Appendix 13.2 – TR595

The potential benefits of barrier easement and removal on populations of shad and Atlantic salmon and other diadromous species in the River Severn and selected Welsh rivers.

THE POTENTIAL BENEFITS OF BARRIER EASEMENT AND REMOVAL ON POPULATIONS OF SHAD AND ATLANTIC SALMON AND OTHER DIADROMOUS SPECIES IN THE RIVER SEVERN AND SELECTED WELSH RIVERS

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BEEMS Technical Report TR595

The potential benefits of barrier easement and removal on populations of shad and Atlantic salmon and other diadromous species in the River Severn and selected Welsh rivers

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1 Introduction and Background

1.1 Background

In 2013, NNB Generation Company (HPC) Limited (NNB) was granted a development consent order (DCO) authorising the construction and operation of a new nuclear power station at Hinkley Point in Somerset. Once operational, Hinkley Point C (HPC) will abstract cooling water from the Severn Estuary (Figure 1). Cooling water abstraction will lead to the entrapment of fish and other biota. To mitigate the impacts of abstraction on fish, three measures were incorporated into the original design of the cooling water system for HPC, as consented by the HPC DCO in 2013, these were:

- Acoustic Fish Deterrent (AFD) system;
- Low Velocity Side-Entry (LVSE) cooling water intake heads with a capped head design; and
- Fish Recovery and Return (FRR) mitigation.

The LVSE intake heads and FRR remain part of the station design. However, on 15 February 2019, NNB made an application to the Environment Agency to vary the Water Discharge Activity (WDA) Permit to remove the requirement to install an AFD system. A public inquiry (an appeal for non-determination) was held by the Planning Inspectorate in June 2021. The basis for the WDA Permit Inquiry was on the grounds that the Environment Agency were not able to conclude the project in the absence of an AFD would not adversely affect the integrity of the European Marine Sites and their qualifying features (Table 1). Seven species identified by the Environment Agency in their Appropriate Assessment[1] as being of concern in relation to the removal of the AFD formed the focus of the WDA Permit Inquiry. These were the marine species European sea bass, Atlantic cod, whiting, and Atlantic herring, and the Annex II / Ramsar Criteria 4 migratory species Atlantic salmon, allis shad, and twaite shad. The Defra Secretary of State (SoS)[2] confirmed the conclusions of the Planning Inspector[3] that adverse effects could not be ruled out beyond reasonable scientific doubt for the Severn Estuary/ Môr Hafren Special Area of Conservation (SAC) and Ramsar site, the River Usk SAC, and the River Wye SAC (Table 1).

[1] Environment Agency. 2020. Appropriate assessment of the application to vary the water discharge activity permit for Hinkley Point C (November 2020). https://ea.sharefile.com/share/view/s3ca03dcf62e34305a368cd5e85a25df0.

[2] Removal of acoustic fish deterrent conditions from Water Discharge Activity (WDA) Permit, Secretary of State for DEFRA Decision Letter: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1101961/hpc-decision-letter-220902.pdf).

[3] Removal of Acoustic Fish Deterrent Conditions from Water Discharge Activity (WDA) Permit, Inspectors Report: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1101903/environmental-permit-appeal-app-epr-573-hinkley-point-c.pdf.

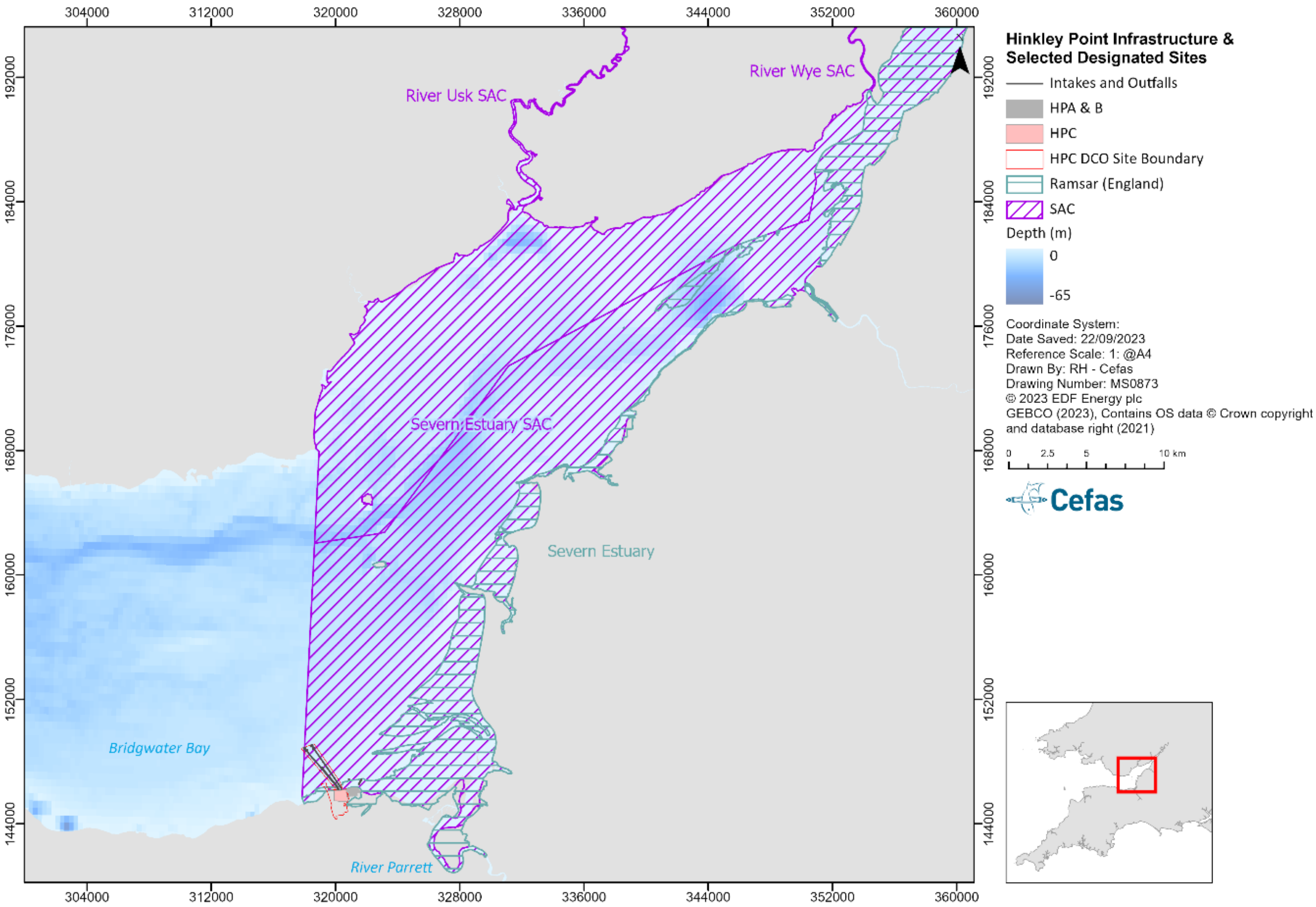

Figure 1 The Severn Estuary/Bristol Channel showing the location of HPC and the National Site Network sites relevant to the entrapment assessments.

Impingement, in the absence of an AFD, will be assessed within an application for a DCO variation of the existing 2013 DCO under the Conservation of Habitats and Species Regulations 2017 (Habitats Regulations). On the assumption that the assessment identifies a risk of adverse effect on integrity of European / Ramsar sites linked to the Annex II qualifying fish species (diadromous species of shad and salmon) or the Ramsar Criterion 4 migratory fish assemblage then compensation measures to improve up/down stream migration and/or riverine habitat quality are being proposed. On the assumption that the assessment identifies a risk of adverse effect on integrity of the Severn Estuary SAC linked to the typical fish species assemblage of the Estuaries qualifying habitat feature then compensation measures such as the creation of saltmarshes, kelp forests, seagrass beds, and native oyster reefs have been proposed.

Table 1 Species and habitats of European Sites of relevance to the WDA Permit Inquiry.

Relevant European site	Interest feature
Severn Estuary SAC	**Annex I qualifying habitat:** **Estuaries** including the typical fish assemblage species of which Atlantic salmon; twaite shad; allis shad; Atlantic cod; European sea bass; Atlantic herring; and whiting were of relevance to the WDA Permit inquiry. **Annex II qualifying species** • Twaite shad
Severn Estuary Ramsar	**Criterion 4 migratory fish assemblage species,** of which Atlantic salmon, allis shad and twaite shad were of relevance to the WDA Permit inquiry.
River Usk SAC	**Annex II qualifying species** • Atlantic salmon • Twaite shad
River Wye SAC	**Annex II qualifying species** • Atlantic salmon • Twaite shad **Present but not a primary reason for site selection** • Allis shad

1.2 Fish passage improvements

The presence of artificial structures in rivers can lead to significant changes in the characteristics of surrounding ecosystems (Fuller *et al*., 2015). Disruptions to connectivity between habitats can be detrimental to local fish populations (Radinger *et al*., 2017). Habitat fragmentation is now widely accepted as a leading factor in the decline of many diadromous fish species, impacting both their upstream and downstream migrations and limiting access to vital spawning or feeding habitats (Verhelst *et al*., 2021). There are also growing concerns that the effects of climate change will progressively worsen the impacts of obstacles on fish migrations (Jaeger *et al*., 2014; Mameri *et al*., 2021). Reduced river flow during key periods of the year may lead to longer migration delays, and lower passage success at obstacles, in turn worsening declines in abundance and breeding success in many of these species (Assunção *et al*., 2014; Moore *et al*., 2019). Recent work has shown that many fish species suffer cumulative impacts from repeatedly passing obstacles (Duarte *et al*., 2021; Dean *et al*., 2023), raising concerns for the conservation of these species in areas with high numbers of obstacles. As such, restoring river connectivity is now seen as a vital consideration in the management and conservation of diadromous fishes (Thieme *et al*., 2023; Verhelst *et al*., 2021). Restoring connectivity can be achieved through several methods, including by completely removing obstacles to migration (Garcia de Leaniz, 2008). However, when complete removal is unachievable, easements can be used to modify the structure or surrounding area and alleviate some of the effects caused by the structure's presence. Easing measures include partially removing obstacles (Raabe and Hightower, 2014); the construction of fish passes to facilitate free movement of fish over, through or around obstacles (Larinier, 1996); modifying parts of an obstacle to improve fish passage success; or even manipulating conditions around a structure, such as modifying water flow (Belo *et al*., 2021; Wiegleb *et al*., 2023). Here, the term *'fish passage improvements'* is coined to encompass the different management measures that are available to benefit migratory movements.

Fish passage improvements, including natural and technical fish pass solutions and partial to full barrier removals, have been suggested among potential compensatory measures to offset impingement impacts on qualifying features allis shad, twaite shad and Atlantic salmon in the Severn Estuary/ Môr Hafren Special Area of Conservation (SAC) and Ramsar site, the River Usk SAC, and the River Wye SAC from the HPC Nuclear New Build Project. Proposed Fish passage improvements at certain weirs in the Severn Estuary catchment, including from the rivers Severn, Usk, and Wye would restore habitat connectivity and improve fish passage, in so doing these measures have the potential to improve network coherence of populations of shad and Atlantic salmon in the region. In the River Tywi (Towy) a weir is also being considered for fish passage improvements to support overall network coherence of the species. NNB preferred proposals for improved fish migration are Maisemore Weir on the River Severn and Trostrey Weir on the River Usk; and one further weir on the River Lugg, the River Tywi, or the River Severn. The weirs currently being considered by NNB for feasibility assessments include (Figure 2):

1) Severn Estuary SAC
    a) Maisemore Weir on the River Severn near Gloucester
    b) Upper Lode Weir on the River Severn near Tewksbury
2) River Usk SAC
    a) Trostrey Weir
3) River Wye SAC
    a) Three weirs on the River Lugg, a tributary in the River Wye catchment
        i) Eyton
        ii) Mousenatch
        iii) Coxall
4) River Tywi
    a) Manorafon Weir.

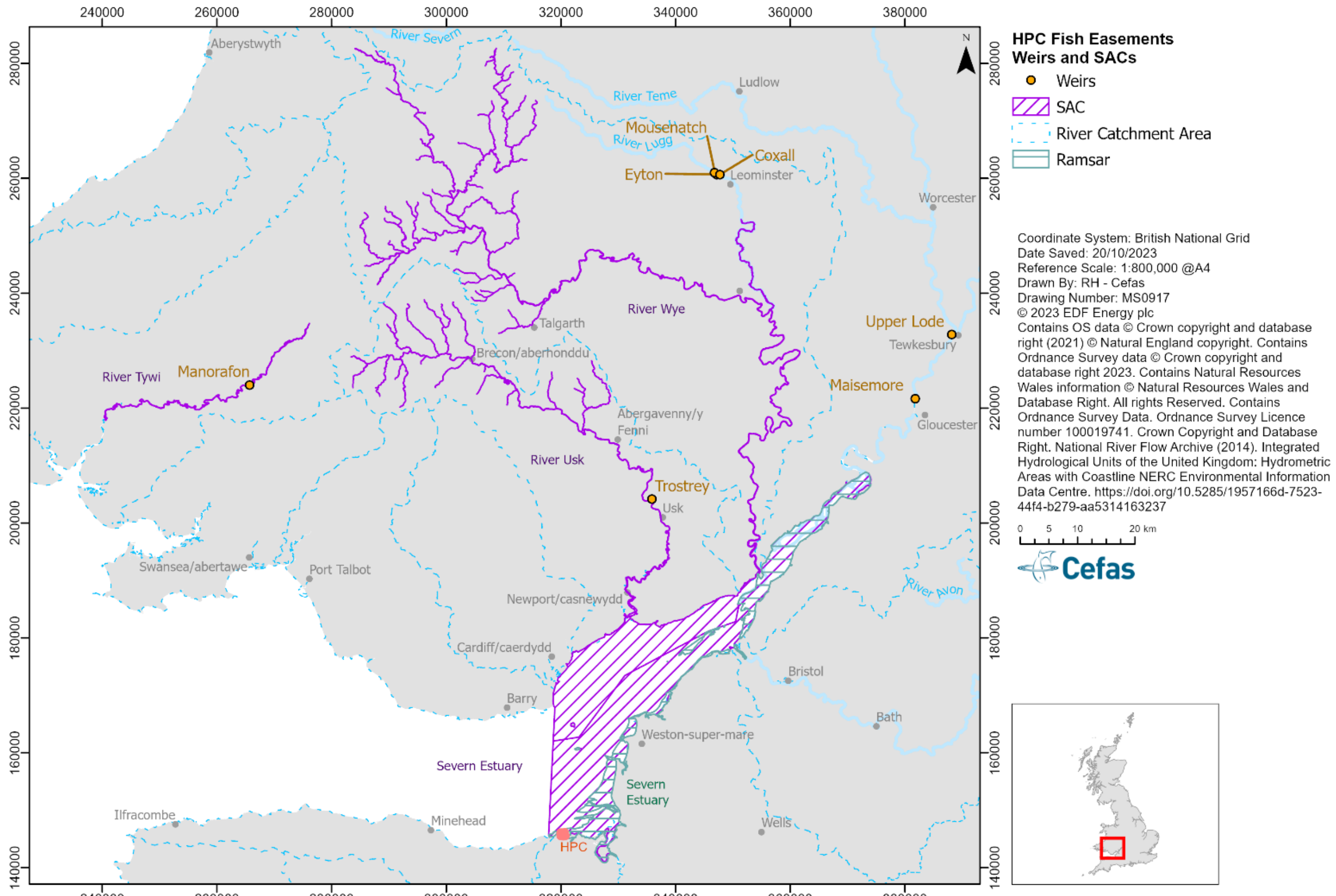

Figure 2 Designated sites and selected weirs being considered for feasibility assessments for fish passage improvements.

1.2.1 Summary of weir sites

NNB are proposing to undertake fish passage improvements at three weirs as part of their compensation package. Maisemore Weir on the River Severn and Trostrey Weir on the River Usk are currently NNBs preferred proposals, with one further weir on the River Lugg (one of Mousenatch Weir, Eyton Weir or Coxall Weir), the River Tywi (Manorafon Weir) or the River Severn (Upper Lode Weir). The selection process and next steps for site feasibility are summarised in Section 4.5.

Maisemore Weir is located on the River Severn in Gloucestershire (Figure 3), approximately 2 miles northwest of Gloucester City Centre. It was constructed in the 1870s, and is a large, shallow, broad crested weir. It is located at the approximate upper tidal limit of the River Severn but is overtopped during spring tides. Further upstream is Upper Lode weir (Figure 4), located approximately half a mile east of Tewkesbury in Gloucestershire. The weir was completed in 1858 and is a large broad crested weir that marks the tidal limit. It is adjacent to the Upper Lode Lock, and the confluence of the River Avon. Upper Lode weir serves an important function of controlling water levels into the marinas on the eastern side of Tewkesbury. A fish pass was constructed at the weir during 1995.

Trostrey Weir is located on the River Usk (Figure 5), some 3.8 km northwest of Usk, directly below the B4598 road. The weir is the site of an existing NRW gauging station. The site is bound by steep topography to the north and lower-level farmland to the south. The weir is located within an engineered channel with a sheet piled bank to the south.

Suitable weirs for potential fish passage improvement works were identified for the River Severn and River Usk as set out above, however, following consultation between NNB, Natural Resources Wales and the Environment Agency, it was not possible to identify a suitable weir on the River Wye. The River Lugg however is a tributary of the River Wye for which weirs have been identified for improvement works. Mousenatch Weir, Eyton Weir or Coxall Weir are located in close proximity to each other in the higher catchment (Figure 2), between 2 and 3.5 km northwest of Leominster. It is understood that the weirs were built in the 1970s as part of the Leominster Flood Defence Scheme and that the Environment Agency is currently considering their functional removal.

Manorafon Weir features two rock weirs, located on the River Tywi in Carmarthenshire, approximately 5.5 km to the west of the town of Llandeilo. NNB is considering the more southerly of the weirs. Works on the River Tywi would provide a potential option to improve fish passage in the wider area to enhance network coherence. This site currently operates as a water extraction site and a gauging station.

Figure 3 The tidal Maisemore Weir on the River Severn near Gloucester.

Figure 4 The tidal limit of the River Severn at Upper Lode Weir near Tewkesbury. Right panel shows the current fish pass.

Figure 5 Trostrey Weir on the River Usk.

1.3 Report objectives

This document provides a concise review of the potential impacts of weirs on populations of diadromous fish, and examines the potential effects of fish passage improvements at weirs on diadromous fishes, with a special focus on species to which the proposed compensation measures are targeted; twaite shad (*Alosa fallax*), allis shad (*Alosa alosa*), and Atlantic salmon (*Salmo salar*).

The report also considers other migratory species that together with the twaite shad, allis shad and Atlantic salmon form part of the assemblage of migratory fish under Criterion 4 of the Severn Estuary/ Môr Hafren Ramsar site. These species include sea lamprey (*Petromyzon marinus*), river lamprey (*Lampetra fluviatilis*), sea trout (*Salmo trutta*) and the European eel (*Anguilla anguilla*). This review draws on information available from the Unlocking the Severn project and selected other national and international studies where different fish passage improvement options were implemented with the aim of benefiting diadromous fish populations.

The potential benefits of barrier easement and removal on the wider assemblage of marine and freshwater species that form part of the typical fish species assemblage of the Severn Estuary/ Môr Hafren SAC *Estuaries* habitat qualifying feature is considered in BEEMS Technical Report TR592.

Finally, this report provides a high-level summary of the next steps involved in site selection and site feasibility studies for fish passage improvements. This work is progressing concurrently. An overarching framework for monitoring whether compensation measures have been successful is also provided. Monitoring approaches are anticipated to become a formal requirement as part of the Adaptive Monitoring and Management Plan (AMMP) and will be developed iteratively with regulators.

2 The potential benefits of fish passage improvements

2.1 The Atlantic Salmon (*Salmo salar*)

2.1.1 The impacts of barriers, and benefits of their easement and/or removal

The Atlantic salmon is a species of high cultural and economic value in the United Kingdom, and throughout its native range (Myrvold *et al*., 2019). Its decline in recent decades has been attributed to a range of causes in marine and freshwater environments (Dadswell *et al*., 2022), with obstructions to migration and habitat alterations being considered large contributing factors in some rivers (Verhelst *et al*., 2021). The presence of weirs can limit the distribution and abundance of salmon in impounded rivers (Thorstad *et al*., 2008; Hogg *et al*., 2015), and can impede on both the upstream breeding migrations of adult salmon (Thorstad *et al*., 2008), and the downstream movements of juveniles, known as smolts (Havn *et al*., 2020). In some cases, obstacles can prevent a large proportion, or even the entirety of migrating salmon from accessing critical habitats, thus causing large numbers of mortalities, or limiting breeding success (Thorstad *et al*., 2008). This is also true for the other migratory salmonids present in the target rivers such as the sea trout.

The presence of obstructions in rivers can also cause considerable delays to migrating salmon, even in cases where the obstruction would not appear to present a significant physical challenge to their passage (Garcia de Leaniz, 2008; Newton *et al*., 2018). Fish will often aggregate in pools present above or below the obstacle and remain there for some time before passing (Thorstad *et al*., 2008; Marschal *et al*., 2011). These delays disrupt the timings of upstream and downstream migrations, which can impact on fitness and survival (Garcia de Leaniz, 2008). High densities of salmon in these areas can also place them at greater risk from opportunistic predators (Bendall and Moore, 2008; Falkegård *et al*., 2023; Sortland *et al*., 2023); can increase the spread of certain diseases and parasites; or can increase the risk of mass mortalities from causes such as pollution events (Garcia de Leaniz, 2008). In addition, significant delays to the downstream migration of salmon smolts may result in de-smoltification (Zydlewski *et al.,* 2005) and the fish missing the “window of opportunity” for entry into the marine environment which is considered critical to their survival (Moore *et al*., 1995).

By reducing both flow velocity and turbulence through surrounding sections of a river, the presence of weirs can increase the deposition of fine sediments and lower oxygen levels (Greig, 2004; Anderson *et al*., 2014). In turn, sedimentation and deoxygenation if they occur high in the catchment, can reduce salmon embryo survival (Greig, 2004; Julien and Bergeron, 2006; Heywood and Walling, 2007), and can produce sub-lethal effects, such as slowing the rate of egg development (Pattibirnson *et al*., 2015). Furthermore, gravel sedimentation can have significant effects on alevin development and survival, leading to earlier alevin emergence, and inhibiting a vital predator avoidance behaviour (Louhi *et al*., 2011). The presence of river impoundments also reduces the availability of suitable spawning habitats, as salmon favour shallower areas with relatively fast-flowing water, and clear gravel (Birnie-Gauvin *et al*., 2017).

Due to the impacts noted above, weir removal is widely regarded as an efficient method of restoring river connectivity, which can also significantly increase the abundance and quality of spawning and rearing habitats for salmon (Garcia de Leaniz, 2008; Fjeldstad *et al*., 2012; Hogg *et al*., 2015). Furthermore, smolt migrations occur earlier after weir removal, indicating a reduction in obstacle-induced delays (Fjeldstad *et al*., 2012). Similar results of weir removal have been observed in populations of brown trout (*Salmo trutta*), for which connectivity restoration projects are believed to have improved spawning success, fry survival and recruitment, and smolt migration success (Birnie-Gauvin *et al*., 2018).

In cases where complete removal is unachievable, other measures such as the installation of fish passes can greatly benefit salmon. As most conventional types of fish pass were specifically designed to provide passage for salmonids (Verhelst *et al*., 2021), their installation often yields greater benefit for these than for other species.

It is recommended that monitoring of juvenile populations and spawning success (presence of redds) is undertaken prior to, and after fish passage improvements to assess and quantify the benefits of these management measures.

2.1.2 Evidence specific to the target weirs for this study

2.1.2.1 River Severn

Maisemore and Upper Lode Weirs are both navigation weirs found on the lower reaches of the River Severn. Maisemore is generally considered to be the tidal limit of the river. However, particularly high tides, including spring tides, will overtop this structure, and reach the Upper Lode Weir, located approximately 16 km upstream (Davies, 2022). Upper Lode Weir is equipped with a notch near the riverbank, which fish can use to pass this structure (Unlocking the Severn, 2022). Recent declines in Atlantic salmon abundance and catches in the River Severn have led to the catchment's population being classified as "Probably at Risk" (Environment Agency, 2021).

There is little direct evidence of the impact of Maisemore and Upper Lode Weirs on Atlantic Salmon and so the benefits to the population of modifying or removing these obstacles is challenging to quantify at present. However, both weirs have been shown to delay upstream passage for twaite shad and in the case of Upper Lode limit upstream migration for a proportion of the population (Section 2.2.2). Any structure across a river will have an impact on connectivity and migration success and so fish passage improvements at these structures would be of benefit to the salmon and sea trout and could result in an increased production of juveniles, as long as upstream spawning and nursery habitats remain suitable. As described previously, even relatively low weirs can present a significant obstacle to downstream-migrating smolts, especially in periods of reduced flow (Gauld *et al*., 2013), resulting in significant delays and higher mortalities. These effects are predicted to worsen under climate change, due to changes in weather patterns and flow regimes resulting in reduced spring and summer flow levels (Watts *et al*., 2015).

2.1.2.2 River Usk

Trostrey Weir, present on the River Usk, is a post-medieval structure believed to have been constructed to direct water to the nearby Gorrats Mill (Coflein.gov.uk). Salmon populations in the River Usk are also regarded as "Probably at Risk", notably due to recent sharp declines in juvenile production in the catchment (Environment Agency, 2021). The removal of any in-river structure is likely to have a beneficial effect on migratory fish such as the salmon although the exact level of benefit is difficult to quantify.

2.1.2.3 River Lugg

Atlantic salmon are in sharp decline throughout the River Wye catchment, including the River Lugg (Wye Salmon Association, 2019), leading to the Wye being considered the weakest stock component in the Severn Estuary mixed-stock fishery (Environment Agency, 2021). Notwithstanding the reduced marine survival affecting most Atlantic salmon stocks (ICES, 2020; Thorstad *et al*., 2021; Dadswell *et al*., 2022), these declines have been attributed to a combination of local factors, including the presence of several partial obstructions to migrations, and due to historic high levels of suspended fine sediment particles throughout the system (Wye Salmon Association, 2019). Large improvements have been made to restore salmon access to the upper reaches of the catchment, notably via the creation of easements and fish passes in the Lugg and Arrow (Wye Salmon Association, 2019). A recent report by the Wye Salmon Association estimates that 60% of the Wye was inaccessible to salmon as recently as 15 years ago, but that recent connectivity restoration work has been undertaken to restore access to the majority of the river length (Wye Salmon Association, 2019). The report also recommended that further assessment and obstacle removal work should be undertaken to aid recovering local salmon populations (Wye Salmon Association, 2019). In the 2019 Wye salmon grades, no parr or fry were identified upstream of the weirs on the River Lugg, whilst juvenile trout were present (Natural Resources Wales, 2019). This suggests the habitat quality is likely to be suitable for salmon. A semi-quantitative assessment using geographical information system (GIS) of the wetted area of habitat upstream of the barriers on the River Lugg can be made to indicate the potential benefits to salmon habitat. The total riverine wetted area of the River Wye SAC (Figure 2) has been estimated at 1,327 ha[4]. The wetted area of the River Lugg (outside the SAC) is 159 ha, 77 ha of which is upstream of the identified weirs. Therefore, measures to increase salmon passage into the upper River Lugg catchment could provide access to historically available habitat equivalent to approximately 5% of the combined River Wye and River Lugg catchment.

2.1.2.4 River Tywi

Atlantic salmon populations in the Tywi are in sharp decline, and most recent assessments have classified the population as being at risk, due to there being less than a 5% chance of this stock meeting its management objective (Environment Agency, 2023). Any factor that impacts populations of salmon which are at such low biological levels will have an increased effect on the stock. Therefore, as weirs and other structures have been demonstrated to have a negative impact on salmon, their removal is likely to have a beneficial effect although quantifying this management measure on the Tywi will require further monitoring. Monitoring approaches are anticipated to become a formal requirement as part of the AMMP and developed iteratively with regulators.

It is understood that telemetry studies of smolts within the Tywi are ongoing and emerging data sources may provide additional information on emigration movements from the catchment (David Clarke, University of Swansea, *pers. coms.*).

2.2 The twaite shad (*Alosa fallax*) and allis shad (*Alosa alosa*)

2.2.1 The impacts of obstructions, and benefits of their removal

Both species of native shads, the twaite shad (*Alosa fallax*) and the allis shad (*Alosa alosa*), have been in sharp decline throughout the United Kingdom in recent decades (Antognazza *et al*., 2022). Twaite shad breeding is now restricted to four rivers in the UK, all of which are situated in Wales and southwest England (the Severn, Tywi, Usk, and Wye) (Davies, 2022), and the allis shad is restricted to the River Tamar (southwest England) and the Solway Firth (on the boundary between England and Scotland), although for the latter shad spawning locations are yet to be identified (Jolly *et al*., 2012; Antognazza *et al*., 2022). Obstacles to migrations and resulting habitat fragmentation are believed to be among the leading causes of their decline, and increased genetic introgression (Antognazza *et al*., 2022). Overall, high levels of hybridisation between the two species have been reported for Great Britain, with the hybrids in the River Severn and Tywi mainly clustered towards twaite shad (Antognazza *et al*., 2022). Allis shad are rare in the Severn Estuary and the Environment Agency found no evidence of the species in the River Usk. Large fish are very uncommon in the impingement record (BEEMS Technical Report TR583, *in prep.*) and morphological and genetic analyses of juvenile shad samples impinged in 2021 and 2022 showed the fish were either twaite shad or hybrids (BEEMS Technical Report TR567). As may be expected, there is no tagging data on allis shad in the rivers considered for feasibility assessment.

Shads face many of the same challenges from obstacles to migration as salmon. However, some of these impacts are greater for shads because they are relatively poor swimmers when compared to the salmonids, presenting much lower sustained swimming speeds (Armstrong *et al*., 2010). As such, they are unable to pass certain areas with particularly high flow rates and have difficulty in ascending large drops in water level

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[4] Data source: https://datamap.gov.wales/layers/inspire-nrw:NRW_SAC (accessed on 31/10/2023)

when migrating upstream (Larinier & Tavarde, 2002). Furthermore, as shad tend to migrate in shoals, it is recommended that any passage measures designed for them should be wide enough to accommodate several fish at once (Larinier & Tavarde, 2002).

If habitat is a limiting factor for shad in the catchments of the Severn Estuary, improvements to fish passage would enhance access to historic spawning grounds and support production. However, such improvements must be contextualised relative to other factors influencing production rates. For example, year class strength (YCS) in juvenile twaite shad is highly variable and dependent on environmental conditions. Monitoring 0+ group twaite shad at HPB has identified that water temperature in June-August has been shown to explain up to 77% of the YCS (Aprahamian and Aprahamian, 2001).

2.2.2 Evidence specific to the target weirs for this study

2.2.2.1 River Severn

Studies undertaken at Maisemore and Upper Lode Weirs as part of the Unlocking the Severn Project have indicated that these are likely to present substantial obstacles to migrating twaite shad (Davies *et al*., 2023). Maisemore Weir is generally considered to be the upper limit of tides on the Severn, but on occasion, notably during the spring, high tides will overtop this weir and will increase water levels up to the Upper Lode Weir (Davies, 2022). As such, both obstacles present a substantial head drop at lower tides (Davies, 2022), which can present a challenge for shad (Larinier & Tavarde, 2002), and cause migration delays (Davies, 2022).

Acoustic tracking studies in the Severn have indicated that 79% of the adults tagged during their upstream migration in 2018 left the river with the rate of freshwater mortality estimated at 21%. The following spring 59% of the post-spawning fish that emigrated from the river returned to fresh water, indicating marine mortality of 41% (Davies *et al*., 2020). Similarly, when combining 2018 and 2019 data, 72% of the adults emigrated from the rivers, and 57% of those fish returned to the river the following year, of which the majority emigrated for a second time (75%) (Davies *et al*., 2023).

Another study assessing upstream passage of shad over barriers, indicated that the majority of the tagged individuals (98 – 100%) approached and successfully passed weirs in the lower reaches (Maisemore and Llanthony) in 2019 and 2020, with median passage times of 1 day (range: 0.4 – 3.9 days) and 1.5 days (range: 1.0 – 2.8 days), respectively (Davies *et al*., 2023.). Reported migration delays could detrimentally affect fish reproductive success and survival and increase predation risks, particularly when stocks are depleted and there are cumulative barrier impacts further upstream. Upstream at Upper Lode, only 50% of the shad were able to pass the weir, averaged across 2018 – 2020 (range: 16 – 81%) with increasing temperature and water levels positively affecting passage rates (Davies *et al*., 2023). Migration delays at the Upper Lode were substantial, ranging from 1.1 to 33 days across all the investigated years (Davies *et al*., 2023). Fish were unlikely to attempt a second passage if they had initially failed to traverse the barrier. Returning fish passed at higher rates than newly tagged individuals (Davies *et al*., 2023).

The adult twaite shad run size has been estimated from data generated from the Unlocking the Severn project and provided by Charles Crundwell of the Environment Agency. Counts of adult shad passing the notch at Upper Lode Weir at Tewksbury are made by citizen scientists and submitted to the Unlocking the Severn project. The observed estimates are verified using a resistivity counter. Recent count data of shad migrating upstream at Upper Lode have declined in the years since 2020. Tagging data show high return rates for adult fish indicating low mortality at sea, and impingement monitoring at HPB has not shown a recent decline in juvenile (0+) fish in the impingement record. Therefore, the reason for the low run estimate at Upper Lode is unclear. It has been suggested that high mortality may be occurring in the marine phase of juvenile fish from the point they emigrate from the estuary as 0+ group fish until they return as first-time spawners (Miran Aprahmian, *pers. coms*.). However, anecdotal evidence suggests that migratory runs on the Rivers Usk and Wye have not seen similarly low levels as in the River Severn in recent years (Charles Crundwell, *pers. coms.*). Data on the length distribution of twaite shad migrating upstream at Upper Lode may provide further insights into the age structure of fish in the spawning migration, allowing a better understanding of the life stages at which mortality may be occurring and limiting the shad population in the River Severn Length-distribution data from the RIMP from 1981 – 2017 shows that the majority of the fish measured in the impingement record were 0-group with 87% of individuals less than 79 mm standard length. Approximately 1% of fish impinged were over 305 mm, a size at which some individuals may be mature. No fish were impinged between the size range of 205 – 305 mm (BEEMS Technical Report TR583, *in pep.*). Little is known about the behaviour and distribution of immature fish of this size and it is anticipated that juvenile shad feed offshore in marine waters before returning to the estuary prior to spawning migrations.

The recent observed decline in the count numbers at Upper Lode have occurred despite the measures undertaken by the Unlocking the Severn project including the installation of the fish pass upstream at Diglis near Worcester. However, the period it takes for twaite shad to attain maturity and return to the rivers as spawning adults is such that benefits of increased production as a result of the creation of the fish pass at Diglis, in terms of increases in returning adults, would not yet be reflected in the count data.

Improving fish passage at either Maisemore or Upper Lode has the potential to increase shad spawning success by reducing delays in migration. Should habitat be limiting population recovery, measures at Upper Lode would allow access to upstream habitat to a greater proportion of the population. To determine the benefits of easing or removing these barriers it is likely that a weight of evidence approach using different monitoring methods would be required as part of the AMMP (Section 4).

2.2.2.2 River Usk

Twaite shad eggs were found above the Trostrey Weir in the River Usk during egg surveys implying that shad are able to successfully pass this structure (Garrett, 2015). However, a more recent Natural Resources Wales report indicated that Trostrey Weir may impede shad migration (Natural Resources Wales, 2022). Following consultation with stakeholders and regulatory bodies and should site feasibility studies identify Trostrey as a priority barrier for easement / removal works, it is anticipated that tagging studies would form part of the AMMP (Section 4). Using a before / after experimental design, the benefits of barrier removal or easement to upstream passage at Trostrey may be quantified in terms of increases in passage rate, or reductions in passage delays.

2.2.2.3 River Lugg

The removal of suggested weirs on the River Lugg is unlikely to yield a significant effect on twaite shad production in this catchment, due to this stretch of river being far upstream, outside of twaite shads usual spawning habitats.

2.2.2.4 River Tywi

Between 2013 and 2015, the spawning success of shad was assessed in the river Tywi through yearly egg surveys (Garrett *et al*., 2015). Shad eggs were found to be present in areas below Manorafon Weir (present at Llandeilo bridge within the report), but eggs were only found above the weir in one of the conducted surveys (Garrett *et al*., 2015). This report suggests that Llandeilo may have historically been the natural limit of shad spawning, in which case it would potentially be incorrect to assume that removing this structure would improve shad production in the area (Garrett *et al*., 2015). A recent report by Natural Resources Wales indicated that ambient temperatures around Llandeilo are currently very close to the lower thermal limit for shad recruitment, leading to intermittent recruitment in the area due to annual variations in temperature (Knights, 2014). The report indicates that breeding success is unlikely to improve in sections upstream of Llandeilo, and that a downstream section known as Whitemill is vital to shad recruitment in the

Tywi. As such, the author suggests that any attempts to conserve shad in this river should focus on this stretch (Knights, 2014). These reports suggest that removing Manorafon Weir would be unlikely to significantly benefit shad migration in this catchment at present. However, conditions for shad recruitment in the upper catchment may improve within decades, as temperatures continue to increase in the context of climate change (Section 2.4).

2.3 Other Species of Conservation Interest

2.3.1 The River Lamprey (*Lampetra fluviatilis*) and Sea Lamprey (*Petromyzon marinus*)

The presence of migration barriers is often cited as a leading cause in the recent declines of both anadromous species of lamprey found in the United Kingdom, the river and sea lamprey (Aronsuu *et al*., 2019). As for other species, obstructions can significantly impact on breeding success and juvenile survival (Moser *et al*., 2021), and passing successive obstacles can cumulatively increase their impacts (Davies *et al*., 2021). Studies have shown that restoring connectivity can allow lampreys to recolonise once inaccessible spawning habitat and can lead to the full recovery of larval abundance within five years (Pess *et al*., 2014; Pereira *et al*., 2016; Moser *et al*., 2021).

Where complete obstacle removal efforts would be impossible, lampreys can benefit from several different easement measures. Most notably, the use of certain kinds of fish passes have shown great success for lampreys (Laine *et al*., 1998; Keefer *et al*., 2010; Moser *et al*., 2021), particularly those designs for which successful passage does not require long periods of swimming against high flow (Foulds & Lucas, 2013). As lampreys can attach themselves to the substrate with their oral disc to rest, they are able to rapidly recover from multiple successive passages (Kirk *et al*., 2016). Simple modifications to existing structures, such as equipping obstacles with studded tiles or bristles along surfaces, or providing rounded edges around openings can increase passage success (Kerr *et al*., 2015; Tummers *et al*., 2018).

2.3.1.1 River Severn

A recent tracking study observed 100% passage over the Maisemore Weir, albeit with a median passage time of 1.6 days, whereas only 89% of the lamprey were able to pass the Upper Lode Weir, and those that did pass had a median delay of 10.4 days (Davies *et al.,* 2021). As such, fish passage improvements at either of these sites may reduce migration delays and at Upper Lode enhance upstream migration success.

2.3.1.2 River Usk

A recent study suggested that adult sea lamprey are able to successfully pass Trostrey Weir in most years (Nunn *et al*., 2017). The stretch upstream of Trostrey presented the highest densities of ammocetes observed in the study, indicating high spawning success within this area (Nunn *et al*., 2017). However, it appears that other obstructions further upstream present greater challenges for adult lamprey passage, and may be more suitable candidates for removal if that would open up more suitable habitat.

2.3.1.3 River Lugg

Information on lamprey populations in the River Lugg is scarce, however data from NRW databases[5] provides evidence of lamprey (not speciated to species level) from electrofishing surveys upstream of the selected weirs, indicating the weirs are not impassible and the areas upstream provide suitable habitats.

[5] Data source Contains Natural Resources Wales information © Natural Resources Wales and database right. All rights reserved.

Measures to improve fish passage at the weirs have the potential to increase lamprey passage to utilise upstream habitat further.

Nunn *et al*. (2017) provides some data on lamprey spawning in the upper reaches of the Wye, but all surveys were conducted far upstream from where the Wye and Lugg separate. Further investigations would be required to assess current lamprey movements around the three structures being considered to estimate the potential benefits of their removal.

2.3.1.4 River Tywi

In by-catch data presented for the 2015 survey of the River Tywi (Garrett *et al*., 2015), lamprey were captured in the lower reaches of the river, and at Llandeilo Bridge. However, it is unclear if the absence of lampreys captured above this point is indicative of a limitation in their movements, or if it is due to a general lack of data.

2.3.2 The European Eel (*Anguilla anguilla*)

As for many other species, migration barriers are considered a key contributing factor in the recent decline of the European eel (Bruijs and Durif, 2009; Piper *et al*., 2013). Obstacles within rivers can significantly impact the upstream migration of juveniles, as well as the downstream migrations of adults (Piper *et al*., 2013). Obstructions can lead to considerable delays in the movements of downstream-migrating adults, known as silver eels (Bruijs and Durif, 2009). In addition to the effects observed in other species, such as increased predation and spread of disease (Verhelst *et al*., 2018), delays can have serious implications for their migrations to the Sargasso Sea, as silver eels do not feed during their downstream migrations, it is believed that any delays deplete their energy reserves and may prevent them from successfully reaching their spawning habitat (Piper *et al*., 2013). Similarly, obstacles can delay or prevent passage for upstream-migrating juvenile glass eel and elver stages, thus restricting their access to certain areas of suitable feeding and rearing habitats (Vowles *et al*., 2019).

Weir removal has been shown to allow rapid recolonisation of upstream areas by juveniles (Sun *et al*., 2021). However, in areas where full removal could not be undertaken, the creation of fish passes has also been proven to be an effective means of allowing passage (Solomon and Beach, 2004; Laffaille *et al*., 2005). Furthermore, as for lamprey, the placement of studded tiles or bristles on the surfaces of weirs and fish passes has been shown to aid in the upstream passage of eels (Vowles *et al*., 2019).

Available information on the passage of eels at the studied sites is very limited. A study by White and Knights (1997) investigated the upstream movements of elvers from the upper tidal limit of the River Severn at Upper Lode Weir. This structure was not considered to pose as much of a significant challenge to elver migrations as other more complex structures further upstream, as the structure has a relatively shallow slope, which the eels would be able to scale. Furthermore, the authors suggested that particularly high tides may carry eels directly over the weir. However, as Upper Lode Weir was the furthest downstream among those in the study, this provides no data on potential passage efficiency or delays caused by the structure. Studies conducted around this area suggest that Tewkesbury Weir, located on the lowest reaches of the River Avon, upstream of Maisemore Weir, presents a significant obstacle to upstream eel migrations, leading to high numbers of glass eels settling in suboptimal habitats downstream of this structure (White and Knights, 1997; Aprahamian and Wood, 2021). As such, management plans to improve passage of eels at Tewkesbury Weir also has the potential to deliver benefits.

A study conducted on Claxton Beck in north-east England provided evidence that eels can rapidly make use of newly available habitat after the removal of a tidal weir, similar to those found at Maisemore and Upper Lode (Sun *et al*., 2021). Surveys conducted around the weir's location showed a significant increase in upstream eel density just five months after the weir's removal, and no significant change in the densities of downstream eels. Furthermore, no significant difference was found between the upstream and downstream eel densities within seventeen months of removal.

There is limited data available for European eel on the Lugg relative to the selected weirs. However, electrofishing survey data provides evidence of eels in the River Lugg upstream of the selected weirs, indicating the weirs are not impassible and the areas upstream provide suitable habitat. Measures to improve fish passage at the weirs have the potential to increase eel passage to utilise upstream habitat further.

2.3.3 Non-native and invasive species.

The removal of weirs to increase connectivity will benefit most of our native diadromous fish species. However, it should be noted that it could aid the colonisation of the river catchments by invasive fish species. Risk assessments for invasive species in UK rivers and streams are available and it is recommended that these are applied to the river systems considered in this report as part of feasibility studies.

2.4 Barriers to migration in the context of climate change

Climate related environmental changes present considerable challenges to fish populations already impacted by habitat loss and fragmentation (Radinger *et al*., 2017; Bao *et al*., 2023). This section considers barriers to migration in the context of climate change. Environmental modelling studies have predicted that river basins in South-west England and Wales are likely to undergo some of the most significant changes in future river flow and temperature trends in the UK (Prudhomme *et al*., 2012; Jonkers and Sharkey, 2016; Moore *et al*., 2019). Most notably, these areas are predicted to experience some of the highest mean temperature increases across most of the year, however, small reductions in mean monthly temperatures in July and August may occur (Jonkers and Sharkey, 2016), along with reduced mean summer discharge and increases in the frequency of high discharge events (flooding) (Hall *et al*., 2003; Prudhomme *et al*., 2012; Hannahford *et al*., 2021).

Most recent reviews indicate climate change has been partly responsible for the current decline of Atlantic salmon populations, with this expected to exacerbate in the future, particularly when coupled with other stressors operating on already depleted stocks (Assunção *et al*., 2014; Gillson and Bašić *et al*., 2022). Changes in river temperatures, flow conditions, and in the composition of surrounding ecosystems have been found to impact on salmon survival, growth, and population recruitment (Assunção *et al*., 2014; Thorstad *et al*., 2021; Gillson and Bašić *et al*., 2022). As a cold-water species, all salmon life stages can suffer both lethal and sub-lethal effects as temperatures increase in freshwater environments (Solomon and Lightfoot, 2008; Dietrich *et al*., 2014). For instance, warmer conditions result in faster egg development and earlier fry emergence (Elliott and Elliott, 2010; Assunção *et al*., 2014), which has been suggested to be detrimental to growth and survival, as fry would emerge before sufficient food resources are available (Thorstad *et al.*, 2021). Furthermore, temperature changes affect the subsequent development of juvenile salmon by altering growth rates, limiting the availability of suitable habitats and food resources (Thorstad *et al*., 2021), and on occasion, exposing salmon to temperatures beyond their lethal limits (Solomon and Lightfoot, 2008). Cold-water thermal refuges are therefore becoming increasingly vital to salmonid survival in warming rivers (Linnansaari *et al*., 2023), by allowing these fish to regulate their body temperatures, and thus minimising thermal stress and energy losses (Breau *et al*., 2011; Moore *et al*., 2012). The presence of barriers can completely change the thermal characteristics of a river, and occasionally limit access to thermal refuges (Meija *et al*., 2020; Linnansaari *et al*., 2023). However, in some cases, deep pools created by the regulation of river flow by manmade structures may also provide artificial thermal refugia as a result of stratification (Linnansaari *et al*., 2023).

Long-term changes in river discharge trends will likely further exacerbate the effects of river impoundments on salmon. Indeed, climate change-induced alterations in river flow can lead to reduced passage successes, notably during periods of extreme flow and can increase migration delays (Assunção *et al*., 2014; Thorstad *et al.*, 2021; Gillson and Bašić *et al*., 2022). Changes in river flow can also alter the timing of migrations by disrupting vital cues for their initiation (Gillson and Bašić *et al*., 2022), and significantly reduce the availability of suitable spawning habitats (Parry *et al*., 2018). Increased fine sediment transportation under higher mean winter discharges can drastically reduce salmon egg survival by reducing available oxygen within redds (Grieg *et al*., 2005; Assunção *et al*., 2014). The increasing occurrence of brief high flow events (flooding) under climate change can also have a range of impacts on salmon, including by inducing egg and fry mortalities by dislodging redds (Assunção *et al*., 2014; Parry *et al*., 2018). As close relatives to Atlantic salmon with similar life histories, sea trout (*Salmo trutta*) are likely to suffer many of the same effects in the context of climate change (Assunção *et al*., 2014). However, as trout are better suited to colder environments (Solomon and Lightfoot, 2008; Assunção *et al*., 2014), they are likely to be more affected by increases in river temperatures.

Unlike salmon and sea trout, estimates made for shad under predicted climate change conditions indicate that these two species are likely to largely benefit from temperature increases, if habitat connectivity and access to suitable spawning habitats are maintained (Aprahamian *et al*. 2010; Moore *et al*., 2019). Shad are Lusitanian species, and warmer conditions have notably been shown to improve survival rates for eggs, larvae, and juveniles (Aprahamian *et al*., 2010; Jatteau *et al*., 2017). Indeed, in the upper sections of the River Tywi twaite shad production is predicted to be limited due to low temperatures that may become more preferable to recruitment in the coming decades (Knights *et al.,* 2014). Furthermore, warmer conditions have been found to be positively correlated with upstream passage success over certain weirs on the River Severn, such as the Upper Lode weir (Davies *et al*., 2021). This is hypothesised to be due to the increased development and maturation of reproductive organs in warmer water, which in turn leads to higher motivation to ascend barriers (Davies *et al*., 2021). As a result, twaite shad population modelling for the River Severn undertaken by Aprahamian *et al*. (2010) indicated that increases of just 1˚C or 2˚C in mean water temperatures over the summer months could result in 3-fold or 6-fold increases in population size, respectively. However, the presence of freshwater migration barriers is considered to be a factor in the recent declines of both shad species (Aprahamian *et al*. 2010; Antognazza *et al*., 2021), and predicted reductions in river discharge during spring and summer months are also likely to inhibit passage over manmade structures, and increase migration delays (Hillman, 2003; Moore *et al*., 2019). As such, restoring and protecting the access to suitable shad spawning habitats is considered vital for their conservation (Moore *et al*., 2019).

The exact causes of the European eel's recent population decline remain highly debated. However, a number of studies have suggested that these declines could be partially attributed to changing environmental conditions in the Sargasso Sea and in the surrounding Atlantic Ocean (Righton *et al*., 2021). Investigations of inter-annual changes in eel larval abundance in estuaries showed strong correlations with factors such as primary production in the Sargasso Sea, and changes in the characteristics of Atlantic currents (Bonhommeau *et al*, 2008; Arribas *et al*., 2012; Righton *et al*., 2021). As such, recent The International Council for the Exploration of the Sea (ICES) advice for European eels has recognised the contribution of climate change impacts on the species and noted that the nature of these effects remain poorly understood (ICES, 2023). Furthermore, many factors contribute to the decline of European eel in freshwater environments are not closely linked to climate change, including water abstraction, mortalities in turbines, and pollution within rivers (Pike *et al*., 2020). However, important environmental cues for the initiation of silver eel migrations, predicted increases in river discharge and rainfall in the autumn (Moore *et al*., 2019) are likely to lead to earlier migrations (Vøllestad *et al*., 1986) and increased migration speed (Drouineau *et al*., 2018).

Long-term changes in ambient temperatures and river discharge in the context of climate change is predicted to have a range of effects on the survival, growth and recruitment of anadromous lampreys. Predictions made by Lassalle and Rochard (2009) indicate that environmental changes in the context of climate change are likely to contribute to population declines in both river and sea lampreys throughout their native ranges. Modelling for both species indicates that sea lamprey populations are likely to largely remain stable in the UK, whereas river lamprey populations will likely decline in the southern British Isles, as a consequence of changing environmental conditions (Moore *et al*., 2019). Higher temperatures have been shown to accelerate egg and larval development rates (Rodríguez-Muñcoz *et al*., 2001), and increase sea lamprey larval dispersal (Derosier *et al*., 2007). In addition, water temperature is largely considered a principal determining factor for the onset of lamprey metamorphosis and spawning migrations (Youson *et al*., 2012; Baer *et al*., 2018), and as such changes in ambient temperatures in key periods may have significant impacts on the timings of these life history events (Baer *et al*., 2018). However, the nature of temperature effects on migration activity levels remains uncertain. Some studies have found that increasing temperatures positively correlate with migration activity levels (Binder *et al*., 2010), whereas others have found little effect of temperature within a certain range, with decreasing activity levels only occurring beyond certain thresholds (Aronsuu *et al*., 2015). Predicted decreases in mean river discharge in spring and early summer could impede their upstream spawning migrations, by delaying the initiation of these migrations (Baer *et al*., 2018; Moore et al., 2019), and by reducing passage success (Rooney *et al*., 2015). High discharge events can cause washouts of eggs from lamprey nests (Smith & Marsden, 2009), and has been observed to result in higher rates of impingement in water abstractions (Moser *et al*., 2015; Moore *et al*., 2019).

3 Potential benefits of fish passage improvements – Example Case Studies

Insights into the potential benefits of fish passage improvement works can be gained by looking at case studies of similar projects in the United Kingdom and mainland Europe. The examples that follow describe the outcomes of previous initiatives aimed at restoring passage for diadromous species.

3.1 River Villestrup, Denmark – Benefits of weir removal on the downstream migrations of salmonids

Between 2004 and 2013, a total of six weirs were removed from the River Villestrup in Jutland, Denmark (Birnie-Gauvin *et al*., 2018). Before their removal, the presence of these structures impeded both the downstream migrations of wild brown trout (*Salmo trutta)* smolts and hindered upstream migration of adult fish. Birnie-Gauvin *et al*. (2018) analysed the size of the smolt run gathered in the Villestrup trap during five years: in 2004, before any of the weirs were removed, in 2008 and 2009, after the first weir was removed, and in 2015 and 2016, after removal of the five remaining weirs.

The initial run in 2004 saw 1,660 smolts migrate downstream in total, with a maximum of 92 smolts captured in a single day. Following the removal of all weirs, the smolt runs amounted to 19,105 and 8,185 smolts in 2015 and 2016 respectively; reaching 5,214 and 1,853 smolts caught in a single day. The authors concluded that the removal of weirs in River Villestrup had restored suitable habitats for spawning and juvenile development, which benefitted trout recruitment in the river. In addition, smolts were on average 3 centimetres smaller after weir removals, which may indicate higher levels of intraspecific competition between fry or parr caused by their higher densities in the restored upstream environments. Finally, the smolt migrations occurred several days earlier in the years after the weirs were removed (Birnie-Gauvin *et al*., 2018). Although this is an expected result of alleviating obstacle-induced delays, periods of high flow may also have been partly responsible for these earlier peaks.

3.2 River Tees Barrage, United Kingdom – Benefits of obstruction removal on salmonid upstream migrations

In 2008, Cefas was commissioned to undertake an assessment of the efficacy of the fish pass present on the River Tees Barrage (Moore and Potter, 2014). The construction of the fish pass with the inclusion of a fish trap had initially been granted provisional approval as part of the Salmon and Freshwater Fisheries Act 1976, but evidence of its effectiveness was required before permanent approval could be granted. Cefas therefore undertook tracking studies of salmon and sea trout moving through the pass in 2008, 2009 and 2013, and analysed data from a fish trap, which was later replaced with a counter, present on the barrage between 1995 and 2013 (Figure 6).

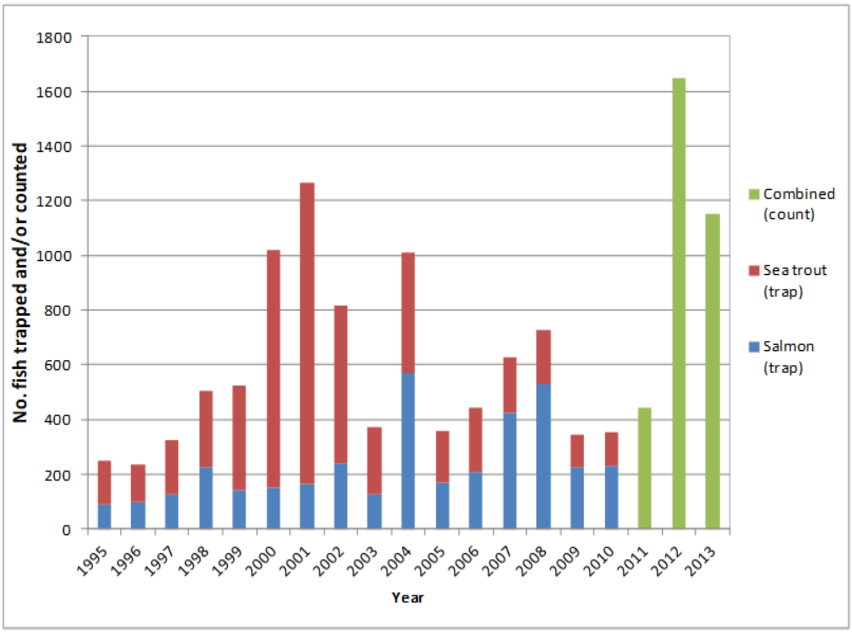

Figure 6 Number of salmon and sea trout caught in the River Tees trap (1995 – 2010) and combined numbers counted (2011 – 13). [NB In 2011 the trap operated from January to June, and the counter for the remainder of the year].

The results of this work indicated that a fish trap present at the top of the barrage's fish pass was causing migrating salmon and trout to return downstream, and therefore blocking upstream passage via this route. Data from the fish trap, and the electronic fish counter installed in the same location after the trap's removal in June 2011 were compared, to estimate the effects that removing the trap had on upstream migrating adults. Results indicated higher numbers of fish passed over the counter in 2012 and 2013 than were trapped in any year between 1995 and 2010, with the exception of 2001. Furthermore, the mean count for 2012 and 2013 was nearly three times higher than the mean number of fish trapped in the five years from 2005 to 2009. Although it seems likely that these increases are at least partly due to the removal of the trap, it is not clear whether this reflects an increase in the numbers of fish entering the river, or just a change in the route used by fish to get past the barrage.

There were also marked changes in the annual timing of the runs following the removal of the trap. The annual run of salmon and sea trout became earlier in the year by approximately two months. The evidence supports the view that removing an obstruction to salmonid migrations allows a significant increase in the upstream movement of spawning fish.

3.3 Coimbra Dam, Portugal – The benefits of fish pass installation on a previously impassable dam for allis shad (*Alosa alosa*), twaite shad (*Alosa fallax*) and sea lampreys (*Petromyzon marinus*)

The Mondego River in Portugal has long provided vital spawning habitat for several anadromous species, notably the allis and twaite shad. Coimbra Dam was constructed in the lower reaches of the river in 1981 (Figure 4). Despite being equipped with a pool-and-weir fish pass, the structure was found to be a complete barrier to fish migrations, blocking access to vital spawning habitats upstream of the dam. As such, all spawning in the following years was restricted to a short and highly modified stretch of river situated downstream of the dam. The construction of a new vertical slot fish pass was therefore undertaken and completed in 2011. Since this date, all shad passage was monitored using visual observation of passing shad through a window installed in the side of the pass. Between 2013 and 2017, a study was undertaken to assess the effects of various environmental factors on shad passage, with the view to informing the design of future passage measures, and delivering further advice on management measures for this species around existing structures (Belo *et al*., 2021). A video camera was placed in the existing window present in the Coimbra vertical slot pass, allowing for the timings of all upstream and downstream adult shad passages to be recorded, along with any relevant environmental information. Due to the unreliability of assessing these fishes based solely on their phenotype, the two shad species were not distinguished.

Information obtained from the visual monitoring of shad passage through the new fish pass showed that the creation of this structure had successfully restored shad access to the upstream reaches of the river, with an average of 5,312 shad observations in the fish pass recorded between 2013 – 2017. However, it is not possible to assess whether this measure has partially or completely restored the fishes' access to the upstream stretches, as the method used cannot account for any unsuccessful passage attempts. Furthermore, the use of visual monitoring cannot provide a measure of migration delays caused by the dam's presence. Analyses of the resulting data showed that over 96% of shad passage occurred between April and June, and that water temperature and river flow rates were the strongest predictors of successful shad passage. As such, Belo *et al*. (2021) recommended that water flow rates through the passes should be regulated to between 35 and 50 $m^3 s^{-1}$ during the period of the year when shad are most likely to pass through these structures, once temperatures have increased to favour the two species' movements. This information could be used in the development of future structures such as fish passes, in the assessment of existing structures, and in the development of management policies for shad.

Figure 7 The Coimbra Dam Vertical Slot Fish Pass. Photograph by Dr A.M. Walker, October 2018.

Another study conducted on the Coimbra Dam vertical slot fish pass established that this structure had also been successful in re-establishing upstream access for the sea lamprey (Pereira *et al*., 2016). A study conducted between 2011 and 2015, used both passive integrated transponder (PIT) and radio telemetry to assess the movements of upstream-migrating adult lampreys through the fish pass, in conjunction with electrofishing surveys upstream of the dam, to provide an assessment of juvenile (ammocoete) abundance around spawning habitats. Two kinds of radio telemetry tags were used in the assessment of lamprey passage through the fish pass, both conventional tags, which were used to record the positions and movements of lampreys, and electromyogram (EMG) tags, which measure the level of muscle activity in the fish. The EMG tags were therefore used both to measure the level of effort required for lampreys to successfully ascend the fish pass, and to provide a fine-scale assessment of their behaviours and activity around the structure. The passage efficiency of the vertical-slot fishway was assessed using a PIT antenna installed in the pass, providing a measure of the proportion of tagged fish which successfully negotiated the structure, as well as the timings of successful passages. The abundance of ammocoetes was assessed by electrofishing surveys. Electrofishing was undertaken at two sites, one upstream of the dam, and another downstream, thus providing a means of comparing the relative densities of juveniles in these two areas.

The results of this study first confirmed that the creation of the new fish pass had indeed restored partial access to upstream spawning habitats, with 31% of PIT tagged lampreys successfully passing the antenna at the top of the fishway. This was corroborated by the data from radio-tagged individuals, 33% of which successfully passed the structure within two weeks. The EMG tags indicated that the lampreys took around three hours to ascend the fish pass itself, and high muscular effort was only registered by the tags in short bursts during passage of the vertical slots themselves, thus indicating that the fish were able to recover in the pools between these, and that ascending the pass was not energetically demanding. Finally, electrofishing surveys showed a gradual increase in ammocoete abundance above the dam. Significantly higher numbers of ammocoete were found below the dam in every year except 2015, when no difference was found in the catch per unit of effort between the two stretches upstream and downstream of the dam (Pereira *et al*., 2016).

4 Potential monitoring methods to determine effectiveness of barrier removal

Undertaking effective monitoring for removal or easing work is necessary to demonstrate the effects of intended fish passage improvements on the target species. Data collected as part of these management programmes can be used in a variety of ways, including determining the outcomes of the approach, and to assess whether the desired goal has been achieved. Data on the methodology and results of successful approaches can be used to prioritise and refine future restoration projects at other locations (Kemp and O'Hanley, 2010; Clark *et al*., 2020).

4.1 Qualitative monitoring methods

Qualitative monitoring methods seek to determine the ability of fish to pass a structure, and therefore can be used to determine whether a structure is a complete barrier to migrations, and whether an approach has been successful at restoring fish passage (Kemp and O'Hanley, 2010). This can be investigated via a range of methods, including visual inspections, fisheries surveys, environmental DNA (eDNA) sampling, fish counters and traps, and telemetry studies. Environmental DNA sampling is a notable example of a specifically qualitative method, as it can provide information on the presence or absence of certain species at a given location (Muha *et al*., 2021). eDNA sampling has been used to assess whether fish species are able to ascend certain obstacles before removal (Garcia de Leaniz and O'Hanley, 2022), or whether such efforts have restored a species' ability to reach a certain section of a river (Antognazza *et al*., 2021). Until recently eDNA surveys have been unable to provide quantitative measures of species abundance and have been used in conjunction with telemetry studies to provide a clearer understanding of passages to fish migrations, thus aiding in prioritising the removal of certain structures. However, recent efforts have been made to develop methods of using eDNA to assess fish abundance (Rourke *et al*., 2022; Spear *et al*., 2023). Environmental DNA surveying was used in the Unlocking the Severn Project, to help estimate the upstream extent of shad, and to identify obstacles to their upstream migrations in the Rivers Severn and River Teme (Antognazza *et al*., 2021).

4.2 Quantitative monitoring methods

In many cases, it is more useful to quantitatively assess the proportion of fish which can successfully pass an obstacle or section of a river, with delay often being considered as a factor in these assessments (Armstrong *et al*., 2010). These assessments can be used in locating impassable barriers, determining the proportion of fish which are able to pass partial obstructions (otherwise called fish passage efficiency, not to be confused with fish pass efficiency), or quantifying obstacle-induced delays (Garcia de Leaniz and O'Hanley, 2022).

It is generally accepted that using telemetry methods is the most informative way of quantitatively assessing the movements of fishes around obstructions (Garcia de Leaniz and O'Hanley, 2022; Davies *et al*., 2023). Telemetry involves implanting a small device (known as a tag) inside a fish and placing a number of receivers in the surrounding environment. When a tagged fish passes sufficiently close to a receiver, the latter will record the tag's identifying code, the time of the tag's detection, and any other information recorded by the tag (Misund, 1997). There are three main kinds of telemetric studies of in-river obstacles. The most common of these is acoustic telemetry, where the tags emit a high-frequency sound at regular intervals, which is recorded by the receiver's hydrophone (Misund, 1997). This method can detect fish movements over relatively long distances (typically tens of metres in flowing water), so can be used to provide information on fish approach, unsuccessful attempts at passage, and delay time (Davies *et al*., 2021). Some studies also use PIT telemetry, which involves placing a small tag containing a ferrite coil and microchip inside the fish (Piper *et al*., 2013; Pereira *et al*., 2016). PIT antennas generate a magnetic field which interacts with the tag's coil, thus powering the microchip. The antenna then records the tag's identifying code, and records the time of detection (Thorstad *et al*., 2013). As PIT tags do not require an internal battery, they can be used to record the same fish over longer time periods, in theory for ever (Foldvik and Kvingedal, 2018). However, as the antennas can only detect tags at very close range (tens of centimetres), this method cannot provide measures of fish approaches, or delays unless they approach very close before turning back (Thorstad *et al*., 2013). They can essentially only record the fishes' movements immediately in the vicinity of the antennas, providing information on the proportion of tagged fish which successfully passed the monitored section of river (Pereira *et al*., 2016). Finally, although less commonly employed than the other two methods, radio telemetry can be used to assess passage success (Pereira *et al*., 2016). In this method, the tag implanted in the animal contains a small radio transmitter emitting a high-frequency signal. Radiotelemetry can be used to track fine-scale movements of fish over relatively short distances, and broader-scale movements over much longer distances (Larinier *et al*., 2005; van Leeuwen *et al*., 2016; Grimardias *et al*., 2022). However, as these tags require considerably more power than acoustic tags, studies involving these may be limited in terms of tag size, or in terms of their life span. Radio telemetry has been used to assess the migrations of fishes through a designated section of river, or past a certain structure (Pereira *et al*., 2016; Grimardias *et al*., 2022).

For salmon, telemetry can be used to monitor the upstream migrations of adults, as well as the downstream movements of smolts (Havn *et al*., 2020). Downstream-migrating juvenile shad are too small to be safely tagged, but telemetry studies have been used to monitor both the upstream and downstream migrations of adults, (Davies *et al*., 2021), with some even succeeding in demonstrating the repeated spawning migrations of the same adults across several years (Davies *et al*., 2023). Furthermore, data on lamprey and shad movements already exists for some of the weirs currently under consideration, which was collected as part of the Unlocking the Severn Project (Davies, 2022).

Deployments of rotary screw traps (RSTs) during key periods of the year are widely used in salmonid research, notably to count and tag smolts. Data from these can be used to estimate upstream adult spawning success and juvenile population size (Fjelstad, 2012). Typically, RSTs are deployed during the spring which is the main period of smolt emigration. However, in some rivers there are also autumn-emigrating smolts, so ideally RSTs would be deployed to monitor these as well.

Other methods can be used to quantitively assess fish passage through an obstruction without needing to capture or handle fish (Noonan *et al*., 2012). For example, visual monitoring using screens can be used to provide counts, and often species-specific data on fish passage. Such methods are already in use on certain fish passes, which were recently installed as part of the Unlocking the Severn Project (Unlocking the Severn, 2022). Visual monitoring could be performed using surveying consultants, supporting volunteering schemes, or even cameras. In recent years, methods of automatically identifying passing fish from video footage have been developed, using artificial intelligence. These seek to make monitoring efforts more efficient and cost-effective (Yu *et al*., 2023). Fish counters can be used to measure both the upstream and downstream passage of fish, by measuring changes in water resistivity (McCubbing and Ignace, 1999). This can quantify the numbers of fish passing in each direction and provide size estimates for the fish, however, resistivity counters cannot distinguish between different species of fish. As such, the use of counters could be combined with the aforementioned visual monitoring, to provide a more comprehensive assessment of fish passage. However, the effectiveness of this approach would heavily depend on water conditions since levels of high turbidity could make such methods highly unreliable. In some areas, Adaptive Resolution Imaging Sonar (ARIS) has been used to record and assess fish movements (Miller *et al*., 2016). This method involves using low-frequency sonar technology to detect the presence of fish so it can be used in dark or turbid conditions when conventional cameras are ineffective (Ogburn *et al*., 2017; Lankowicz *et al*., 2020; Helminen and Linnansaari, 2021). Furthermore, beyond counting passing fish and providing data on their lengths (Helminen *et al*., 2020), methods are being developed to automatically distinguish between fish species in both ARIS and video footage using artificial intelligence systems (Jalal *et al*., 2020; Helminen and Linnansaari, 2021; Knausgård *et al*., 2022). However, species identification may be unreliable or impossible in certain cases, especially where morphological distinctions between species are limited. Therefore, it has been suggested that sonar imaging should be used in conjunction with other methods if species identification is key to the aims of the monitoring (Helminen and Linnansaari, 2021).

4.3 Monitoring surrounding fish populations

There are also “semi-quantitative” methods, which aim to estimate the numbers of fish successfully passing upstream of a structure to spawn. These estimates can either be derived from direct measures of spawning activity, from counts of eggs or nests present upstream of the structure, or from comparing the results of population surveys upstream and downstream of an obstruction. Egg surveys, or redd surveys for salmonids, seek to provide an estimate of fish passage from breeding success (Garrett, 2015). Alternatively, acoustic methods of spawning activity can be applied to provide estimates of the area and timing of fish spawning, as well as providing an estimate of the numbers of spawning fish (Poulet *et al*., 2022). These have proven effective for shad, by capturing the sounds created by splashing and sediment disturbances caused by spawning behaviours (Poulet *et al*., 2022). Finally, methods of assessing fish population sizes or densities, such as performing electrofishing surveys, can be used to compare population sizes of diadromous fishes both upstream and downstream of a structure. In many cases, this data can be used to infer fish passage through a certain structure (Pereira *et al*., 2016). Electrofishing surveys involve performing transects of a designated section of a river and using a low electrical current temporarily stun and capture any nearby fish (Pereira *et al*., 2016). The results of these are provided as a standardised value of “catch per unit of effort” (CPUE), allowing for different areas to effectively be compared Pereira *et al*., 2016).

In the principal salmon rivers in England and Wales, including the Severn, Wye, Usk and Tywi, the Environment Agency and Natural Resources Wales carry out annual juvenile abundance surveys for salmon and trout using electrofishing methods. Data recorded include densities, individual lengths and age composition and are used to evaluate recruitment at different spatial scales, complement measures of adult stock performance and inform environmental management in rivers (UK Data Coordination Group, 2023). In addition, there is an automated resistivity fish counter on the River Tanat, a salmon spawning tributary on the upper Severn, providing annual returning stock estimates since 2010. However, collected data are not used in the national assessment because they are not considered representative of the whole catchment due to it being so high up in the system, but it represents an important annual index of stock performance within the catchment (Environment Agency, 2021).

4.4 Population modelling

All collected information on fish passage success, timing, and delays can be used in the development and optimisation of models, which in turn can serve to inform management efforts (Silva *et al*., 2018). Habitat assessment tools, such as the HABSCORE tool developed for salmonids, are designed to provide an estimate of the numbers of fish which a habitat is likely to support (Milner *et al*., 1998). HABSCORE is a habitat quality assessment tool for Atlantic salmon and brown trout. HABSCORE produces a Habitat Quality Score (HQS) which is a prediction of the density of a species that the habitat is likely to support. The HQS is derived from habitat and catchment features, allowing comparison between the present state and the potential or reference state under the assumption that neither water quality nor recruitment were limiting the population. A Habitat Utilisation Index (HUI) statistically compares actual survey results with predicted densities (Environment Agency, 2014). A before/after study design for monitoring could utilise frameworks such as HABSCORE to determine whether increases in fish density occur in upstream sections of the catchment following additional management measures. Furthermore, recent work on river network connectivity has provided a means of estimating the amount of habitat which would be made available by restoring connectivity through certain areas (Buddendorf *et al*., 2019). Such methods can be used to prioritise the removal of certain obstructions, by assessing the size and quality of upstream habitats which fish passage improvements would seek to restore (Environment Agency, 2014), and can be used to estimate the potential effects of constructing new structures in given locations (Silva *et al*., 2018).

A number of different models have been developed to provide assessments of potential population impacts of barrier creation/removal for salmonids, including the SALSIM model, designed to estimate future changes in a catchment's population under different scenarios (Moore, 2018), and the IBSEM, which predicts changes in the demographics and population genetics of salmon throughout life cycles (Castelliani *et al.*, 2015). The framework of population models therefore exists, however, collecting sufficient data for the different life-history stages at the catchment levels to confidently parameterise model input terms for the specific rivers/tributaries of interest would likely be a substantial undertaking. However, the application of models such as SALSIM using a combination of some general principles of fish production alongside some details about the target rivers may be developed. This could provide an initial sensitivity test to demonstrate the potential for success and to identify key parameters influencing the model predictions that could be targeted by future monitoring to support advanced model-based investigations.

A lack of models such as SALSIM for species other than salmonids hinders the ability to demonstrate the results of obstacle removal. Recent work has highlighted the importance of behavioural metrics such as motivation, which can be used as an indicator of passage success (Goerig and Castro-Santos, 2017), by quantifying the rate and duration of effort exerted by passing fishes (Silva *et al*., 2018). There have been a number of recent calls for greater collaboration and discussion on the means by which passage is assessed, with a view to reaching an agreement on an optimal analysis of the factors that could optimise future management efforts. To achieve the best possible approaches and monitoring methods for the compensation package, measures through the AMMP will continue to be explored via engagement with stakeholders, practitioners and regulators. This will ensure that the latest developments for monitoring and modelling the outcomes of fish passage improvements can be considered and incorporated where appropriate as part of the AMMP.

4.5 Site and management measure selection, and implementation of an Adaptive Monitoring and Management Plan (AMMP)

The identification of sites and weirs to enhance fish passage has been informed by discussions with Natural Resources Wales (NRW) and the Environment Agency. At each site feasibility studies are being undertaken to determine the potential to implement measures that will provide benefits for the target species.

The process of weir selection and next steps to be taken by NNB are summarised by NNB as follows: "*The weirs have been identified by NNB in conjunction with Environment Agency and NRW. It was identified early that, if possible, compensation should be undertaken in the Rivers Severn, Wye and Usk. Environment Agency staff have been involved in the Unlocking the Severn Project, and as part of that involvement they have identified a number of barriers to migration in the Severn. Maisemore Weir was identified in early meetings with the Environment Agency as a weir that with easement could bring significant benefits to the migratory species in that river. Similarly discussions with NRW suggested a number of weirs on the River Usk itself or its tributaries. Through further discussion and desk top review Trostrey Wier was identified as the most promising. Identification of easement opportunities on the River Wye has proved more difficult partly as there are fewer obstacles to migration. A joint meeting between the Environment Agency and NRW led to discussions with EA around options on the River Lugg, a tributary of the Wye. The Environment Agency explained that they had identified a group of weirs on the River Lugg that would be suitable candidates for easement with strong evidence of migratory fish in the locality.*

NNB are continuing to engage with the Environment Agency and the Canal and Rivers Trust regarding Maisemore Weir, and the Environment Agency are preparing to share some easement feasibility work they *have undertaken on the weir. NNB are also continuing to engage with the Environment Agency on the River Lugg weirs where they have indicated they have outline design solutions for the identified weirs.*

Trostrey Weir is a river gauging station and as such removal or easement will significantly disrupt the data set it provides, as a consequence NNB is in the process of reviewing the gauging data from Trostrey and Chainbridge to establish if there is sufficient correlation for Chainbridge to act as a surrogate for Trostrey, early indications suggest a high degree of correlation between the 2 data sets which would facilitate the easement of Trostrey.

As the feasibility process matures and the suitability of the chosen options is confirmed, NNB and their supporting consultants will move forward into developing design solutions for either fish passes or weir removal and riverbed and bank re-profiling."

As part of the feasibility study, investigations on the effects of management measures at each site will consider how these would be influenced by surrounding environmental conditions, such as tides and changes in river flow. Furthermore, detailed surveys of surrounding habitats, both upstream and downstream from each structure, and assessments of other potential stressors or impacts on populations of target fish species in the river (such as pollutants) can be used to assess whether an approach is likely to achieve the desired outcomes for the population. The status of the target species' populations in the river, characteristics of their life cycle, and available information on the abundances of different life stages both above and below the structure, and species-specific passage success through the target structure, can all be used to determine the most effective sites and management measures to achieve the greatest impact on these species. Site selection and feasibility studies will also consider the resilience of the measures to climate change and the potential for unintended consequences such as introduction of non-native and invasive species (Section 2.3.3). Collaboration with stakeholders, practitioners and regulatory bodies is central to determine which management measures are practicable and can be implemented by NNB, whilst optimising the potential for success at any given site.

Whilst measures to improve fish passage at barriers are recognised as important for supporting populations of diadromous species, the benefits to populations of Atlantic salmon and shad across the network of SACs cannot currently be quantified. The AMMP will provide the framework within which monitoring approaches to assess the success of barrier removal / easements will be established. The AMMP is a formal document that will be developed iteratively with regulators to outline the site-specific objectives of fish passage improvements against which success or failure of the management measures can be monitored.

The purpose of the AMMP is to provide reliable information on the effectiveness and success of the implemented measures and provide the means to adapt the measures where necessary. The iterative development of an AMMP is an important element of the compensation package to:

- quantify the impacts of HPC entrapment relative to predictions;
- determine appropriate compensation objectives including indicators and associated targets to determine success criteria;
- provide evidence for the successful implementation of compensation measures; and
- set out a framework for additional monitoring and potential adaptive management should measures fail to achieve objectives.

As such, an AMMP supporting these aims is in development and a draft AMMP will be submitted by NNB as part of the DCO Material Change Application.

4.5.1 Proposed approach to monitoring

The desired increases in production following fish passage improvements rely on the assumption that existing barriers create a bottleneck in production by either impeding adult spawning success or limiting habitat availability. Barrier removal, therefore, increases system productivity (rather than simply redistributing fish over a wider area) and allows fish to reach habitats essential to complete their life-cycle. Removal of barriers may also enhance productivity by reducing energy demands on spawning adults thereby increasing the likelihood of successful spawning and subsequent return to sea for those species with the capacity to spawn over multiple years. The easement of upstream/downstream bottlenecks may also reduce mortality in the juvenile and adult stages.

These assumptions whilst generally valid, are challenging to quantifiably prove in terms of attributing and demonstrating catchment level benefits due to a vast number of additional factors acting on the population. Consequently, a body of evidence approach is likely to be required. Indicators and associated targets to determine success criteria may include:

- **Indicator:** Availability of wetted area of catchment or priority habitat.
  - **Target:** Increase in availability of wetted area or priority habitat following fish passage improvements.
- **Indicator:** The number/proportion of fish passing the barrier.
  - **Target:** Increase in passage numbers/rates compared to baseline following fish passage improvements.
- **Indicator:** Time taken to ascend/descend the barrier during migration.
  - **Target:** Reduction in passage time compared to baseline following fish passage improvements.
- **Indicator:** Abundance of juvenile stages in sections of the catchment upstream of the barriers.
  - **Target:** Increase in abundance of juvenile stages compared to baseline following fish passage improvements.
- **Indicator:** Emigration rates of Atlantic salmon smolts from selected sections of the catchment.
  - **Target:** Increase in emigration rates following fish passage improvements.

A robust baseline will need to be established prior to implementation of management measures to increase fish passage. Initial assessments will make use of existing data sources and targeted monitoring to enable a robust baseline against which to measure success criteria.

The availability of habitat and habitat quality, including the presence of spawning substrates in the case of salmonids, will be established at the sites selected for the implementation of management measures as part of the compensation package. Given natural fluctuations in populations and environmental conditions over time, monitoring of juvenile density or emigration rates would require data ideally for a minimum of three years to provide a baseline that incorporates interannual variability before fish passage improvement measures are implemented. Such monitoring may utilise both existing data sources and targeted monitoring. For example, the deployment of rotary screw traps at strategic locations could be used to estimate smolt emigration. After the fish passage improvement measures are implemented, monitoring would be required for a number of years to determine changes relative to the baseline.

It is anticipated that monitoring of the success of any of the fish passage improvement measures would involve tagging studies to quantify the proportion of fish passaging a barrier and any changes to delay times in migration rates. A before/after design would be implemented to establish benefits of barrier removal. Monitoring approaches will be adaptive and developed iteratively through the AMMP.

5 Conclusions

The presence of artificial structures in rivers can lead to significant changes in the characteristics of the surrounding ecosystems. Disruptions to connectivity between habitats can be detrimental to local fish populations and habitat fragmentation is widely accepted as a leading factor in the decline of many diadromous fish species, impacting both their upstream and downstream migrations and limiting access to spawning or feeding habitats. Restoring river connectivity is now seen as a vital consideration in the management and conservation of diadromous fishes.

There has been a wealth of research and development for new fish passage measures, and new methods of assessing their effectiveness in recent years. Data available on target species and rivers as well as studies of similar structures in other regions and countries can be used to draw parallels with the weirs of interest and provide an indication of how removing or easing barriers may affect surrounding diadromous fish populations. Potential benefits have been presented for the removal or easement of structures on the Rivers Severn, Usk, Tywi and Lugg (a tributary of the Wye).

Fish passage improvements have the potential to benefit a wider range of diadromous species beyond allis shad, twaite shad and Atlantic salmon. European eel, sea trout, sea lamprey, and river lamprey form part of the Severn Estuary Ramsar Criteria 4 assemblage of migratory species and are likely to benefit from fish passage improvements. Equally, Water Framework Directive (WFD) fish monitoring data collected in the transitional and freshwater reaches of the Severn suggest that management works at Maisemore Weir, for example, may increase access to upstream habitat for the predominantly marine species such as thin-lipped grey mullet, European sea bass, flounder, and gobies, all of which are common in the impingement record. Further upstream at Upper Lode Weir, where reduced salinity may preclude movements of all but the most euryhaline marine species, such as gobies and flounder from further passage, management measures would also increase interconnectivity for freshwater species (BEEMS Technical Report TR592).

Site feasibility studies are underway to identify the most appropriate sites and management measures to optimise benefits to target species and a wider range of fish species. Measures to improve fish passage at barriers are recognised as important for supporting populations of diadromous species, however, whilst access to available habitat and improvements to passage may be determined, the benefits to populations of Atlantic salmon and shad across the network of SACs cannot currently be quantified. The development of the AMMP will provide a formal means to determine if management measures have been successful relative to site-specific monitoring objectives.

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