Wye & Usk Foundation

Severn Tidal Power Generation
Response to Call for
Environmental Evidence
July 2008

Contents

Summary

The Severn estuary has important stocks of migratory fish that would be affected by tidal power generation. The rivers draining to the estuary upstream of the Cardiff-Weston line cover almost a quarter of the existing salmon spawning areas in England and Wales and three quarters of those for twaite shad, notably the Rivers Wye, Usk and Severn. For much of the 20th century, the Wye was the leading salmon angling river in England & Wales, with the other rivers also supporting major fisheries.

In addition to salmon and twaite shad, rare and protected species like allis shad, sea lamprey and river lamprey also migrate through the estuary and up the main rivers. The national importance of the fish community has been recognised by designating the estuary itself and the entire Wye and Usk catchments as Special Areas for Conservation.

Over the past 30 years the salmon fisheries have been severely affected by over-exploitation, pollution, barriers to migration and acid rain, greatly reducing the stocks in these rivers. However, there have been major efforts to reverse the decline, both locally and internationally, over the past 15 years. Actions have included almost total cessation of netting in the high seas and estuary, removal of barriers, neutralising the effects of acid rain and habitat improvements within the rivers. These measures are starting to take effect, with excellent prospects of full stock recovery.

All the stock enhancement activities are jeopardised by the threat of tidal power generation. For schemes spanning the full width of the estuary, all the migratory species would have to pass through the barrage at least twice in their lives, including at least once while the turbines were generating. Experience from much researched other schemes suggests mortality rates in the region of 10 to 60% for each passage through the turbines. Research has shown that some fish pass several times to and fro during a single migration, multiplying the losses. The scope for reduction of impact through improved design or operation of the scheme, and for mitigation, appears very limited.

With stocks at their current fragile levels, tidal power generation threatens total eradication of the migratory species. If tidal generation in the estuary is to be pursued, despite the likely impact on fisheries, it will be essential that the existing programmes of habitat and stock enhancement be greatly increased and hastened so that they will be in the strongest possible state to withstand the inevitable impact if and when a scheme is implemented.

Much more research is needed to investigate impacts and approaches to reducing them. This should build on world-wide experience, much of it gained since the last major study of tidal power generation in the 1980s.

This report presents evidence to support the views summarised above and provides extensive references to other relevant work.

1 Introduction

1.1 Purpose of this report

This report was prepared by the Wye and Usk Foundation as an input to the evidence-gathering exercise detailed in the document entitled "Call for Evidence" produced by Parsons Brinckerhoff in May 2008. It covers potential impacts upon individuals and stocks of migratory fish passing between the Rivers Usk, Wye and Severn and the sea.

1.2 The Wye & Usk Foundation

The Foundation was formed in the mid '90s in response to alarming declines in salmonid populations in the Wye. Following successful bids to the EU and government bodies, the organisation built sufficient capacity to undertake projects on a scale significant enough to make improvements to the wide range and scope of issues that affect fish and the riverine environment.

The Foundation is a registered Charity No 1080319 with the following objectives:

To conserve, protect, rehabilitate and improve the salmon and other indigenous species of animal and plant life of the rivers Wye and Usk, their tributaries, streams and watercourses ("the rivers") and the banks, riparian lands and catchments of the rivers ("the river corridors") and;

To advance the education of the public in the conservation of rivers, river corridors and their animal and plant life and the need for conservation, protection, rehabilitation and improvement of such environments.

In addition to purely ecological improvements, the Foundation – through its involvement with EU structural funding and in its role as a registered charity – has found original ways of ensuing that the benefits of these environmental improvements are transferred to the rural economy

Details of the Wye and Usk Foundation including its past and current projects, the method employed to restore the rivers, milestones and details our staff may be found on our website http://www.wyeuskfoundation.org/

2 Status of Fisheries

2.1 Rivers and species affected by tidal power generation

The Severn Estuary, upstream of the proposed barrage, includes the estuaries of the following rivers:

- Ely
- Taff
- Rhymni
- Ebbw/ Sirhowy
- Usk
- Wye
- Severn
- Avon (Bristol)
- Axe (North Somerset)

(For the purposes of this discussion, Nedern, Cam, Sharpness canal, Yeo etc are not included).

While the Foundation is principally concerned with the Wye and Usk, much of the information concerning these rivers applies to the others regarding reduced access for migratory fish.

The Severn estuary is an essential conduit for a number of migratory species:

- Salmon *(Salmo salar)*
- Sea Trout *(Salmo trutta)*
- Allis shad *(Alosa alsoa)*
- Twaite shad *(Alosa fallax)*
- Sea lamprey *(Petromyzon marinus)*
- River lamprey *(Lampetra fluviatilis)*
- Eel *(Anguilla anguilla)*

In addition to these, a number of sea fish enter the estuary from time to time: eg Bass, Cod, Mullet and Flounder and it is an important site for Honeycomb eelworm (*Sabellaria alveolata*) and Eel Grass (*Zostera*)

2.2 Statutory designations

Of particular relevance to the consideration of a barrage are both the designations of rivers and species (of fish) that use the estuary and what effect the barrage might have on their populations.

Both Wye and Usk are listed as Special Areas of Conservation (SAC) under the EU Habitats Directive, while the Severn Estuary is a candidate Special Area of Conservation (cSAC). The rivers Wye and Usk also carry the designation Site of Special Scientific Interest (SSSI) which is the UK's means of managing them for the EU designation.

Crucial in understanding the significance of these designations is:

"The Habitats Directive introduces for the first time for protected areas, the precautionary principle; that is that projects can only be permitted having ascertained no adverse effect on the integrity of the site. Projects may still be permitted if there are no alternatives, and there are imperative reasons of overriding public interest. In such cases compensation measures will be necessary to ensure the overall integrity of network of sites. As a consequence of amendments to the Birds Directive these measures are to be applied to SPAs also. Member States shall also endeavour to encourage the management of features of the landscape to support the Natura 2000 network." [1]

With each listing comes a description of the site and its habitats in Annex 1 and details of the species in Annex 2, together with a brief description of their importance and vulnerability. These descriptions may be found with their Natura 2000 details for the Wye[2], Usk[3] and Severn[4] estuary. Each website enables inspection of the listed species, habitats and other information via the link to the Natura 2000 proforma

In respect of the Usk and Wye, salmon, twaite shad, and two species of lamprey receive the following description:

"….for which this is considered to be one of the best areas in the United Kingdom"

2.3 History of salmon stocks

2.3.1 Population changes

There have been both rises and falls in salmon stocks in all the rivers over time and these are well chronicled: for over a century various Royal Commissions have shed light on the estuary's salmon stocks, and the many declines and recoveries that have taken place.

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[1] Joint Nature Conservation Committee www.jncc.gov.uk/page-1374

[2] Natura 20000 http://www.jncc.gov.uk/ProtectedSites/SACselection/sac.asp?EUCode=UK0012642

[3] Natura 2000 http://www.jncc.gov.uk/ProtectedSites/SACselection/sac.asp?EUCode=UK0013007

[4] Natura 2000 http://www.jncc.gov.uk/ProtectedSites/SACselection/sac.asp?EUCode=UK0013030

The industrial revolution had a significant impact on the rivers that drain the south Wales valleys, for example Taff, Rhymni and Ebbw. During the coal, iron and steel era, these rivers experienced a complete loss of their salmon runs and, we must assume other migratory fish too[5].

Wye, Usk and Severn never entirely escaped the effects of industrialisation or urbanisation running as they do through a number of centres of population, but damage of that sort was never sufficient to prevent fish returning to their natal spawning streams and successfully spawning.

However, over-exploitation by nets and putchers both in the estuary and throughout the river had reduced the stocks of fish on the Wye to a catch of a few hundred by 1898 [67]. Following the purchase of the majority of the commercial fisheries at the end of the 19th century, Wye salmon stocks recovered within 10 to 12 years, roughly two spawning generations.

During the 20th century, sea survival rates of salmon rose dramatically giving rise to many years of successful and productive fishings on Usk, Wye and Severn, as illustrated in Figure 1.

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[5] Minutes of Evidence, Royal Commission on salmon Fisheries 1900

[6] JA Hutton Wye Salmon and other fish 1949

[7] WA Gilbert Tale of a Wye Fisherman 1929

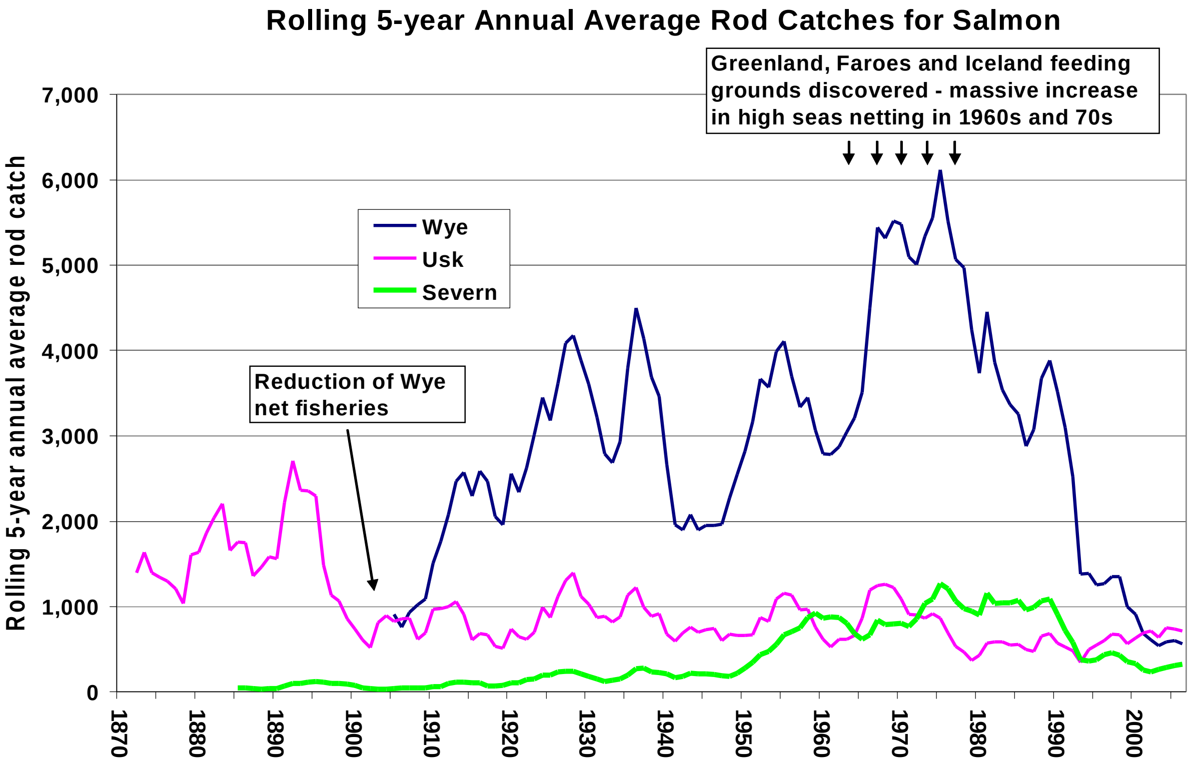

Figure 1 – *Rolling 5-year Annual rod catches in the Rivers Wye, Usk and Severn*

Typically annual total catches, including commercial nets, exceeding 30,000 were made in the rivers and estuary. However, this gradually declined from the mid '70s onwards for reasons discussed later.

The "industrial" rivers, e.g. Taff, Rhymni and Ebbw, have recovered over the past 30 years as a result of declining industry and improved wastewater treatment, but only to the extent that populations remain limited by barriers such as the Cardiff Bay Barrage, Treforest, Merthyr, Bassaleg and Aberbeeg weirs. Nearly all these rivers have parts of their catchment dammed for water supplies, further limiting available spawning territory. However, salmon and sea trout are now running these rivers in increasing numbers, though stocks have been supported by artificial rearing in some circumstances.

Wye, Usk and Severn salmon have experienced mixed fortunes over the last 100 years, as shown on Figure 1. The stocks have been affected by poor management of exploitation (both at sea and in rivers), the construction of impassable barriers, pollution and poor land and river bank management.

However, the stocks have shown remarkable resilience which can be explained by the natural variability of spawning cycles. The life cycle of Wye, Usk and Severn salmon generally involve two years in the sea and two years in the river. However, a proportion spends either one or three years in the river, while some spend one, three or four years at sea. This is illustrated in some original scale reading research[6,8] on a sample of over 54,000 fish and shows the species' ability to compensate for a disaster in any part of its life cycle as the losses in one year will be made up by the varying life cycles of fish from other years.

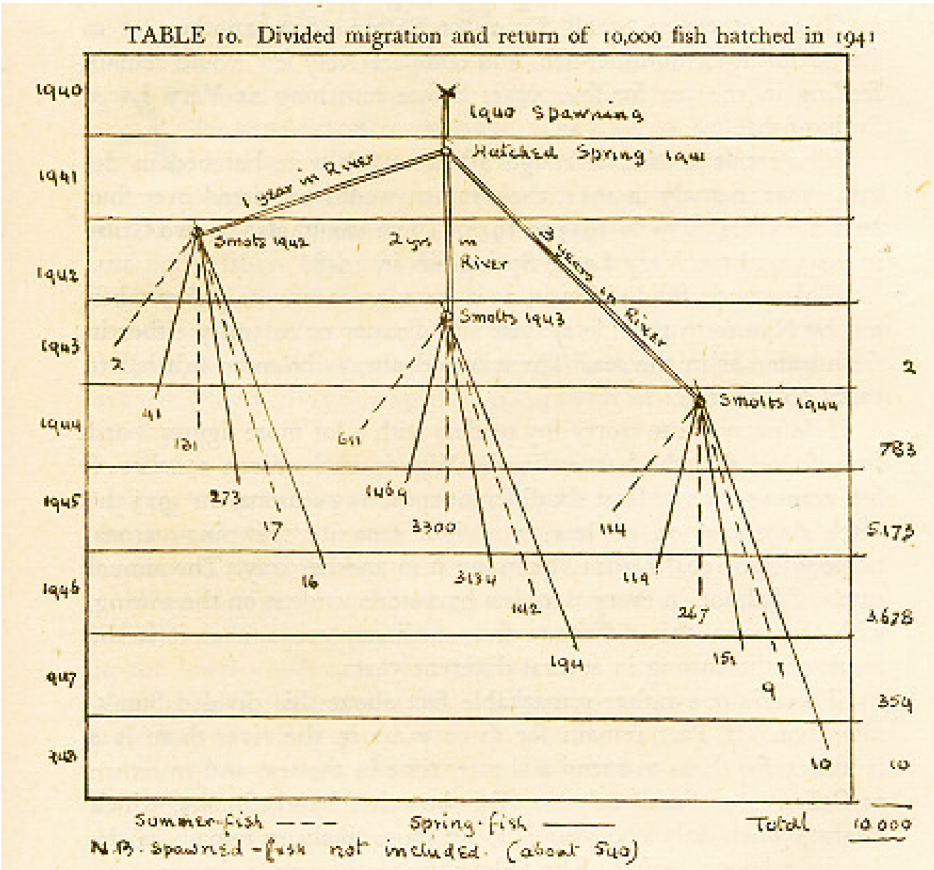

Figure 2 - *Variations in the life cycle of Wye Salmon*[6]

This diagram shows how smolts migrate after one, two or three years in the river and adults return after one to four years at sea. This natural variability enables the species to ride out the impact of poor spawning years by inter-breeding of fish originating in other years.

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[6] Wye salmon and other fish 1948 J A Hutton

This resilience justifies the numerous stock enhancement activities of the past 20 years, many of which are starting to take effect, with the real prospect of returning to the excellent populations of much of the 20th century. These activities have been aimed at both the sea survival and river stages of the life cycle. However, all will be jeopardized by the threat of tidal power generation.

2.4 *Stock enhancement activities*

2.4.1 *Sea survival:*

Sea survival has reduced from an estimated peak of 30% in the '60s and '70s to as little as 5% or even less. Adjustment to this has been slow leading to excess exploitation (taking more than just the "harvestable surplus") which has in turn put further pressures on stocks.

Extensive local, national and international actions have been taken in to reduce exploitation as shown in Table 1.

Year	Action
1985	Remaining Wye commercial river nets stopped
1991	Faroes net fisheries reduced to subsistence level
1992 -1999	Illegal estuary netting controlled by new by-laws
2000	Eight Severn estuary drift nets removed
2000	Wye and Goldcliff Putchers removed
2002	Greenland and Iceland nets reduced to subsistence level
2007	Irish legal drift net fishery stopped

Table 1 - *Recent history of salmon net reductions*

In 1985, the remaining in river netting on the Wye was discontinued. In 2000 the eight Severn estuary driftnets were bought off and the Goldcliff Putcher ranks were bought out for a period of time and then subsequently bought out for good. Only one Putcher fishery of any size remains at Lydney Park plus a number of seine and lave netters, of limited effect

The illegal estuary net fishery was effectively ended when byelaws enacted in 1992 removed white fish boats from the incidental catching salmon. A series of byelaws reduced the legal netting season in the mid 90's, through moving the opening of the season from 15th February to 15th May. Subsequently, the

National Byelaws 1999 reduced the season further with a start date on 1st June.

On the high seas, international agreements have reduced the Greenland and Faroese fisheries to "subsistence" catches only. Today, the 'Salsea' project seeks to find the cause of low sea survival rates. In 2007, the extensive drift net fishery off the west coast of Ireland, which intercepted grilse returning to rivers throughout the western part of the Bristish Isles, was paid off. At one time, it was estimated that 30% of Welsh fish were taken in this fishery[9].

All actions except the Wye river net fishery removal will have benefited all the rivers in the estuary. Although these actions appear to have halted the decline, there has not yet been any significant recovery. However, noting the experience of the early 20th century, when removal of commercial fisheries led to a big recovery of Wye salmon stocks, but over two generations, a sharp improvement can be expected in the next 10 years, provided legal fishing is not superseded by illegal activity. These improvements will be further enhanced by the big programme of land-based stock enhancement activities that the Wye & Usk foundation has pursued since the mid-1990s.

2.4.2 *In - River Survival*

Early salmon stock management focused on protecting fish from excessive illegal and legal exploitation and the occasional enhancement through hatchery schemes. For more than three quarters of a century, the importance of good water quality, juvenile habitat in good condition and unobstructed access for migrating fish was largely ignored. Historically, a natural high sea survival rate reduced the need to be concerned with river survival rates.

Additionally a series of land-based problems beset the species: A disease known as Ulcerative Dermal Necrosis affected the early running fish in the late '60s and 70's while intermittent pollutions and adverse weather conditions such as the severe drought in 1976 all contrived to reduce numbers intermittently. However, recovery from each disaster amply demonstrates the resilience of the species.

The Common Agricultural Policy, intensive forestry and demands on water for urbanisation are all recognised drivers for the current poor state of our fisheries, nationally. However many of these issues can be resolved satisfactorily and that is what the Wye and Usk Foundation has set about achieving since the mid 1990s. These are described in the following section.

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[9] National Rivers Authority 1984 -1993: Report on tagging of hatchery and wild smolts.G Harris et al

2.4.3 *Barriers to Migration*

Removal of barriers heads the list of issues that have been tackled by the Wye & Usk Foundation. Many tributaries were dammed for water-power, roads and abstraction denying fish access to the upstream sections. Walk-over surveys and subsequent GIS mapping of the Wye and Usk indicated that some 49% of Wye and 28% of Usk catchment was not available to salmon. We understand that the figure for the Severn is likely to be somewhere between the two

Sub-catchment	No of barriers removed or passes built	> 2nd order Length opened up	% catchment benefiting
Monnow	3	107km	16% of Wye
Lugg and Arrow u/s Hampton Court)	18	162km	17 % of Wye
Upper Wye u/s of Hay	24+	>100km	12 % of Wye
Usk	13	46km	21 % of Usk

***Table 2**- Re-opening of spawning streams in Wye and Usk catchments*

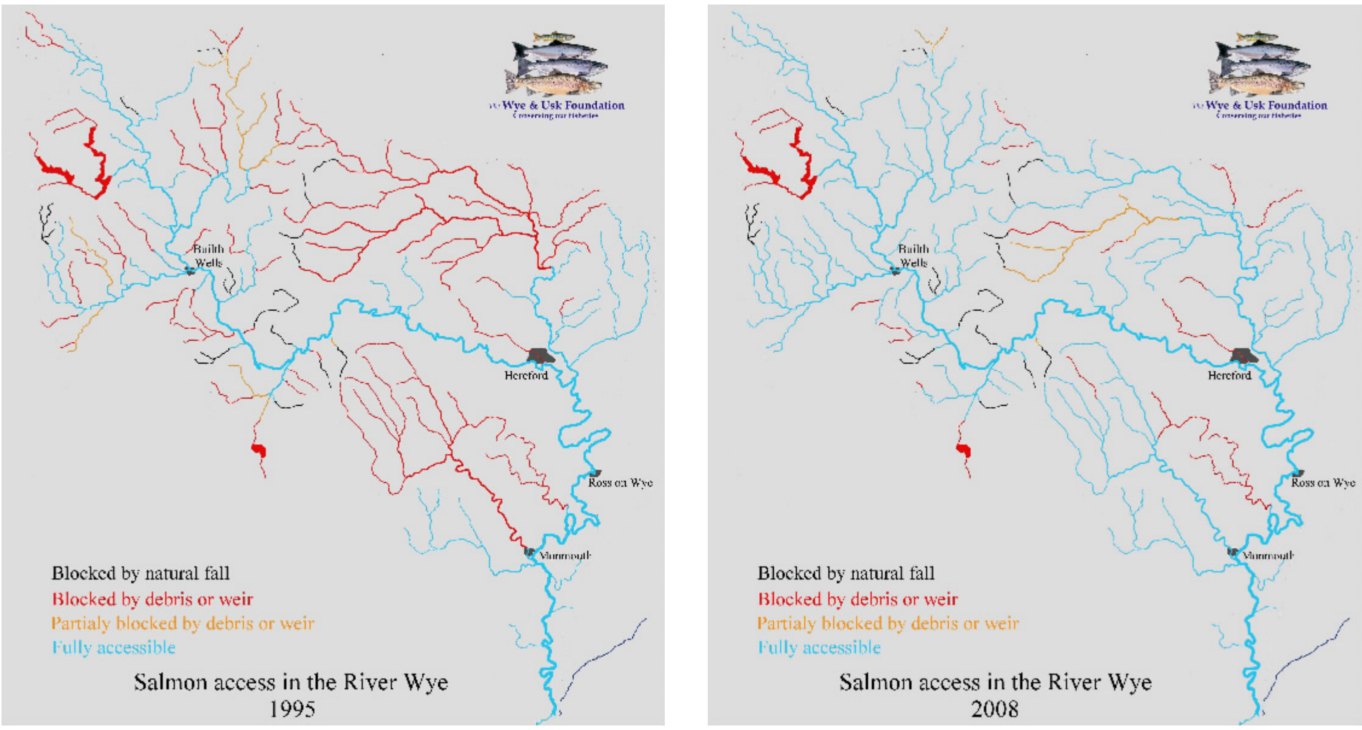


Figure 2 – *improved salmon access in the Wye catchment 1995 to 2008*

Much of this was caused by man-made structures, ill advised and poorly designed usually without fish passes (now illegal) such as Leominster flood alleviation scheme (R Lugg 1982) and Osbaston on R Monnow (c1917) which effectively denied salmon and other species access to the Wyes two largest tributaries.

The Foundation has removed weirs and constructed fish passes as have our partners, Environment Agency Wales. The extent of this work is illustrated in Table 2 and Figure 2 below.

Most of this work has been instigated or undertaken by the Wye and Usk Foundation and partners. Total spend on barrier removal and the habitat restoration described below is illustrated in Figure 3.

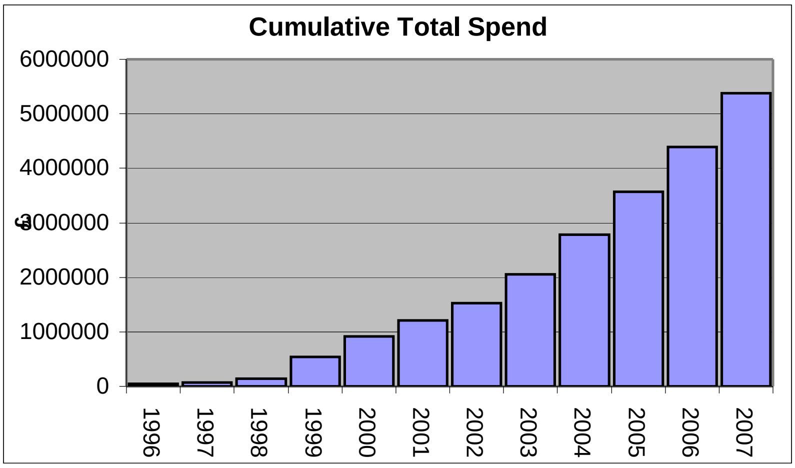


Figure 3 - Cumulative spend on Usk and Wye by Wye and Usk Foundation total £5,375,753 to end 2007.

2.4.4 *Habitat Restoration*

Much of the uplands of Wales is given over to sheep grazing. Sheep numbers have quadrupled since the introduction of CAP. The upshot of this massively impacting industry is that streamside vegetation is denuded and arboreal cover restricted to trees that are over 45 years old. Tree cover is typically alder and willow and historically, these threes were rotationally coppiced. Now multi-stemmed and superannuated trees coupled with heavy grazing give rise to wide and shallow nursery streams that then become unfavourable for salmonid production. It should be understood that salmon spawn in surprisingly small streams for their size. Habitat restoration is most effective on tributaries between 1 and 5 m wide.

The Foundation has engaged in a series of projects to fence off and manage tree cover in such a way as to restore natural stream features and thus increase salmon production. Additional benefits are marked reductions in siltation, pesticides and other water quality problems, which are showing positive benefits to migratory fish populations. The natural narrowing of stream width and growth of young trees and riparian vegetation assist in reducing the effects of climate change.

An example of habitat restoration is illustrated in Figure 4 and an example of the potential benefits in Figure 5.

Figure 4 - *Before and after habitat restoration. Clywedog showing the naturalisation following fencing out stock.*

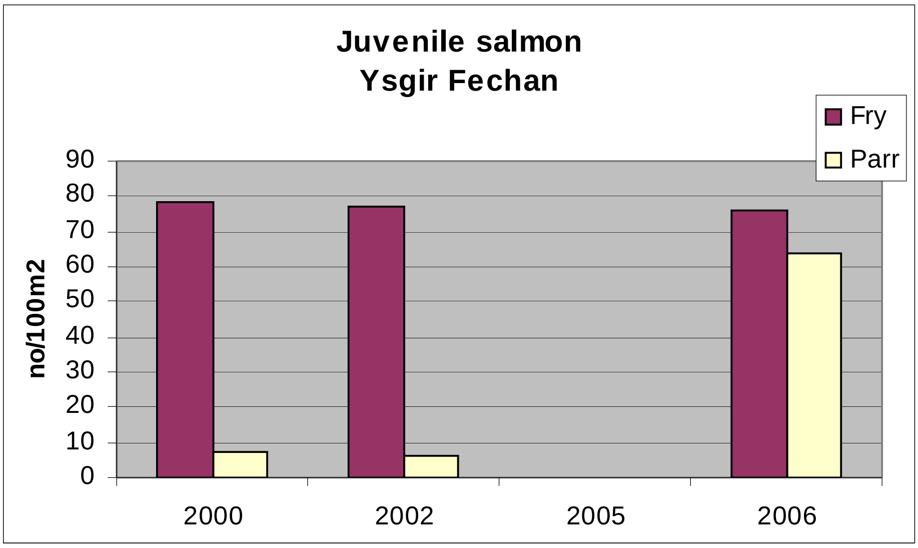


Figure 5 - *The benefit of habitat restoration is shown by the increased survival of salmon parr following work carried out in 2004/5*

2.4.5 *Water Quality*

Acid rain affects much of the upper Irfon (Western Wye tributary), upper Wye and Severn. The effects are linked with commercial forestry that was often planted in the less well buffered geologies of the wet uplands in the belief that losses to the farming industry would be minimised.

The Foundation has recently completed a six year project "pHish" which has investigated and found a means of neutralising the worst effects of acidification over some 62km of stream.[10]. Monitoring of this substantial project used long term diatom analysis[11] and was able to show a permanent change had been effected and salmon were now found in hitherto unpopulated streams.

[10] Scoping study for Acid waters in Wales Strategy 2002 B Reynolds, S Ormerod S et al
[11] Juettner I Report to Wales Assembly Government 2008 Monitoring Recovery of Streams from Acidification in the Wye catchment using diatoms as part of pHish 2002

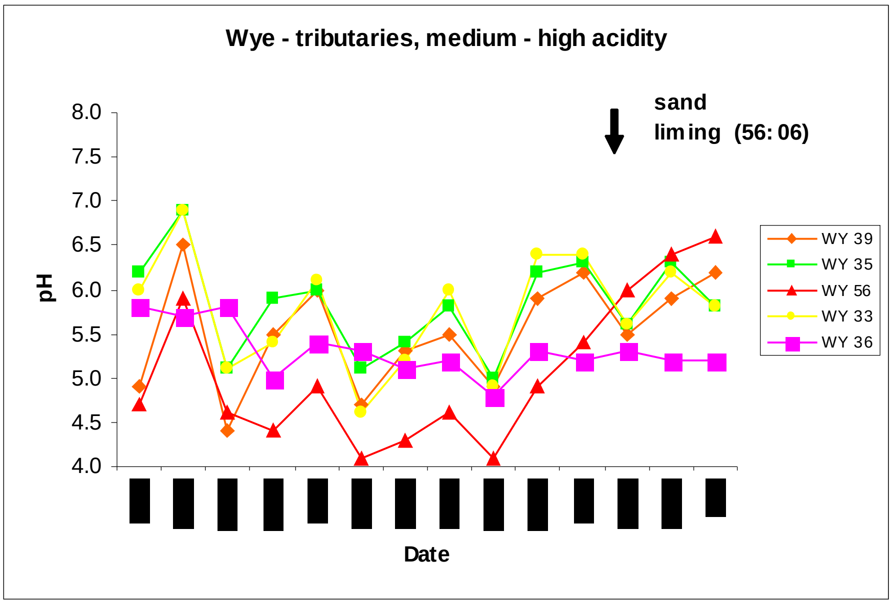
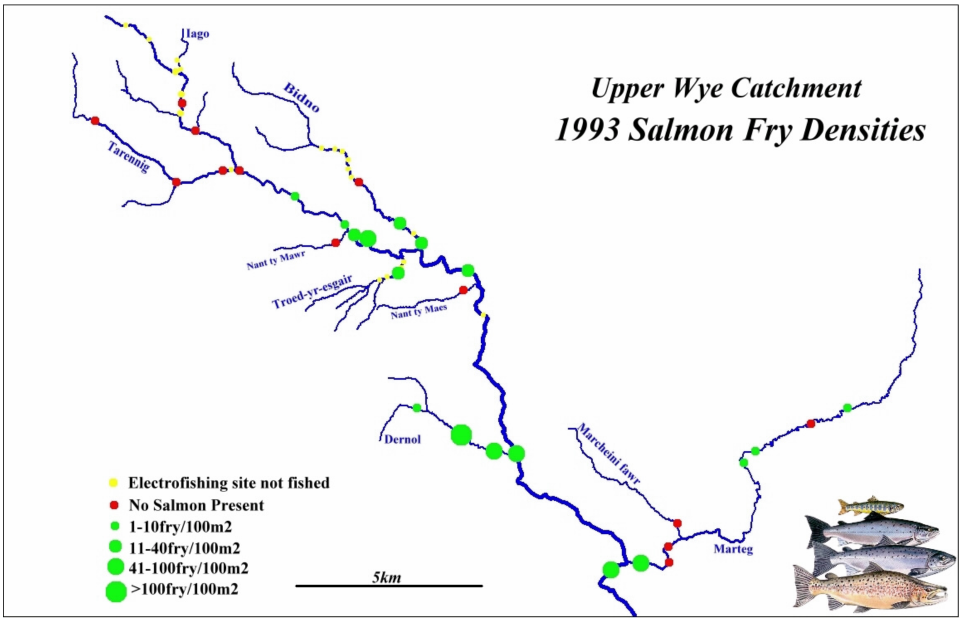


Figure 6 - *Sand liming Upper Wye: site 56 was sand limed in September 2006 and despite being the most adversely affected tributary on the upper Wye has remained at a satisfactory pH since treatment*

Commercial forestry is perceived to require extensive draining and this is achieved with deep drainage cuts so that water is transported rapidly from hill slopes with very negative consequences for both salmon and flood defences. The Foundation has delivered a project which has enabled fish to re-colonise formerly fishless parts of the catchment. The Usk does not suffer these effects as it rises from more basic geology.

The Foundation has entered into schemes with sheep farmers that in combination with stricter regulation, has allowed them to forgo the use of toxic sheep dips. This has also contributed to a better environment for all species.



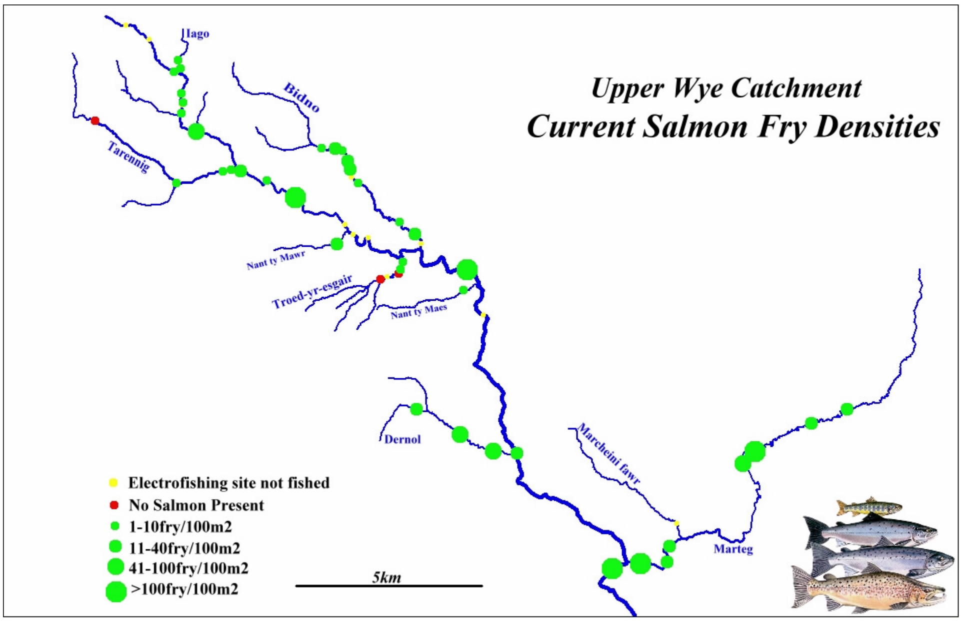


Figure 7 - *Above maps show improvement to fry densities and distribution of upper Wye and tributaries*

2.5 *Value of fisheries to the economy*

Atlantic salmon has played a major part in the economy of the Severn basin. There is evidence of trapping of salmon in the estuary from Roman times. The estuary itself is host to a considerable number of "heritage" fishing instruments and rights such as Putchers and Lave net fishing.. These are methods of catching fish unique to the 40' tides and high turbidity associated with the estuary. There are also seine netters in the lower Severn.

A further contribution to the local economy comes from elver fishing. Elvers – the juvenile of the European eel - have returned in prodigious numbers to the Severn, Wye and to a lesser extent, the Usk. These fish are used as a source of commercial eels and as a delicacy in their own right.

The Usk is currently the most productive salmon river in Wales and for much of the last 100 years the Wye has been the best in England and Wales. There are now clear signs of a recovery of the salmon on the Wye. Restoration of the Severn is starting to gather momentum. The salmon rivers that might be impacted on by the barrage account for approximately 24% of the salmonid territory in England and Wales, leaving little opportunity for replacement elsewhere in the UK

Just how much a thriving economy is associated with productive salmon rivers is illustrated by a recent survey of the Tweed [12] showed the following:

	Borders	**Scotland**
Output	£17.9m	£18.2m (1)
GVA	£7.0m	£7.1m (2)
Employment	487	496 (3)

Source: SQW estimate

Table 3 – *Economic benefits of Tweed rod fishery*

(1) Uses STMS multipliers to calculate Scottish level output
(2) Uses 2004 Annual Business Inquiry data for Scottish economy which indicates that GVA is on average 39% of total turnover
(3) Assumes the same turnover per job ratio, but includes employment generated by the additional output (£300,000 at a Scottish level).

[12] http://www.rtc.org.uk/About_/Tweed_Economic_Survey/tweed_economic_survey.html

The Tweed is a river with a catchment size slightly bigger than the Wye and before the commencement of the restoration programme on that river, it returned the lower rod catch. Recent improvement work there and mirrored on Wye and Usk has made this river the best in Europe with considerable benefits to the rural economy. In consideration of this potential it should be understood that the Severn Estuary Rivers amount to at least three time that in respect of size and potential of the Tweed.

The current estimates of the benefit of the estuarine and river fisheries do not reflect their potential and values are depressed by the effects of poor management and the adverse impacts of intensive land uses.

3 Impact on fisheries

3.1 *Schemes to be assessed*

There is a range of options under consideration and the potential impact will be largely dependent upon the option actually promoted. Three major options are listed (a barrage on the Cardiff Weston line, a barrage at English Stones, and a bunded "blind" enclosure within the estuary). Within these three major options there is a further range of operating scenarios (for example ebb or flood-only generation, possibility of pumping with an ebb-generation scheme, ebb and flood generation) and details of design (type and size of turbines, layout of turbines and sluices, depth of turbine centre-line). All these variables can have a fundamental influence on the potential impact of a scheme, and on the potential for mitigation.

A considerable volume of work was conducted in the 1980's in connection with an earlier proposal for a barrage on the Cardiff Weston line. The favoured scheme was for ebb-generation using bulb turbines, with the turbines also being used to pump water landwards to increase the generating head on small and medium tides. Much of this work was conducted under the auspices of the Severn Tidal Power Group and the Department of Energy Technology Support Unit (ETSU). This included assessment of fishery impacts, especially those associated with passage through or past the turbines. This note will draw heavily on that earlier work. There is also a considerable volume of relevant experience from hydro-electric dams on rivers, especially in North America. To a very large extent the impacts of a barrage on the Cardiff Weston line and the English Stones line will be similar (although the latter would involve fish from fewer rivers), whereas those of a bunded reservoir will be somewhat different. For this reason the bulk of this report will deal with the barrage line concept, and the bunded reservoir will be discussed separately later.

There are a number of aspects of a barrage scheme that might affect migratory fish, i.e. fish species that must pass through the estuary at least twice during their life cycle. The species considered here are:-

- Atlantic salmon (*Salmo salar*)
- Sea trout (*Salmo trutta*)
- Twaite Shad *(Alosa fallax)*
- Allis shad *(Alosa alosa)*
- Sea lamprey *(Petromyzon marinus)*
- River lamprey *(Lampetra fluviatilis)*
- Eel (*Anguilla anguilla*)

Most of these species are listed as interest features in the citations for the River Wye cSAC, the River Usk cSAC and the Severn Estuary pSAC.

3.2 Potential mechanisms of impact

The aspects of the presence and operation of a power-generating barrage that have potential to impact on migratory fish are predominantly the following:-

- The machinery of the barrage, such as the turbines and sluice gates, represent a physical hazard for fish due to strike, pressure flux and shear.

- Fish which are temporarily disoriented and confused by the turbulent flow associated with passage through a head-retaining structure are vulnerable to predation. Structures such as dams and barrages attract large numbers of bird, mammal and fish predators.

- The presence of the barrier and the modified hydrological regime may interfere with the free and timely passage of fish both landwards and seawards.

- The modified hydrological regime will have some effects upon water quality, especially suspended sediments and salinity, but also possibly other impacts.

These four potential sources of impact are discussed in detail below. Earlier documents that will be quoted extensively here include:-

Severn Tidal Power Group (1986) Tidal power from the Severn [13]. This document described the preferred scheme (Cardiff Weston line, ebb-only generation, landwards pumping near the top of neap and medium tides, 192 bulb turbines of 8.2 m diameter) and other design and operating criteria which allowed a detailed assessment of the potential impacts on fish.

Solomon D J (1988a) Fish passage through tidal energy barrages[14]. This was a desk study based upon experience elsewhere (including dams on the Columbia River and Connecticut River (USA), and tidal energy barrages at La Rance (France) and Annapolis Royal (Nova Scotia, Canada), on experimental studies and on modelling the effect of the proposed Severn Barrage on fish. This identified a number of potential impacts and made recommendations for further investigation.

Solomon D J (1988b) Aspects of the behaviour of migratory fish[15]. This report was a desk study of the behaviour of salmon, shad, eels and lampreys relevant to the assessment of the impact of the proposed Severn Barrage. Aspects examined included run timing, swimming depths, routes taken and likely responses to approaching a turbine.

Turnpenny A W H, Davis J, Fleming J M and Davies J K (1992) Experimental studies relating to the passage of fish and shrimps through tidal power turbines[16]. This work was largely based on the recommendations for further work made by Solomon (1988a). The experimental results were applied to predicted operations of the Severn Barrage and important conclusions drawn regarding significant levels of damage.

3.3 Passage through the turbines

3.3.1 What fish would pass the barrage line?

Fish moving seawards from the rivers landwards of the barrage would have to pass through the turbines or through alternative routes provided. Such fish include the juveniles of salmon, sea trout, twaite shad, allis shad, sea

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[13] Severn Tidal Power Group (1986). Tidal power from the Severn –Report. 97 pp

[14] Solomon D J (1988a) Fish passage through tidal energy barrages. Department of Energy, Energy Technology Support Unit, ETSU TID 4056, 63 +13 pp.

[15] Solomon D J (1988b) Aspects of the behaviour of migratory fish. Severn Barrage development Project, document reference SBDP/DJS/3.7(ii)d2. 46 pp.

[16] Turnpenny A W H, Davis J, Fleming J M and Davies J K (1992) Experimental studies relating to the passage of fish and shrimps through tidal power turbines. AEA Technology, Harwell, and National Power. 45 pp plus figures and tables.

lamprey and river lamprey; adult eels, and the kelts (post-spawning adults) of salmon and sea trout. In addition, it is likely that many adult salmon returning to the rivers to spawn will move up and down the estuary, passing the barrage line in both directions at least once. Evidence for such behaviour comes from tagging studies reported by Solomon (1973)[17] and Swain (1975)[18]. Wild salmon smolts were trapped and tagged on their seawards migration on the Usk, Wye and Severn over several years. Of the 104 tagged adults recaptured within the rivers, i.e. upstream of the tidal limit, 96 (92%) were in the river of origin, indicating a high level of homing fidelity; later tracking studies elsewhere suggest that many if not all the fish in the "wrong" river would have returned seawards and entered their native river before spawning. However, recaptures in the Severn estuary nets between Lydney and Gloucester represented an unbiased sample of fish from the three rivers. This indicates a considerable degree of "overshooting" by Usk and Wye fish - Lydney is 16 km landwards of the mouth of the Wye, and 40 km landwards of the mouth of the Usk. Had they not been caught these fish would subsequently have returned seawards and entered their home rivers.

Fish moving landwards include adults of salmon, sea trout, allis shad, twaite shad, river lamprey and sea lamprey, and juvenile eels. These fish could pass through operating turbines (if generation was taking place on the flood tide), free-wheeling or locked turbines if they were being used as sluices, or sluice gates.

Further details of the relevant migratory behaviour and timing of these species is provided by Solomon (1988b).

3.3.2 *Potential damage to fish associated with turbine passage*

This is a well-researched and complex subject area that cannot be fully analysed here. Reference to Solomon (1988a) and Turnpenny *et al* (1992) is strongly recommended.

Strike damage can be caused by collision with fixed (e.g. guide vanes) and moving (rotor blades) parts of axial-flow turbines, such as the bulb turbines

[17] Solomon D J (1973) Evidence for pheromone influenced homing by migrating Atlantic salmon. Nature 244-5413, 231-2.

[18] Swain A (1975) The migrations of salmon (Salmo salar L.) from three rivers entering the Severn estuary. ICES Anadromous and Catadromous Fish Committee CM 1975/M:10.

likely to be specified for the Severn Barrage. Although relatively slow-turning in terms of RPM, the velocity of the blade tip in a large (2-10 m diameter) axial flow turbine is typically of the order of 30 m per second. Mortality rates of salmon smolts observed at almost twenty such sites have ranged from 2 to more than 20%, varying both between stations and also at the same site according to operating conditions. Modelling and experimental studies indicate that most of this mortality can be explained by mechanical strike events.

Figure 8: *Juvenile Pacific salmon killed passing through a large diameter Kaplan turbine in a dam in the Columbia River, USA. In terms of damage to fish this site is equivalent to the likely equipment that would be deployed in the Severn Barrage.*

Much higher mortality rates have been observed for juvenile shad, ranging from 50 to 80%; as these fish are similar in size or smaller than salmon smolts this indicates that some mechanism is implicated in addition to mechanical strikes. The experimental work undertaken by Turnpenny *et al* (1992) identified the most likely additional cause as shear. Juvenile clupeids (including a small number of twaite shad) exposed to the lowest non-control levels of shear (206 Newtons/m^2) were either killed outright or died within an hour, probably as a result of osmotic stress following epithelial damage. Juvenile salmonids were unaffected by shear except at the highest level tested (3410 Newtons/m^2).

Based upon a hypothetical 9 m diameter bulb turbine rotating at 50 rpm (a model proposed by STPG for assessment of impact of the Severn Barrage), Solomon calculated the following ranges of mortality due to blade strike for fish passing through:-

		Range of mortality predicted	
Species	**Size**	**Fish not swimming**	**Fish swimming**
Salmon smolt	150 mm	1.9 – 3.1 %	1.9 – 3.2 %
Salmon adult	1000 mm	12.1 – 20.4 %	25.1 – 100 %
Shad adult	400 mm	5.1 – 8.2 %	6.3 – 12.1 %

Table 4 - *Mortality from blade strike passing bulb turbine (Solomon calculation)*

The range is due to variation in operating conditions (volume of water passing and guide vane angle vary with head difference over the tidal cycle). The "fish swimming" column assumes that the fish are swimming as fast as they are able against the flow, an expected reaction on approaching an unsettling set of conditions. Such behaviour would effectively slow the passage of the fish through the plane of the turbine rotation, increasing collision probability. The effect of swimming is greater with large fish as their swimming speed is higher.

Turnpenny *et al* used the same theoretical turbine for their predictions, but had better experimental data with respect to fish damage. Their calculations of mortality due to blade strike were:-

		Range of mortality predicted	
Species	**Size**	**Fish not swimming**	**Fish swimming**
Salmon smolt	150 mm	2.6 – 4.9 %	2.8 – 5.7 %
Salmon adult	1000 mm	15 – 30 %	31 – 100 %
Shad adult	75 mm	1.3 – 2.5 %	1.4 – 2.7 %

Table 5 - *Mortality from blade strike passing bulb turbine (using experimental data)*

Note that the shad considered in these two tables were of quite different sizes. Turnpenny *et al* went further and calculated the overall losses to seaward migrating stocks based upon the predictions of operating conditions throughout the year, and assuming a single pass through the barrage. This time factors other than mechanical strikes are also included:

	Source of damage			
Fish	**Pressure**	**Shear**	**Strike**	**Total**
Salmon smolt 150 mm	1.3 %	2.2 %	6 %	9.5 %
Salmon kelt 1000 mm	1.3 %	2.2 %	40 %	44 %
Juvenile shad 70 mm	0 %	48 %	4.9 %	53 %
Adult eel 700 mm	0 %	0 %	28 %	28 %

Table 6 – *Total mortality of fish passing seaward through turbines*

To these loss figures must be added any impact of landward passage through the turbines during sluicing or pumping, and any impact of multiple passage.

Landward passage through the turbines, for example during sluicing or pumping on the flood tide, is of particular concern as it is likely to involve adult salmon. Turnpenny et al (1992) calculated a mortality rate of 24-46% for a 1000 mm salmon passing through a sluicing turbine (assuming fish aligned with the flow but not swimming). Mortality rates are likely to be higher during pumping as the turbine runner is likely to be revolving faster, and the discharge would decrease as the landward head increased.

Figure 9: *Leading edge of a runner blade of a 7.2 m diameter bulb turbine at Racine on the Ohio River, USA.*

The operating head of the turbine shown in Figure 9 is 6.7 m. Rotating at 62.1 rpm, the velocity of the tip of the blade is about 25 m/sec and is likely to prove fatal to any fish coming into contact with it. This is the type of turbine that is likely to be specified for the Severn Barrage.

Multiple passages will clearly increase mortality rates. If the mortality of adult salmon is 40% for a single pass through an operating turbine, cummulative mortality would be more than 78% for three passes and over 92% for five. Such multiple passes are quite feasible given what we know of the estuarine behaviour of salmon.

3.4 Predation associated with passage through the barrage

Small fish such as salmon smolts and juvenile shad may be subjected to significant mortality if they are temporarily disoriented or trapped in eddies, and bird and fish predators quickly learn that downstream of dams is a good place to feed. Long *et al* (1986)[19] studied smolt mortality at Ice harbour Dam on the Snake river (a Columbia River tributary in the USA) and noted a 33% predation rate by fish and gulls on smolts that become entrained in the "backroll" above the outflow from the deep-set turbines; this compared to a turbine passage mortality of 10-19%. Observations at La Rance reported in Solomon (1988a) indicated predation by over 500 gulls and also bass on a disorientated shoal of small clupeids in the tailrace. Large numbers of bass are present at times immediately seawards of the sluices at the Cardiff Bay Barrage.

Structures such as barrages may also attract mammalian predators such as seals, which may be able to trap salmon and other fish against the structure and catch them more effectively than in open water. On occasions a seal has taken up residence within the fish pass at the Swansea Barrage. A major problem developed at a barrage in Seattle where large numbers of sea lions predate upon salmon approaching the fish pass. Various non-lethal means of mitigation have been attempted including tranquillising and transporting the animals to some distance away, though most return with little delay.

3.5 Delay in migration

Possible impacts will depend upon whether ebb or flood tide generation is taking place. It is likely that passage during the sluicing part of the cycle, be

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[19] Long C W, Krema R F and Ossiander F J (1986) Reserch on fingerling mortality in Kaplan turbines – 1986. Bureau of Commercial Fisheries, Seattle. Progress Report, 7pp.

it landwards or seawards, will be largely unaffected as the barrage will effectively be "porous" with all channels fully open. However, delays are likely during the generation part of the cycle; if ebb generation is in force this will affect seaward migrants, and if flood generation is in force this will affect landward migrants.

The delays are likely to occur as the main route through the barrage during generation will be via the turbines, which are likely to be set beneath the bed of the estuary and will be a noisy and potentially scary route for fish to take. There is doubt about the willingness of salmon and other fish to "sound" and they may remain in the surface layers and not pass through the turbines for some time.

This is a matter of some concern as the survival of adult salmon delayed in the estuary for some weeks is known to be reduced (Solomon and Sambrook 2004)[20]. There is also a widespread perception that delay of days or weeks in smolt migration is associated with reduced survival, though specific evidence for Atlantic salmon is hard to find. There is strong evidence of the timing of smolt runs being critical for survival in Pacific coho salmon (Bilton *et al* 1982)[21].

Any tendency for fish to refuse to pass through turbine passages may be exploitable for guiding them to safe alternative routes; this is considered further in Section 4.

3.6 Modified environment landwards of the barrage

If ebb-only generation were to be employed the environment landwards of the barrage would be considerably modified. Based on the STPG predictions the tidal range would be less than half that occurring at present (basically restricted to the upper part of the existing range). This is likely to result in other major environmental changes including reductions in both current speeds and suspended solids, and a much larger permanently-

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[20] Solomon D J and Sambrook H T (2004) Effects of hot dry summers on the loss of Atlantic salmon, S*almo salar*, from estuaries in South West England. Fisheries Management and Ecology 11, 353-363.

[21] Bilton H T, Alderdice D F and Schnute J T (1982) Influence of time and size at release of juvenile coho salmon (*Onchorhyncus kisutch*) on returns at maturity. Canadian Journal of Fisheries and Aquatic Science 39, 426-477.

inundated bed area. This is likely to have little adverse impact on migratory species and may represent an enhancement for eels and juvenile shad.

3.7 Impact of a barrage at the English Stones

Clearly a barrage on the English Stones site (Beachley to Aust) potentially imapcts on fewer river stocks as it is landwards of most of the rivers enclosed by the Cardiff Weston line; only the Severn is thus enclosed. Although seawards migrants (eg salmon smolts and juvenile shad) from rivers seawards of the barrage line would not have to pass the barrage line ther is nevertheless potential for significant impact on stocks due to the "overshooting" behaviour of adult salmon and quite possibly other fish (Section 3.3.1). This will need to be carefully considered in any proposal for deveopment at this site.

3.8 Potential impacts of a bund scheme

A scheme based on a blind bund, would represent a somewhat different set of conditions. In contrast to the line barrages there would be no seawards migration of juveniles from upstream. However, any fish moving with the flood tide are likely to find themselves drawn into the bund. Such fish could include both landward and seaward migrants and they would have little or no perception that they were not in fact moving landwards up the estuary. They would have to leave the bund again to continue their journey to the sea or up river. They would thus cross the generator line at least once in each direction, and are likely to have to pass through or past generating turbines at least once. Any added complexity such as division of the bunded area into two or more generating reservoirs would further increase the risks.

4 Possible impact reduction and mitigation

4.1 Introduction

The main potential impacts of a barrage arise from damage and death to fish passing through turbines, and from predation in the immediate vicinity. There are a number of potential approaches to reduction and mitigation; these are now considered in turn.

4.2 Use of more "fish friendly" turbines

There are developments in turbine design that may represent a less damaging situation for fish passing through them. This work is being conducted mainly in North America and the results so far appear to be limited; indeed, the small improvement in fish survival is at the cost of turbine efficiency, so that there is little gain in terms of fish killed per unit of power generated. Clearly, however, this is an important area and a detailed review of progress and future potential is essential.

4.3 Use of physical screens to divert fish

Physical screens are often used to divert fish from intakes into safer routes (Solomon 1995[22], Turnpenny and O'Feeffe 2005[23]). However, the use of any screen capable of totally excluding salmon smolts and juvenile shad, coupled with the requirement for a low-enough approach velocity for fish to swim to alternative safe routes, is impractical in this situation (Solomon 1988a). Partial screening is a possibility for salmon smolts, which are known to travel in the upper layers of the water column (see Solomon 1988a, and next section).

4.4 Exploiting fish behaviour to avoid turbine passage

As already mentioned in Section 3.4, any tendency for fish to avoid turbine passage, and to arrive at the face of the barrage in the surface water, could be exploited by providing surface collectors and spillways to provide safe passage. These options are discussed in detail by Solomon (1988a).

The use of acoustic signals to divert fish from intakes has been explored for many years (Solomon 1995, Turnpenny and O'Keeffe 2005) and developments are still being made. A detailed review of the current technology and future potential is strongly recommended.

While a number of behavioural diversion systems have worked to a greater or lesser extent on small intakes, the sheer volumes and the approach velocities involved in this situation mean that finding even a partially effective solution is far from certain.

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22 Solomon D J (1992) Diversion and entrapment of fish at water intakes and outfalls. R & D Report 1, National Rivers authority, Bristol. 51 pp.

23 Turnpenny A W H and O'Keeffe N (2005) Screening for intakes and outfalls: a best practice guide. Science Report CS030231, Environment Agency, Bristol. 153 pp.

Figure 10: *Catches of juvenile salmon from six nets positioned at different vertical positions in the intake of a dam on the Columbia river, net 1 being at the top and net 6 at the bottom, indicating the tendency for salmon smolts to be located in the upper layers of the flow.*

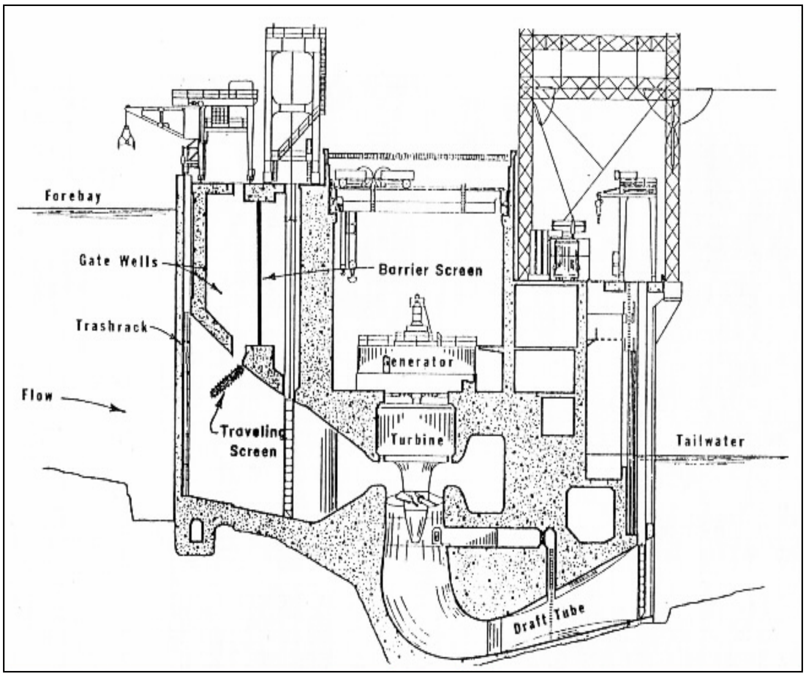

Figure 11: *Section through a Kaplan turbine installation at a dam on the Columbia River, showing the location of a travelling band screen set to exploit the behaviour shown in Figure 10. Smolts in the upper layers of water are diverted into the gate wells, from where they are led to a safe exit in the tailrace*

Perhaps the greatest scope for physical screening lies in the option of installations in the upper part of the intake tunnel, where the greatest concentration of smolts might be expected, which could guide the fish to a safe alternative route. This approach is used to reduce mortality of Pacific salmon smolts at dams on the Columbia River (see Figures 10 and 11). Investigation is needed to establish how effective it would be for juvenile Atlantic salmon and shad, both in terms of tendency to be located in the upper part of the water column, and reactions to screening installations

4.5 Reducing predation

There is no obvious approach to reducing predation around the barrage by fish, birds and mammals. Programmes to reduce predator populations are fraught with problems, not least that of public perception.

4.6 Stock enhancement

If a barrage scheme is to go ahead in spite of an inevitable level of impact on migratory fish, it is appropriate to consider options for stock enhancement to mitigate for the losses. There are two basic approaches available: habitat enhancements to increase natural production, and hatcheries to boost numbers through artificial rearing. These two approaches are now considered in turn, but it must be recognised that the juveniles resulting from both approaches would also have to pass the barrage line in exactly the same way as wild fish as already discussed, with equivalent losses.

Enhancement through improvement of habitat can be very effective but this pre-supposes there is sub-optimal or under-utilised habitat available within the catchment. This is indeed currently the case for juvenile salmonid habitat at least within the Wye catchment, due to barriers, degradation through agricultural practices and acid precipitation. All are being addressed at present, and in the absence of a barrage it is likely that these actions will continue and eventually allow stocks to regain the full carrying capacity. Thus any contribution by the scheme promoters to programmes of stock recovery cannot be considered as mitigation for the impacts of the barrage.

Too little is known of the limiting factors for the other migratory species to assess whether habitat enhancement is a practical approach to mitigation.

Hatchery production of salmon is feasible and has often been used in mitigation for impact of engineering or water resource scheme impacts. However, large-scale hatchery mitigation is generally considered to be unsatisfactory for two main reasons. First, it is relatively ineffective. Survival of hatchery-produced smolts is generally poor, several times less that that of naturally-produced fish. Where eggs have to be obtained from the wild stock it is usually considered better to allow the fish to spawn and rear naturally. Second, there are likely to be genetic impacts, depending upon the source and management of broodstock, including inbreeding, inadvertent selection and genetic drift. Where the fish deriving from such hatchery production mix with and interbreed with wild fish this can have genetic repercussions for the whole river stock (Cross *et al* 2007[24]). Salmon populations in different river systems are genetically isolated to a large extent and have evolved to be well-suited to the conditions prevailing in their home river and the routes to and from the marine feeding grounds. It is likely that large-scale salmon hatchery would be deemed unacceptable where the species is a named feature of interest in an SAC citation.

No production-scale hatchery programmes are believed to exist for allis shad, twaite shad, river lamprey or sea lamprey, so the practicability of such a programme is not known.

5 Conclusions

5.1 Importance of the rivers flowing into the Severn estuary

The Severn estuary has important stocks of migratory fish that would be affected by tidal power generation. The rivers draining to the estuary upstream of the Cardiff-Weston line cover 24 % of the existing salmon spawning areas in England and Wales. For much of the 20th century, the Wye was the leading salmon angling river in England & Wales, with the other rivers also supporting major fisheries. The area is even more important for twaite shad, comprising more than 75% of the current UK population.

In addition other rare and protected species like allis shad, river lamprey and sea lamprey also migrate through the estuary and up the main rivers. The national importance of the local fisheries has been recognised by designating the entire Wye and Usk catchments, and the Severn Estuary, as Special Areas for Conservation.

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[24] Cross T F, McGinnity P, Coughlan J, Dillane E, Ferguson A, Koljonen M-L, Milner N, O'Reilly P and Vasmagi A (2007). Stocking and ranching. Pp 325-356 in Verspoor E, Stradmeyer L and Nielsen J L (Eds) The Atlantic salmon – genetics, conservation and management. Blackwell, Oxford.

Over the past 30 years the salmon fisheries have been severely affected by over-exploitation, pollution, barriers to migration and acid rain, bringing the species almost to extinction in these rivers. However, there have been major efforts to reverse the decline, both locally and internationally, over the past 15 years. Actions have included almost total cessation of netting in the high seas and estuary, removal of barriers, neutralising the effects of acid rain and habitat improvements within the rivers. Theses measures are starting to take affect, but there is a long way to go to full stock recovery.

5.2 Likely impacts of tidal power generation

The greatest potential for impact on migratory fish species comes from damage caused by passage through the turbines, and increased predation in the vicinity of the structure. Based upon experience elsewhere, experimental results and a description of a likely design of barrage proposed by STPG the following conclusions are drawn for fish involved in a single turbine passage:-

- Losses of salmon smolts are likely to be of the order of 9.5%, mainly due to runner blade strike damage.
- Losses of adult salmon are likely to be of the order of 44%, mainly due to runner blade strike damage.
- Losses of juvenile shad are likely to be of the order of 53%, mainly due to shear damage.
- Losses of adult eels are likely to be of the order of 28%, entirely due to runner blade strike damage.

Overall losses would depend upon what proportion of the population experienced turbine passage, and how many times.

Predation by fish and birds on juvenile fish temporarily disorientated after turbine passage may be of a similar order of magnitude to losses due to turbine damage.

Stocks of migratory fish are very vulnerable to developments which interfere with their migration between the rivers and the sea. Without effective mitigation, development of a barrage could eradicate altogether runs of migratory fish from the rivers entering the Severn estuary/Bristol Channel landwards of the barrage, or at the very least cause them to perform at very much below optimum levels.

5.3 *Potential for reduction of impact and mitigation*

Potential for impact reduction is limited. Preventing turbine passage is problematic and unlikely to be completely achievable, although some reduction should to be feasible at a significant cost. Developments in "fish-friendly" turbine design must be explored but again appear very limited in effectiveness. No approach to reduction in the predation that will inevitably be associated with passage through the barrage is apparent. Thus the scope for limiting impact appears to be very limited.

The scope for mitigation of impact appears even more restricted. Stock enhancement through habitat management is effective but this is happening anyway, and is thus cannot be considered as an option for barrage mitigation. Hatchery production of salmon smolts is feasible but is likely to be an unacceptable option in rivers of high conservation value such as the Wye and Usk. Hatchery production for other species is an unknown potential. In any event, replacement stocks produced in hatcheries would itself be subjected to a similar impact of the barrage as the wild fish.

Even with the best conceivable scenario of impact management and mitigation the effects of a barrage will be highly injurious to the wellbeing of migratory fish, and could well lead to their eradication from the affected rivers. If the barrage proposal is to be taken further it will be essential that all possible actions are taken to ensure that the stocks of migratory fish are in the finest possible health in the hope (rather than expectation) that they will then be robust enough to withstand the impact. Such actions must be considered to be long-term and the earliest possible start is required to optimise the potential.

5.4 *Recommendations for further work*

Much of the assessment undertaken here is based upon work produced in the 1980's and 1990's. There have been developments in several areas since that time, and thorough reviews of several areas will be important. These should include:-

- Damage to fish caused by turbine passage. This subject was thoroughly investigated during the earlier studies and recent advances in understanding are probably limited, but it is of such fundamental importance that updating is considered essential.

- The scope for turbine designs which are more fish-friendly than those of the past.

- Developments in the technology of excluding fish from intakes have been made, especially in the area of behavioural diversion. Again of fundamental importance for assessing the impact of the barrage proposal and scope for amelioration.

- We need a better understanding of aspects of the behaviour of migratory fish which are relevant to assessing the impact of the barrage and the likely effectiveness of diversion techniques. This would effectively build on the earlier review by Solomon (1988b) and should cover timing of migration on seasonal, tidal and diurnal scales, vertical distribution of migrating fish in the water column, and perhaps most critically the routes taken by fish and any tendency to multiple passage past the possible barrage lines. It is likely that further field investigation will be required using telemetry tracking of tagged fish. Good advances in telemetry technology have been made in the past 20 years.

- Assessment of the scope for stock enhancement through habitat engineering and hatchery development. Although the scope to mitigate in this way is probably limited it is important to establish this as part of the decision-making process.

The earliest possible start must be made to enhancing the existing programme of habitat and stock recovery to ensure that stocks of migratory fish are in the best possible position to withstand the impact of a barrage. The optimal approach must be investigated and implemented as long as possible before any development commences. An immediate start to this process is a moral imperative for the proposers of the scheme, even before a decision to proceed is taken.

This list is not considered to be exhaustive and doubtless considerable further work will be required, if the barrage proposal is to be progressed, to assess and manage the predicted fundamental impacts on resources of such enormous conservation, historic, cultural, recreational and economic importance.

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