Evidence

Cumulative effects of hydropower schemes on fish migration and populations

Report – SC120078

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T: 03708 506506

Email: enquiries@environment-agency.gov.uk

Author(s):
Dr David Fraser, Simon Palmer & Dr Iain Stewart-Russon

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Research Contractor:
APEM Ltd, Centre for Innovation & Enterprise
Oxford University
Begbroke Science Park, Begbroke Hill
Woodstock Road
Begbroke, OX5 1PF
Tel: 01865 854 853

Environment Agency's Project Manager:
Stephanie Cole, Evidence Directorate

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Miranda Kavanagh

Director of Evidence

Executive summary

Guidance for run-of-river hydropower schemes in England is designed to minimise environmental impacts. This report describes an investigation into whether small impacts from single sites, compounded across multiple schemes within a catchment, cumulatively produce significant adverse impacts. We use salmon as an example to illustrate whether cumulative effects on migratory fish populations can be assessed and whether they are likely to occur.

The literature review indicated that multiple hydropower schemes have the potential to result in negative cumulative impacts but most of the available evidence is from much larger schemes in other countries not typical of schemes being developed in England. The literature does indicate the main aspects of hydropower schemes that may affect fish populations and these informed the development of a cumulative effects model. The model was applied to a test catchment, the River Coquet, to explore a range of hypothetical scenarios around the installation of hydropower schemes.

Critically, hydropower schemes, which include mitigating measures such as an associated fish pass, can have a positive, neutral or negative effect, depending on scheme design and location. Consequently, whether multiple schemes have cumulative effects, and whether such effects are negative, neutral or positive, depends on the net effects from each individual scheme, considered collectively across all schemes. Such an approach is necessarily sensitive to the accuracy with which individual site effects can be quantified.

To model cumulative effects, three model elements were used: (i) hydropower scheme impacts, (ii) spatial variations in the fish population and (iii) changes in the fish life-cycle. The hydropower scheme element identifies impacts of run-of-river hydropower schemes based on their importance in terms of migratory fish, and the likelihood of being able to quantify them. Impacts included were:

- impediment to upstream and downstream migration from the scheme;
- alleviation of upstream and downstream migratory impediment with fish passage solutions;
- mortality through impingement or entrainment of fish on scheme intakes and through contact with turbines;
- an option to include freshwater habitat loss as a result of the scheme (via any depleted on inaccessible reach).

A range of sources were used to attribute values to model components. These included available guidance, literature and scientific judgement. The spatial population model element, developed using salmon as a demonstration species, uses the Environment Agency’s Detailed River Network, combined with generic, scientifically accepted juvenile salmon population values. The scheme effects element, reflecting hypothetical hydropower schemes, was then applied to the spatial population element. This enabled the salmon population upstream of the scheme, and (via the life-cycle model element) returning adults requiring passage past the scheme, to be quantified, and benefits and dis-benefits from the schemes to be applied to the population. Some factors that may be important but will be highly site specific (e.g. increased predation) or changes in flow apportionment between a turbine and a fish pass can be added if required but were not used in this study. The sequential evaluation of multiple schemes in this way allowed assessment of cumulative effects. Overall effects were quantified as the change in the numbers of returning adult salmon.

Within the River Coquet test catchment a theoretical maximum population of salmon was defined; this took no account of other pressures that might be operating within the catchment. The aim of the work was specifically to address impacts from hydropower. A range of scenarios considered the impacts of installing between one and six hydropower schemes; these are realistic but hypothetical situations designed to test the model. We show that the impact of each scheme and the cumulative effects of several schemes could be either positive or negative, with impacts on the number of returning adult fish ranging from +18% to -12% for the range of scenarios tested. The scenario testing assumed that values for upstream passage from new mitigation measures such as fish passes would meet Environment Agency guidance, which aims for greater than 90% efficiencies. Whether such efficiencies are achieved in practice may depend on site-specific conditions and design implementation. We included a scenario to illustrate the effect of a scheme operating below best practice passage efficiency levels.

Impacts are highly dependent on the pre-scheme passability of existing barriers and any benefit achieved by mitigating measures such as improved fish passage. Other significant factors include the location of schemes and the amount of potential upstream habitat affected. In this analysis schemes located in the upper catchment have less potential for negative impacts, but in the case of the test scenarios a large improvement in fish passage at an existing barrier in the lower catchment created very significant improvements that more than compensated for some negative scheme impacts upstream. Such improvements could also be made without the installation of hydropower and the model facilitates evaluation of such options. The status of catchment populations would also influence the resulting impacts of schemes on salmon populations.

The model was developed based on the biological values used for deriving salmon conservation limits and, thus, is scientifically robust, familiar to fisheries practitioners, and transferable (in principle) to other migratory species and rivers. However, a significant advantage is that, unlike conventional conservation limits, which are essentially static and do not allow spatial interrogation, the GIS format of the current spatial model enables the number of migrants at any point of the catchment (and hence subject to the effects of individual schemes) to be quantified.

The model developed during this project enables predictions of the cumulative effects of hypothetical, planned or actual hydropower schemes by employing generically available data. However, such data sources (most notably the effects of barriers pre-scheme and with-scheme) do potentially introduce significant model uncertainty and error. This highlights the benefits of undertaking bespoke barrier passability assessment, or capitalising on local knowledge of the catchment and barriers, in assigning model input values (as was done in this study). The model is flexible and can be updated with more accurate parameter values if available and site-specific information can be used to override the default model values.

The model enables the impact of individual, multiple, actual or hypothetical, schemes to be illustrated including the effects of different options at sites. Thus, potential for catchment-scale cumulative effects can be forecast, which may assist with strategic planning around hydropower. The model is inherently amenable to the evaluation of non-hydropower scheme related impacts and improvement measures, which might be extant or planned in catchment restoration initiatives. The model framework could be used to predict benefits of different management measures in terms of numbers of migratory fish gained, and thus provides a basis for objective cost–benefit-based management decisions, and evaluation of hydropower scheme related effects, in the context of wider catchment impact and improvement measures.

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1 Introduction

The European Renewable Energy Directive (2009/28/EC) (the RED) set out mandatory targets for Member States to meet 20% of total energy consumption from renewable sources by 2020. The Directive also advocates measures to support small renewable schemes through direct price initiatives such as feed-in tariffs. The number of hydropower schemes licensed by the Environment Agency increased following the introduction of the feed-in tariffs in 2009, and is currently in the region of 40 new schemes each year, not all of which are subsequently developed (Stephen Oates, Environment Agency, personal communication); 313 schemes were permitted between 1966 and 2013. Responsibility for assessment of potential impacts of schemes resides with Member States, but the RED does state 'the coherence between the objectives of this RE Directive and the Community's other environmental legislation should be ensured'. Therefore, in licensing hydropower schemes, the Environment Agency has a duty to comply with existing European legislation such as the Habitats Directive (92/43/EC), the Water Framework Directive (WFD) (2000/60/EC) and the Eel Regulation (1100/2007/EC), each of which is embedded in domestic legislation.

Within the freshwater environment the effect of hydropower on diadromous fish, such as salmonids and eels, is envisaged to be one of the more important issues, due to their requirement for unhindered connectivity within a watercourse to complete their life-cycle. The potential effects of run-of-river hydropower schemes in inhibiting connectivity are well documented, with a thorough review of these effects recently produced by Robson *et al*. (2011). In recognition of these effects, the Environment Agency has produced guidelines for hydropower scheme developers to protect fish populations (Environment Agency 2013 [first published in 2009, subsequently updated in 2012, and then in December 2013]), and it is recognised that if such guidelines are followed, individual hydropower schemes are considered to have significantly reduced potential for adverse impacts (Robson *et al*. 2011).

Hydropower schemes are regulated on a scheme-by-scheme basis. However, as the number of hydropower schemes within a catchment increases, there is a greater chance that residual effects may cumulatively become significant to fish populations. This may result from effects which are either (a) recognised at the consenting stage but deemed to be acceptably small (or negligible) for individual schemes; or (b) assumed at the consenting stage to have been fully mitigated for, whereas, in practice, small residual adverse effects remain. This risk has been identified in several studies, and is summarised in the WFD114 SNIFFER report (Robson *et al*. 2011). Such cumulative effects are increasingly regarded as requiring assessment in light of the current scale of prospective hydropower developments being proposed across the UK. This project will explore cumulative impact that might occur as a result of an accumulation of residual site impacts (a). Whether small residual effects remain after consenting (b) can only be investigated from monitoring environmental impacts.

For the purpose of this study, the term hydropower 'scheme' is considered to include the turbine, housing and associated mitigation measures, including appropriate screening and fish passage facilities for upstream and downstream movement. It assumes that the scheme will be situated on an existing head loss creating structure (e.g. a weir or an existing mill leat). This approach is supported by current trends in hydropower applications, and reflects Environment Agency guidance (which generally excludes the creation of new barriers). Between 2009 and 2013, the Environment Agency permitted 150 new hydropower schemes in England; of these 31% utilised former mill leats and 44% were located on or adjacent to an existing weir. Twenty four percent were classified as high head schemes (Stephen Oates, Environment Agency, personal communication).

It should be noted that the scheme effects are distinguished from the effects of the existing barrier, in accordance with the range of current regulation and management objectives that makes the construction of new barriers within watercourses unlikely in most locations. A key point of consideration for this study was whether the barrier should be included as part of the hydropower scheme effect in the event that the scheme prevents the removal of such a structure for a number of decades. It was determined by the project steering group that for the evaluation of hydropower effects on fish populations the presence of existing barriers should be considered separately to a scheme (Harriet Orr, Environment Agency, personal communication). This therefore excludes the potential, or ongoing effects, of legacy activities on fish populations, which was considered outside the scope of this project. In effect the impact of existing barriers is quantified in the model by determining a pre-scheme passability to any existing barrier. The impact of any subsequent scheme is evaluated separately; this also allows the impact of any new fish passage easement to be quantified.

The purpose of this project is to evaluate whether cumulative impacts from hydropower schemes can be detected and to inform future discussions on how and when to manage the potential for cumulative effects from hydropower developments. This work considers both potential benefits and dis-benefits resulting from the introduction of hydropower schemes, and whether it is appropriate to manage hydropower schemes independently of other activities that give rise to similar pressures within catchments.

1.1 Project aims

This project aims to:

- Identify the types of effects associated with run-of-river hydropower scheme developments that have the potential to affect migratory fish on a cumulative basis at a catchment level in England.
- Develop a methodology and tool to assess the cumulative effects of hydropower schemes.
- Apply the methodology and tool to identify to what extent the effects of individual hydropower schemes act cumulatively on fish populations.
- Identify whether hydropower scheme effects should be considered in isolation or in combination with other pressures affecting migratory fish.

This report is structured in the following way:

Section 2 provides a summary of the findings of a literature review concerning hydropower scheme effects and their potential to act cumulatively.

Section 3 summarises the conceptual development of a model to determine the magnitude of effect of hydropower schemes, which was undertaken as a key part of this project.

Section 4 provides a detailed technical summary of how the model operates.

Section 5 illustrates the model via running a number of scenarios, which show the effects of multiple hydropower schemes on a catchment.

Section 6 provides the conclusions of the project, including the strengths and limitations of the model, and recommends areas for further work.

2 Potential effects of hydropower schemes on fish

2.1 Summary of scheme effects

Sources of information reviewed to identify potential effects of hydropower schemes on fish included: (i) the recent review of the potential effects of individual run-of-river hydropower schemes undertaken by Robson *et al*. (2011); (ii) peer-reviewed and grey literature (reviewed directly by APEM for this project); and (iii) literature supplied directly to APEM by Environment Agency project steering group members. Based on these information sources it is evident that the majority of research concerning the effects of hydropower schemes on fish concern large schemes, which are not directly applicable to the situation in England. For example, Robson *et al*. (2011) state ‘findings and conclusions [*of their report*], drawn from the primary and grey literature, relate mostly to larger impoundment schemes but also small-scale schemes elsewhere in the world; nevertheless the potential impacts largely remain the same, irrespective of the scale of the scheme’.

To avoid replicating previous comprehensive reviews on this subject (i.e. Robson *et al*. 2011), this section provides an overview of the **main** effects of hydropower schemes that can be accounted for in the cumulative effects model development. These effects are summarised in Table 2.1. This list is not exhaustive but considers the key effects brought out in the literature.

Table 2.1 Summary of the potential effects of hydropower schemes on fish

Effect type	Broad effect category	Specific effect	Addressed in Environment Agency guidance (Environment Agency 2013)
Negative	Losses via mechanical damage (on downstream migrants)	a) Entrainment b) Impingement	✓
	Reduced upstream and downstream migratory ability (on all migratory life-stages)	a) Impediment of migration in depleted reach (where present) due to modified flow b) Migratory interference from attraction to tailrace c) Reduced ability to ascend or descend the existing weir, fish pass or bypass, increased predation	✓
	Reduction in extent or quality of habitat for freshwater resident life-stages	a) Habitat fragmentation (with new impoundment) b) Impounded upstream reach (with new impoundment) c) Increased deposition of suspended sediment in depleted reach (with raised or new impoundment) d) Increased deposition of suspended sediment upstream of existing impoundment due to reduced flows e) Reduced sediment transport affecting downstream (with new impoundment) f) Reduction in available habitat via reduced wetted perimeter (useable habitat) in depleted reach g) Reduced habitat complexity	✓

Effect type	Broad effect category	Specific effect	Addressed in Environment Agency guidance (Environment Agency 2013)
Positive	Improved passage at existing impoundment (for upstream migrants)	a) Fish pass or fish passage measures installed or improved on anthropogenic barrier	✓

For the purposes of the development of a model to assess cumulative effects, it is assumed that all new schemes will adhere to Environment Agency good practice; however, an allowance for schemes that deviate from good practice is important to account for older (existing) schemes that predate the hydropower development guidance (Environment Agency 2013), such that their existing effects can be accounted for in the model. Furthermore, it is acknowledged that even when the guidelines are applied, a residual but small impact may remain that could become significant when considered cumulatively, hence the requirement for this project.

2.1.1 Negative effects

Impediment to migration

In England, hydropower schemes are generally proposed and installed where anthropogenic impoundments are already in place (or adjacent to large natural drops such as waterfalls). Where an anthropogenic barrier to fish migration already exists, the ideal environmental solution is generally removal of the structure, and this is the first option considered by the Environment Agency when mitigating for migratory barriers (Graeme Peirson, Environment Agency, personal communication; Environment Agency 2003, 2013). However, in many situations the existing barrier cannot be removed due to its continued function (e.g. water level control, morphological stability, abstraction for water supply, historic importance or integrity with other built structures). The costs of weir removal may also limit removal in some situations.

Barriers cause an impediment to migration that can potentially disrupt the life-cycle of many fish species by hindering access between key spawning, residential, feeding and refuge habitats (e.g. McDowall 1992, Lucas and Baras 2001, Amoros and Bornette 2002, Cote *et al*. 2009, Kemp and O’Hanley 2010). Such fragmentation can result in significant delays to migrations (Larinier 2002) or, dependent on the size of the impoundment, prevent access to suitable habitat, ultimately reducing the size of a population. Even small, low head structures can significantly impact passage success of both upstream and downstream migrating fish (Gauld *et al*. 2013). However, as noted earlier, hydropower schemes will typically be established on existing barriers, and thus, the focus of this impact assessment is on aspects of the scheme that render the existing barrier or river less passable (although this takes no account of scenarios where weirs may become redundant over time, be removed or decay). These include:

- Reduced flows over an existing weir (see Gauld *et al*. 2013; for salmon smolts) due to greater flow through the turbine (primarily low head schemes).
- Reduced flows within the depleted reach (primarily high head or mill leat schemes).
- An attraction to the tailrace of a scheme and away from the primary passage route (see Lundqvist *et al*. 2008; for adult salmon).

Each of these points is considered in greater detail below.

Reduced flow over an existing weir can hinder fish passage by, for example, providing insufficient water depth for passage. These effects may be felt at all stages of the hydrograph but it is likely that the effect of reduced flows will be of greater significance during low flow conditions, where abstraction will lead to a higher proportionate impact, compared to periods of high flow. Therefore, the level of effect will vary dependent on the species and life-stage in question, with the most significant negative effects occurring on fish migrating during summer low flows, whereas during high flows the effects may be neutral.

Hydropower schemes may reduce the natural heterogeneous flow regime within a watercourse, delaying or preventing fish movement (e.g. Malcolm *et al*. 2012, Milner *et al*. 2012, Newson *et al*. 2012, Birkel *et al*. 2014). For example, peak migrations of smolt (young fish preparing to go out to sea) and adult salmon (Baxter 1961, McCormick *et al.* 1998, Tetzlaff *et al.* 2008, Enders *et al.* 2009 a and b, Bradley *et al.* 2012) and eel (Tesch 2003, Acou *et al.* 2009) are typically triggered by spate conditions. Therefore, variation in the natural flow regime can significantly reduce the triggers for migration (Rosenberg *et al.* 1997), delaying, or completely inhibiting it, effectively reducing access to suitable habitat. Accordingly, it is important to manage flows in the depleted reach to mimic the natural flow regime of the watercourse (Environment Agency 2013), which has further advantages such as maintaining sediment mobility and geomorphic processes (Poff *et al.* 1997, Milner *et al.* 2010, APEM 2013).

Hydropower schemes may adversely affect fish passage due to variation in hydraulic conditions within the immediate vicinity of the scheme. If, for example, a localised concentration of high velocity flow is present at the tailrace of a scheme, upstream moving fish may be attracted to the higher velocity water exiting the non-passable tailrace (SEPA 2010), rather than the main migration route (e.g. main channel or fish pass). Indeed, significant delays to fish migration can occur in the absence of a large physical structure due to changes in water depth, velocity and variation in discharge caused by in-river anthropogenic activities. For example, Kemp *et al*. (2005, 2008a) observed that under controlled conditions in a flume, downstream migrating Pacific salmonid smolts avoided accelerating flow, with similar results being observed for brown trout (*Salmo trutta*) (Russon and Kemp (2011). In addition, reduced flow down a fish pass on a weir where a hydropower scheme is installed may reduce attraction towards the fish pass, causing delay (e.g. Kibel and Coe 2011).

Delay in migration can cause a number of issues for fish populations, including preventing migratory species reaching spawning grounds at the correct time (Jungwirth 1996). For some species (e.g. salmonid smolts) there is an optimal period for acclimation to sea water, which if missed could significantly adversely affect fish survival and growth (Karppinen *et al.* 2014). If delayed for significant periods, some salmonid smolts may de-smolt, remaining in freshwater and adversely affecting their growth and survival (Jonsson and Jonsson 2011).

Delayed migration may also cause an accumulation of fish immediately upstream (e.g. silver eels) and/or downstream (e.g. elvers) of a structure. This delay could result in elevated predation pressure and increased susceptibility to disease (Scruton *et al.* 2008). Additionally, delay may lead to increased energy expenditure (Osbourne 1961), causing a reduction in reproductive capacity of fish (Geen 1975) or even resulting in fish possessing insufficient energy to reach the spawning grounds, ultimately impacting recruitment success (Schlosser 1991, Deegan 1993).

Variation from the natural hydrodynamics of the watercourse

Hydropower schemes both impound and abstract/divert water from a river, and thus there are many potential ways they can affect the natural hydrodynamics of the watercourse (e.g. vary water depth, velocity and annual flow regime). Many run-of-river schemes will deposit water almost immediately downstream of the scheme, and they will therefore have relatively little effect and most effects will be localised. For high head and mill leat hydropower schemes, there is potential for the creation of an extensive depleted reach where a percentage of river flow is diverted from the main channel, through a bypass, which supplies flow to the hydropower turbines. Where water is diverted from the main river channel, the reach from the upstream diversion point to its downstream re-connection will have a depleted flow, which may change the suitability of habitat in the reach to freshwater life-stages. (Note: this is distinct from migratory effects; covered in the previous subsection).

Robson *et al*. (2011) identified a number of key effects that variation in flow regime caused by run-of-river hydropower schemes can have on fish. These include:

- Reduction in the wetted perimeter of the channel, thus decreasing the quantity of suitable habitat for residential life-stages (e.g. salmon fry and parr, yellow phase eels and lamprey ammocoetes), ultimately reducing the productivity of the reach (Kubecka *et al.* 1997).
- An increased propensity for any suspended fine sediment present to deposit within the depleted reach. Sedimentation can reduce the suitability of spawning habitat; for example, salmonids require clean, well-oxygenated gravel substrate to lay eggs in, sedimentation of which can increase egg mortality (Barlaup *et al.* 1994).
- A reduction in the complex array of habitats (e.g. pools, riffles and backwaters) often required to support a healthy fish community (Bisson *et al.* 1992), which may be lost in the depleted reach, further reducing the availability of suitable habitat.
- Where an anthropogenic structure is already installed in a river and the weir pool formed downstream provides habitat for lithophilic coarse species as well as salmonids. Although an originally unnatural situation, weir pools may be the only hydro-morphologically diverse habitat in rivers where extensive impounded reaches occur, and such a change could impact on the achievement of legislative targets such as the WFD’s target of Good Ecological Status (Robson *et al.* 2011). Alteration to these hydraulic conditions due to the installation of a hydropower scheme on the weir could adversely affect these unnaturally formed but potentially productive habitats, perhaps leading to a poorer fish community in the weir pool. Evidence for such impacts is currently limited and the subject of ongoing study (Environment Agency project on weir pool habitats).
- Where a new impoundment is created as part of a hydropower scheme. In such cases the impounding effect upstream of the weir may reduce habitat suitability for some species (e.g. by changing depth and flow velocity, which may alter substrate composition via the increased propensity for deposition of fine sediment, and/or prevent downstream sediment transport leading to a paucity of suitable spawning habitat).

Mechanical damage

Mechanical damage due to hydropower schemes can take two forms:

- **Entrainment:** Defined as ‘the drawing in of fish of any life stage at a water intake’ (Turnpenny and O’Keeffe 2005), in the case of hydropower schemes this entails passage through the turbine.
- **Impingement:** Defined as ‘the accidental pinning of fish onto the surface of a screen by the water current’ (Turnpenny and O’Keeffe 2005).

Entrainment through hydropower turbines with no protection measures can be a major source of mortality for downstream migrating life-stages of fish (e.g. salmon smolts, silver eels, and lamprey transformers; see Anderson 1988, Cada *et al.* 2006, Winter *et al.* 2006, 2007) dependent on the type of scheme installed (e.g. Kaplan turbines are less fish friendly than Archimedes screws). Turbine-induced mortality can be due to blade strike from moving parts, and sudden changes in pressure, cavitation and velocity (Larinier 2008). Mortality and survival rates through various hydropower schemes have been measured, but are highly variable (see Table 2 in Robson *et al*. [2011] which cites mortality rates ranging from 5 to 90% for passage through Francis turbines, and Ferguson *et al*. [2006] which cites delayed mortality after turbine passage to comprise approximately 46–70% of total fish mortality due to sub-lethal impacts to fish sensory systems). Such variation in measured mortality rates makes assigning accurate values to a given turbine type difficult.

Screening facilities are often used to prevent entrainment of downstream migrants through hydropower schemes, although poorly designed facilities can lead to significant delay, and high mortality rates due to fish being impinged (Russon *et al.* 2010). Impingement mortality is likely to be species and size dependent; smaller fish with weaker swimming ability may be particularly susceptible but larger silver eels are more likely to be impinged than salmon smolts (Calles *et al.* 2010). Telemetry studies undertaken by Calles *et al*. (2010) observed 18% of European eel (*Anguilla anguilla*) approaches to a bar rack at a hydropower scheme on the River Ätran (Sweden) resulted in impingement, with 100% mortality. Smaller individuals managed to pass through the rack, but subsequently 44% of these died via turbine entrainment.

There is also a behavioural element meaning that some species are more susceptible to impingement and entrainment than others. For example, European eel tend to be thigmotactic (i.e. preferring to inhabit channel bed and margins), and demonstrate little or no response to changes in velocity, only reacting to the presence of a screen or other obstructions once contact has been made (Russon *et al.* 2010, Russon and Kemp 2011). In contrast, brown trout tend to respond to changes in velocity gradients, and thus avoid contact with physical structures (e.g. Enders *et al.* 2009 a and b, Russon and Kemp 2011). These differing behavioural characteristics could result in eels being relatively susceptible to impingement compared to salmonids, as it will be too late for eels to escape once they have contacted the screen.

It is important to note that the Environment Agency requires screening of the turbine intake (dependent on turbine type) to prevent entrainment (Environment Agency 2013). Such screening should conform to the Environment Agency screening good practice guidelines (Turnpenny and O’Keeffe 2005), and therefore the risk to fish from entrainment and impingement should be minimal for any given scheme. However, best practice screening is unlikely to prevent entrainment or impingement entirely, meaning that some degree of fish mortality is likely, compared to a situation with no hydropower scheme (Graeme Storey, Environment Agency, personal communication). Screening efficiencies are a subject of an ongoing Environment Agency study, the results of which will aid in assessing the effects of hydropower schemes on fish.

2.1.2 Positive effects

Mitigation via improved fish passage

A number of legislative drivers exist requiring the protection of migratory fish throughout the watercourse. Consequently, the Environment Agency guidance for run-of-river hydropower development (Environment Agency 2013) requires a newly constructed or altered dam to include a fish pass, or that any existing fish pass is modified to ensure fish passage is not made worse by the scheme. In each case, the fish passage improvements must fulfil the requirements of the legislation (e.g. the Salmon and Freshwater Fisheries Act [SAFFA] and the Eel Regulations, in the event that migratory salmonids and eels are present). Therefore, if constructed correctly (meeting Environment Agency guidance and technical standards), the installation of a fish pass at a structure, coinciding with the installation of a hydropower scheme, should maintain or improve the ability of fish to pass the structure.

The potential magnitude of the benefits will depend on the current passability/impassability of the structure and the effectiveness and efficiency of any existing fish pass. For the purposes of this report, passage efficiency is defined as ‘the proportion of upstream or downstream migrants approaching a structure that are able to pass without significant delay’. Barriers may have an existing fish pass on them, in which case scope for benefits from a new fish pass will be reduced (compared to a scenario where no fish pass was originally present), although this will in turn depend entirely on the efficiency of the existing fish pass concerned (e.g. many older fish passes have relatively poor performance, and may be suitable only for certain species). Where a fish pass does exist, unless a hydropower scheme outfall is co-located with it, it could draw fish away from the pass. The Environment Agency requires that all new fish passes it consents must meet good practice guidance and the technical standards outlined in this guidance aim to deliver an efficiency of at least 90–95% (J. Gregory, Environment Agency, personal communication). Where such efficiencies are actually achieved may be variable. Equally the benefits from improved fish passage can be achieved without the introduction of a hydropower scheme.

2.2 Multiple scheme cumulative effects

Having established that a range of positive and negative effects potentially arise as a result of individual hydropower schemes, the next question is whether and how these effects interact across multiple schemes to create cumulative effects.

The cumulative effects of a number of hydropower schemes, and more general migratory barriers, within a watercourse have been demonstrated for a variety of diadromous fish species and taxa including Pacific lamprey (*Lampetra tridentate*)(Moser *et al.* 2002), River lamprey (*L. Fluviatilis*) (Lucas *et al.* 2009), Chinook salmon, (*Oncorhynchus tshawytscha*) and steelhead (*O. Mykiss*) (Williams *et al.* 2001), and Atlantic salmon (*Salmo salar*) (Chanseau *et al.* 1999, Gowans *et al.* 2003, Larinier 2008). These and other examples are discussed further in Appendix A of this report.

The examples cited above relate primarily to large hydropower schemes, as the literature was deficient in studies seeking to address cumulative effects arising as a result of multiple schemes of the scale being developed in England. However, as stated earlier, Robson *et al*. (2011) conclude ‘… potential impacts largely remain the same, irrespective of the scale of the scheme’. Based on scientific reasoning, we conclude that for hydropower schemes of the scale and type being proposed in England, any effects from single schemes, multiplied across many schemes, must result in effects which are a cumulative result of those individual schemes.

Cumulative effects can be classified as:

- **Antagonistic**: The overall impact of multiple effects is less than the sum of their separate effects (e.g. two hydropower schemes on a catchment each cause 5% fish mortality but the combined effect is only 6%).
- **Additive:** Where the sum of multiple effects is equal to the sum of the functional values of each effect (e.g. two hydropower schemes on a catchment each cause 5% fish mortality and the combined effect is 10%, or one scheme causes 5% mortality, the other 5% population rise, and the combined effect is 0%).
- **Synergistic**: The overall effect of multiple effects is greater than the sum of their separate effects (e.g. two hydropower schemes on a catchment each cause 5% fish mortality, but the combined effect is 20%).

Again, scientific reasoning leads to the conclusion that multiple hydropower scheme effects are additive, and this is the approach taken in recent work such as Bracken and Lucas (2013), when describing the potential for cumulative effects of small-scale schemes. This reasoning of effects being additive is made throughout this project.

Based on the conclusion that cumulative effects of hydropower schemes are additive, Figure 2.1 demonstrates how various scheme passage rates (SPRs) applied across multiple schemes affect the population within a catchment. (SPR is the percentage of the population that survives migration past a particular scheme.) At an SPR of 99% (i.e. a 1% mortality rate) per individual scheme, and assuming mortality rate remains constant at each scheme, ten hydropower schemes could be installed on a catchment before reducing the effective population by 10%, whereas only two hydropower schemes could be installed if they had a 95% SPR.

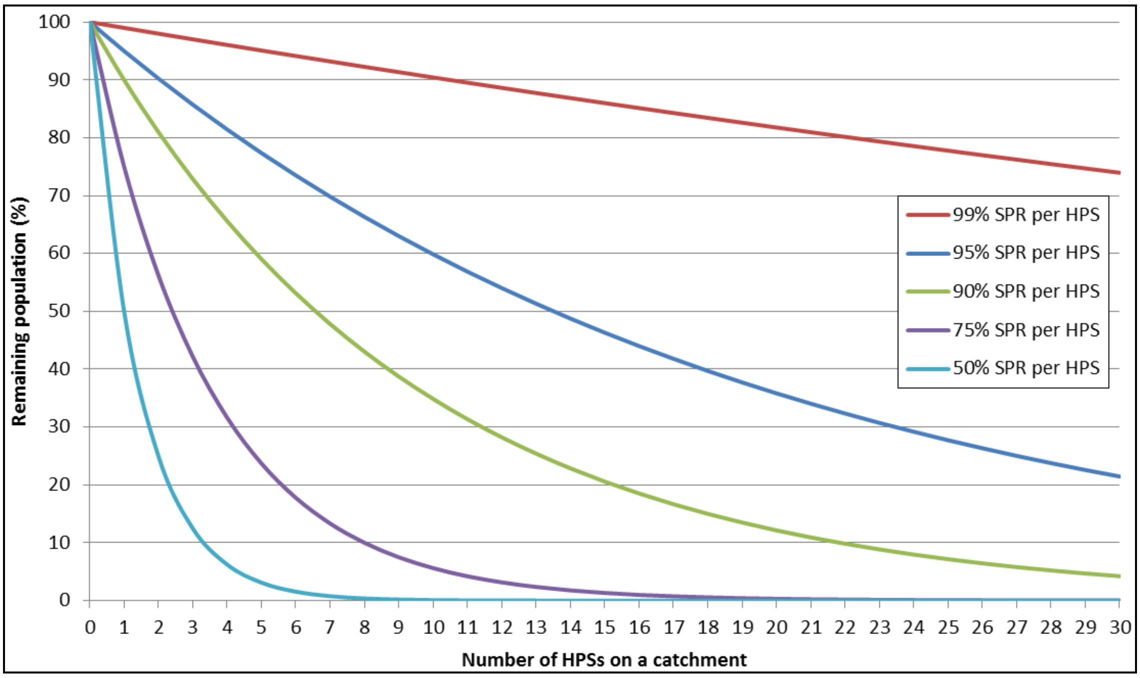

Figure 2.1 Cumulative effects of multiple hydropower schemes on a theoretical fish population, based on scheme passage rates (SPRs)

2.2.1 Population response to cumulative effects

A critical consideration closely allied to but distinct from the manner in which effects from single schemes manifest cumulative effects (i.e. antagonistic, additive or synergistic) is how these effects are reflected in changes to the fish population in question. For example, some species are known to exhibit density dependent survival, in which case, although the mechanism of impact increases additively, the population may respond to linear effects in a non-linear (i.e. non-additive) way. Thus, if we imagine an abundant population, exceeding the carrying capacity of its environment (catchment), loss of individuals that does not result in the population falling below its carrying capacity will have no effect on subsequent generations of that species. In other words, compensatory survival mechanisms will operate. However, further losses, which do result in the population declining below its carrying capacity, may result in a declining population size in the next generation. Thus, for some species it is the status of the population which determines the linearity, or otherwise, of the response to hydropower scheme effects. This highlights the value of possessing a good understanding of population dynamics of the species in question (i.e. the stock–recruitment relationship and knowledge of current stock status/size) when considering cumulative effects on fish populations. This principle will be considered further in section 3.

3 Model development

The development of the model was informed via a review of the literature (section 2) and discussions with the Environment Agency steering group members. During this process it was determined that three model elements would be required to assess the effects of hydropower schemes on fish populations:

- Hydropower single scheme effects assessment model
- Spatial population model
- Life-cycle model.

This section provides a summary of the model development. Further detail of the model assumptions and input data can be found in Appendices B–D.

3.1 Scheme effects assessment element

While it is recognised that all the effects identified in section 2 are potentially of concern in relation to migratory fish, for the purposes of deriving a practical, cumulative effects model for this project, the objective was to identify a manageable number of effects, particularly focusing on those of most importance to migratory fish. The mechanisms identified for incorporation into the scheme effects element were:

- Impingement and entrainment.
- Impediment to upstream and downstream migration:
    - at the barrier, where a barrier is present, albeit only related to the additional impediment caused by the scheme (e.g. flow modification over the barrier, rather than the pre-existing barrier per se);
    - in the depleted reach, where one is present.
- Alleviation of migratory impediment resulting from scheme-associated fish passage measures.
- Population loss of freshwater resident stages as a result of reduced extent and quality of habitat in a depleted reach (where present).

Each of these mechanisms is considered further in the following sections.

It is important to consider that the impact of delay to migration (see the first part of section 2.1.1) from any of the scheme effects elements is not specifically considered in the model. Delay is incorporated via the overall passability score; for example, the WFD111 methodology (see section 3.2.1) incorporated into the model provides a score based on both instantaneous passability and related to the likely effects of delays to migration (see Table D1 in Appendix D).

3.1.1 Mortality and delay from impingement and entrainment

Based on the available literature it is apparent that a general mortality figure cannot be applied to a specific screen type. Instead, it is dependent on the species, life-stage, screen design and turbine type. For existing sites, the quantification of impingement risk is therefore required to be species and site specific, with a detailed knowledge of site layout, flow distribution and bar spacing. However, for the purpose of the model, it is assumed that screen efficacy rates would be relatively high (between 95 and 99%;

Environment Agency steering group, personal communication) where screening installed at a hydropower scheme accords with Environment Agency best practice documents (including maintenance of the structure; e.g. see Turnpenny and O'Keeffe 2005).

3.1.2 Impediment to upstream and downstream migration

Where the approach to quantifying the effects of any existing barriers is outlined in section 3.2.1, 'impediment to upstream and downstream migration' as defined in this section, relates to additional migratory impediment resulting from the scheme (excluding the effects of any fish pass or fish passage measures). This is likely to include changes in flow over the structure or in the river (the depleted reach), and interference in migration due to turbine outflow (tailrace). For the purpose of the model, these effects are incorporated into a single upstream and downstream passability score which includes the effects of the barrier, fish pass and hydropower scheme, each element of which must comply with Environment Agency good practice guidelines. This is discussed further in section 3.1.3.

3.1.3 Alleviation in migratory impediment resulting from scheme-associated fish passage measures

The literature review presented information on the efficiency of different fish passage technologies. In reality, the actual efficiency of any fish passage technology is likely to be influenced significantly by the specifics of the site concerned. However, hydropower schemes in England must meet Environment Agency good practice guidelines to be consented so that adverse impacts are managed.

Thus, upstream passability of a currently installed barrier to migration on which a hydropower scheme is installed should not be made worse, and should meet good practice, ensuring upstream passability of at least 90–95% for diadromous fish. Similarly for downstream passability (e.g. accounting for entrainment and impingement), the hydropower scheme should be designed in such a way as to ensure a minimum of 95–99% passability for diadromous fish.

These good practice passability values are assigned to a hydropower scheme in the model, but can be overridden in the event of local knowledge being available or new evidence from research or monitoring studies. Fish passage efficiency is also evaluated in the context of the passability of the existing barrier (see section 3.2.1), with the most effective passage route (i.e. the weir or the fish pass) being used to provide the total passability rating for the structure in question. It is possible that on old structures that have collapsed, the weir itself may be more passable than an associated fish pass (e.g. if all water flows through the collapsed weir, and no longer passes down an old fish pass).

3.1.4 Population loss of freshwater resident stages due to flow modification

The effects of flow depletion from hydropower schemes are common to other water resource scenarios (such as cooling water and public water supply abstraction), and a number of tools have been developed to assess these effects, the most well established being the physical habitat simulation PHABSIM (Stalnaker *et al.* 1995). However, such methods are data intensive, requiring both habitat mapping and cross-section survey of the site.

Consideration of the method by which fish population losses due to flow modification are quantified was beyond the scope of this project. The model is constructed such that population losses due to flow modification can be fed in, but the model is not prescriptive as to how this value is arrived at. Thus, the values fed in could be the result of a stand-alone PHABSIM study of the reach concerned. Alternatively, a less data intensive approach might entail applying an impact factor (percentage reduction in the freshwater population), based on a site-specific understanding of the approximate channel geometry (i.e. its flow sensitivity) and the percentage flow reduction this habitat would experience (e.g. during the most flow sensitive time period). This impact factor would then be applied to the length of river concerned, and population within that, to produce an actual population reduction. The latter component of this calculation (the population and length of river concerned) is automatically accounted for by the spatial population model element (see section 3.2).

3.2 Spatial population element

This approach relies on determining the extent of naturally accessible physical habitat available in the catchment (e.g. using GIS), and applying expected fish densities from reference values, to initially calculate a pristine condition carrying capacity of a catchment's habitat (see Appendix B for further information). The use of the carrying capacity results in the production of a 'reference population'. Spatially characterising the population in this way enables determination for any point in the catchment of the overall population that will be subject to (a) any adverse effects arising from the scheme, and (b) any benefits of the scheme (i.e. via improved fish passage measures).

This approach is applicable to any diadromous species. However, for the purposes of this study, Atlantic salmon (*Salmo salar*) was selected as the model species, as it meets more favourable criteria than other species; for example, established generic reference population densities, an established numerical population benchmark, and an ongoing monitoring programme (see Appendix C for more information). Additionally, the approach is based on that used by the Environment Agency in the production of salmon conservation limits.

Reference generic juvenile salmon densities were obtained from Wyatt and Barnard (1997a; Table 3.1), classed according to stream order and altitude. These were then applied to the Environment Agency's Detailed River Network for the Coquet Catchment, resulting in continuous reach-specific densities. Further information on the assumptions and methodology can be found in section 4 and Appendix B**.**

Table 3.1 Mean salmon fry and parr densities (per 100 m^2) at carrying capacity, for rivers in England and Wales (adapted from Wyatt and Barnard 1997a)

Altitude class (m)	**Stream order**							
	1		**2**		**3**		**4**	
	Fry	**Parr**	**Fry**	**Parr**	**Fry**	**Parr**	**Fry**	**Parr**
0–49	9.65	1.87	14.11	3.49	18.73	3.93	22.58	2.66
50–99	4.79	3.33	12.06	5.33	19.62	6.39	20.62	5.73
100–149	5.09	6.39	17.04	7.27	34.15	7.70	40.94	7.59
150–199	8.77	11.51	27.27	8.87	50.20	7.93	54.68	8.21
200–299	26.38	18.06	30.34	9.70	14.83	8.39	3.08	11.68
300–399	44.64	7.02	1.56	7.40	–	–	–	–

3.2.1 Pre-scheme impediment to upstream and downstream migration

An additional step in deriving the spatial population element is accounting for the effects of existing barriers, such that the spatial population derived, as described above, is pseudo-corrected to reflect actual conditions within the catchment. Understanding the passability of existing barriers is also important in determining the benefits of fish passage measures associated with new hydropower schemes.

Quantifying passability of a barrier to any given species is a particular challenge, with passability being influenced by the barrier’s vertical height, length, gradient, material and prevailing river discharge, all of which influence the flow hydraulics including head difference, velocity and depth (SNIFFER 2010). Behavioural stimuli are also an important criteria and aspects such as overhead cover, illumination, sudden changes in velocity or the height at which fish swim in the water column can all influence a barrier’s passability (SNIFFER 2010).

The approach to assigning passability scores in the model is centred on the SNIFFER WFD111 methodology, which is the only established approach available for assessing upstream and downstream passability of barriers. The model allows input of a subset of the key barrier variables included in calculating WFD111 scores. These include vertical hydraulic head, effective weir pool depth, levels of turbulence and the presence/absence of a standing wave. However, a critical consideration is that information on these variables is unlikely to exist in universally available datasets, and is likely to require a bespoke barrier assessment. Thus, the model also allows the option of determining passability based solely on the only barrier variable which is universally available: barrier height (or head loss), obtainable from the Environment Agency Obstructions database, which is itself a key requirement of the cumulative effects model. It should be noted that the obstructions database has a low level of accuracy at some sites and on its own is not a good surrogate for passability. WFD passability scores thus derived are in turn converted to ‘absolute passability scores’ within the model. Where an existing fish pass was present on a pre-existing barrier, its effects on passability were factored in when determining the structure’s passability.

It is important to stress that quantification of barrier passability is unavoidably the area of greatest potential error in the model. This highlights the need to recognise this area of potential error in both ascribing passability values in the model, and in interpreting model outputs and the benefits of ascribing values, based on bespoke barrier passability assessments.

Again, as with other model elements, passability values derived independently (e.g. from bespoke radio tracking studies) can be input directly to the model spreadsheet, thus overriding the calculation process described above. Further details of the barrier assessment methodology are provided in Appendix D.

3.3 Life-cycle element

To assess the potential effects of hydropower schemes on diadromous fish it is necessary to divide out the hydropower effects on each species life-cycle stage, as they will have differing effects during the upstream, resident and downstream stages. Furthermore, due to natural mortality rates, the abundance of each life-stage changes compared to the preceding life-stage. Thus, a life-cycle element was incorporated into the model which adopted the survival rates between life-stages as utilised in the derivation of conservation limits within salmon action plans (SAPs), (e.g. APEM 2008). Thus, the life-cycle values used within the model were:

- Marine survival = 11% for grilse (comprising 72% of returning adults) and 5% for multi-sea winter salmon (comprising 28% of returning adults)
- Rod exploitation: 20%[1] (i.e. 20% of adults are harvested by rods)
- Fecundity: 5,723 eggs per female
- Percentage of females in total population = 54%
- Egg to fry survival = 10%
- Fry to parr survival = 33%
- Parr to smolt survival = 44%.

Both the spatial population and life-cycle elements are adopted from the process, and values used for deriving conservation limits, and have the advantage of both being recognised and accepted by fisheries practitioners.

It should be noted that the application of the SAP values creates a substantial surplus of adults. This resilience in the population is thought to be partly a characteristic of the Coquet population but also likely to be due to the limitation of the simplistic life-cycle model. The consequence of such population resilience in the life-cycle model is that it masks to a large extent the (positive and negative) effects of hydropower schemes and barriers. Moreover, the production of such a substantial sustainable surplus is likely to be atypical of English rivers and so, for the purposes of this study, a more typical scenario was created by reducing the fry to parr survival rate from 33 to 11% (the survival rate of any of the resident freshwater stages could be manipulated to produce the same results due to the linear model). This effectively creates a population in equilibrium (i.e. the number of returning adults are just sufficient to meet the carrying capacity). Consequently, the results from this work, although based on the Coquet Catchment, are a theoretical test of the model, its versatility and a range of hydropower scenarios and resultant impacts on a typical salmon population.

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[1] No value of current rod exploitation for the Coquet was available at the time of development. Therefore, it was estimated from the original rod catch exploitation rate of 27%, which reduced upon the introduction of a byelaw in 1999 imposing compulsory catch and release of spring run salmon.

4 Model set-up and calculation routine

Each element discussed in section 3, has been incorporated into a single Microsoft Excel spreadsheet based model. The model was tested using a hypothetical spatial model element, based on the River Coquet Catchment, with life-cycle values adapted from the Coquet SAP (APEM 2008).

As discussed in section 3.1.3, an assumption is made that hydropower schemes will meet Environment Agency guidance. The steering group determined that an upstream passability of at least 90–95%, when including the effects of the barrier, fish passage facility, depleted reach and tailrace effects, was realistic with application of Environment Agency good practice guidance. Similarly for downstream passability (e.g. accounting for barrier effects, entrainment and impingement), the hydropower scheme should be designed in such a way as to ensure a minimum of 95–99% passability. Thus, the hydropower scheme effects element was simplified to amalgamate these effects into a single upstream and single downstream passability score, aiming for the range of passability specified in Environment Agency best practice, although the model has the ability to simulate specific effects (of, for example, entrainment) if required.

The model set-up, calculation routine and results generation process is described below. Each step is further illustrated in Figure 4.1.

Step 1. Spatial population model set-up

Values for stream order, altitude and channel dimensions were generated for each discrete reach of the River Coquet Catchment, from the Environment Agency Detailed River Network. The GIS data was then exported into Microsoft Excel, and Wyatt and Barnard fry densities per 100 m^2 (Table 3.1) were allocated according to stream order and altitude. Multiplication by reach channel length and width then allowed determination of reach carrying capacity (i.e. the maximum number of juvenile salmon the reach can support, as dictated by the inherent constraints of the natural river characteristics).

The corresponding number of adults in the previous generation required to produce the calculated juvenile densities was then back-calculated, using fry to parr and egg to fry survival rates, plus sex ratio and average fecundity values for adults. This calculated number of adults reflects a population in the absence of significant anthropogenic effects, and is termed the ‘reference adult population’.

Step 2. Pre-hydropower and hydropower scheme model set-up

To enable the effects of existing barriers to be established, the existing barriers must be incorporated into the spatial population model. These barriers are superimposed on the catchment population, thus dividing the catchment into a series of segments between barriers. In the current example, barriers included were those where hypothetical hydropower schemes were to be modelled.

For each barrier, the pre-scheme upstream and downstream passability was determined using barrier attributes obtained from the Environment Agency obstructions database (head loss and presence of a fish pass; see section 3.2.1). The effects of the hydropower scheme were then incorporated into the scheme effects model element by selecting an appropriate Environment Agency best practice upstream and downstream passability score, to provide a second set of passability values at each barrier.

Both the pre-scheme (incorporating barriers only) and the hydropower scheme scenarios are then run through the spatial population model (as described in Step 3), by switching on the user-specified number and combination of hydropower schemes.

Step 3 (a and b). Pre-hydropower and hydropower scheme model run

The pre-hydropower scheme and hydropower scheme scenarios are run simultaneously through the model. The reference starting population of returning adults entering the river, calculated in Step 1, is ‘routed’ through each segment of the spatial population model (from downstream to upstream) and subjected to each barrier (in the pre-scheme scenario), and barrier and scheme effect (in the hydropower scheme scenario).

Adult salmon in the model ‘behave’ such that they seek to distribute themselves within the various reaches in accordance with the population values derived in Step 1. Thus, a proportion of the adult spawners will reside (and ultimately spawn) within the habitat in each segment in proportion to the area and quality of that habitat, while the remaining migrants will seek to move past the barrier and distribute in proportion to quality and extent of the habitat as previously described. Thus, the model assumes an ‘ideal free distribution’ of fish. These migrants are subject to the impediment of the upstream barrier plus any effects of the hydropower scheme (Equation 1).

$$\text{Equation 1: } A^2 = S^0 \times H^1 \times B^2_{e\,or\,p}$$

where A^2 = adults migrating upstream into the upstream segment, S^0 = starting population entering the segment from downstream, H^1 = fraction of habitat upstream of segment relative to total amount of habitat at and upstream of the segment, $B^2_{e\,or\,p}$ = upstream existing (B_e) or proposed (with hydropower scheme [B_p]) barrier passability.

The difference between the starting population entering the segment (S^0) and the population moving upstream (A^2) are those adult spawners seeking to utilise the segment habitat, plus those prevented from accessing their upstream target segment. Those adults unable to pass will attempt to spawn in the habitat downstream of the barrier. This aspect of the model assumes that fish will spawn further downstream, which may not happen; some fish may fail to spawn and return to sea. However, no data were forthcoming to quantify this eventuality. **Where these impeded individuals cause the resultant egg deposition and fry densities to exceed the carrying capacity, their progeny are assumed to perish** (through density dependent effects such as reduced growth and survival, and increased competition and intraspecific effects [e.g. redd superimposition; McNeil 1964]). Those adult migrants successfully passing the barrier will then seek to either spawn in that segment, or migrate upstream and be subject to the effects of any further barriers.

Using segment-specific egg deposition from these spawners, a smolt population is calculated from the egg to smolt survival rates, but limited to the carrying capacity. This serves as the starting point for the seaward-migrating smolt population. These smolts are then subject to the effects of downstream migratory impediment as a result of one or multiple barriers (pre-scheme scenario) and multiple barriers with hydropower schemes (hydropower scheme scenario). Resultant numerical losses of smolts are then applied to the outward migrating smolt population.

Of the population successfully migrating to the sea, a marine survival rate is applied. The resulting population for each pre-scheme and hydropower scheme scenario is the number of returning adults to the catchment (after the marine life-cycle phase) measured prior to river entry. This forms the model end-point, and thus the model calculates the effect of a hydropower scheme over a single generation only[2] and therefore indicates the population trajectory as opposed to absolute viability.

Step 4. Cumulative effects results

As described in Step 3, the resulting population for each pre-scheme and hydropower scheme scenario is the number of returning adults to the catchment measured prior to river entry. The (cumulative) effects of the hydropower scheme(s) is then calculated through subtraction of the pre-scheme population from the hydropower scheme population. The resultant change in number of returning adults, expressed in terms of percentage change, provides the level of (cumulative) effect.

Although not shown in Figure 4.1, to be consistent with the Environment Agency conservation limit approach for managing salmon, the final measurement of population effect is also expressed as the potential egg production of the returning adults, which can be compared to the conservation limit for the catchment (also expressed in terms of potential egg numbers) as a possible means for management.

To provide the user with additional information, the model generates pre-scheme and hydropower scenario graphs to illustrate the location and magnitude of fish gains/losses to first generation upstream migrating adults, on a segment by segment basis. Graphs are also generated to illustrate the location and magnitude of change in smolts migrating out to sea from each segment.

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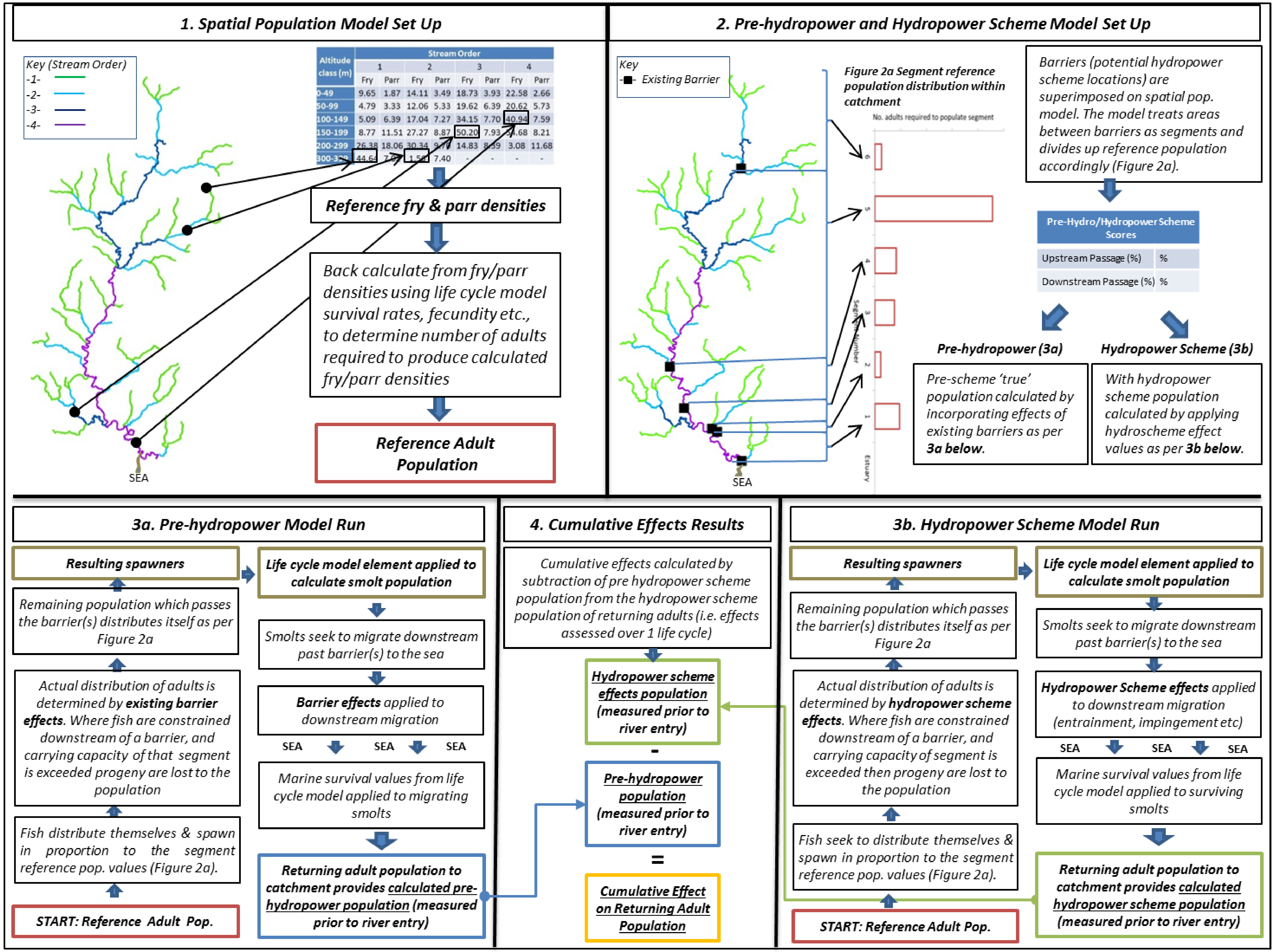
[2] A single life-cycle phase involves the freshwater phase (adults entering the watercourse, moving upstream, spawning, and the subsequent progeny of smolts having survived the fry and parr stage swimming downstream to the sea which typically takes 2–3 years), and the adult marine phase, which typically lasts 1–3 years through to these adults returning once more to the freshwater phase. The marine survival used in the model is taken from the Environment Agency’s conservation limit calculations, which averages for one and multiple year marine fish. Most Atlantic salmon (particularly males) die after spawning, but some survive to return to the sea as kelts and return to spawn again (some fish are known to have spawned three times).



1. Spatial Population Model Set Up

Altitude class (m)	Stream Order 1 Fry	1 Parr	2 Fry	2 Parr	3 Fry	3 Parr	4 Fry	4 Parr
0-49	9.65	1.87	14.11	3.49	18.73	3.93	22.58	2.66
50-99	4.79	3.33	12.06	5.33	19.62	6.39	20.62	5.73
100-149	5.09	6.39	17.04	7.27	34.15	7.70	40.94	7.59
150-199	8.77	11.51	27.27	8.87	50.20	7.93	[illegible]	8.21
200-299	26.38	18.06	30.34	[illegible]	14.83	[illegible]	3.08	11.68
[illegible]	44.64	[illegible]	[illegible]	7.40	-	-	-	-

Reference fry & parr densities

Back calculate from fry/parr densities using life cycle model survival rates, fecundity etc., to determine number of adults required to produce calculated fry/parr densities

Reference Adult Population

2. Pre-hydropower and Hydropower Scheme Model Set Up

Barriers (potential hydropower scheme locations) are superimposed on spatial pop. model. The model treats areas between barriers as segments and divides up reference population accordingly (Figure 2a).

Pre-Hydro/Hydropower Scheme Scores	
Upstream Passage (%)	%
Downstream Passage (%)	%

Pre-hydropower (3a)

Pre-scheme ‘true’ population calculated by incorporating effects of existing barriers as per ***3a below.***

Hydropower Scheme (3b)

With hydropower scheme population calculated by applying hydroscheme effect values as per ***3b below.***

3a. Pre-hydropower Model Run

START: Reference Adult Pop.

Fish distribute themselves & spawn in proportion to the segment reference pop. values (Figure 2a).

Actual distribution of adults is determined by ***existing barrier effects.*** *Where fish are constrained downstream of a barrier, and carrying capacity of that segment is exceeded progeny are lost to the population*

Remaining population which passes the barrier(s) distributes itself as per Figure 2a

Resulting spawners

Life cycle model element applied to calculate smolt population

Smolts seek to migrate downstream past barrier(s) to the sea

Barrier effects *applied to downstream migration*

Marine survival values from life cycle model applied to migrating smolts

Returning adult population to catchment provides <u>calculated pre-hydropower population</u> (measured prior to river entry)

4. Cumulative Effects Results

Cumulative effects calculated by subtraction of pre hydropower scheme population from the hydropower scheme population of returning adults (i.e. effects assessed over 1 life cycle)

<u>Hydropower scheme effects population</u> (measured prior to river entry)

-

<u>Pre-hydropower population</u> (measured prior to river entry)

=

<u>Cumulative Effect on Returning Adult Population</u>

3b. Hydropower Scheme Model Run

START: Reference Adult Pop.

Fish seek to distribute themselves & spawn in proportion to the segment reference pop. values (Figure 2a).

Actual distribution of adults is determined by ***hydropower scheme effects.*** *Where fish are constrained downstream of a barrier, and carrying capacity of segment is exceeded then progeny are lost to the population*

Remaining population which passes the barrier(s) distributes itself as per Figure 2a

Resulting spawners

Life cycle model element applied to calculate smolt population

Smolts seek to migrate downstream past barrier(s) to the sea

Hydropower Scheme effects *applied to downstream migration (entrainment, impingement etc)*

Marine survival values from life cycle model applied to surviving smolts

Returning adult population to catchment provides <u>calculated hydropower scheme population</u> (measured prior to river entry)

Figure 4.1 Summary of model set-up and calculation routine

5 Scenario testing

5.1 Introduction to scenario testing

Scenarios comprising between one and six hydropower schemes at different locations (Table 5.1) were agreed through discussion with the Environment Agency steering group to test how the model works, to explore cumulative effects in a realistic catchment where salmon are present and to assess how scheme positioning within the catchment affects cumulative effects on the resident salmon population. The model scenarios were deliberately set up using hypothetical situations to demonstrate the functionality of the model and the capacity to measure cumulative effects; results are therefore theoretical and do not necessarily represent a real catchment situation.

Table 5.1 Summary of hypothetical scenarios tested

Scenario	No.	Description
Cumulative effects assessment of one to six hydropower (HP) schemes	1a	Single HP scheme in the lower catchment (at barrier 1)
	1b	Two HP schemes (at barriers 1 and 2)
	1c	Three HP schemes (at barriers 1, 2 and 3)
	1d	Four HP schemes (at barriers 1, 2, 3 and 4)
	1e	Five HP schemes (at barriers 1, 2, 3, 4 and 5)
	1f	Six HP schemes (at barriers 1, 2, 3, 4, 5 and 6)
Scheme location effects	2	Single HP scheme in the upper catchment (at barrier 6)

The model used the River Coquet Catchment for the spatial population model (i.e. by superimposing reference salmon population values onto the naturally accessible parts of the Detailed River Network. Six pre-existing (actual) barriers were incorporated into the model, on which the effects of between one and six hypothetical hydropower schemes were modelled (Figure 5.1). The Environment Agency obstructions database was used to obtain information on barrier height and presence of a fish pass, enabling pre-hydropower scheme passability scores to be generated (barrier data entered into the model is shown in Figure 5.2). A final scenario was run to demonstrate the importance of scheme positioning within the catchment. Table 5.1 provides a summary of these scenarios.

The River Coquet was selected to give the spatial model element a level of reality, thus making it less abstract and easier to relate to. However, the parameters applied to represent the catchment (e.g. total number of structures), salmon population, existing barrier passability and proposed hydropower scheme passability should be treated as being illustrative of the model's functionality and not used to infer the effects of installing hydropower schemes on the Coquet Catchment.

Hydropower scheme scenarios were run in three sets to demonstrate the effects of using different types of information as input data on the model outputs. These were:

- Existing structure passabilities based on barrier height as obtained from the Environment Agency obstructions database, and fish pass passability scores dependent on type of fish pass, and incorporating local knowledge about the condition of barriers and fish passes not available from a desk-based approach.
- Existing structure passabilities based on barrier height and fish pass passability type from the Environment Agency barrier obstructions data only (desk-based approach).

- Incorporating a single hydropower scheme where mitigation in the form of a new fish pass associated with the scheme does not function as well as expected even though designed to work at best practice levels of passability (i.e. a reduction of 5% for both upstream and downstream passability compared to Environment Agency best practice estimates). Existing structure passability scores were based solely on the Environment Agency obstructions database and theoretical fish pass passability scores.

The Environment Agency steering group requested that hydropower schemes were assigned a generic passability score specified as:

- Upstream passability of 90% (reflecting passability of a fish pass built in accordance with best practice).
- Downstream passability of 95% (reflecting best practice mitigation such as screens and bypasses).

These scores provide indicative values that might be achieved when following Environment Agency best practice hydropower development guidelines. As outlined in section 4, downstream passability as employed in the scenarios subsumes entrainment, impingement and barrier effects, which can also be treated as separate entities within the model. Upstream passability as employed in the scenarios embodies the full range of specific mechanisms by which fish may be impeded, including attraction to a tailrace.

5.1.1 Scenario set 1 input data

The Environment Agency obstructions database was used to obtain information on barrier height and presence of a fish pass, enabling pre-hydropower scheme passability scores to be generated. Head values from the obstructions database are based on upstream and downstream water levels extracted from LiDAR or SAR remotely sensed topographic data.

As the accuracy of height/head loss values derived from this source is known to be low, a manual adjustment option has been included in the model to allow expert judgement and local knowledge to be used to override automated passability values derived from head loss obtained from the obstructions database (which the model in turn converts to a passability value). To demonstrate this function it was decided to incorporate local Environment Agency knowledge at two of the structures represented in the model, barriers 2 and 4. This knowledge suggests a higher passability than the 0.75 calculated from fish pass passability detailed in the obstructions database:

Barrier 2: '[weir in] poor condition partially collapsed, gentle gradient with broken flow and areas of low velocity, not thought to be a major problem for fish passage'.

Barrier 4: '[pool and traverse fish pass] in good condition discharges at base of weir, good attraction'.

Consequently, upstream baseline (pre-scheme) passability was manually adjusted to 0.91 and 0.93 at barriers 2 and 4 respectively. The data incorporated into the model to test the scenarios are provided in Table 5.2. For illustrative purposes, Figure 5.3 is a screenshot of the data incorporated into the model. The proposed hydropower scenarios and passability scores are hypothetical and do not relate to any actual situation on the Coquet Catchment.

Table 5.2 Scenarios run using the Environment Agency obstructions database and local knowledge for determining passability of existing structures (scenario set 1)

Barrier/HP scheme no.	Pre-scheme passability (obstructions database)		Pre-scheme manual adjustment passability using local knowledge*		HP scheme passability	
	Upstream	Downstream	Upstream	Downstream	Upstream	Downstream
1	0.72	1.00	N/A	N/A	0.90	0.95
2	0.75	1.00	0.91	N/A	0.90	0.95
3	1.00	1.00	N/A	N/A	0.90	0.95
4	0.75	1.00	0.93	N/A	0.90	0.95
5	1.00	1.00	N/A	N/A	0.90	0.95
6	1.00	1.00	N/A	N/A	0.90	0.95

*Manually entered passability scores override those calculated by the model itself using the obstructions database information.

For illustrative purposes the various calculation routines for scenario set 1 are shown in Figures 5.4 to 5.6. For each scenario, column 27 (highlighted in Figure 5.6 by a red oval) was amended to ‘switch on’ the number of schemes required for a specific scenario.

The results for scenario set 1 are located in sections 5.2.1 and 5.2.2. The graphical outputs as included in the results for scenario set 1 are not provided for scenario sets 2 and 3.

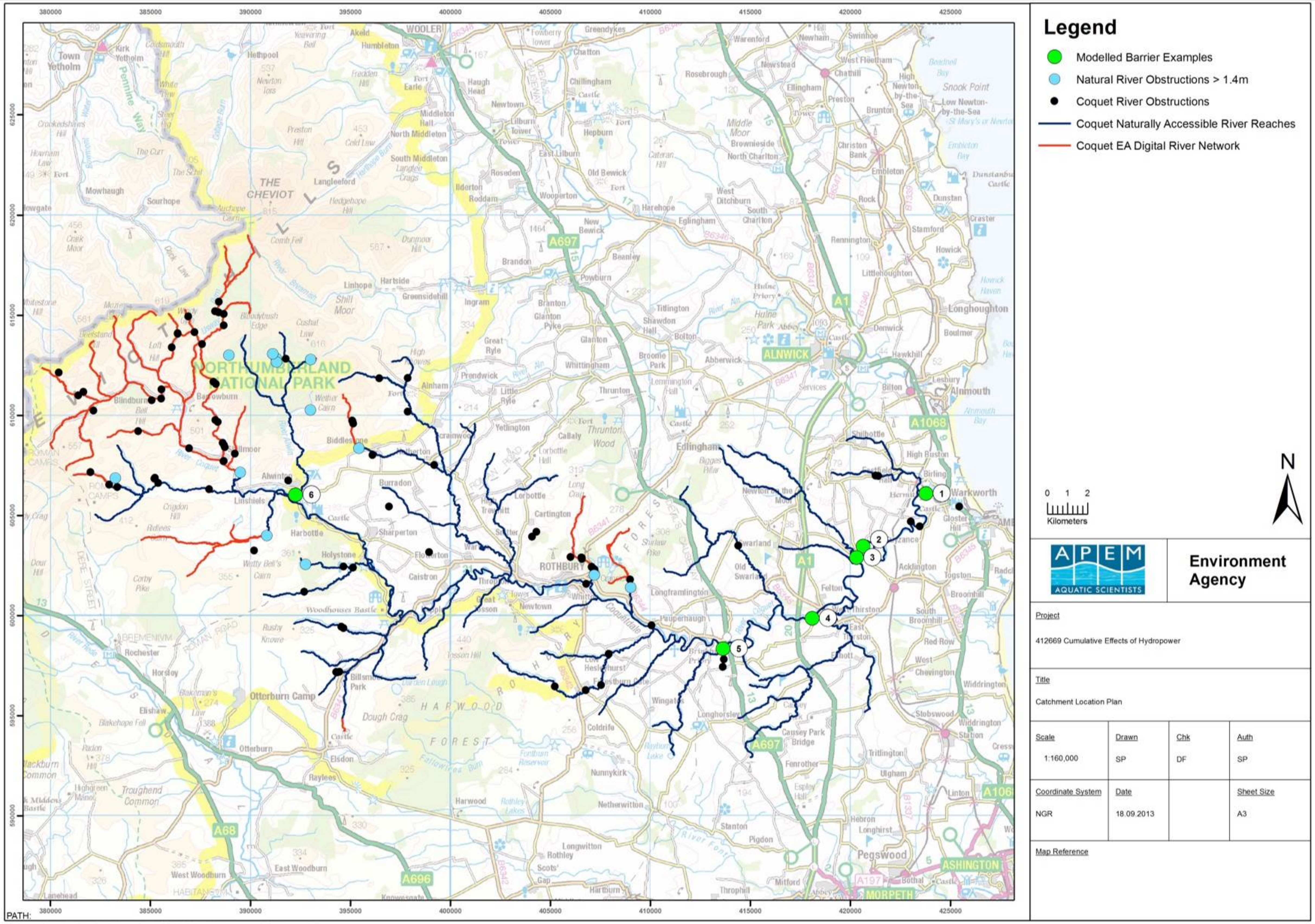


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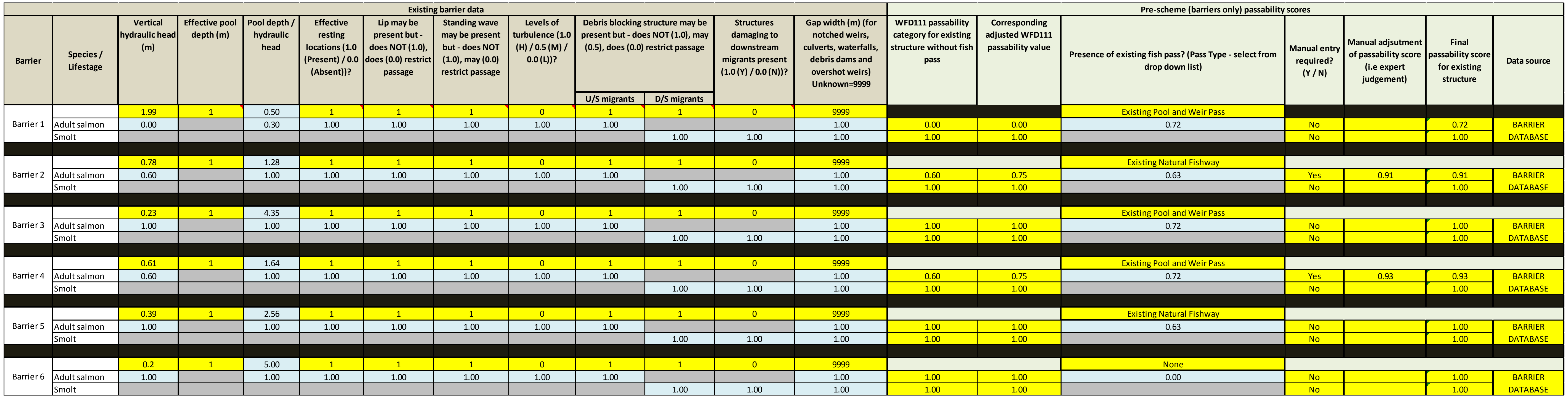
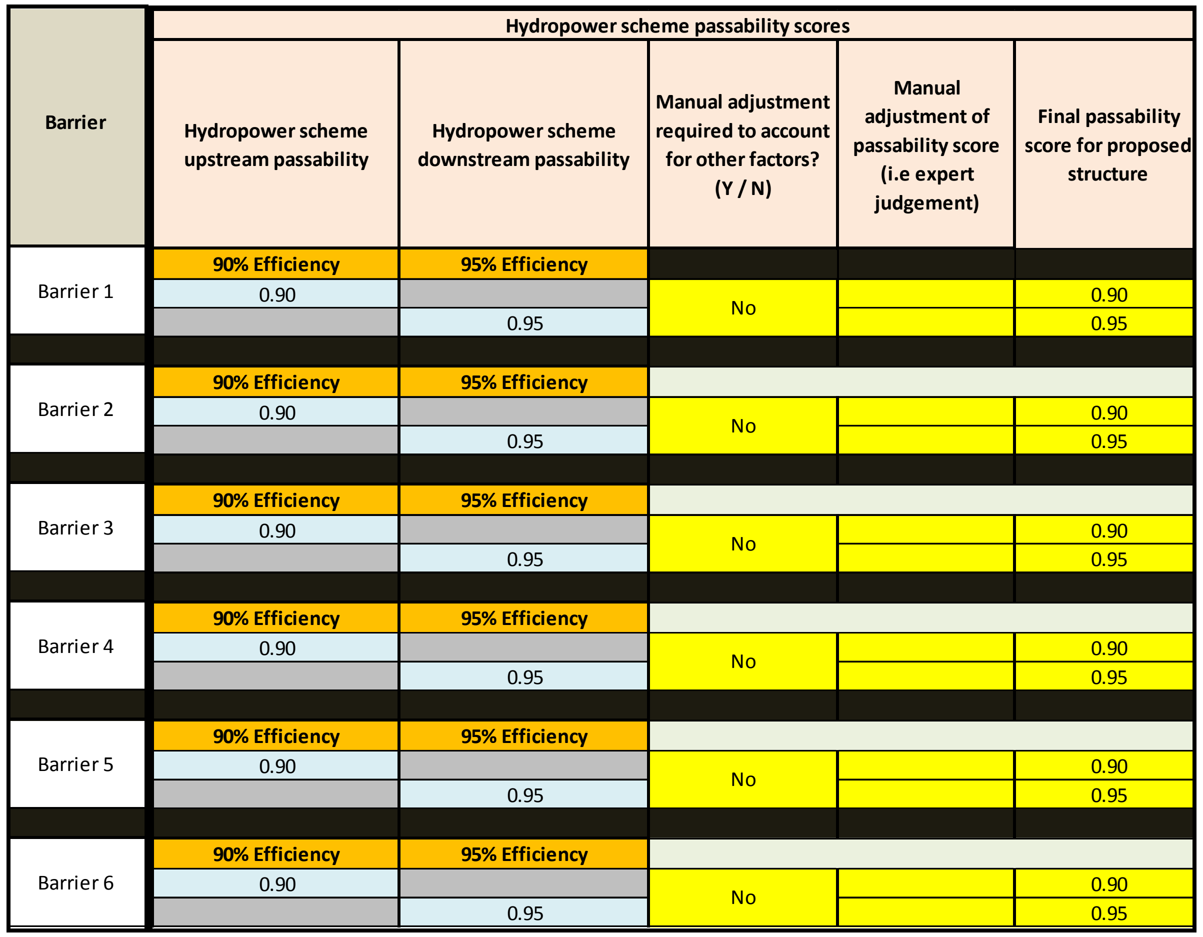
Figure 5.1 River Coquet test catchment and barrier locations



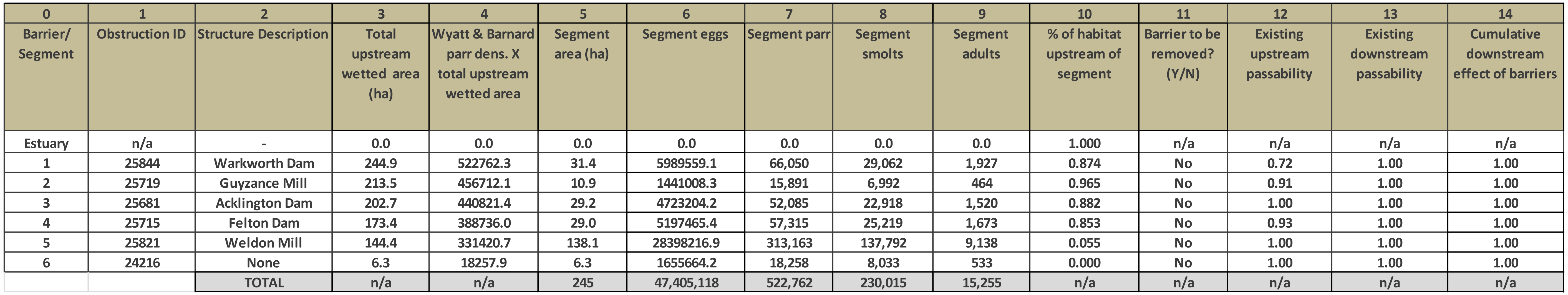
Existing barrier data													Pre-scheme (barriers only) passability scores						
Barrier	Species / Lifestage	Vertical hydraulic head (m)	Effective pool depth (m)	Pool depth / hydraulic head	Effective resting locations (1.0 (Present) / 0.0 (Absent))?	Lip may be present but - does NOT (1.0), does (0.0) restrict passage	Standing wave may be present but - does NOT (1.0), may (0.0) restrict passage	Levels of turbulence (1.0 (H) / 0.5 (M) / 0.0 (L))?	Debris blocking structure may be present but - does NOT (1.0), may (0.5), does (0.0) restrict passage		Structures damaging to downstream migrants present (1.0 (Y) / 0.0 (N))?	Gap width (m) (for notched weirs, culverts, waterfalls, debris dams and overshot weirs) Unknown=9999	WFD111 passability category for existing structure without fish pass	Corresponding adjusted WFD111 passability value	Presence of existing fish pass? (Pass Type - select from drop down list)	Manual entry required? (Y / N)	Manual adjsutment of passability score (i.e expert judgement)	Final passability score for existing structure	Data source
									U/S migrants	D/S migrants									
Barrier 1		1.99	1	0.50	1	1	1	0	1	1	0	9999			Existing Pool and Weir Pass				
	Adult salmon	0.00		0.30	1.00	1.00	1.00	1.00	1.00			1.00	0.00	0.00	0.72	No		0.72	BARRIER DATABASE
	Smolt									1.00	1.00	1.00	1.00	1.00		No		1.00	
Barrier 2		0.78	1	1.28	1	1	1	0	1	1	0	9999			Existing Natural Fishway				
	Adult salmon	0.60		1.00	1.00	1.00	1.00	1.00	1.00			1.00	0.60	0.75	0.63	Yes	0.91	0.91	BARRIER DATABASE
	Smolt									1.00	1.00	1.00	1.00	1.00		No		1.00	
Barrier 3		0.23	1	4.35	1	1	1	0	1	1	0	9999			Existing Pool and Weir Pass				
	Adult salmon	1.00		1.00	1.00	1.00	1.00	1.00	1.00			1.00	1.00	1.00	0.72	No		1.00	BARRIER DATABASE
	Smolt									1.00	1.00	1.00	1.00	1.00		No		1.00	
Barrier 4		0.61	1	1.64	1	1	1	0	1	1	0	9999			Existing Pool and Weir Pass				
	Adult salmon	0.60		1.00	1.00	1.00	1.00	1.00	1.00			1.00	0.60	0.75	0.72	Yes	0.93	0.93	BARRIER DATABASE
	Smolt									1.00	1.00	1.00	1.00	1.00		No		1.00	
Barrier 5		0.39	1	2.56	1	1	1	0	1	1	0	9999			Existing Natural Fishway				
	Adult salmon	1.00		1.00	1.00	1.00	1.00	1.00	1.00			1.00	1.00	1.00	0.63	No		1.00	BARRIER DATABASE
	Smolt									1.00	1.00	1.00	1.00	1.00		No		1.00	
Barrier 6		0.2	1	5.00	1	1	1	0	1	1	0	9999			None				
	Adult salmon	1.00		1.00	1.00	1.00	1.00	1.00	1.00			1.00	1.00	1.00	0.00	No		1.00	BARRIER DATABASE
	Smolt									1.00	1.00	1.00	1.00	1.00		No		1.00	

Figure 5.2 Existing barrier assessment input data for scenario testing of the model (incorporating local Environment Agency barrier passability knowledge – scenario set 1)



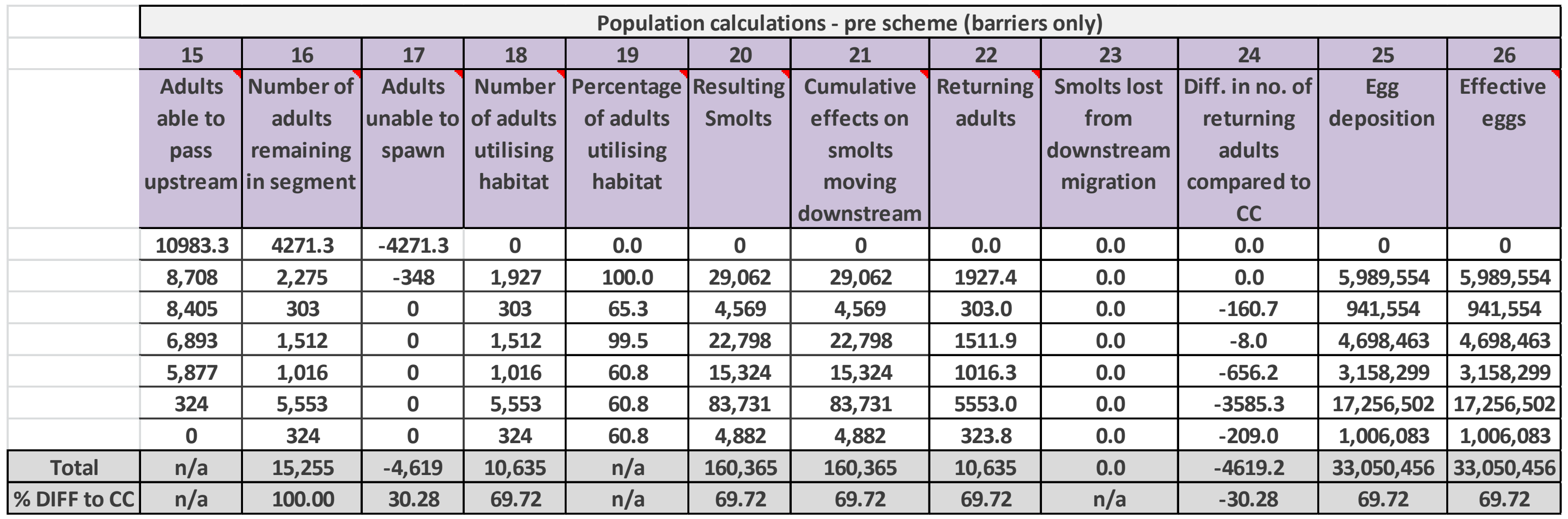
Barrier	Hydropower scheme passability scores				
	Hydropower scheme upstream passability	Hydropower scheme downstream passability	Manual adjustment required to account for other factors? (Y / N)	Manual adjustment of passability score (i.e expert judgement)	Final passability score for proposed structure
Barrier 1	90% Efficiency	95% Efficiency			
	0.90		No		0.90
		0.95			0.95
Barrier 2	90% Efficiency	95% Efficiency			
	0.90		No		0.90
		0.95			0.95
Barrier 3	90% Efficiency	95% Efficiency			
	0.90		No		0.90
		0.95			0.95
Barrier 4	90% Efficiency	95% Efficiency			
	0.90		No		0.90
		0.95			0.95
Barrier 5	90% Efficiency	95% Efficiency			
	0.90		No		0.90
		0.95			0.95
Barrier 6	90% Efficiency	95% Efficiency			
	0.90		No		0.90
		0.95			0.95

Figure 5.3 Hydropower scheme effects (with best practice passability scores – scenario set 1)



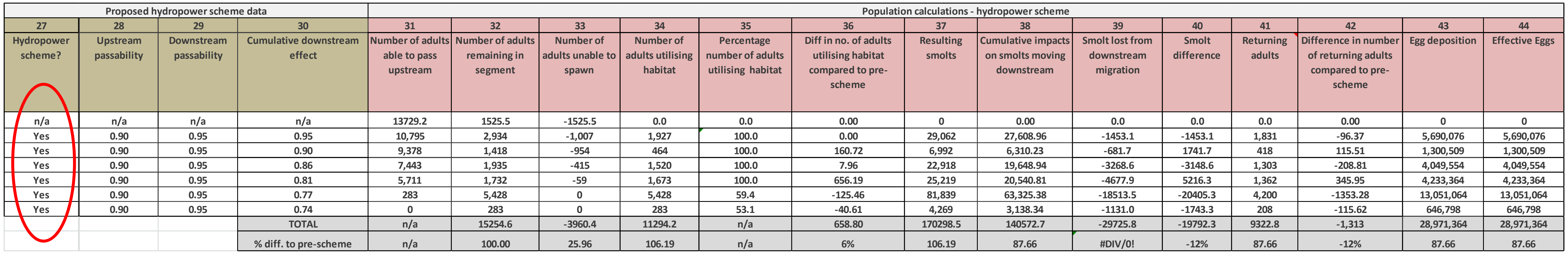
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Barrier/ Segment	Obstruction ID	Structure Description	Total upstream wetted area (ha)	Wyatt & Barnard parr dens. X total upstream wetted area	Segment area (ha)	Segment eggs	Segment parr	Segment smolts	Segment adults	% of habitat upstream of segment	Barrier to be removed? (Y/N)	Existing upstream passability	Existing downstream passability	Cumulative downstream effect of barriers
Estuary	n/a	-	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.000	n/a	n/a	n/a	n/a
1	25844	Warkworth Dam	244.9	522762.3	31.4	5989559.1	66,050	29,062	1,927	0.874	No	0.72	1.00	1.00
2	25719	Guyzance Mill	213.5	456712.1	10.9	1441008.3	15,891	6,992	464	0.965	No	0.91	1.00	1.00
3	25681	Acklington Dam	202.7	440821.4	29.2	4723204.2	52,085	22,918	1,520	0.882	No	1.00	1.00	1.00
4	25715	Felton Dam	173.4	388736.0	29.0	5197465.4	57,315	25,219	1,673	0.853	No	0.93	1.00	1.00
5	25821	Weldon Mill	144.4	331420.7	138.1	28398216.9	313,163	137,792	9,138	0.055	No	1.00	1.00	1.00
6	24216	None	6.3	18257.9	6.3	1655664.2	18,258	8,033	533	0.000	No	1.00	1.00	1.00
		TOTAL	n/a	n/a	245	47,405,118	522,762	230,015	15,255	n/a	n/a	n/a	n/a	n/a

Figure 5.4 Segment carrying capacity calculation (scenario set 1)



	Population calculations - pre scheme (barriers only)											
	15	16	17	18	19	20	21	22	23	24	25	26
	Adults able to pass upstream	Number of adults remaining in segment	Adults unable to spawn	Number of adults utilising habitat	Percentage of adults utilising habitat	Resulting Smolts	Cumulative effects on smolts moving downstream	Returning adults	Smolts lost from downstream migration	Diff. in no. of returning adults compared to CC	Egg deposition	Effective eggs
	10983.3	4271.3	-4271.3	0	0.0	0	0	0.0	0.0	0.0	0	0
	8,708	2,275	-348	1,927	100.0	29,062	29,062	1927.4	0.0	0.0	5,989,554	5,989,554
	8,405	303	0	303	65.3	4,569	4,569	303.0	0.0	-160.7	941,554	941,554
	6,893	1,512	0	1,512	99.5	22,798	22,798	1511.9	0.0	-8.0	4,698,463	4,698,463
	5,877	1,016	0	1,016	60.8	15,324	15,324	1016.3	0.0	-656.2	3,158,299	3,158,299
	324	5,553	0	5,553	60.8	83,731	83,731	5553.0	0.0	-3585.3	17,256,502	17,256,502
	0	324	0	324	60.8	4,882	4,882	323.8	0.0	-209.0	1,006,083	1,006,083
Total	n/a	15,255	-4,619	10,635	n/a	160,365	160,365	10,635	0.0	-4619.2	33,050,456	33,050,456
% DIFF to CC	n/a	100.00	30.28	69.72	n/a	69.72	69.72	69.72	n/a	-30.28	69.72	69.72

Figure 5.5 Pre-scheme population calculation (scenario set 1)



Proposed hydropower scheme data				Population calculations - hydropower scheme													
27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44
Hydropower scheme?	Upstream passability	Downstream passability	Cumulative downstream effect	Number of adults able to pass upstream	Number of adults remaining in segment	Number of adults unable to spawn	Number of adults utilising habitat	Percentage number of adults utilising habitat	Diff in no. of adults utilising habitat compared to pre-scheme	Resulting smolts	Cumulative impacts on smolts moving downstream	Smolt lost from downstream migration	Smolt difference	Returning adults	Difference in number of returning adults compared to pre-scheme	Egg deposition	Effective Eggs
n/a	n/a	n/a	n/a	13729.2	1525.5	-1525.5	0.0	0.0	0.00	0	0.00	0.0	0.0	0.0	0.00	0	0
Yes	0.90	0.95	0.95	10,795	2,934	-1,007	1,927	100.0	0.00	29,062	27,608.96	-1453.1	-1453.1	1,831	-96.37	5,690,076	5,690,076
Yes	0.90	0.95	0.90	9,378	1,418	-954	464	100.0	160.72	6,992	6,310.23	-681.7	1741.7	418	115.51	1,300,509	1,300,509
Yes	0.90	0.95	0.86	7,443	1,935	-415	1,520	100.0	7.96	22,918	19,648.94	-3268.6	-3148.6	1,303	-208.81	4,049,554	4,049,554
Yes	0.90	0.95	0.81	5,711	1,732	-59	1,673	100.0	656.19	25,219	20,540.81	-4677.9	5216.3	1,362	345.95	4,233,364	4,233,364
Yes	0.90	0.95	0.77	283	5,428	0	5,428	59.4	-125.46	81,839	63,325.38	-18513.5	-20405.3	4,200	-1353.28	13,051,064	13,051,064
Yes	0.90	0.95	0.74	0	283	0	283	53.1	-40.61	4,269	3,138.34	-1131.0	-1743.3	208	-115.62	646,798	646,798
			TOTAL	n/a	15254.6	-3960.4	11294.2	n/a	658.80	170298.5	140572.7	-29725.8	-19792.3	9322.8	-1,313	28,971,364	28,971,364
			% diff. to pre-scheme	n/a	100.00	25.96	106.19	n/a	6%	106.19	87.66	#DIV/0!	-12%	87.66	-12%	87.66	87.66

Figure 5.6 Hydropower scheme effect on population calculation (scenario set 1). (Red oval represents column changed for running of the various scenarios)

5.1.2 Scenario set 2 input data

The second set of scenarios demonstrates the results of running the model based on passability values obtained from the Environment Agency obstructions database only (Table 5.3).

Table 5.3 Scenarios run using the Environment Agency obstructions database only for determining passability of existing structures (scenario set 2)

Barrier/HP scheme no.	Pre-scheme passability		HP scheme passability	
	Upstream	Downstream	Upstream	Downstream
1	0.72	1.00	0.90	0.95
2	0.75	1.00	0.90	0.95
3	1.00	1.00	0.90	0.95
4	0.75	1.00	0.90	0.95
5	1.00	1.00	0.90	0.95
6	1.00	1.00	0.90	0.95

The results for scenario set 2 are located in section 5.2.3. The graphical outputs as included in the results for scenario set 1 are not provided for scenario set 2.

5.1.3 Scenario set 3 input data

The final set of scenarios demonstrate the effect of a hydropower scheme where, although originally designed to meet Environment Agency guidance, passage mitigation does not function as expected (e.g. determined after post-installation monitoring), as shown in Table 5.4.

Table 5.4 Scenarios run where passage migration for a hypothetical hydropower scheme installed at site 3 does not function as expected, and using the Environment Agency obstructions database for determining passability of existing structures (scenario set 3)

Barrier/HP scheme no.	Pre-scheme passability		HP scheme passability	
	Upstream	Downstream	Upstream	Downstream
1	0.72	1.00	0.90	0.95
2	0.75	1.00	0.90	0.95
3	1.00	1.00	0.85	0.90
4	0.75	1.00	0.90	0.95
5	1.00	1.00	0.90	0.95
6	1.00	1.00	0.90	0.95

The results for scenario set 3 are located in section 5.2.3. The graphical outputs as included in the results for scenario set 1 are not provided for scenario set 3.

5.2 Scenario results and discussion

To demonstrate the model outputs, for each scenario run in set 1, the results are displayed graphically in sections 5.2.1 and 5.2.2, as follows:

- The number of adults which ultimately reach, and effectively spawn in, their riverine destination (segment): (a) pre-scheme (accounting for the effects of barriers alone); (b) with scheme effects in place; and (c) the difference between (a) and (b). The concept of the number of effective spawners is critical, and reflects the upper number of adults that a segment can support, in terms of its capacity to support the progeny of the adults (as defined by the spatial population model). Thus, more adults may physically gain access to the segment in question, but where numbers exceed the carrying capacity, progeny in the next generation are lost to the overall population.
- For each segment, the number of smolts (resulting from the effective adult spawners above) which ultimately escape to sea: (a) pre-scheme (accounting for the effects of barriers alone); (b) with scheme effects in place; and (c) the difference between (a) and (b).
- The cumulative effect of the hydropower scheme for each life-stage (upstream migrating adults and downstream migrating smolts).
- The effects of existing barriers and illustrative hydropower schemes on the total number of returning adults calculated from the smolts able to successfully survive to adulthood.
- The cumulative effect on the population from the hydropower scheme, expressed as a percentage change compared to the pre-scheme (accounting for barriers alone) number of returning adults.

The scenario results are expressed graphically (e.g. Figure 5.7). The pre-scheme graphs (a and b) represent the carrying capacity of each river section (red box), and the number of adults successfully spawning and smolts successfully migrating to the sea within each segment respectively, calculated as a result of the existing impoundments (blue bars), and displayed for the upstream (adult) and downstream (smolt) migrants separately.

The hydropower scheme graphs (c and d) again represent the carrying capacity of each river section (red box), but now provide the number of fish located in each segment, calculated as a result of one or more hydropower schemes being installed on the existing impoundments (green bars). The upstream (adult) and downstream (smolt) migrants are calculated separately.

The hydropower effects graphs (e and f) represent the difference in the number of fish within each segment between the pre-scheme and the hydropower scheme calculations. The upstream (adult) and downstream (smolt) migrants are calculated separately.

The cumulative life-stage effects graphs (g and h) represent the total percentage change in fish population within a catchment due to hydropower scheme installations, compared to the pre-scheme (i.e. barriers only). The upstream (adult) and downstream (smolt) migrants are calculated separately from each other and do not incorporate the marine life-stage.

Graph i illustrates the number of adults returning to the catchment following a single life-cycle (assuming no multi-year spawning fish), incorporating the effects of marine survival. Graph j displays the total percentage change in the number of returning adults due to the hydropower scheme scenario tested, compared to the pre-scheme (i.e. barriers only). The results for scenario set 1 are summarised in section 5.2.3.

5.2.1 Scenario set 1 – Scenario 1: Effect of single and multiple hydropower schemes on salmon populations

The purpose of scenario 1 is to demonstrate how between one and six hydropower schemes in a catchment may affect a hypothetical population of salmon. The model was run six times (sub-scenarios 1a to 1f), adding an additional hydropower scheme on a barrier during each successive run. Hydropower schemes were added successively from the downstream-most barrier in sub-scenario 1a, to the upstream-most in sub-scenario 1f.

Sub-scenario 1a

Sub-scenario 1a demonstrates the effects of a single hypothetical hydropower scheme at barrier 1, near the mouth of the river. To simulate the effects of the scenario the passability of barrier 1 was changed from the pre-scheme value as shown in Table 5.5. The downstream passability at barrier 1 is lower after a hydropower scheme is installed; this is due to the passability score incorporating all mechanisms which influence downstream passability (see section 5.1). Thus the reduced passability scenario is possible as a result of adverse effects from those mechanisms, combined with the beneficial effects of fish screening etc.

Table 5.5 Summary of pre-scheme and with-scheme passability scores for one hydropower scheme

Barrier/HP scheme no.	Pre-scheme passability		HP scheme passability	
	Upstream	Downstream	Upstream	Downstream
1	0.72	1.00	0.90	0.95
2	0.91	1.00	Pre-scheme	Pre-scheme
3	1.00	1.00	Pre-scheme	Pre-scheme
4	0.93	1.00	Pre-scheme	Pre-scheme
5	1.00	1.00	Pre-scheme	Pre-scheme
6	1.00	1.00	Pre-scheme	Pre-scheme

When run through the model, the scenario reveals (Figure 5.7):

- A net 17% increase in number of adults spawning upstream of barrier 1 as a result of the improved upstream passability associated with the hydropower scheme (Figure 5.7g). Note, as the carrying capacity of segments 1 and 3 are effectively fully utilised in the pre-scheme scenario, then no benefit is accrued in these segments under the hydropower scenario (Figure 5.7e).
- A net 11% increase in the number of smolts successfully migrating to sea (Figure 5.7h). Note there is a net reduction in smolts reaching the sea from segments 1 and 3, as the starting population of smolts is effectively the same between the pre-scheme and hydropower scheme scenarios, thus the net reduction in downstream passability at barrier 1 causes a negative effect on smolts derived from these segments (Figure 5.7f). Within the other segments, the increase in adult spawners from the increased upstream passability more than offsets the negative effect caused by the decrease in downstream passability.

Thus, the effect of the hydropower scheme installed on the model catchment is an 11% increase in the number of returning adults, compared to the pre-scheme population, after one life-cycle (Figure 5.7j).

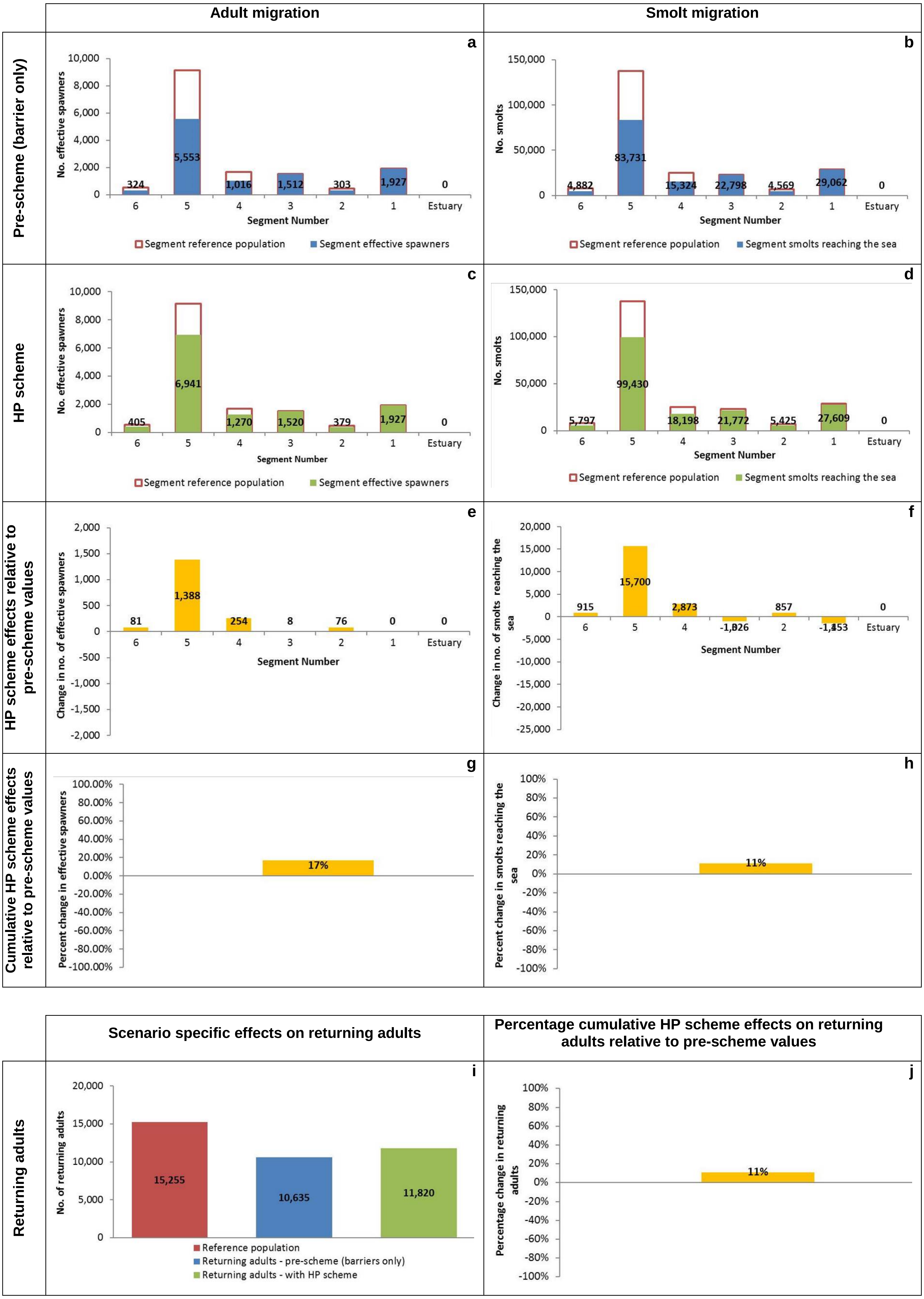


Figure 5.7 Scenario 1a results: effects of a single hydropower scheme on the Coquet salmon population

Sub-scenario 1b

Sub-scenario 1b demonstrates the effects of two hypothetical hydropower schemes at barriers 1 and 2. To simulate the effects of the scenario the passability of barriers 1 and 2 were changed from the pre-scheme value as shown in Table 5.6. Similar to sub-scenario 1a, the upstream passability at barrier 2 is lower after a hydropower scheme is installed; this is due to the passability score incorporating all mechanisms which influence upstream passability (see section 5.1). Thus the reduced passability scenario is possible as a result of adverse effects from, for example, attraction to the turbine tailrace, and the depleted reach, combined with the beneficial effects of a fish pass.

Table 5.6 Summary of pre-scheme and hydropower scheme passability scores for two hydropower schemes

Barrier/HP scheme no.	Pre-scheme passability		HP scheme passability	
	Upstream	Downstream	Upstream	Downstream
1	0.72	1.00	0.90	0.95
2	0.91	1.00	0.90	0.95
3	1.00	1.00	Pre-scheme	Pre-scheme
4	0.93	1.00	Pre-scheme	Pre-scheme
5	1.00	1.00	Pre-scheme	Pre-scheme
6	1.00	1.00	Pre-scheme	Pre-scheme

When run through the model, the scenario reveals (Figure 5.8):

- A net 16% increase in number of effective adult spawners as a result of the greater upstream passability due to the barrier 1 hydropower scheme (Figure 5.8g), which offsets any negative impact on upstream passability from the hydropower scheme on barrier 2.
- A net 6% increase in the number of smolts successfully migrating to sea (Figure 5.8h). Note, while the number of smolts lost from segment 1 is the same as in scenario 1a, a greater number of smolts are lost from segments 2 to 6, as these populations are subject to the cumulative effects of reduced downstream passability at two barriers (Figure 5.8f).

Thus, the cumulative effect of two hydropower schemes installed on the model catchment is a 6% increase in the number of returning adults, compared to the pre-scheme population, after one life-cycle (Figure 5.8j).

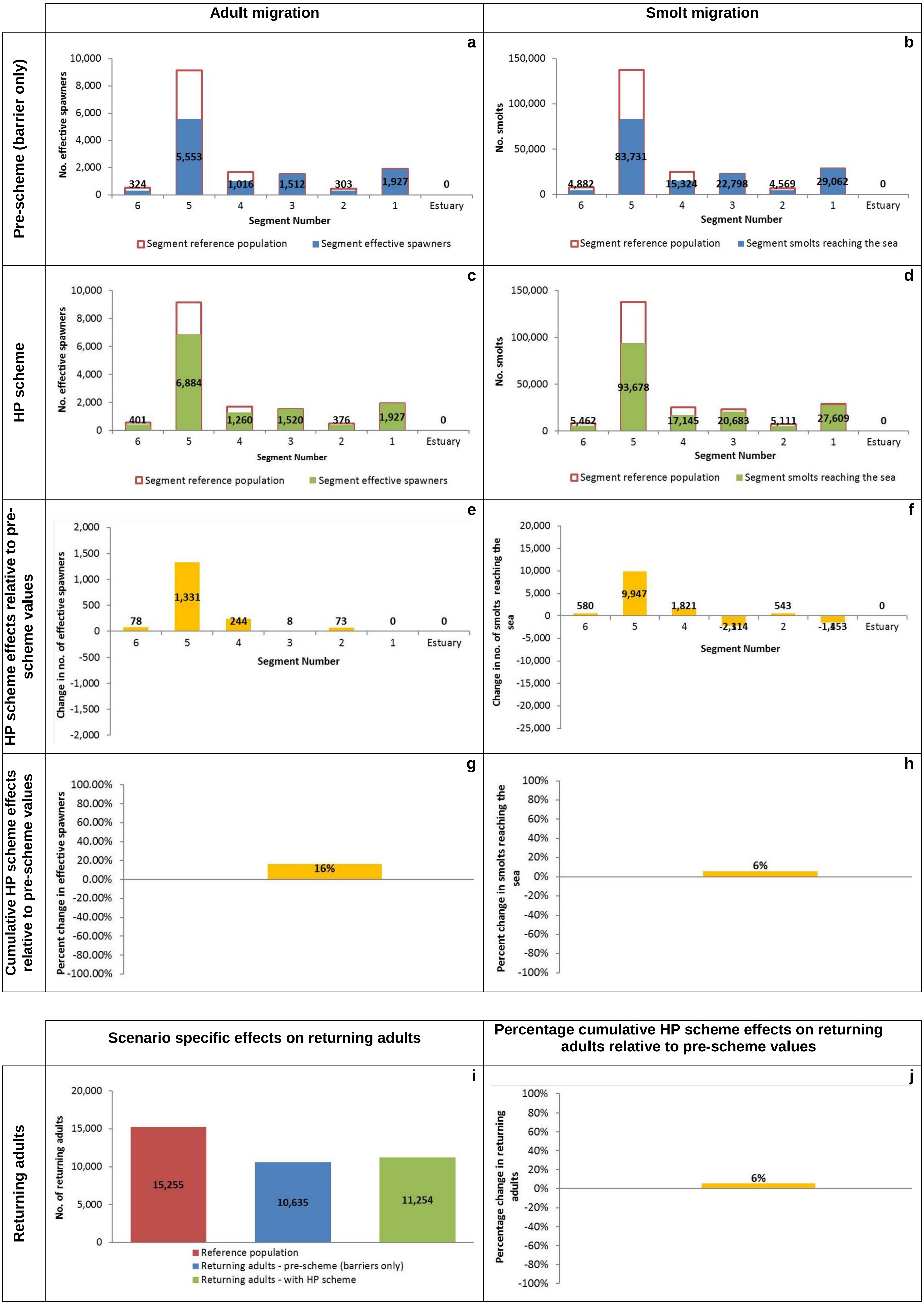


Figure 5.8 Scenario 1b results: effects of two hydropower schemes on the Coquet salmon population

Sub-scenario 1c

Sub-scenario 1c demonstrates the effects of three hypothetical hydropower schemes at barriers 1, 2 and 3. To simulate the effects of the scenario, the passability of barriers 1 to 3 was changed from the pre-scheme value as shown in Table 5.7.

Table 5.7 Summary of pre-scheme and with-scheme passability scores for three hydropower schemes

Barrier/HP scheme no.	Pre-scheme passability		HP scheme passability	
	Upstream	Downstream	Upstream	Downstream
1	0.72	1.00	0.90	0.95
2	0.91	1.00	0.90	0.95
3	1.00	1.00	0.90	0.95
4	0.93	1.00	Pre-scheme	Pre-scheme
5	1.00	1.00	Pre-scheme	Pre-scheme
6	1.00	1.00	Pre-scheme	Pre-scheme

When run through the model, the scenario reveals (Figure 5.9):

- A 9% increase in number of effective adult spawners as a result of the greater upstream passability due to the barrier 1 hydropower scheme (Figure 5.9g). However, the full benefits are offset by reduced upstream passability due to the hydropower schemes at barriers 2 and 3.
- The net benefit to the population from the increased number of effective adult spawners is offset by the reduced downstream passability at all three hydropower schemes, causing a net 5% reduction in the population of smolts successfully migrating to sea (Figure 5.9h).

Thus, the cumulative effect of three hydropower schemes installed on the model catchment is a 5% loss due to the number of returning adults, compared to the pre-scheme population, after one life-cycle (Figure 5.9j).

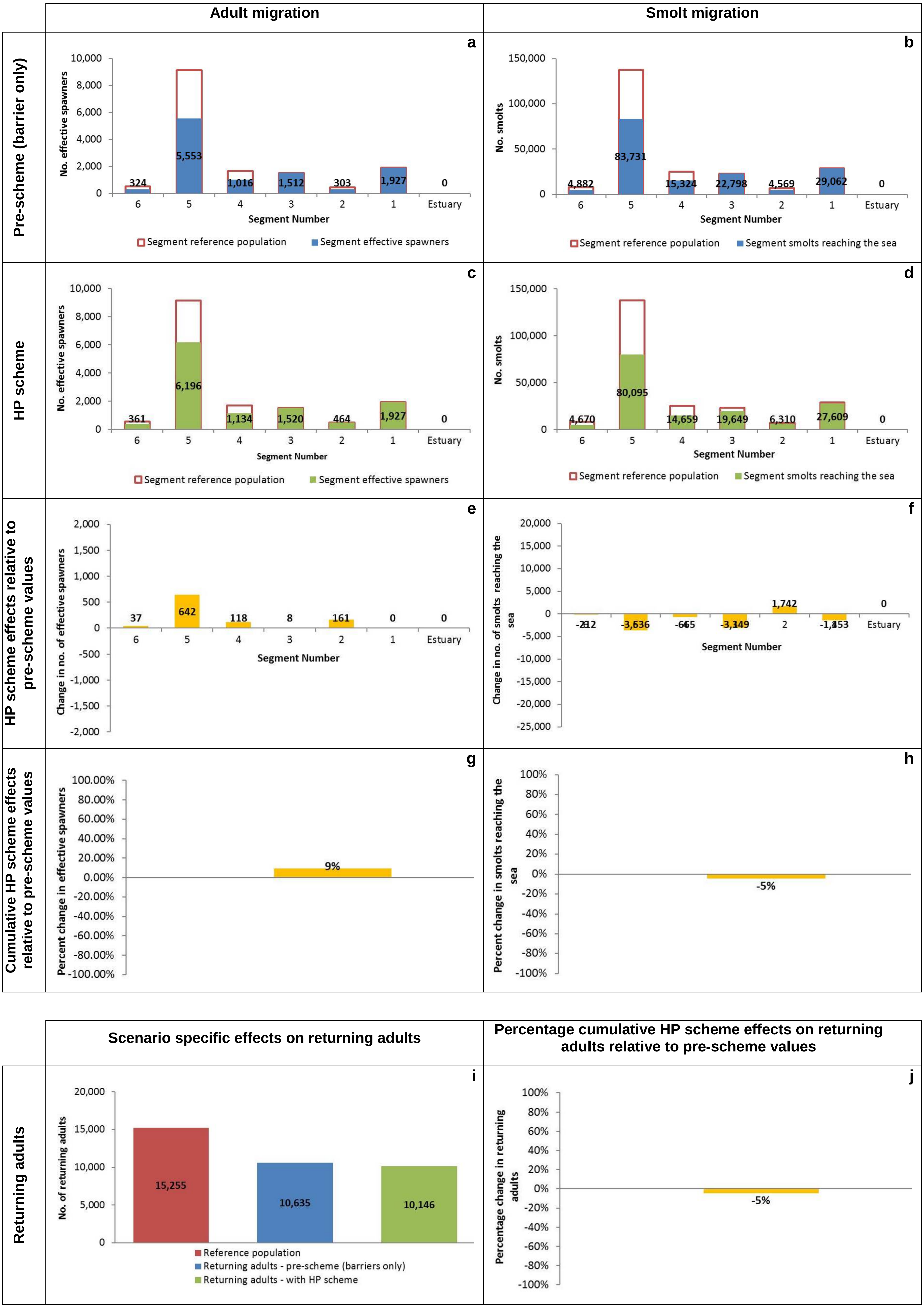


Figure 5.9 Scenario 1c results: effects of three hydropower schemes on the Coquet salmon population

Sub-scenario 1d

Sub-scenario 1d demonstrates the effects of four hypothetical hydropower schemes at barriers 1, 2, 3 and 4. To simulate the effects of the scenario, the passability of barriers 1 to 4 was changed from the pre-scheme value as shown in Table 5.8.

Table 5.8 Summary of pre-scheme and with-scheme passability scores for four hydropower schemes

Barrier/HP scheme no.	Pre-scheme passability		HP scheme passability	
	Upstream	Downstream	Upstream	Downstream
1	0.72	1.00	0.90	0.95
2	0.91	1.00	0.90	0.95
3	1.00	1.00	0.90	0.95
4	0.93	1.00	0.90	0.95
5	1.00	1.00	Pre-scheme	Pre-scheme
6	1.00	1.00	Pre-scheme	Pre-scheme

When run through the model, the scenario reveals (Figure 5.10):

- A net 7% increase in number of effective adult spawners as a result of the greater upstream passability due to the barrier 1 hydropower scheme (Figure 5.10g). However, the full benefits are offset by reduced upstream passability due to the hydropower schemes at barriers 2, 3 and 4.
- The net benefit to the population from the increased number of effective adult spawners is offset by the reduced downstream passability at all four hydropower schemes, causing a 10% reduction in the population of smolts successfully migrating to sea (Figure 5.10h).

Thus, the cumulative effect of four hydropower schemes installed on the model catchment is a 10% loss to the number of returning adults, compared to the pre-scheme population, after one life-cycle (Figure 5.10j).

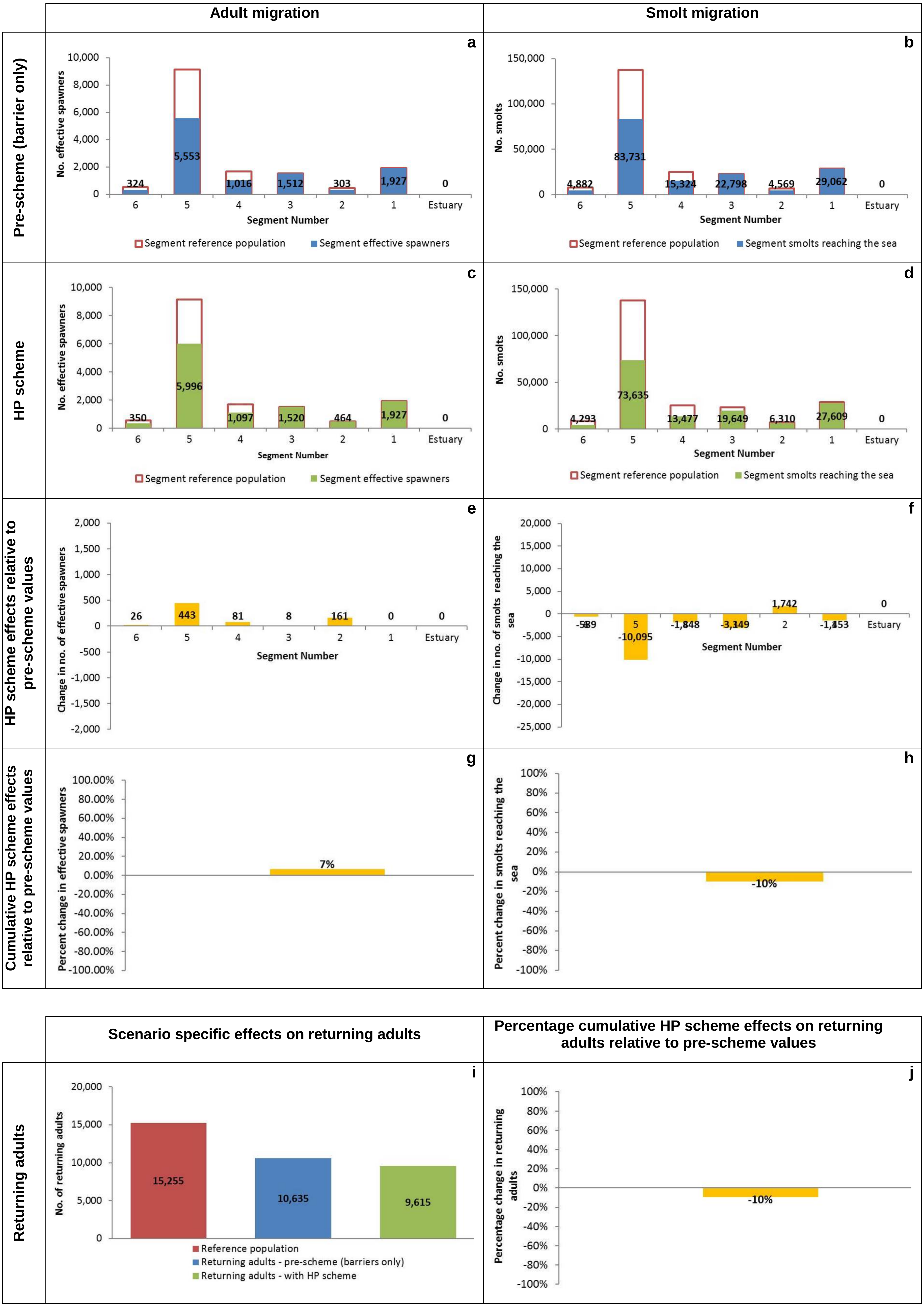


Figure 5.10 Scenario 1d results: effects of four hydropower schemes on the Coquet salmon population

Sub-scenario 1e

Sub-scenario 1e demonstrates the effects of five hypothetical hydropower schemes at barriers 1, 2, 3, 4 and 5. To simulate the effects of the scenario, the passability of barriers 1 to 5 was changed from the pre-scheme value as shown in Table 5.9.

Table 5.9 Summary of pre-scheme and with-scheme passability scores for five hydropower schemes

Barrier/HP scheme no.	Pre-scheme passability		HP scheme passability	
	Upstream	Downstream	Upstream	Downstream
1	0.72	1.00	0.90	0.95
2	0.91	1.00	0.90	0.95
3	1.00	1.00	0.90	0.95
4	0.93	1.00	0.90	0.95
5	1.00	1.00	0.90	0.95
6	1.00	1.00	Pre-scheme	Pre-scheme

When run through the model, the scenario reveals (Figure 5.11):

- A net 6% increase in number of the effective adult spawners as a result of the greater upstream passability due to the barrier 1 hydropower scheme (Figure 5.11g). However, the full benefits are offset by reduced upstream passability due to the hydropower schemes at barriers 2, 3, 4 and 5.

- The net benefit to the population from the increased number of adult spawners is offset by the reduced downstream passability of all five hydropower schemes, causing a 12% reduction in the population of smolts successfully migrating to sea (Figure 5.11h).

Thus, the cumulative effect of five hydropower schemes installed on the model catchment is a 12% loss in the number of returning adults, compared to the pre-scheme population, after one life-cycle (Figure 5.11j).

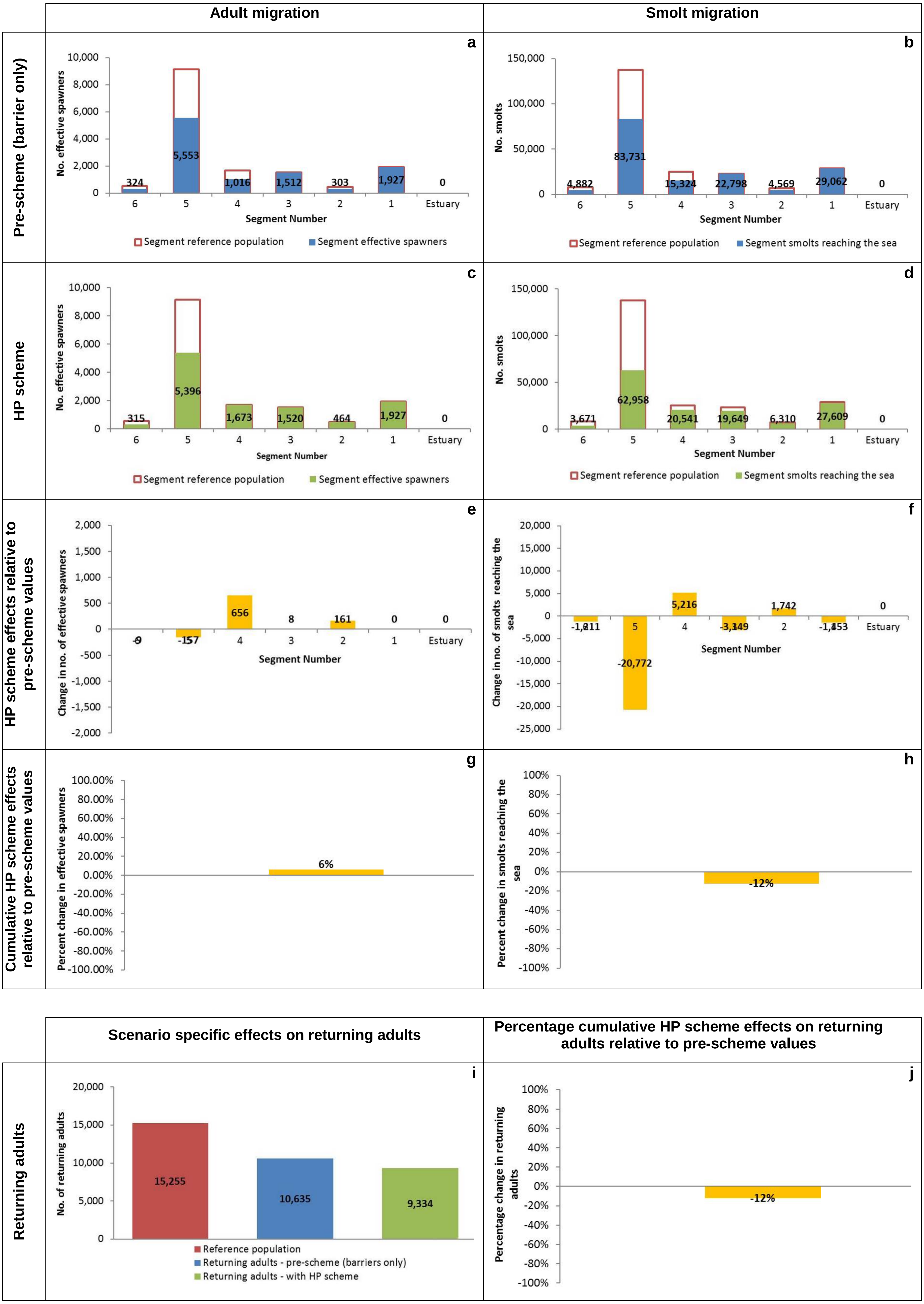


Figure 5.11 Scenario 1e results: effects of five hydropower schemes on the Coquet salmon population

Sub-scenario 1f

Sub-scenario 1f demonstrates the effects of six hypothetical hydropower schemes at barriers 1, 2, 3 4, 5 and 6. To simulate the effects of the scenario, the passability of barriers 1 to 6 was changed from the pre-scheme value as shown in Table 5.10.

Table 5.10 Summary of pre-scheme and with-scheme passability scores for six hydropower schemes

Barrier/HP scheme no.	Pre-scheme passability		HP scheme passability	
	Upstream	Downstream	Upstream	Downstream
1	0.72	1.00	0.90	0.95
2	0.91	1.00	0.90	0.95
3	1.00	1.00	0.90	0.95
4	0.93	1.00	0.90	0.95
5	1.00	1.00	0.90	0.95
6	1.00	1.00	0.90	0.95

When run through the model, the scenario reveals (Figure 5.12**)**:

- A net 6% increase in number of effective adult spawners as a result of the greater upstream passability due to the barrier 1 hydropower scheme (Figure 5.12g). However, the full benefits are offset by reduced upstream passability due to the hydropower schemes at barriers 2 to 6.
- The net benefit to the population from the increased number of effective adult spawners is offset by the reduced downstream passability of all six hydropower schemes, causing a 12% reduction in the population of smolts successfully migrating to sea (Figure 5.12h).

Thus, the cumulative effect of six hydropower schemes installed on the model catchment is a 12% loss to the number of returning adults, compared to the pre-scheme population, after one life-cycle (Figure 5.12j).

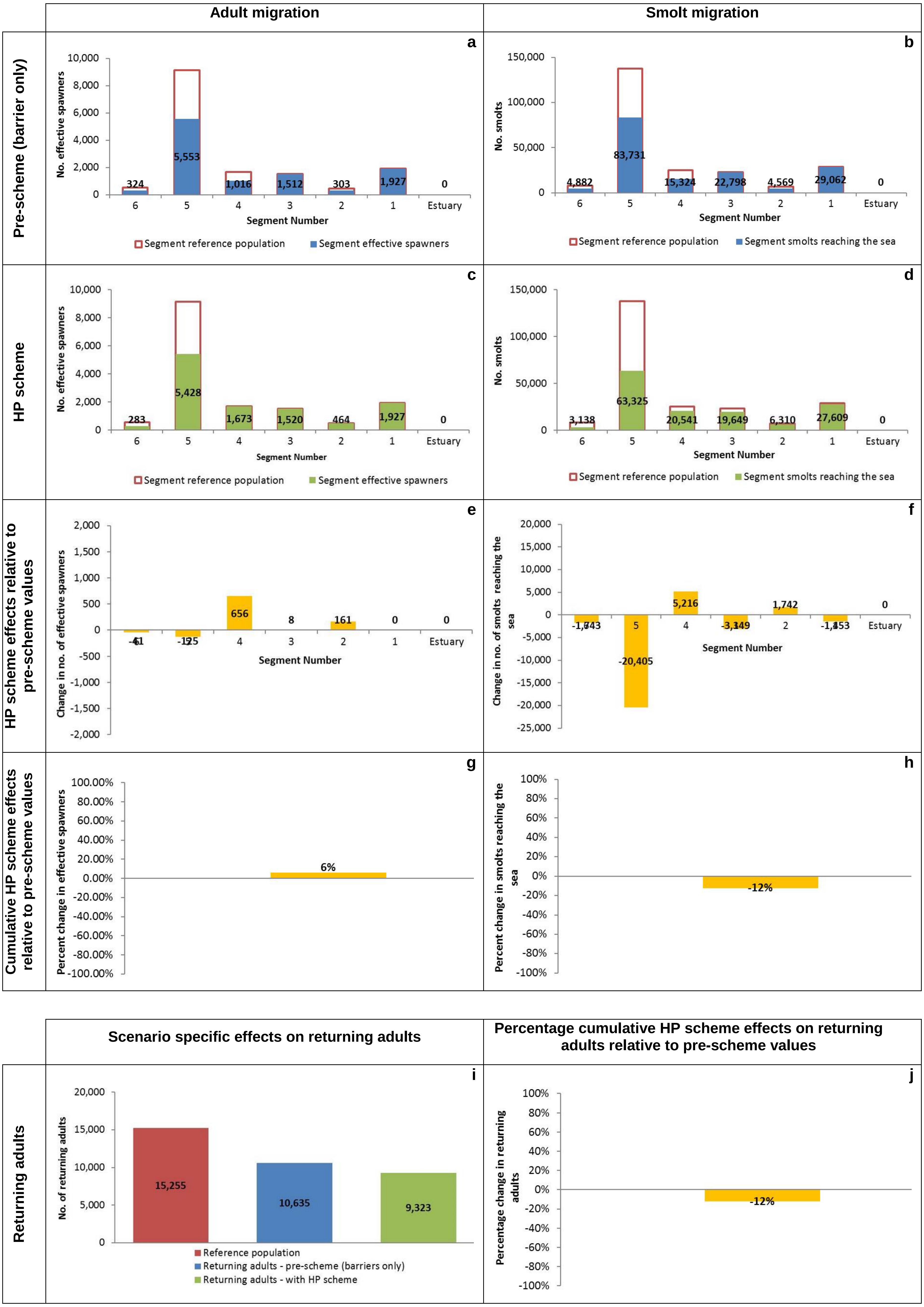


Figure 5.12 Scenario 1f results: effects of six hydropower schemes on the Coquet salmon population

5.2.2 Scenario set 1 – Scenario 2: Comparative effect on the population from a low and high catchment located hydropower scheme

Scenario 2 incorporates a single hypothetical hydropower scheme installed on the upstream-most of the six barriers (barrier 6). To simulate the effects of the scenario, the passability of barrier 6 was changed from the pre-scheme value as shown in Table 5.11.

Table 5.11 Summary of pre-scheme and with-scheme passability scores for one hydropower scheme in the upper catchment

Barrier/HP scheme no.	Pre-scheme passability		HP scheme passability	
	Upstream	Downstream	Upstream	Downstream
1	0.72	1.00	Pre-scheme	Pre-scheme
2	0.91	1.00	Pre-scheme	Pre-scheme
3	1.00	1.00	Pre-scheme	Pre-scheme
4	0.93	1.00	Pre-scheme	Pre-scheme
5	1.00	1.00	Pre-scheme	Pre-scheme
6	1.00	1.00	0.90	0.95

When run through the model, the scenario reveals (Figure 5.13):

- A reduction (compared to pre-scheme) of 32 adults able to obtain passage into segment 6. However, due to a surplus of habitat in segment 5 (caused by barriers further downstream preventing this segment being populated by adults to the extent required to enable its reference population to be met), these adults unable to pass the barrier are able to effectively spawn in segment 5 (Figure 5.13e). There is therefore no net reduction in effective spawning adults as a result of the hydropower scheme.

- From the fish able to spawn in segment 6, 4,393 smolts are produced, of which 220 are lost as a result of the reduced downstream passability of the hydropower scheme (figures not shown on graphs). Thus the net effect of reduced smolt production in segment 6, and reduced downstream passability, leads to a reduction of 708 smolts reaching the sea from segment 6 compared to the pre-scheme scenario.

- This adverse effect is, however, offset by the additional smolts that are produced and successfully migrate to sea from segment 5. Thus the total reduction in smolts compared to the pre-scheme population is 220 fish which equates to a 0.14% reduction in total catchment smolts, compared to the pre-scheme population; as shown in Figure 5.13h.

Thus, the effect of the hydropower scheme installed on the model catchment is a 0.14% loss to the number of returning adults, compared to the pre-scheme population, after one life-cycle, which equates to 15 adult fish (Figure 5.13j).

As would be expected, this effect is significantly smaller compared to the impact of a comparable scheme at the mouth of the river (sub-scenario 1a), highlighting the importance of catchment location. For example, due to the upstream location of barrier 6, the hydropower scheme can only affect a maximum of 3% of adult fish in the catchment compared to the sub-scenario 1a hydropower scheme, which may affect 100% of the population that are seeking to migrate past the scheme.

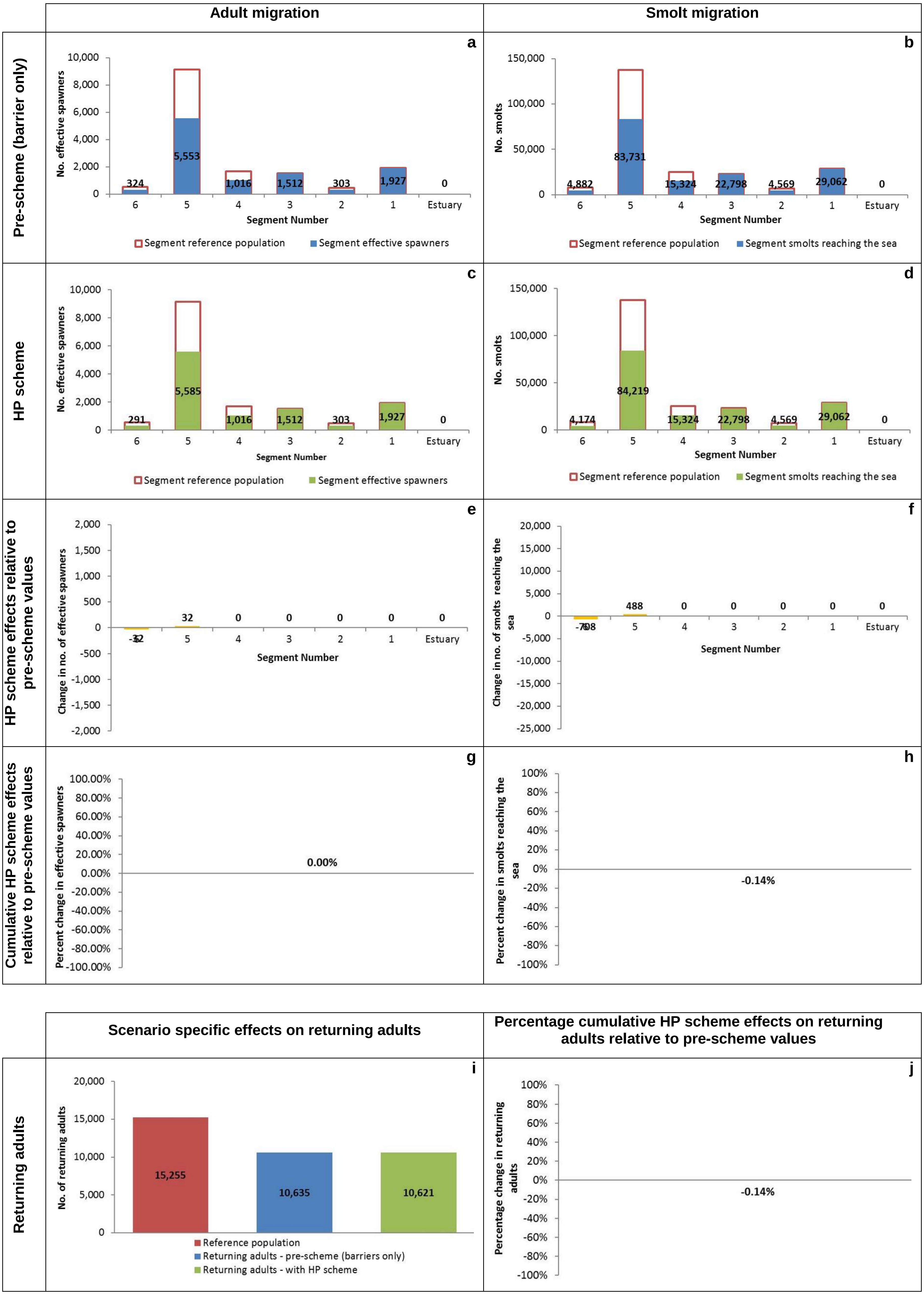


Figure 5.13 Scenario 2 results: effects of one hydropower scheme situated at the top of the catchment, on the Coquet salmon population

5.2.3 Summary of scenario results

For the scenarios run through the model, the overall effects on the population size of returning adults can be seen in Tables 5.12, 5.13 and 5.14 for scenario sets 1, 2 and 3 respectively.

Table 5.12 Results for scenario set 1, run using the Environment Agency obstructions database and local knowledge for determining passability of existing structures

Scenario	No.	Description	% change in adults from the pre-scheme population
Cumulative effects assessment of one to six hydropower schemes	1a	Single HP scheme in the lower catchment (at barrier 1)	11%
	1b	Two HP schemes (at barriers 1 and 2)	6%
	1c	Three HP schemes (at barriers 1, 2 and 3)	-5%
	1d	Four HP schemes (at barriers 1, 2, 3 and 4)	-10%
	1e	Five HP schemes (at barriers 1, 2, 3, 4 and 5)	-12%
	1f	Six HP schemes (at barriers 1, 2, 3, 4, 5 and 6)	-12%
Scheme location effects	2	Single HP scheme in the upper catchment (at barrier 6)	-0.14%

Table 5.13 Results for scenario set 2, run using the Environment Agency obstructions database only for determining passability of existing structures

Scenario	No.	Description	% change in adults from the pre-scheme population
Cumulative effects assessment of one to six hydropower schemes	1a	Single HP scheme in the lower catchment (at barrier 1)	9%
	1b	Two HP schemes (at barriers 1 and 2)	18%
	1c	Three HP schemes (at barriers 1, 2 and 3)	7%
	1d	Four HP schemes (at barriers 1, 2, 3 and 4)	16%
	1e	Five HP schemes (at barriers 1, 2, 3, 4 and 5)	13%
	1f	Six HP schemes (at barriers 1, 2, 3, 4, 5 and 6)	12%
Scheme location effects	2	Single HP scheme in the upper catchment (at barrier 6)	-0.12%

Table 5.14 Results from scenario set 3, run where passage mitigation at a hypothetical hydropower scheme installed at site 3 does not function as expected, and using the Environment Agency obstructions database for determining passability of existing structures

Scenario	No.	Description	% change in adults from the pre-scheme population
Cumulative effects assessment of one to six hydropower schemes	1a	Single HP scheme in the lower catchment (at barrier 1)	9%
	1b	Two HP schemes (at barriers 1 and 2)	18%
	1c	Three HP schemes (at barriers 1, 2 and 3)	-1%
	1d	Four HP schemes (at barriers 1, 2, 3 and 4)	7%
	1e	Five HP schemes (at barriers 1, 2, 3, 4 and 5)	5%
	1f	Six HP schemes (at barriers 1, 2, 3, 4, 5 and 6)	5%
Scheme location effects	2	Single HP scheme in the upper catchment (at barrier 6)	-0.12%

The results in Table 5.12 show that an individual scheme can have positive and negative effects, with the magnitude of effect controlled by: (1) position in the catchment, (2) scheme design and (3) pre-scheme (existing barriers only) effects. Based on the passability scores selected for the proposed scheme, the results show that cumulative effects are measurable; however, the magnitude of effect is controlled by the site-specific aforementioned three variables.

These scenarios therefore draw out some interesting management opportunities; for instance, due to the hypothetical low passability at barrier 1, the benefits in fish passage from the placement of a hydropower scheme (specifically its improved fish pass) mean that the adverse effect of any one scheme on barriers 2 to 5 can be offset. However, this benefit is rapidly reduced with multiple schemes. In the event of an adverse effect at barrier 1, the net effect of multiple schemes upstream would be much worse. This demonstrates that the effect of a hydropower scheme (positive or negative) is increased when a scheme is installed lower in the catchment (i.e. position of the scheme in the catchment can have significantly different effects on the fish populations).

The results in Tables 5.13 and 5.14 demonstrate the importance of data input quality. By running the various sets of scenarios with two different data sources for determining the existing structure passability scores (i.e. using only the Environment Agency obstructions database versus the addition of local knowledge), it can be seen that there is a large effect on the percentage change in adult salmon as a result of the incorporation of local knowledge. When only the Environment Agency obstructions database is used, the passability of structures 2 and 4 are much lower, and thus the baseline population (prior to the installation of hypothetical hydropower schemes) is lower and the installation of a best practice hydropower scheme can create a significant benefit. However, when the passability scores at barriers 2 and 4 are validated against local knowledge, and, in this case, adjusted upwards, the benefit accrued by a fish pass as part of a hydropower scheme is much less. This demonstrates how the accuracy of the data input into the model is key for accurately determining the potential effects of hydropower schemes on fish populations. In other locations the opposite effect might have been observed.

Furthermore, when the mitigation provided in a single hypothetical hydropower scheme does not operate as expected (i.e. the hydropower scheme passability scores at site 3 (scenario set 3) were operating 5% lower than expected), there was a large effect on the subsequent percentage change in adult salmon numbers predicted by the model. For example, when six hypothetical hydropower schemes were installed on the catchment the model predicted a 12% increase in population under best practice functioning hydropower schemes (scenario set 2), whereas this reduced to 5% when only one scheme was operating at just 5% less efficiency. This demonstrates (a) the effects that uncertainty relating to passability at hydropower schemes can have on the model results and (b) the importance of ensuring that mitigating measures function to the minimum expected level of passability; this may require post-installation monitoring to evaluate.

The range of potential impacts generated by the scenarios we tested is from -12% (negative impact) to +18% (positive impact) on the catchment salmon population (for one whole Salmon life cycle). To put these impacts into context salmon exploitation rates by angling for the nearby Tyne catchment, where data are available, are estimated to be between 10 and 20% although the % of fish caught (but later released) is up to 40%; based on date for the year 2013 (International Council for the Exploration of the Seas (ICES) 2013). Quantitative impacts from other types of pressures on salmon are not readily available for comparison.

From the scenarios run, the following conclusions can, therefore, be drawn:

Scenario conclusion 1: The magnitude of a single hydropower scheme effect is determined by the:

- effect of the existing structure (if one is present);
- scheme design;
- scheme location within the catchment.

Scenario conclusion 2: Based on a limited set of scenarios the cumulative effect of multiple schemes can be beneficial or adverse, dependent upon the number of schemes, and the site-specific effects at each individual scheme.

Scenario conclusion 3: Model accuracy is highly dependent upon both accurate assessment of baseline barrier effects and accurate prediction (verified where possible by monitoring) of hydropower effects including mitigation efficacy.

6 Conclusions and recommendations

The primary hypothesis tested during this study was ‘can hydroelectric power schemes result in cumulative effects upon migratory fish populations, and are these significant?’ The findings are that cumulative effects can occur, but these can be positive or negative depending on the net consequence of many individual schemes, each of which can have a positive or negative effect.

Critically, fish passage measures are included within the model as part of the ‘scheme’, reflecting the requirement in most instances for new hydropower schemes to incorporate fish passes. Consequently, there is significant potential for schemes to have net (i.e. accounting for other aspects of the scheme, which may be adverse) beneficial effects in terms of allowing improved fish passage, and this effect was demonstrated in the modelled scenarios. The potential for such beneficial effects will depend on the impacts of pre-existing barriers, and the scope for beneficial effects from hydropower schemes (via associated fish passage measures) which will be less where the effect of pre-existing barriers on fish migration is low. The reliability of model outputs is highly dependent on quantification of barrier passability.

The significance both of pre-existing barriers and scheme-associated fish passes in determining model outcomes, highlights the potential constraints to the model associated with the challenges of reliably assigning values to these attributes. Thus, it is desirable to reduce this uncertainty as much as possible, by basing barrier impact scores on bespoke assessment of barrier passability (e.g. by using the WFD111 assessment methodology). If such information is not available or attainable, the uncertainty associated with estimating passability based on less robust information should be recognised in operating the model, and interpreting its outputs.

A key feature of hydropower scheme effects, as reflected in the model, is that the effects are dependent in part on the status of the population, and in particular the utilisation of habitat in adjacent segments. This is illustrated well in scenario 2 (for all scenario sets), where despite a reduction in upstream passability preventing salmon from spawning in the upstream reach, the availability of habitat in the downstream reach results in no effective loss to the population due to reduced upstream passage, and only a marginal net loss factoring in entrainment/impingement losses. This conclusion assumes that a salmon will spawn anywhere if it cannot reach its preferred spawning ground, which may not always happen. The scenarios also highlight the importance of scheme position in the catchment, with schemes lower down having greater potential benefit and dis-benefit on the population as a whole compared to schemes located upstream (although this is complicated by the presence of available habitat; as discussed above).

The scenarios tested in this study used hypothetical schemes with a hypothetical salmon population, albeit in a realistic situation. The conclusions are not necessarily transferable to other species and the model outputs may be quite different in catchments with different types of in-river barriers and choice of schemes.

6.1 Wider applicability of the model

A further aim of this study was to determine if and how wider impacts on, or benefits to, migratory fish, can be considered alongside hydropower scheme effects. Barriers are a key constraint for many diadromous fish species, and this impact was incorporated as a core part of the model, while enabling barrier effects to be expressed distinctly from the effects of hydropower schemes.

The model can already be used to explore the impact of different existing barriers on salmon populations. But the model also lends itself ideally to incorporation of wider influences, by enabling attribution of different survival rates to various life-stages in the model (e.g. simulating improved riverine habitat conditions), or numerical losses (e.g. increased rod exploitation or predation) or gains (e.g. stocking or increased rate of catch and release). Additionally, the spatially explicit nature of the model enables effects to be quantitatively attributed to specific parts of the catchment, which means that localised population effects (e.g. on a particular tributary) can be elucidated as well as effects to be fed through to the catchment population level. For many of the more abstract non-hydropower scheme influences (e.g. adoption of sympathetic land management) the challenge will be in relating the effect in question to changes in survival, which need to be manually entered into the model.

The model can provide decision-makers with a means to quantify the individual and cumulative effects of schemes, where sufficient information on barrier passability is available. At present this is not an operational permitting tool but it could be developed to explore catchment-scale effects of hydropower in more detail with the potential to account for wider catchment pressures. A number of model strengths, limitations and areas requiring further development have been identified, and are summarised in the following sections.

6.2 Model strengths

The development of a cumulative effects model first required a method for quantifying single scheme effects. The subsequent model component developed for this purpose provides a new tool in the quantification of hydropower effects on salmon, with potential for extension to other species.

Through incorporation of the spatial and life-cycle model components, the model links multiple hydropower scheme effects on all stages of the salmon life-cycle population, allowing the impacts at each stage to be quantified.

The scenario testing has demonstrated the value in applying the model in a strategic capacity to facilitate forward planning. However, with development, the model is flexible enough to be used in a real-time role to inform the consenting process.

Other strengths include:

- The model was developed in Microsoft Excel, and does not require GIS beyond the initial catchment set-up process, thus extending its potential.
- The model utilises universally available datasets that are widely applicable to other catchments.
- There are no ‘hard wired’ values in the model, and therefore it is possible to update/amend various values (e.g. the life-cycle model, the barrier passability values, or the specific impingement/entrainment values) according to expert judgement or new evidence (e.g. actual fish population values from surveys).
- The spatial population model utilises the same factors as the Environment Agency’s conservation limit calculations; however, using the Detailed River Network database provided a greater level of efficiency, transferability and transparency in determining catchment carrying capacity, compared to the conservation limit paper based approach.

Finally, other than the hydropower scheme effects, currently the model only incorporates the additional pressure of impoundments on the watercourse (these could not be ignored due to the inherent association of hydropower schemes with a barrier causing a head loss). Due to its interrogative nature, the model will allow the incorporation of any other pressures on the fish population. By using the spatial population element of the model, and also because of the way the Excel spreadsheet has been designed, the effects of each pressure on the fish population can be assessed separately, and thus the most important pressures on a catchment can be isolated and used to inform targeted management and mitigation.

6.3 Model limitations

The model in its current form provides a prototype tool, with the functionality for strategic planning of hydropower schemes, at least in terms of understanding their impacts on salmon populations. There are, however, model limitations associated with (i) the input data, (ii) our knowledge of hydropower effects, (iii) how these effects are applied to the salmon population and (iv) how the species life-cycle is simulated. The most significant limitation of the model is the availability and accuracy of input data (e.g. Table 6.1**)**. A key strength of the model is its use of universal Environment Agency datasets, such as the river obstructions database and the Detailed River Network; however, the study has demonstrated that such datasets incur large error margins, which currently can only be addressed through site-specific investigations.

Our understanding of hydropower direct effects such as fish pass efficiency, turbine entrainment and screen impingement are limited to case studies that predominantly focus on high head schemes. Our understanding of indirect effects, such as increased predation caused by delay and delay in general, is even less well understood. Where possible, values have been obtained from the literature; however, for indirect effects we relied on expert judgement.

Table 6.1 Summary of the major levels of uncertainty in the data available for use in the model

Factor	Level of uncertainty (%)	Method uncertainty attained
Height of existing barrier	251 to 2,609%*	Difference between Environment Agency staff observations and the Environment Agency obstructions database
Fish pass efficiency	25 to 100% efficient	Environment Agency fish pass manual (Environment Agency 2010a)
	21.1 to 61.7% efficient	Noonan *et al*. (2012) – review of 65 articles
Accessible wetted area	69.4%	Difference between the area calculated for deriving the original Environment Agency conservation limit and that used in the current model derived from the Detailed River Network
Structure passability	±25% (although likely higher due to a lack of structure-specific information)	WFD111 method

* Obstructions database indicates existence of structures well but is unreliable as a source of height data on its own.

Other limitations include:

- The model has been designed to readily allow incorporation of other species. However, information concerning the spatial population and life-cycle elements may not yet be available for many other species.
- The model utilises a linear relationship between spawners/egg deposition and fry in the next generation, up to a point where density dependence caps fry numbers in the next generation. A function for non-linear density

dependence (e.g. the Ricker stock–recruitment curves) may better reflect the actual stock– recruitment relationship. However, this is likely to be a less significant constraint to the model than the ability to assign structure passability, for example.

- The model provides information on the relative population effects of hydropower schemes compared to a barrier without such a scheme. The model is not currently set up to include the full range of non-hydropower scheme pressures required to determine absolute effects on populations, although a solution to this could be achieved by incorporating actual (observed), rather than reference, fish population densities. Observed densities would effectively account for all pressures acting on the population.
- Finally, the model only simulates one full life-cycle (generation). Developing the model to account for multiple successive generations would require incorporation of environmental and demographic stochastic processes beyond the scope of this study.

6.4 Further development of the model

A number of additional steps could help to develop the model further. These are outlined below, in order of suggested priority:

- ***Improved estimates of hydropower scheme effects:*** The values used for passability of fish passes, turbines and screens are taken from peer-reviewed and grey literature. However, as more accurate information becomes available (e.g. via the Environment Agency's ongoing project, 'Testing the effectiveness of fish screens for hydropower intakes') this could be incorporated into the model.
- ***A programme of sensitivity testing:*** The scenarios run as part of the current project provide an initial insight into the functioning of the model, and the consequences of a small number of hydropower scheme scenarios. However, the model would benefit from a more comprehensive programme of sensitivity testing, via manipulation of the three model elements (spatial population, scheme effects and life-cycle elements). This would seek to:
    - increase understanding of the relationships between input and output variables;
    - identify model inputs that cause significant uncertainty in the output, which should therefore be the focus of attention if the robustness is to be increased;
    - simplify the model, for example by fixing model inputs that have little or no bearing on the output;
    - enhance communication from modellers to decision-makers.
- ***Clarification of the significance of flow-related impacts on productivity of freshwater life-stages:*** Although the model makes provision for incorporating population-level effects resulting from reduction in habitat in any depleted reach, detailed development of this element was beyond the scope of the current study. Furthermore, it was not specified as an element to be tested within the scenarios. It is likely that such effects are relatively unimportant compared to other modelled hydropower scheme

effects, but a fuller clarification of this, as part of the sensitivity analysis, would determine to what extent, if any, this scheme effect needs to be further developed.

- ***Clarification of the significance of flow-related impacts on migration through the depleted reach:*** Migratory impediment in the depleted reach was identified as being a specific concern in section 3. However, its significance was not tested within the scenarios. The importance of this effect could be explored as part of the sensitivity analysis. This will require applying a likely range of effect values for this parameter, which will itself require investigation, as flow effects on fish migration are a notoriously difficult impact to quantify.

- ***Knowledge exchange:*** Following any refinement of the model based on the sensitivity analysis undertaken, a user manual and training course for a group of trial users/developers may be required.

- ***Trial set-up of the model*:** The model established under this project uses hypothetical values for a number of elements – most notably in respect of the life-cycle element. A valuable exercise might be for an independent practitioner with detailed knowledge of a catchment to set up the model (i.e. spatial population and life-cycle elements, and barrier passability) *de novo* for that catchment, seeking to accurately reflect conditions and stock status therein. This exercise would: (a) determine the practicalities of an independent party (i.e. not one of the report authors) establishing the model, in terms of technical challenges and time requirements, thus informing the scale of resources required for a wider roll-out, and (b) provide a further element of sensitivity testing.

- ***Incorporation of a more sophisticated salmon life-cycle element:*** The incorporation of a more sophisticated life-cycle element will provide a more accurate output concerning the effect of hydropower schemes on the catchment population (e.g. to account for survival rates fluctuating dependent on the population status). The current model developed for this study utilises a simplistic life-cycle model, based on fixed survival rates between salmon life-stages taken from the Environment Agency's conservation limit calculations for the River Coquet. Extensive and ongoing research has been carried out into the salmon life-cycle, and sophisticated models have been developed to incorporate, for example, environmental and genetic stochasticity (Wyatt and Barnard 1997b). The incorporation of such models into the method may improve simulation of intra-life-stage effects and project hydropower scheme (and barrier) effects beyond one life-cycle, to determine long-term viability.

- ***Extending the model to other species:*** The model could be explored for a number of other species. However, eel is arguably the species with the greatest need for assessment (based on its vulnerability to hydropower effects and conservation significance), and that which provides the best prospects of producing a useable output, due to the increasing development of eel life-history data for input into the model (e.g. Walker *et al.* 2013). A constraint in using the model for other species relates to the relative absence of comparable life-cycle and stock–recruitment models for species other than salmon (and in part, eel).

- ***Improved existing barrier passability data and how this in turn relates to population effects:*** Reliable estimation of passability of existing barriers is dependent on structure dimensions and hydraulic conditions. As with any model, accuracy is dependent on the quality of input data, and improvements to data quality may significantly improve model output accuracy. In addition, a better understanding of indirect barrier and hydropower effects (associated with delay) is likely to improve the accuracy of the model output.

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List of abbreviations

BAP = Biodiversity Action Plan

CC = carrying capacity

DRN = Detailed River Network

DS = downstream

GIS = Geographical Information System

LiDAR = light detection and ranging (or light radar) remote sensing

RBD = River Basin District

HP = HydroPower

SAC = Special Area of Conservation

SAP = Salmon Action Plan

SAR = synthetic aperture radar (remote sensing)

SEPA = Scottish Environmental Protection Agency

SNIFFER = Scotland and Northern Ireland Forum for Environmental Research

SPR = scheme passage rate

US = upstream

WFD = Water Framework Directive

Appendix A: Case studies

As discussed in section 2.1, cumulative effects of multiple hydropower schemes described in the literature are, in many cases, not directly applicable to the situation in England. Research is focused on large-scale hydropower schemes, mainly in the Pacific North West of the USA (i.e. the Colombia River system) and China, with some research undertaken at large schemes in the Nordic region. Much of the research for cumulative effects concerns barriers rather than hydropower schemes. Furthermore, the overwhelming majority of research (58%) concerning fish passage facilities has focused on salmonids (Roscoe and Hinch 2010). These research biases are reflected in the studies presented in this appendix. Generally, the case studies are based on larger schemes than found in England; however, the principles by which fish migration is impacted in a cumulative way are still applicable. Indeed, Robson *et al*. (2011) identified that although the available literature concerning the impacts of hydropower schemes on fish generally concerns larger schemes than those in the UK, the potential impacts largely remain the same, irrespective of the scale of the scheme. Studies concerning the effect of low and high head schemes and barriers on fish are reviewed here, to demonstrate the high variation in effects from such schemes. A review of projects where cumulative effect assessment modelling has been carried out is also provided.

Single site and cumulative effect migration studies

Upstream migration – high head schemes

High head barriers can have dramatic effects on fish populations including diminished access to upstream spawning habitat and increased mortality for downstream migrants. A number of detailed studies on their effects on diadromous species have been undertaken, including in the USA, UK and Sweden. The following studies describe the cumulative effects on fish passage from hydropower schemes that **comprise either a single or series of high head barriers made passable by fish lifts or ladders**. The studies illustrate the potential effects of hydropower schemes and impoundments on fish, but are not necessarily the types that would be licensed through the Environment Agency guidance for run-of-river hydropower development (Environment Agency 2013).

Gowans *et al*. (2003) carried out a radio tracking and electromyogram study on Atlantic salmon migrating up the River Conon in Ross-shire, northern Scotland. The river was developed for hydropower generation between 1941 and 1961 and includes a system of tunnels and dams, with fish passage provided by two Borland fish lifts for the larger dams and two pool and over-fall passes for smaller barriers. Between 63 and 100% of tagged fish passed individual barriers. The cumulative effect was that only 4 of the 54 tagged fish reached suitable spawning habitat, with mortality from predation, fungal disease and stranding during passage being identified as some of the limiting factors, in addition to the barrier itself hindering passage, and unwillingness of fish to enter the fish passes. Fish were delayed by up to 41 days at the pool and over-fall fish passes and up to 52 days at the Borland fish lifts. A further potential factor limiting the number of migrants reaching the upstream spawning grounds (not mentioned in the article) is whether they would have naturally migrated to the region upstream of the barriers. The fish were trapped and tagged downstream of the identified spawning grounds as returning adults, and thus it is uncertain as to whether they would naturally have opted to migrate upstream of all of the barriers.

A number of studies on the effects of hydropower on anadromous fish have been carried out on the Columbia River, USA. Moser *et al.* (2002) analysed the effects of three dams (Bonneville, The Dalles and John Day) on upstream passage of Pacific lamprey (*Lampetra tridentata*) by radio tagging 147–299 fish annually between 1997 and 2000. Passage efficiency and time to pass ranged between 38 and 82% and 2.0 and 5.7 days per scheme respectively. Only 3% of fish passed upstream of all three dams. Lamprey took four times longer to pass Bonneville Dam than Chinook salmon (the fish passes were designed for salmonids), and passage efficiency never exceeded 50% (Chinook salmon efficiency was observed at 96%; Bjorn *et al.* 2000). Water velocity was found not to be a limiting factor affecting passage, instead cumulative physical affects including bright lighting and confusing currents were thought to be responsible.

Long-term studies on Atlantic salmon migration have been carried out at Stornorrfors hydropower station, Sweden, consisting of four Francis turbines and a fish ladder providing passage mitigation. Flow from the turbines is discharged several kilometres downstream. In 1997 only 26% of wild salmon migrating upstream from the river mouth (32 km downstream of the hydropower scheme) successfully reached the fish ladder. Discharge through the turbines had a significant effect of diverting salmon to the turbine outlet, away from the fish pass entrance (Rivinoja *et al.* 2001). A further radio tracking study on the same system was undertaken between 1995 and 2005. Of 2,651 fish radio tagged at the river mouth, only 0–47% per year (mean = 30%) successfully reached the fish pass. The average duration to swim the 32-km stretch was 44 days, with delays incurred at both natural (e.g. waterfalls) and anthropogenic obstacles, including a diversion to the hydropower scheme outlet during high turbine flows relative to the main river (Lundqvist *et al.* 2008). Whether the fish would naturally have migrated upstream of the barriers is uncertain, and natural losses due to, for example, predation are also potentially attributable to the overall loss of fish.

Downstream migration – high head schemes

Survival estimates for downstream migrating juvenile Chinook salmon and steelhead, were calculated by Williams *et al.* (2001) through the hydropower system on the upper Snake and Columbia Rivers, USA. Three distinct time periods were analysed over which hydropower development changed significantly. During the 1960s the rivers had four hydropower schemes with overall downstream migration survival rates of 32–56%. A further four schemes were constructed in the 1970s, reducing downstream migrant Chinook salmon survival to 10–30% (but only 3% during drought years). Structural and operational changes to the hydropower system in the 1990s, including the construction of juvenile bypass systems and modification to the spill conditions, returned survival rates to the approximate levels observed during the 1960s (31–59%). Details of the factors contributing to mortality change were not included in the article.

The downstream migrations of Atlantic salmon and brown trout smolts were studied at two Swedish hydropower stations (Stornorrfors and Piteälven) on the rivers Umeälven and Vindelälven respectively (Rivinoja *et al.* 2004). No passage facility was provided at the hydropower schemes for downstream migration and thus smolts passed via the fish ladder, dam spillway or turbines. Smolts mainly migrated within the region of the river where water velocities were highest. Fish migration was tested under both normal and altered dam spills; the majority of flow was through the turbines and thus all migrants at Stornorrfors and the majority at Piteälven passed via this route. No downstream migrants utilised an alternative and relatively safe passage route (i.e. the fish ladder, or dam spillway). Mortality through the turbines was not included in the article.

Upstream migration – low head schemes

Low head barrier effects are less dramatic than high head; however, there are generally far more of them, thus the cumulative effects may be greater (Lucas and Baras 2001). Lucas *et al*. (2009) undertook a radio tracking study on adult river lamprey in the lower River Derwent between 2002 and 2006, to assess their ability to pass a series of low head (2–3 m) barriers, including the Barmby Tidal Barrage at the river mouth. Only 18% (annual variation of 0–39%) of the lamprey released downstream of the barrage (n = 57) ascended it, attributed to locking of the gates for much of the tide cycle. The next barrier upstream (Elvington Sluices) passed 64% of the lamprey reaching it due to elevated flows accommodating passage (as opposed to via a combined fish pass and bypass channel located at the site). Only 17% of lamprey passing Elvington Sluices passed Stamford Bridge, the next barrier upstream. The majority (98%) of the suitable lamprey spawning habitat was located 51 km upstream of the river mouth (above Stamford Bridge); however, only 1.8% of lamprey spawners were recorded there. There is little evidence of the additional impact of hydropower schemes beyond in-river barriers.

Downstream migration – low head schemes

To assess the impact of small weirs associated with fish farms on downstream smolt migration, Aarestrup and Koed (2003) studied sea trout and Atlantic salmon smolts passing five weirs on two small Danish rivers. Weir heights ranged from 0.6 to 2.5 m and the fish farm intakes, upstream of the weirs, were screened with 10 mm mesh. Smolts (n = 3,362) were split into treatment groups (ten treatments in total) and dye marked according to group. Groups of fish were released upstream or downstream of each of the weirs, and recaptured downstream of each weir using smolt traps and/or fyke nets. Smolts released upstream of a weir were delayed for between 0 and 9 days, with 18–71% lost (dependent on the weir where fish were released), attributed to predation by pike and large brown trout, entrainment through the intake screens, and delays possibly leading to de-smoltification. Salmon smolt loss was found to be greater than brown trout in all treatments (attributed to salmon smolts being smaller, increasing risk of entrainment through the screens). A smolt bypass channel is installed at one of the weirs, with the entrance about 200 m upstream of it. Increasing the proportion of discharge through the bypass led to more smolts utilising it, and an increase from 15 to 30% discharge was estimated to increase smolt recapture rates by 11.4%. This study demonstrates the potential effects that may require mitigation if a hydropower scheme is installed; that is, sufficient flow should be allocated to a fish pass to provide sufficient levels of passability, as required by the Environment Agency (Environment Agency 2013).

Hydropower opportunity case studies

A number of methods to quantify the potential effects of hydropower in the UK have been attempted. It is important to understand how these were designed and assessed, to both apply the knowledge to the development of a working tool and to learn from any mistakes or shortcomings of the methods developed.

The Environment Agency mapping hydropower opportunities project (Environment Agency 2010b) provided a high-level desk-based screening of possible locations for low head run-of-the-river hydropower schemes in England and Wales. Phase 2 of this project (Environment Agency 2010c) included further environmental and ecological datasets that have national coverage. As part of phase 2, sites were screened for high Habitat Quality Assessment scores and degree of river modification (according to WFD) to indicate either 'win–win' situations, or where a hydropower scheme may have a disproportionately negative impact. A GIS-based model was developed, incorporating the Environment Agency Detailed River Network, obstructions database and environmental constraints polygons, to evaluate the environmental sensitivity of each barrier to hydropower development. Phase 2 also aimed to develop tools to investigate the cumulative catchment-wide impact of barriers and hydropower schemes on fish. A preliminary GIS model on the River Wye Catchment was produced to address this aim, and included information from the environmental sensitivity model (that incorporated barriers and associated upstream and downstream area), modified to include variables such as average annual numbers of fish entering the catchment, upstream and downstream passability at each barrier, and upstream habitat quality. A GIS routine calculated the numbers of fish passing upstream and spawning, total numbers of fish after spawning, and numbers of young returning to the sea. The tool was not developed beyond the ‘proof of concept’ stage. Following an Environment Agency review, the tool was considered not fully developed to apply across England (Miran Aprahamian, Environment Agency, personal communication).

A variety of other studies reference environmental impacts of hydropower. For example, the Middle Severn Catchment Hydropower Pre-Feasibility study was undertaken for Telford and Wrekin Council and the Environment Agency, to provide evidence to support planning and permitting authorities in the determination of development applications. This was achieved by presenting the power generation and environmental sensitivity data for a number of existing weir structures assessed as having hydropower development potential. Environmental sensitivity was determined based on the presence of designated sites, habitats or species at/near the scheme. Cumulative effects on upstream fish passage were assessed by quantifying the number of potential hydropower opportunities downstream of the site, and the total available upstream habitat. Hydromorphological sensitivity was assessed based on river habitat survey data. An overall environmental sensitivity weighting was assigned to each structure to give a final sensitivity score.

Cumulative effects modelling methods

Generally, attempts to model the cumulative effects of hydropower schemes on fish have involved complex models, requiring detailed site and catchment specific data. Voegtle and Larinier (2008) developed a method to evaluate cumulative effects of hydropower schemes on downstream migrating European eel. The method required in-depth knowledge of the migratory conditions (e.g. timing in the catchment), the distribution of the fish at a scheme (e.g. turbine intake or bypass channel), and mortality rates associated with passing through spillways and turbines. This in-depth knowledge was acquired through a specific R&D programme in France (Voegtle and Larinier 2008) and incorporated into a model via the use of three sub-models that:

- estimated variations in the numbers of silver eels arriving at hydropower schemes;
- determined eel distribution between the turbine intakes and other passage routes at a scheme (route choice was correlated with proportion of flow);
- estimated the potential mortality of the eels transiting turbines.

These models were initially used to estimate single scheme effects, and estimations for multiple schemes on a catchment were then undertaken based on the eels arriving upstream of each installation, from either the habitats just upstream or after passing the upstream installations. The product of the method is a percentage of surviving eels for each individual installation, and the overall percentage of survivors for all schemes on a catchment for given periods annually, which was dependent on the specifics of the schemes. This method proved useful where detailed data was available for specific fish species, life-stages, river systems and the already existing hydropower schemes (i.e. this model is not applicable to determine the effect of a potentially new hydropower scheme). In the majority of cases this detailed information is not yet available and could take a significant amount of time and expense to obtain. With the addition of hydropower scheme effects on upstream migration to be taken into account, the already complex and specific data dependent method would become further convoluted.

Case studies summary

Table A1 summarises some of the available literature (which may not have already been discussed) concerning the effects of hydropower schemes and in-river structures on fish. Not all of the literature in the table is directly relevant to the type of schemes licensed in England (represented in the penultimate column), but provides a background of potential effects. Quantifiable levels of effect may not be able to be applied to this project.

Table A1 Summary of literature providing information on the effects and cumulative effects of barriers and hydropower schemes on fish

Location	Type of scheme	Turbine type	Fish pass	Species	Method and sample size (*n*)	Passability per barrier		Multi-scheme cumulative effects	Delay	Contributing effects	Applicability to England (low head schemes)	Reference
						US	DS					
River Conon, Scotland	Four high head hydropower schemes	Unknown	Borlands fish lift; pool and traverse	Atlantic salmon	Radio tracking (n=54)	63–100% passed	-	93% failure to migrate US past all structures	Up to 52 days	Unwilling to utilise fish pass, stress due to accumulation of fish DS of scheme, predation, fungal disease and stranding	Low	Gowans *et al.* (2003)
Columbia River, USA	Three high head hydropower schemes	Kaplan and Francis	Pool and traverse	Pacific lamprey	Radio tracking (n=147–299)	38–82% passed	-	97% failure to migrate US past all structures	2 to 5.7 days per scheme	Bright lighting and confusing currents hindered passage	Low	Moser *et al.* (2002)
Stornorrfors Sweden	One high head hydropower scheme	Francis	Pool and traverse	Atlantic salmon	Multiple season radio tracking (n=2,651)	0–47% were able to pass depleted reach	-	N/A	Yes	Attraction to tailrace	Low	Rivinoja *et al.* (2001); Lundqvist *et al.* (2008).
Snake and Columbia Rivers, USA	Four or eight (dependent on observation period) high head schemes	Includes Kaplan and Francis	Downstream bypass	Chinook salmon and steelhead	Extrapolated from various studies on the catchment	-	-	32–56% failure to migrate DS past all structures when four schemes; 31–59% failure when eight schemes (but all modified)	-	-	Low	Williams *et al.* (2001)
Stornorrfors and Piteälven, Sweden	One high head hydropower scheme (two separate rivers)	Francis and Kaplan	Fish ladder, and altered dam spillway	Atlantic salmon and brown trout	Radio tracking (n=90 salmon and 56 trout)	-	-	-	-	Majority of fish passed through turbines with greatest flow	Low	Rivinoja *et al.* (2004)

Table A1 (continued)

Location	Type of scheme	Turbine type	Fish pass	Species	Method and sample size (*n*)	Passability per barrier		Multi-scheme cumulative effects	Delay	Contributing effects	Applicability to England (low head schemes)	Reference
River Derwent, England	Five low head barriers and one tidal barrage	None	Yes (type varies incl. pool and traverse, Denil and Larinier)	River lamprey	Radio tracking (n=113)	0–39% passed barrage; 64% passed 1st, and 17% passed 2nd barrier	-	1.8% of lamprey utilised 98% of total spawning habitat located US of barriers	Up to several weeks	Tidal conditions and flows at barrage; Water velocity and head loss at other barriers too large	High	Lucas *et al.* (2009)
Rivers Salten and Mattrup, Denmark	Two low head weirs on each watercourse	None	Downstream bypass	Sea trout and Atlantic salmon	Mark-recapture (n=3362)	-	18–71% smolt loss	-	Up to 9 days	Entrainment into fish farms via flow abstraction, predation and delay	High	Aarestrup and Koed, (2003)
River Gudenaa, Denmark	One high head hydropower scheme	3 x Francis turbines	Denil fish pass and a bypass	European eel	Acoustic tracking (n=45)	-	58% silver eel loss	-	Up to 35 hours in forebay, and 21 days (±1–70) in vicinity of detector directly US of hydropower scheme	Difficulty finding bypass entrance, located at surface (eels = substrate oriented; Tesch 2003)	Low	Pedersen *et al.* (2012)
River Meuse, The Netherlands	Two high head hydropower schemes	Both have four Kaplan turbines	Not described, but appear to have pool and traverse passes	European eel	Radio telemetry (n=150)	-	-	63% silver eel loss. Estimated 16–26% loss due to schemes	40% of eels approached multiple times	-	Low	Winter *et al.* (2006)
River Meuse, The Netherlands	Two high head hydropower schemes	Both have four Kaplan turbines	Not described, appear to have pool and traverse	European eel	Radio telemetry (n=121 in 2002; n=105 in 2004)	-	-	2002 = 16–26% loss and 2004 = 25–34% loss due to schemes	Multiple approaches by eels	-	Low	Winter *et al.* (2007)

DS = downstream, US = upstream

Appendix B: Spatial population element assumptions

As discussed in section 3, for this project Atlantic salmon were used as a model species, and the River Coquet as a demonstration catchment. Maximum salmon productivity values were calculated by combining spatial catchment data (wetted channel area) from the Detailed River Network, and population data from the Wyatt and Barnard (1997b) methodology.

The wetted channel area was **limited in the catchment to the 'naturally accessible' wetted area**, which APEM determined by removing reaches upstream of natural barriers shown in the Environment Agency obstructions database to exceed 1.4 m, the threshold at which a barrier becomes impassable to adult salmon according to the WFD111 method (SNIFFER 2010). As assumed in the calculation of conservation limits, the calculation of carrying capacity ignores anthropogenic barriers and thus reflects the naturally, as opposed to the actual, accessible area.

An original aspiration of this project was to re-create the spatial population data in GIS to reflect the values used by the Environment Agency to derive the conservation limit, such that there would be compatibility with the existing conservation limit. A detailed spatial breakdown used in the original calculations was not available, thus it was not possible to re-create the original data. Furthermore, the wetted area dimensions used by the Environment Agency to calculate the original conservation limits were measured from lower resolution paper maps (Grant McMellin, Environment Agency, personal communication). Considerable discrepancy exists between the original wetted area calculations and those used in this study based on the Detailed River Network (e.g. the original accessible wetted area of the Coquet Catchment used to calculate the conservation limit was measured as 144 ha, whereas this project calculated the accessible wetted area to be 244 ha). The difference between these estimates is attributable to the method of estimation of channel width, the channel reach resolution, and the classification of which reaches are impassable or utilised by salmon. The implication is that the revised catchment carrying capacity calculated for use in the current project is larger than that calculated when determining the original conservation limit. Therefore, if the conservation limit were calculated using the revised area data as obtained in this project, it would be higher than that originally calculated. By using the relatively high revised carrying capacity data in the developing model, but keeping the original conservation limit, a far greater proportion of the population can be lost before the existing conservation limit is failed. To solve this issue, a revised conservation limit would be required, calculated with the GIS-based methods used in this study. For the purposes of demonstrating the functionality of the model a new conservation limit was derived based on the data obtained from the Detailed River Network. In the original conservation limit calculations for the Coquet, the conservation limit was approximately half the size of the maximum population. Therefore, the carrying capacity of the catchment derived from the Detailed River Network was halved to provide a new 'conservation limit' for use in this hypothetical catchment.

Appendix C: Model species selection

A number of attributes are desirable for adopting a model species on which to test and develop a hydropower scheme impact assessment methodology. These include:

- an established and recognised, river-specific numerical population benchmark, or target for the species;
- an ongoing monitoring process against which river-specific population assessments can be made;
- reliable information on density and distribution within each catchment;
- a good understanding of how the species is affected by hydropower scheme developments;
- parallels with other migratory species such that the principle of the model can ultimately be extended to these;
- geographical correspondence of the species with rivers with hydropower scheme development potential.

Evaluation of how each of the migratory species within the remit of the project meets the criteria is provided in Table C1. Salmon were shown to meet more of the desirable criteria than any other species, and were thus adopted as the model species for the study. Each of the criteria is discussed in relation to salmon below.

Table C1 Evaluation of migratory species in terms of desirable attributes for model development

Attribute	Salmon	Eel	Sea trout	Sea lamprey	River lamprey	Shad	Smelt	Potadromous species
Established river-specific population benchmark(s) available?	Y	S	N	N	N	N	N	N
Ongoing monitoring programme?	Y	Y	Y	S	S	S[3]	N	S
Reliable information on density and distribution?	Y	S	Y	S	S	N	N	S
Understanding of hydropower effects on species?	Y	Y	Y	S	S	S	N	S
Parallels with/ transferability to other species?	S	S	S	S	S	S	N	S
Correspondence of the species with hydropower scheme development potential rivers?	Y	Y	Y	S	S	S	N[4]	S

Key: Y = Yes; S = Some; N = No.

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[3] Some sampling in Wales, but none in England (Miran Aprahamian, Environment Agency, personal communication).

[4] Species typically utilises estuaries and lower river reaches only.

Established river-specific population benchmarks are available for each salmon river, in the form of the conservation limit, and an additional inter-annual compliance assessment measure, the management target (the management target being based on the conservation limit). A conservation limit and management target is published for each of the 64 principal salmon rivers in England and Wales via a Salmon Action Plan (SAP) which is produced by the Environment Agency.

Ongoing monitoring process (against the conservation limit) is undertaken for each of the principal salmon rivers, using rod catch as a proxy for annual adult population size, and/or fish counters (where installed). In a few instances smolt emigration is also measured.

Reliable information on density and distribution. Juvenile salmon monitoring is undertaken to some extent on each river via the Environment Agency's national fisheries monitoring programme, providing a reliable picture of the spatial distribution and density of salmon within a catchment. Juvenile density can also be inferred via generic published values (Wyatt and Barnard 1997a) for different stream orders and altitudes; these have the advantage of being generically applicable, and not dependent on ongoing monitoring.

Understanding the cumulative impacts of hydropower schemes is arguably best tested with salmonid species, specifically Atlantic salmon.

Parallels with/transferability to other migratory species:

- Sea trout *(Salmo trutta)* – Given the similarities in biology and life history between salmon and sea trout, the model adopted for salmon is applicable to sea trout, although direct transferability is complicated by the fact that sea trout are iteroparous (repeat spawning) as opposed to salmon, which are predominantly semelparous (single spawning). Furthermore, there is a complex and dynamic relationship between sea trout and resident brown trout in the same catchment, whereby each may be part of the same population.

- Lamprey (river, brook and sea species) *(Lampetra fluviatilis, L. planeri and Petromyzon marinus)* – have received increasing focus since the advent of the EU Habitats Directive, and the listing of all three UK lamprey species on Annex 2 of the Directive, which has required the designation of a number of riverine Special Areas of Conservation (SACs) for these species. A monitoring protocol for lampreys has been developed via the Life in UK Rivers Project (Harvey and Cowx 2003). This focuses on densities of juvenile lamprey in the freshwater environment, and although recommendations for adult monitoring are made within the document, in practice only juveniles have been monitored to date. Thus, little understanding exists of the relationship between the extent and quality of habitat and adult production and, in turn, the typical sizes of adult populations at a catchment scale. Hence a catchment-scale adult population target does not exist. Furthermore, other than in a few instances (e.g. the quantification of the lamprey population in the River Ouse; Masters *et al.* 2006), no fisheries exist which serve as a proxy to measure annual adult run size. Despite the listing of river and sea lamprey on the UK BAP list, lamprey species have received little monitoring focus outside SACs, and together with the lack of any significant commercial or recreational interest in the species, there is little prospect for wide-scale monitoring of stocks, or establishment of river-specific population benchmarks. Notwithstanding the above limitations, the fact that sea and river lamprey, like salmon, are anadromous, means that in principle the model developed for salmon should be applicable to these species.

- Eel (*Anguilla anguilla)* – After many years of receiving relatively little monitoring or management attention, eels are now the focus of significant activity in these respects, as a result primarily of the European-wide population declines, and the resultant adoption of the EU Eel Regulation. One requirement of the regulation is the establishment of a management target for each WFD River Basin District (RBD). This has necessitated the estimation of reference population sizes for each RBD, against which a 40% adult escapement target can be set. Although a population target thus exists for eels, this is set at the RBD rather than the catchment level. It should be stressed that the understanding of how habitat availability determines eel density in freshwater is in its infancy, and thus relatively poor compared to salmon. However, this area is receiving significant attention currently, with the Environment Agency recently concluding a review of eel population models (Walker *et al.* 2013), and the prospect of more robust population targets and models for eels, on a catchment basis, is good. Although eels are catadromous rather than anadromous, the principles of a model based on salmon should be applicable to eel, particularly given the improving information base regarding eel populations.

- Shad *(Alosa fallax and A. alosa*) – As with lamprey, shad have received significantly increased focus in light of their inclusion on the EU Habitats Directive, and the designation of a number of riverine SACs for twaite and allis shad. The result is that on the rivers for which shad are a qualifying feature of the SAC (the majority if rivers where viable shad populations occur), population monitoring is undertaken. However, this population monitoring is relatively infrequent (typically once every 6 years, as dictated by the reporting periodicity for designated sites) and has only recently been implemented. Consequently, population sizes and dynamics are not as well understood relative to Atlantic salmon (but see Aprahamian *et al*. [2010] and Rougier *et al*. [2012]). However, the anadromous nature of shad, in common with salmon, means that the principles developed for salmon should be adaptable to shad.

- Smelt *(Osmerus eperlanus)* – Smelt have a high conservation importance, being a UK BAP species, although no specific systematic monitoring programmes are in place, and little is known in terms of population sizes or stock–recruitment relationships. Despite being an anadromous species, smelt only make transient use of the tidal and lower reaches of rivers to spawn, with juveniles migrating seaward within a few weeks of hatching. Thus, the co-incidence of smelt with hydropower schemes is likely to be low.

Correspondence of the species to rivers with hydropower scheme development potential. There is an excellent correspondence in this respect, as salmon are relatively ubiquitous in high gradient and high energy rivers, corresponding with the greatest potential for hydropower schemes.

Appendix D: Existing barriers effects estimation

A clear distinction needs to be made between the effects of hydropower schemes and the effects of barriers on which they are sited/depend. Our ability to quantify these separate effects is discussed in this appendix.

It is assumed that passage efficacy rates would be relatively high (between 90 and 95% minimum; Environment Agency steering group, personal communication) where structures such as weirs and fish passes accord with Environment Agency best practice documents (including best practice guidance for maintenance of the structure; see for example the Environment Agency fish pass manual [Environment Agency 2010a]), or where fish friendly turbines such as Archimedes screws have been installed. Where no mitigation has yet been installed, or Environment Agency best practice has not been followed, a categorisation approach would be required to better understand the passability of the structures to fish. Although a variety of rapid-assessment methods are currently being employed to prioritise structures for further action, the WFD111 barrier assessment methodology (Kemp *et al.* 2008b, SNIFFER 2010) provides a standardised method that assigns barriers to four passability categories by comparing direct measurements of variables, such as water depth and velocity over the face of the barrier and head difference, to swimming and leaping capabilities of different fish species. Scores are then assigned to the barrier for upstream and downstream passage, and the barrier is placed in one of the four categories shown in Table D1, which could be used in the model to determine the passability of individual structures.

Table D1 WFD111 passability scores (adapted from SNIFFER 2010)

Passability score	Definition
1	***No barrier:*** *the obstacle does not represent a significant impediment to the target species/life-stage, or species guild, and the majority of the population will pass during the majority of the period of migration (movement). This does not mean that the obstacle poses no costs in terms of delay, e.g. increased energetics, or that all fish will be able to pass*
0.6	***Partial barrier low impact:*** *the obstacle represents a significant impediment to the target species/life-stage, or species guild, but* ***most of the population (e.g. > 2/3) will pass eventually****; or the obstacle is impassable for a significant proportion of the time (e.g. < 1/3)*
0.3	***Partial barrier high impact:*** *the obstacle represents a highly significant impediment to the target species/life-stage, or species guild, but* ***some of the population (e.g. < 1/3) will pass eventually****; or the obstacle is impassable for a significant proportion of the time (e.g. > 2/3)*
0	***Complete barrier:*** *the target species/life-stage, or species guild cannot pass the obstacle*

The relatively coarse passability categories of the WFD111 method reflect the large uncertainty associated with a multitude of factors, including our understanding of fish movement, behaviour and capabilities, and the variation in hydraulic conditions with flow, even when a direct survey is carried out at the structure. While completely passable (1) and not passable (0) scenarios provide absolute values on passability (Table D1), the 0.3 (partial barrier high impact) and 0.6 (partial barrier low impact) scores should not be taken as only 33% or 66% of fish are able to pass the barrier (indeed, a second edition of the WFD111 methodology is likely to remove the numerical categories and replace them with output classes of ‘impassable’, ‘high impact’, ‘low impact’ and ‘passable’; Dr Colin Bull, University of Stirling, personal communication). The original WFD111 definition defines these passability scores as either the proportion of the population that does not pass, or that the structure is passable for only 1/3 or 2/3 of the time respectively (Table D1). The reality is that

WFD111 is more accurately a measure of instantaneous passability, and that over the period that adults seek upstream migration past a barrier extensive flow variability will occur, such that suitable passage conditions will be encountered. Therefore, in the absence of data from case studies supporting actual passability rates, the WFD111 scores have been translated based on assumed absolute passability rates, as described in Table D2. These new ‘absolute passability scores’ are based on the authors’ own expert judgement, through discussion with Dr Colin Bull (who has undertaken significant work to produce the final WFD111 methodology, which he is currently updating), and are thus subject to refinement should more detailed information become available.

Table D2 Translated WFD111 absolute passability scores

WFD111 score	Percentage of fish passing structure
0	0%
0.3	50% (after significant delay)
0.6	75% (after relatively minor delay)
1	100%

Delay is also considered when accounting for the new absolute passability score, in that it may lead to a level of mortality, or the increased energy expended while waiting to pass would reduce reproductive success (see section 2.1.1). The actual passability values will be subject to site and species specific variability, but for the purposes of providing a universally applicable tool, the generic values were applied in the model. The WFD111 pro-forma has been integrated into the model to provide an automated process for assigning barrier scores based on ten attributes (see Figure 5.2).

In reality a number of mechanisms associated with the barrier exist which are likely to have an impact on migratory fish populations, including injury and loss of energy reserves associated with repeat attempts to pass the structure, increased susceptibility to predation or anthropogenic removal due to concentration of fish at a particular point, and actual restriction of access to spawning grounds. However, the ultimate metric of interest for modelling the effects of barriers is loss of individuals to the population. Thus, the model simplifies the effects of a barrier on migratory fish and treats them solely in terms of loss to the population via restriction of access to spawning grounds, and exceedance of carrying capacity in the section to which these individuals are constrained. Therefore, the values outlined in Table D2 are treated by the model as losses to the population. The existing barrier may already have a fish pass installed, which will alter the passability score, and this is incorporated into the model. Quantification of fish pass benefits is covered below.

Estimation of fish passage efficiency

Fish passes are rarely 100% efficient, but general passability scores are available for a variety of types. For example, Noonan *et al*. (2012) reviewed 65 articles from between 1960 and 2011, concerning fish pass efficiencies, finding overall passage efficiency values of 61.7 and 21.1% for upstream migrating salmonids and non-salmonids respectively. Downstream passage efficiency was slightly higher at 74.6 and 39.6% for salmonids and non-salmonids respectively. However, the passage efficiencies varied significantly dependent on pass type, species, life-stage and location. Further evidence concerning the range of passage efficiency information is provided in Table D3. Such passage efficiency values have been applied in the model as a means to score already existing structures that do not comply to Environment Agency best practice; however, it is assumed that passage efficacy rates would be relatively high (between 90 and 95% minimum; Environment Agency steering group, personal communication) where new fish passes are constructed (or old ones improved) as part of a hydropower scheme, thus allowing the scheme to provide a potential net benefit.

Table D3 Efficiency of various fish passes for salmon (adapted from the Environment Agency fish pass manual [Environment Agency 2010a])

Type of pass	Location (river)	Efficiency	Reference
Denil	Blackweir (Taff)	25–39%	Gough (pers. comm.)
Denil	Pau River	34%	Chanseau and Larinier (1999)
Submerged orifice	Pitlochry (Tummel)	45.5% 86–100%	Webb (1990) Gowans *et al*. (1996)
Various (31 sites)	Pau River	35–100%	Chanseau *et al*. (1999)
Borland fish lift	Kilmorack (Beauly)	40%	Smith *et al*. (1996)
Various (6 sites)	River Conon	63–100%	Gowans *et al*. (1996)
Various (21 sites)	River Thames	65–100%	Clifton-Dey (pers. comm.)
Total range of passage efficiencies		**25–100%**	

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