-stock coastal fisheries are prohibited. Several management measures have been implemented to conserve and restore salmon stocks including fishery closures, fishing effort controls, the setting of total allowable catches (TAC's), bag limits, catch-and-release-only fishing, river restoration efforts and stock enhancement programmes. | | • Numbers of adult returns are based on catches raised by exploitation rates or count data from fish counters/traps over the last 5 years.<br>• Egg deposition is calculated from the ratio of 1SW:MSW fish in the weight frequency distribution of rod catches and a relationship between weight and fecundity for wild stripped salmon.<br>• A Bayesian hierarchical stock and recruitment forecast analysis based on wetted area and latitude transported from a Ricker stock-recruitment analysis of index rivers estimates the egg deposition required to achieve MSY.<br>• Uncertainties in estimates of adult returns, fecundity, the egg deposition requirement, and the ratio of 1SW:MSW salmon are considered in the calculation of compliance estimates and the categorisation of the stock status of each river.<br>• An index of age-0+ abundance is used as an indicator of stock status in instances of data paucity, | 2) A 0.75 probability of meeting 50−100% of the conservation limit in the following year, or the river must exceed the minimum average fry threshold of at least 15 fry per five minute catchment-wide electric fishing survey. The river is open for catch-and-release-only angling.<br>3) A 0.75 probability of meeting less than 50% of the conservation limit in the following year or insufficient data to estimate stock status. The river is closed to salmon fishing until stock status improves or more information become available. |

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| | | | | where there is insufficient information to estimate stock size (e.g. in rivers closed to salmon fishing or without fish counters). | |
| | France | The National Strategy for Amphihaline Migratory Fish (2010) is the main regulatory framework for the management of wild Atlantic salmon stocks and fisheries. Accompanying legislation includes the Environmental Code, which incorporates successive environmental laws. Seven regional diadromous fish committees (comité de gestion des poissons migrateurs, CoGePoMi) are responsible for establishing management plans to conserve and restore stocks and their critical habitats. A range of management measures have been implemented including fishery closures, fishing effort controls, the setting of TACs and allocation of quotas, | A 1.0 probability that the stock will meet or exceed its conservation limit in a given year. | • Stock status is assessed based on estimated adult returns compared to egg deposition and spawner requirements. Juvenile abundance metrics (e.g. parr densities, survival rates and smolt production) from electric fishing surveys, trapping, and mark-recapture experiments are also used as indicators of stock status.<br>• Catches are reported by weight group considered to represent the sizes of 1SW and MSW salmon.<br>• Returns of wild adult salmon are estimated in a hierarchical Bayesian modelling framework based on count data from fish traps and redd surveys for index rivers, or derived from catches raised by exploitation rates for non-index rivers.<br>• Annual egg deposition is estimated from the number of adult returns and the | 1) Rivers with at least a 1.0 probability of meeting or exceeding their conservation limit in a given year are considered to be 'not threatened with loss'. The river is open to salmon fishing until the TAC is reached. No further management action is required.<br>2) Rivers with less than a 1.0 probability of meeting their conservation limit in a given year are 'threatened with loss'. Management actions are required to improve stock status and reduce exploitation.<br>3) Rivers that contain stocks managed through human intervention are regarded as 'maintained'. No additional |

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| | | seasonal fishing restrictions, river restoration efforts, and stock enhancement programmes. | | biological characteristics of the population (e.g. fecundity, sex ratio and size data).<br>• Conservation limits have been developed for all salmon producing rivers, except the River Adour. River-specific conservation limits specify the egg deposition required to maximise harvestable surplus.<br>• Egg deposition requirements are estimated in a Bayesian hierarchical modelling framework that transports stock-recruitment relationships for the index rivers Oir and Scorff to recipient rivers based on wetted area, maximum egg-smolt survival, and standardised carrying capacity (relative local parr abundance indices).<br>• Environmental variables influencing productivity and carrying capacity as well as uncertainty in estimates of fecundity and the egg deposition requirement are taken into account in the Bayesian hierarchical framework. | management actions are required.<br>4) Rivers in which the natural stock has been lost in the past but now contains a self-sustaining stock due to restoration efforts or natural recolonisation are classified as 'restored'.<br>5) Rivers that no longer contain a natural or maintained salmon stock are 'lost'. |

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| | | | | • Annual TACs for each river are calculated based on the harvestable surplus above the conservation limit. | |
| | Scotland | The Conservation of Salmon (Scotland) Regulations 2018 prohibit the retention of catches in coastal waters, permit the killing of salmon in inland waters for stocks with category 1 or 2 status, and require mandatory catch-and-release in areas where stocks have category 3 status. Annual updates to the regulations ensure that fisheries controls are tailored to the ever-changing needs of salmon stocks and fisheries. | A 0.8 probability that each river or group of rivers has met its conservation limit over the last five years. | • Rod catches are converted to numbers of adult returns using a correction factor accounting for seasonality, changes in river flow, and location (north/south component).<br>• Numbers of spawning females are estimated by combining numbers of adult returns with the percentage of females by age-class using sex ratio data.<br>• Egg deposition is calculated by combining numbers of spawning females with fecundity estimates.<br>• An egg deposition requirement for each river is calculated by multiplying estimates of the egg deposition required to achieve MSY and the wetted area.<br>• Uncertainties in estimates of egg deposition, the egg deposition requirement and wetted area are combined to calculate compliance estimates and categorise the | 1) More than an 0.8 probability of meeting the conservation limit over the last five years. Sustainable exploitation. No additional management action required.<br>2) A 0.6–0.8 probability of meeting the conservation limit over the last five years. Management action required to reduce exploitation. Mandatory catch-and-release not immediately required, but subject to annual review.<br>3) Less than a 0.6 probability of meeting the conservation limit over the last five years. Unsustainable exploitation. Management actions required to reduce exploitation for one |

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| | | | | stock status of each river or group of rivers. | year. Mandatory catch-and-release required. |
| | Northern Ireland | The Fisheries Act (Northern Ireland) 1966 is the main regulatory framework for the management of Atlantic salmon stocks and fisheries. Accompanying legislation includes the Fisheries Regulations (Northern Ireland) 2014, which prohibit commercial fishing and require mandatory catch-and-release in recreational fisheries without an identifiable surplus above the conservation limit in areas managed by the Department of Agriculture, Environment and Rural Affairs (DAERA) and the Loughs Agency of the Foyle and Carlingford catchments. Salmon fishing in the Foyle and Carlingford catchments is managed under the Foyle Fisheries Act (Northern Ireland) 1952. | The average escapement or spawning stock relative to the CL in 3 out of 5 of the previous years. Management measures reviewed and applied annually.<br><br>The average escapement or spawning stock relative to the CL in 3 out of 5 of the previous years. Management measures reviewed and applied annually. | • Numbers of adult returns are estimated from fish count data for the Rivers Bush and Bann, along with a scaling factor used to raise the counts for other rivers.<br>• Egg deposition estimates are derived from the weight frequency distribution of rod catches and a relationship between weight and fecundity for wild stripped salmon.<br>• Optimal productivity metrics from a stock–recruitment analysis for the River Bush are transported to measured habitat parameters for each recipient river to the estimate egg deposition required to achieve MSY.<br>• Uncertainty in assessment outputs has increased due to the very low number of retained salmon in catches. As a result, fish count data is now more informative about the number of adult returns than catches. | Commercial fishing:<br><br>1) Escapement should be at least 125% of the CL in three out of five of the most recent years for which data are available. Rivers with an identifiable surplus over the CL are open to commercial fishing<br>2) Less than 125% of the CL in three out of five of the most recent years for which data are available. Rivers closed to commercial fishing until stock status improves or more data become available.<br>Recreational fishing<br>1) Escapement should be at least 115% of the CL in 3 out of 5 years of the most recent years for which data are available.<br>Harvestable surplus |

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| | | | | | available for recreational fishing.<br>2) Less than 115% of the CL in 3 out of 5 years of the most recent years for which data are available. Recreational fishing restricted to mandatory catch-and-release until stock status improves or more data become available. |
| | England and Wales | The Salmon and Freshwater Fisheries Act (1975) and the Salmon Act (1986) provide the main regulatory frameworks for the management of wild Atlantic salmon stocks and fisheries. Most net and fixed engine fisheries are regulated by net limitation orders and byelaws. National spring salmon byelaws (1999) prohibit netsmen from exploiting salmon before 1 June and require mandatory catch-and-release in rod fisheries prior to 16 June. A policy | Stocks are assessed annually against a management objective that requires them to meet their conservation limit for four years out of five and allocated into one of four categories. The resulting categories inform management action based on a decision structure. Rivers that have a ≥ 0.95 probability of meeting the | • Stock status at the catchment scale is assessed based on estimated adult/spawner returns compared to river-specific conservation limits expressed in terms of eggs deposited. Juvenile abundance metrics (e.g. densities) from electric fishing surveys are used to assess stock status at a sub-catchment scale and identify limiting factors to inform local management.<br>• Net catches are reported in two weight classes (small <3.6 kg or large ≥3.6 kg) that are considered to represent the sizes of 1SW and MSW salmon, while the proportion | 1) A river that has a ≥ 0.95 probability of meeting its management objective five years into the future is considered to be ‘not at risk’ and no further management action is required. For rivers in this category, the possibility of relaxing fisheries controls will be considered if stakeholders agree and stock status can be protected.<br>2) A river that has a 0.5–0.94 probability of meeting its management objective |

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| | | to phase out mixed-stock fisheries in coastal waters has been in place since 1996, and a ban on the sale of rod-caught salmon together with a carcass tagging scheme for salmon retained in net fisheries was introduced in 2009. Numerous other management measures have been implemented to conserve and restore stocks including fishery closures, fishing effort controls, daily and seasonal fishing restrictions and catch retention limits, catch-and-release fishing, river restoration efforts and stock enhancement programmes. | management objective are considered to be 'not at risk'. | of 1SW and MSW salmon in rod catches is estimated using monthly age-weight keys for salmon caught in fish traps in the rivers Dee and Tamar and the reported weights of rod caught fish.<br>• Rivers with validated counters and/or traps provide 'direct' estimates of returning adult stocks. For most rivers, adult returns are derived from rod catches raised by extant exploitation rates obtained from rivers with fish counters and/or traps.<br>• Egg deposition is estimated from the number of adult returns and the biological characteristics of the population (e.g. fecundity, sex ratio, and weight data). Biological characteristics are based on samples from rod catch returns, except for rivers where samples are taken from trapping programmes. Fecundity is estimated using the size-fecundity relationship of Pope *et al*. (1961), applied to 1 lb size classes established from catch returns. Sex ratios are derived from a relationship | five years into the future is 'probably not at risk'. If the trend in adult returns is not stable and positive, management actions are required to reverse the decline in spawning escapement within five years.<br>3) A river that has a 0.05–0.49 probability of meeting its management objective five years into the future is classified as 'probably at risk'. Management actions are required to ensure sufficient spawning escapement to achieve more than a 0.5 probability of meeting the management objective within five years. If the river has a decreasing trend in adult returns, an annual catch of more than 20 salmon and a catch-and-release rate below 90%, then voluntary catch-and-release is promoted for 1 year. If this fails to |

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| | | | | between the percentage of females and catchment area for 1SW salmon and a mean of ~69% females for MSW salmon.<br>• Ricker Stock and recruitment (SR) relationships (egg-to-smolt) have been derived for all 64 principal salmon rivers based on map-based catchment characteristics and including SR parameters transported from the River Bush in Northern Ireland. These SR relationships along with smolt-to-adult return estimates have been used to obtain conservation limits at MSY for each river stock.<br>• Compliance with conservation limits is assessed using Bayesian 20-percentile regression with an autoregressive term, which is fitted to the latest 10-year time-series of egg deposition estimates and extrapolated 5-years into the future. This approach is designed to evaluate compliance with the management objective of meeting the conservation limit for four years out of five. | significantly improve catch-and-release rates, mandatory catch-and-release or closure of the fishery will be considered.<br>4) A river that has < 0.05 probability of meeting its management objective five years into the future is regarded as 'at risk'. Management actions are urgently required to reduce fisheries exploitation to zero. If a river has an annual catch of more than 20 salmon and a catch-and-release rate of less than 90%, then voluntary catch-and-release fishing will be promoted for 1 year. If this fails to significantly improve catch-and-release rates, mandatory catch-and-release fishing or closure of the fishery will be considered.<br>5) A river without a conservation limit (e.g. one that has been recovering from |

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| | | | | • A national fisheries classification scheme is used to group juvenile density estimates from electric fishing survey sites into one of six salmon abundance classes (A–F). The scheme compares fry and parr density scores from the last six years to average baseline scores from the early 1990s. Sites are classed as at or above average (A–C), below average (D) and well below average or fishless (E or F). The proportion of sites in each class provides an indication of juvenile recruitment.<br>• Standardised catch-per-unit-effort for net and rod fisheries is also used as a proxy of stock abundance. | historical degradation) is deemed to have < 0.05 probability of meeting the management objective, unless available information suggests otherwise. If there is potential for the river to have an annual average rod catch of 20 salmon, then mandatory catch-and-release fishing is considered throughout the season as an interim measure. However, controlled development of fisheries may be permitted on these rivers in parallel with the recovery of stocks. |
| | Iceland – south/west regions | Identical to the north/east regions of Iceland, described above. | An identical basis to the north/east regions of Iceland. | • Stock status is assessed based on temporal trends in annual catch numbers. Juvenile abundance metrics (e.g. densities, survival rates and smolt production) from electric fishing surveys and mark-recapture experiments are also used as indicators of stock status. | None specified because there is no formal requirement to estimate compliance with conservation limits under the Icelandic Salmonid Fisheries Act (2006). |

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| | | | | • Returns of wild and hatchery-reared adult salmon are estimated using count data from a fish counter for the index river Ellidaar or derived from rod catches raised by exploitation rates for non-index rivers.<br>• Conservation limits for all salmon producing rivers are under development. Progress has been hindered by a lack of field-based measurements of wetted area. A conservation limit was set at 3.5 eggs per $m^2$ of juvenile rearing habitat for the River Gljufurá in 2018. River-specific conservation limits will be established in the future by transferring stock-recruitment relationships from data-rich to data-poor rivers based on carrying capacity.<br>• Genetic stock identification estimates the proportion of wild and hatchery-reared salmon in the catches. | |

## 14.3 Annex 3: Proposals for future developments

There is recognition that the stock assessment process and the parameters used within it should be reviewed and updated periodically to take account of new data and methodologies. The review group have identified a number of areas that could potentially be developed further in the future. These 'proposals' have all been presented in the main document but are listed here again for ease of location.

**Proposal 1, Section 4.1**

*For all Principal Salmon Rivers, confirm the full extent of salmon access in each catchment, taking account of newly accessible areas arising from removal of barriers or improvements in water quality, using a nationally agreed, consistent, auditable and reproducible approach.*

**Proposal 2, Section 4.1**

*Consider the inclusion of on-line lakes in our estimates of juvenile salmon carrying capacity.*

**Proposal 3, Section 4.2**

*Examine time series of fry and parr densities in the more frequently monitored survey sites across all Principal Salmon Rivers to determine if 1990's densities were likely to represent truly maximum or pristine levels of juvenile production.*

**Proposal 4, Section 4.2**

*Evaluate juvenile survey data for Principal Salmon Rivers contained in the National Fish Population Database to understand and scrutinise levels of abundance over the last 20+ years with respect to potential carrying capacities.*

**Proposal 5, Section 4.3**

*Investigate whether there have been substantial changes in in-river survival of salmon fry and parr and in smoltification rates and assess whether these could have implications for estimation of biological reference points.*

**Proposal 6, Section 5.2.2**

*Fishery-dependent data on angler catches and effort should be reliable and representative and negate the need for correction factors. Furthermore, fishery-independent returning stock estimates should be available for more Principal Salmon Rivers in England and Wales. For the time being, however, options to better utilise online catch return data, including more direct application of the method of Small (1991) or related methods in generating national catch Correction Factors, should be further explored.*

**Proposal 7, Section 5.2.3**

*In future only use the published statutory national salmon and sea trout catch return statistics as the primary source of rod catch data for salmon fisheries management purposes in England and Wales.*

**Proposal 8, Section 5.2.3**

*A targeted survey of non-declaring anglers should be undertaken to better quantify the extent of, and understand the current reasons for, the non-declaration of catch returns. Results of such a survey would be used to help update and improve the catch return process.*

**Proposal 9, Section 5.3.1.1**

*Consider automating the optimisation procedures for calibrating the sea-age specific exploitation rate Correction Factors and coupling/embedding this with the exploitation rate model to generate sea-age specific exploitation rates by river.*

**Proposal 10, Section 5.3.2.4**

*If the method to estimate annual salmon rod exploitation rates presented in this review is used, as recommended (Recommendation 3), then it should be extended to provide one-sea-winter (1SW)- and multi-sea-winter (MSW)-specific exploitation rates (and associated uncertainties) directly as model outputs, rather than deriving them from post-treatment of the combined (posterior) estimate.*

**Proposal 11, Section 5.4**

*Research studies are required to better inform the derivation and application of recapture rates based on season, sea-age and river types. The method of calculating the annual egg deposition of the salmon stock should be re-structured to more accurately reflect and account for the frequency of recaptures.*

**Proposal 12, Section 5.5**

*In addition to assessing the percentage of repeat rod and line captures, there is a need to evaluate whether levels of natural mortality have also varied over time as a consequence of environmental change, disease risk and changes in predator distribution, all of which may have significant consequences for egg deposition and future smolt output.*

**Proposal 13, Section 5.6**

*Given that the Dee and Tamar trap length to weight keys are based upon fork length and not total length of measured salmon, it is necessary to increase awareness within the angling community of the need to assess captured fish weights based upon the fork length rather than total length, so as to maximise use of these data.*

**Proposal 14, Section 5.7.2**

*Future work should seek to identify a more objective basis, such as geographical or other grounds, for the application of separate age-weight keys and/or consider the merits/demerits of combining data from the rivers Dee and Tamar into one age-weight key. Consider developing an age-weight key using data from the River Frome index river, to apply to chalk stream salmon populations, subject to the availability of suitable data.*

**Proposal 15, Section 5.8**

*Undertake further genetic analysis to determine sex ratios by sea-age for the rivers Dee and Tamar to periodically update sex ratio estimates for all Principal Salmon Rivers. Consider including genetic samples from the River Frome Index River to update sex ratios for the chalk streams, subject to the availability and suitability of data.*

**Proposal 16, Section 5.9**

*Other sources of salmon size-fecundity data for England and Wales should be explored – including the possibility of obtaining contemporary data from the Kielder hatchery on the Tyne. Similarly, more sophisticated options for estimating fecundity (and its uncertainty) in English and Welsh rivers should be examined to incorporate influential (but widely available) covariates in addition to body size.*

**Proposal 17, Section 7.8**

*Salmon stock rebuilding plans based upon the North Atlantic Salmon Conservation Organisation (NASCO) stock rebuilding guidance should be developed for all rivers which fall into river grades 2 and 3. Recognising the value and strength of existing catchment partnership approaches to tackle issues at a catchment scale, the lead organisation for the development of a salmon stock rebuilding plan does not necessarily need to be a Governmental organisation.*

**Proposal 18, Section 7.11**

*Recognising that assessments of stock abundance based on fishery-dependent data sources (e.g. catches) have an inherent uncertainty (which may be increasing as an unintended consequence of catch-and-release), other information sources, especially fishery-independent, e.g., juvenile surveys, counter and trap data, should be used to support stock status assessments and management decision-making.*

**Proposal 19, Section 7.11**

*The means of communicating the process and results of annual stock status categories and river gradings needs to be reviewed and updated to reflect today's audiences and their methods of being informed.*

**Proposal 20, Section 7.11**

*Regulatory mechanisms should be developed to implement management actions more quickly than at present.*

**Proposal 21, Section 9.1.2**

*Continue supporting efforts to explore the use of advanced computing to automate the collection, storage, and analysis of data for salmon stock assessment.*

**Proposal 22, Section 9.2**

*Examine whether juvenile (fry and parr) density estimates from electric fishing surveys could be used as surrogates of smolt output in rivers where the annual numbers of downstream migrating smolts are not monitored. This would require exploratory analysis of the use of fry and parr density estimates from electric fishing surveys at the site scale to provide indices of juvenile production averaged across the catchment relative to benchmarked levels (carrying capacity) from a habitat model (e.g. HABSCORE).*

**Proposal 23, Section 9.3.1**

*Consideration should be given to the appointment of an independent scientific panel to work with the Environment Agency, Natural Resources Wales, and the Centre of Environment, Fisheries and Aquaculture (Cefas) to review the provisional annual national salmon stock assessments.*

**Proposal 24, Section 9.3.2**

*Improve the level of annual juvenile salmon monitoring on all Principal Salmon Rivers that are subject to annual salmon stock assessments. A juvenile salmon monitoring programme should be established on each principal salmon river based on best practice salmon monitoring guidelines to provide an annual index of juvenile salmon fry and parr recruitment. In addition, existing juvenile salmon electric fishing survey data collected by the Environment Agency and Natural Resources Wales should be combined, where possible, with comparable data obtained from third parties, e.g., Rivers Trust fisheries monitoring programmes, to ensure that the availability of data is maximised.*

**Proposal 25, Section 9.4.1**

*Explore the sensitivity of the national salmon stock assessment, including all its pragmatic decisions and simplifying assumptions, to trigger suitable management actions in response to changes in the underlying numbers of salmon.*