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Títol

Fish Habitat Modelling for the Severn Estuary

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Abstract

This study describes estuary associated fish species characteristics together with the factors influencing their habitats, migrations and dynamics. The Severn Estuary ecosystem is briefly described with special detail to its physical characteristics and its fish fauna. The suitable habitat conditions for the Dover sole and the European eel are examined in particular and the Suitability Index curves against various environmental variables are designed. The configuration of different environmental variables spatially in the estuary is obtained by different means such as long term studies, GIS data or predictions from an eco-hydraulics model. The habitat requirements of the two fish species are linked with the environmental conditions and the distribution of the Habitat Suitability Index values of 1 and 0.5 is estimated. Some of the effects of developing the marine renewable schemes across the estuary are discussed as well as a number of predicted consequences that the climate change will have on the habitat of the two analysed species. The study shows that the effects induced by the tidal energy array in the habitat of the sole and the eel would be generally positive mainly due to the decrease of water depths and water flow velocities among other aspects. However the temperature and salinity profiles alteration together with the turbine associated injuries to migrant fish are key issues to consider regarding the negative impact of the tidal structure. The climate change effects are predicted to have a few positive aspects on some species habitat such as changes on certain variables; nevertheless the combination of changes in different environmental parameters is likely to have a negative overall impact.

Content

1. Introduction

Estuaries perform an essential role in the life cycle of many fish including a wide range of species with different environmental affinities and astonishing ecological patterns. According to their guilds and origin, fish species use estuaries in different ways, for example as an area for spawning or feeding, and some others only enter estuaries sporadically in certain times of the year. In addition estuaries configure fascinating locations, where the conditions are continuously under change and unique biodiversity with extraordinarily diverse ecological requirements develops. Moreover fish dynamics in estuaries are highly complex and their seasonal movements and migrations are in some occasions poorly understood. Particularly the factors controlling the changes in their migration patterns from time to time are rather ambiguous.

The Severn Estuary is likely to face different changes in its physical characteristics and environmental conditions in the near future, involving significant losses of habitat induced by the Climate Change and by the possible development of the controversial tidal energy schemes across the estuary. This report provides an approach on the way that these matters are predicted to affect the habitats of some of the numerous fish species that each year occur the Severn Estuary and also the barren areas of this extensive system, constantly affected by the high energy currents. This will be achieved by the obtaining of the Suitability Index curves against different environmental variables for two chosen fish species from literature review. Subsequently, the arrangement of relevant environmental parameters such as bed sediment, bathymetry or water flow velocity within the estuary will also be acquired. Linking the ecological requirements obtained of fish species with the spatial distribution of the physical parameters in the estuary, the

Habitat Suitability Index arrangement for two chosen fish species will be estimated. This will be done by considering the maps of bed sediment, water flow velocity and bathymetry of the estuary, together with the sea distance. The areas where the optimum values of these variables coincide for each fish species will be mapped with the higher values of the index (i.e. 1 and 0.5) in accordance with the grade of fulfilment of these (entirely or partially).

2. The Estuarine Ecosystem

Estuaries have for long been relevant environments to society, being important places of navigation and main centres of man's development. However the promotion of trade and industry is nowadays threatening estuaries altering the natural balance within their ecosystems by adapting their topography to urban development and by large scale pollution produced, mainly from industrial processes and domestic waste. Estuaries configure vital feeding areas for many species of birds, areas where amazing vegetation is developed and also essential places for some animals to complete part of their life cycle, being for others their only possible habitat. The estuarine environment is characterized by continuous changes in water properties, having constant inlets of salt and freshwater (McLusky and Elliot, 2004). From the hydrological point of view an estuary is a partially enclosed body of water which is formed where freshwater from rivers and streams meet the seawater of the oceans. Although these areas are high influenced by tides, they are protected from the full force of the ocean waves, winds and storms by reefs, barrier islands or fingers of land. The salinity of seawater is approximately 35‰, and that of freshwater is always less than 0.5‰. Thus, the salinity of estuarine waters is between 0.5 and 35‰, and it is extremely variable. One of the most characteristic features of estuaries are the fine sedimentary deposits or mud. Sedimentary material is transported into the estuary both from rivers or the sea or it is also washed in from the land surrounding the estuary (McLusky and Elliot, 2004). Whatever the source of the sediments, the deposition of it within the estuary is controlled by the speed of the currents and the particle size of the sediments (Dyer, 1979).

3. Fishes in Estuaries

3.1 Estuarine Habitat Utilisation

In the evaluation of fish habitat use in estuaries there are mainly four different functions that habitats may satisfy. Habitats can be spawning grounds, nursery areas, feeding grounds and pathways in diadromous migrations (Elliot and Hemingway, 2002). For the deposition of eggs and mate, fish select particular zones depending on the environmental characteristics which optimise the survival of the eggs or of the early larval stages.

3.2 Ecological Guilds

Ecological guilds for fish consist in a number of categories which describe the main features of the fishes' biology together with the use they make of the estuary (Elliott et al., 2007). As such, species can be identified to guilds which indicate their estuarine uses according to their seasonal movements and their biological properties. However, it has recently been argued by Selleslagh and Amara, (2008) that certain fish species may have different life history styles in different geographic areas and for this reason, there are further difficulties in the standardisation of fish guild definitions.

3.2.1 Estuarine Use Functional Group

Elliot and Dewailly (1995) defined six main categories for estuarine fish through ecological guilds based on fish migrations together with feeding and spawning patterns. A new classification was defined by Elliott et al. (2007) as a result of further developing the guild concept.

Table 3.1. *Estuarine use functional group adapted from Elliott et al. (2007)*

Term	Subterms	Definition	Synonyms	Cool/warm temperate Examples	Subtropical/Tropical Examples
Marine stragglers (MS)		Species that spawn at sea and enter estuaries in low numbers in the lower reaches.	Marine adventitious.	Western school sillago, Blue runner, Whiting.	Spanish mackerel.
Marine migrants (MM)		Species that spawn at sea and often enter estuaries in large numbers, particularly as juveniles. They are subdivided into:	Marine seasonal, marine juveniles, marine immigrants.	Atlantic herring, European seabass, Atlantic menhaden, Thinlip mullet, Cape stumpnose, Spotted sillago, Sole.	Mangrove red snapper, Tenpounder, Giant trevally
	1. Marine estuarine opportunist (**MMO**): marine species which regularly enter estuaries in substantial numbers.				
	2. Marine estuarine dependent (**MMD**): marine species which require estuarine habitats as juveniles.				
Estuarine species (ES)		Species that complete their whole life cycle within the estuary	Strictly estuarine species.	Common goby, Atlantic silverside, Gilchrist's round herring, Black bream.	Commerson's glassy, Celebes goby
	1. Estuarine residents (**ER**): Species able of completing their entire life cycle within the estuary.				
	2. Estuarine migrants (**EM**): Species that have larval stages completed outside the estuary.				
Anadromous (AN)		Species that experience their greatest growth at sea and migrate into rivers to spawn.		Chinook salmon, Pouched lamprey.	Hilsa shad.
Catadromous (CA)		Species that spend all of their trophic life in freshwater and migrate to sea to spawn.		European eel, American eel.	African longfin eel.
Amphidromous (AM)		Species which migrate between the sea and freshwater without relating the migration to reproduction		Bay anchovy.	Fat sleeper.
Freshwater migrants(FM)		Freshwater species found regularly in estuaries.	Freshwater species.	Three-spined, Stickleback.	Mozambique tilapia.
Freshwater stragglers (FS)		Freshwater species which occupy estuaries in low numbers. Their distribution is limited to the low salinity.	Freshwater species.	Least killifish, Northern pike.	North African catfish.

For further understanding of the life cycle categories defined by the Table 3.1 it may be worth to consider the following graphics designed by Elliott et al. (2007)

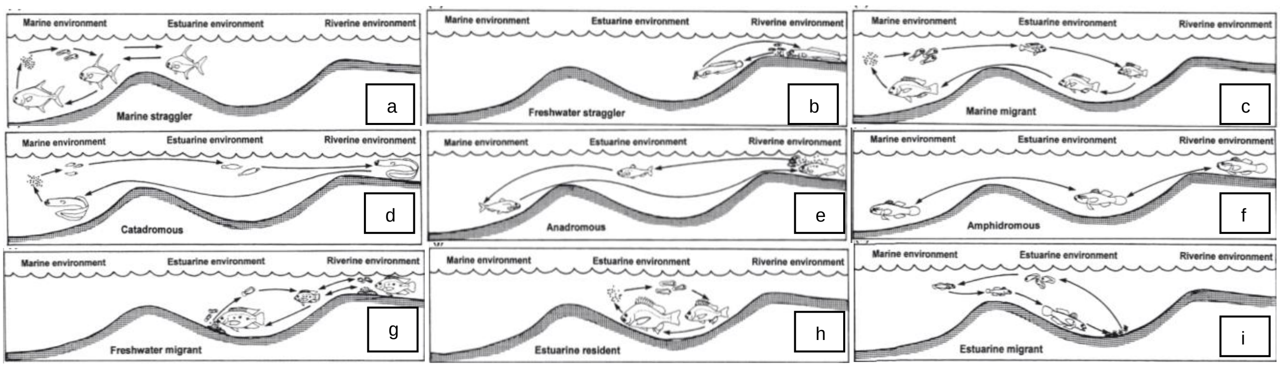

Fig.3.1. *Marine straggler (a), Freshwater straggler (b), Marine migrant (c), Catadromous (d), Anadromous (e), Amphidromous (f), Freshwater migrant (g), Estuarine resident (h) and Estuarine migrant (i) life cycles reproduced from Elliott et al. (2007)*

As shown in Fig.3.1, the term straggler is used to define a low level introduction of individuals being predominantly freshwater species. The majority of them is salinity-restricted and thus occupies the estuary for very short periods of time and in limited areas. Freshwater stragglers are species which occur in estuaries typically due to large freshwater flows from the river to the estuary or flooding conditions. Marine migrants are usually referred to a temporary occupation of the estuary and after a return to the original habitat. Catadromy, as well as anadromy is related to an ability of a fish to change its physiology when moving between waters with variable salinities. Anadromous species undertake movements from sea to freshwaters and hence they experience a major physiological adjustment to tolerate new salinities. Amphidromous species are those ones which live in rivers or estuaries and whose eggs and larvae may be deposited in the sea during the ebb tide. Freshwater migrants are species which often migrate into estuaries. Estuarine resident species complete their whole life cycle in the estuary, thus, they are able to tolerate spatial and temporal variations of conditions. Estuarine migrant species migrate to the sea in their post-larval stages and after, they return to the estuarine environment to complete their life cycle.

3.2.2 Feeding and Reproductive Mode Functional Group

These classifications were derived by Elliot et al (2007) and define the feeding modes within estuaries partly based on the fish feeding guilds previously developed by Elliott and Dewailly (1995).

Table 3.2. *Feeding Mode Functional Group reproduced from Elliott et al. (2007)*

Category	Subterm	Definition	Cool/warm temperate	Subtropical/tropical
Zooplanktivore (ZP)		Feeding predominantly on zooplankton (e.g. fish eggs/larvae)	European sprat, Australian anchovy.	Toli shad, Orangemouth glassnose.
Detritivore (DV)		Feeding predominantly on detritus and/or microphytobenthos	White mullet, South African mullet.	Flathead mullet, Mozambique tilapia
Herbivore (HV)		Grazing predominantly on living macroalgal and macrophyte material or phytoplankton	Southern sea garfish.	Redbreast tilapia
	Herbivore-phytoplankton (HV-P)			
	Herbivore-macroalgae/macrophytes (HV-M)			
Omnivore (OV)		Feeding predominantly on algae, macrophytes, periphyton[1], epifauna[2] and infauna[3]	White seabream, Cape stumpnose, Cape halfbeak.	Milkfish, Northern snubnose garfish, Vermiculated spinefoot.
Piscivore (PV)		Feeding predominantly on finfish	Japanese meagre, Leerfish, Bluefish.	Pickhandle barracuda
Zoobenthivore (ZB)		Feeding predominantly on invertebrates including hyperbenthos[4], epifauna and infauna	European plaice, Clobber, Spotted sillago, Atlantic cod, Yank flathead.	Surf bream, Smallspotted grunter, Javelin grunter, Bay anchovy
	Zoobenthivore-hyperbenthos (ZB-H)			
	Zoobenthivore-epifauna (ZB-E)			
	Zoobenthivore-infauna (ZB-I)			
Miscellaneous/opportunist (OP)		Feeding on a diverse range of food.	Flounder, Southern black bream.	Sheepshead minnow.

Table 3.3. *Reproductive Mode Functional Group reproduced from Elliott et al. (2007)*

Term	Subterm	Definition	Cool/warm temperate	Subtropical/tropical
Viviparous(V)		Species in which the female produces live progeny.	Viviparous blenny, Super klipfish.	Mosquitofish, Bull shark.
Ovoviviparous (W)		Species producing an egg case in which the young develop.	Piked dogfish.	Common eagle ray.
Oviparous (O)		Species producing eggs that are liberated into the surrounding waters.		
	Op	Species producing pelagic eggs.	Flounder, White mullet.	Flathead mullet
	Ob	Species that produce eggs which settle on the substratum.	European smelt, American shad.	Australian river
	Ov	Species that produce adhesive eggs that become attached to substrata and/or vegetation	Striped seasnail	Burrowing goby, Cape silverside
	Og	Species in which one of the parents guards their eggs externally, e.g. in a nest.	Three-spined Stickleback.	
	Os	Species that shed their eggs and then protect them for a period in a part of their body, e.g. brood pouch or mouth.	Nilsson's pipefish, Hardhead sea catfish.	Mozambique tilapia, Barred mudskipper.

The feeding categories include seven wide groups showed in the Table 3.2 and the reproductive functional group defines three main types of reproduction modes, shown in the Table 3.3

3.3 Factors Influencing the Fish Communities of Estuaries

Fish communities within estuaries are configured by numerous environmental variables and with the variation of these it can be experienced a response in the

[1] Periphyton: Miscellaneous assemblage of organisms (both plants and animals) attached to all free surfaces of objects submerged in water (Baretta-Bekker et al. 1992)
[2] Epifauna: Animals that live on the sediment. (Elliot et al. 2007)
[3] Infauna: Animals that live in the sediment. (Elliot et al. 2007)
[4] Hyperbenthos: Mobile organisms that live just above the sediment. (Elliot et al. 2007)

biota of which only a little is known about. Whitfield and Elliott (2002) developed a graphic where the interactions between the ichthyological and most relevant environmental variables are summarised.

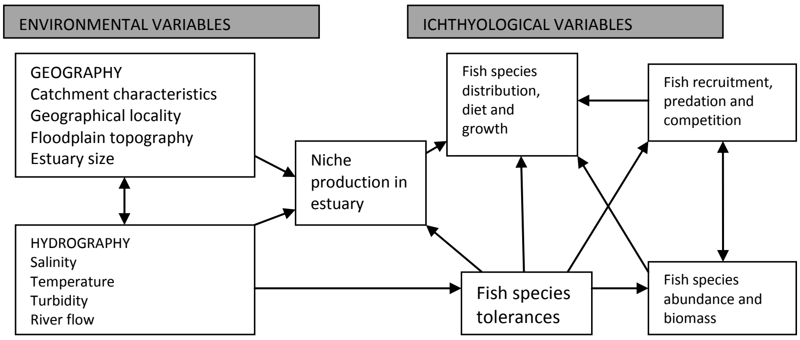

Fig.3.2. *Interactions between selected environmental reproduced from Whitfield and Elliott (2002)*

The Fig.3.2 shows that the main factors controlling the biological functioning of estuaries are based on hydrographical and geographical elements. The fish abundance within estuaries is controlled by biological parameters such as recruitment and fish tolerances to environmental variables. Both environmental and biological variables regulate the niche production; however the parameters which control the response of the biota are the physical ones. In addition, some studies suggested that the main physical factors influencing estuarine fish communities in the northern hemisphere are salinity, temperature and North Atlantic Oscillation Index (Henderson and Bird, 2010; Henderson, Seaby and Somes, 2011) which is also consistent with Fig.3.2.

3.4 Natural Factors Influencing the Fish Recruitment Processes

The strength of a fish population is predominantly determined by the survival of the earliest life stages of the fish (Elliott and Hemingway, 2002). Therefore the recruitment success is one of the most decisive factors for the prospering of the species population. The factors that control fish recruitment processes may be divided into biotic and abiotic factors. The biotic factors include the predation, particularly attributed to shrimps in the nursery area (Selleslagh and Amara, 2008) and cannibalism in addition to sediment and vegetation. The abiotic factors consist mainly in temperature, salinity, oxygen concentration, hydrodynamics, wind stresses in addition to turbulence and turbidity.

3.5 Seasonal Changes in Estuarine Fish Assemblages

It is widely agreed that ichthyofaunal composition varies with the region and the years, indeed the variations are especially produced in marine migrant species which use estuaries as nursery areas. Such variations are due to changes in the recruitment success among seasons (Potter, Claridge and Warwick, 1986). Also the fish compositions of estuaries experience seasonal cyclical changes due to the alterations on the time of the migrations of certain species (Chuwen, Hoeksema and Potter, 2009). Some authors suggest that these changes are related to temperature and salinity in addition with the level of eutrophication[2], being the most oligotrophic[3] estuaries poor in species, and having the highly eutrophic estuaries the highest richness in species. However Potter, Claridge and Warwick, (1986) proved that these changes are attributable to migrations of different species and therefore they were not related to variations in water temperature, salinity or river flow. By contrast, Henderson and Seaby (1994) found the variations in seawater temperature to be the major parameter influencing flatfish species in the Bristol Channel.

[4] Eutrophication: Enrichment of natural waters with inorganic nutrients by which phytoplankton growth is simulated. (Baretta-Bekker et al. 1992)
[5] Oligotrophic: Low productivity and nutrient content (Baretta-Bekker et al. 1992)

4. The Severn Estuary

4.1 Introduction

The Severn Estuary is the second larger estuary in the United Kingdom, constituted by a considerable body of tidal waters in southwest coast of Britain (Fig.4.1). The Severn is a hypertidal estuary, having the third highest tidal range in the world (mean tidal range >6.0 m) it has also a relevant natural and cultural heritage. The coast of the Estuary supports significant urban areas such as Cardiff, Bristol and Newport and its ports are a gateway to the Atlantic Ocean. Two motorways cross the Estuary waters, linking Wales and South West of England (Severn Estuary Partnership, 2001).

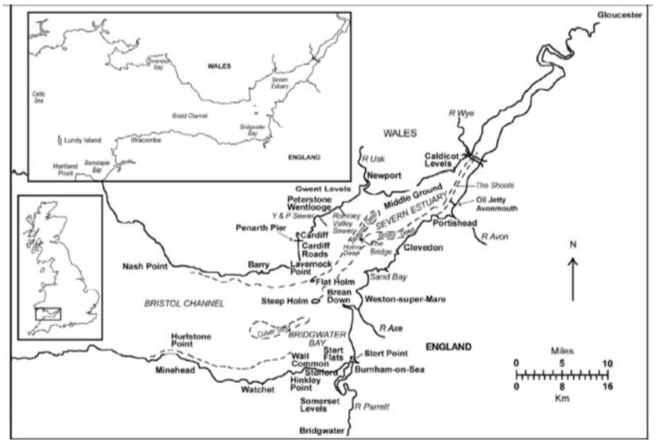

Fig.4.1. *Bristol Channel and Severn Estuary with locality map showing some of the sites around the Estuary's and Channel's shore. Reproduced from Kirby (2010).*

4.2 Natural Habitat

The results of this high energy system are strong tidal streams, mobile sediments and high turbidity, developing a particular animal and plant communities typical of the extreme physical conditions. Also, this astronomical tidal range leads to a large intertidal zone, amounting about 22,000 ha. The Severn is a large, part coastal plain, part high cliffed, estuary (Kirby, 2010) produced from the outlet of five major rivers, the Severn, the Wye, the Usk, the Parret and the Avon. Furthermore, the Estuary has a classic funnel shape which amplifies its tidal range. In addition the estuary is aligned with the predominant wind direction, producing significant waves. The Severn Estuary itself and its surrounding areas are recognised as Sites of Special Scientific Interest (SSSIs). The possible Special Areas of Conservation involve nearly all the enclosed body of waters while the Special Protection Area (SPA) covers from the mouth of the estuary until approximately the point where the river meets the estuary. The Estuary is also a Wetland of International Importance (Ramsar).

4.3 Physical Properties of the Severn Estuary

4.3.1 Introduction

The Severn Estuary and Bristol Channel constitute a system of approximately 250 km long. Its highest tide is of 14.7 m, with a mean of 12.3 m and a mean neap range of 6.5 m (Kirby, 2010). Its energetic currents produce strong mixing and high bed stresses in different spatial directions, and as a result there is a remarkable horizontal dispersion together with vertical uniformity in salinity, temperature and phytoplankton, leading also to a tide-dominated bed sediment transport, different sediment distributions and presence of benthic faunal communities (Uncles, 2010).

4.3.1 Physical and Water-Column Properties.

Within the Estuary and the Channel, the water level is a factor that may be considered, as the mean sea level is found to be rising. The increase on the water level depends on the region, and in the Severn Estuary, this increase is about 5 mm per year. In the Severn Estuary the maximum tidal currents at mean spring tides (MST) exceed a speed of 1m s^{-1} in the mouth of the Channel being higher than 2.5m s^{-1} in the upper reaches (Uncles, 2010). The wind speed also varies with the shelter of the areas within the Estuary and the season. Salinity in the

Severn reaches its lower value in winter when the input flow from the River Severn is greater. The largest freshwater flow rate is 100 $m^3 s^{-1}$. The salinity where the River Severn meets the Estuary may be below 20‰, being the maximum salinity about 35‰, near the Channel mouth (Uncles, 2010). Turbidity and tidal both increase from the Estuary's mouth upwards, where the suspended particulate matter is less than 10 mg l^{-1} in the outer Channel and exceeding 500mg l^{-1} in the lower Severn (Kirby, 2010). The temperatures are typically in their minimums during February, when at the mouth are less than 6 ºC. During the summer, temperatures may exceed 20 ºC in the inner Channel. In addition, in the Channel and also in the upper Severn (due to the strong turbulence) the water temperature and salinity remain vertically mixed throughout the year (Uncles, 2010).

4.3.2 Sedimentation

The Severn Estuary is composed essentially of fine cohesive sediment and in less proportion, medium grained sediments. However in some areas, also coarse materials could be found, developing estuarine banks (English Nature Somerset Team, 1997). There is a threshold in the concentration of SPM which is about 500 m gl^{-1} and divides the "low turbidity phase" from "high turbidity phase" (Kirby, 2010). In the high turbidity phase some important characteristics may be taken into account. Firstly the sunlight penetration in these zones is inexistent. Secondly the oxygen dissolved concentration in the water body may be eliminated due to the organic-rich fine particles. In the third place, as there is no presence of sunlight penetration, the pathogens, bacteria and other micro-organism sewage-derived which are eliminated by the combination of UV radiation and saltwater, are destroyed in a small proportion. In addition, during low neap tides, a large amount of fluid mud dewaters progressively, moving possible pollutant and anaerobic waters into the overlying water body. This fact affects the near-bed zone where the populations of benthic invertebrates and fish concentrate, having negative consequences on these. The decrease in dissolved oxygen is prejudicial especially for the benthic feeding fish (Henderson and Bird, 2010).

4.3.1 Future Changes that will affect Habitats in the Severn Estuary

According to the Coastal Habitat Management Plan (CHaMP) (ABPmer, et al., 2006), nowadays the Severn Estuary is experiencing variations and it is expected to change more in the future. The sea level rise will force coast to squeeze and this may lead to loss of intertidal habitat. A migration upstream of the water body is also predicted with the water level increase and small short term alterations in the habitats are foreseen. For further comprehension of the future habitat looses expected in the Severn Estuary it may be considered the table 4.1.

Table.4.1. *Results as a percentage change of the estimated extent in 2005. Reproduced from ABPmer, et al., 2006*

Total Estuary Change (As compared to 2005)	Estimate Area in 2005 (ha)	20 year %change	50 year %change	100 year %change
Intertidal Area	22,500	-7	-7	-11
Intertidal mudflat and sandflat	20,000	-6	-5	-9
Saltmarsh	1,600	-13	-41	-38
Transitional Grassland	1,600	13	6	6
Subtidal	46,000	3	3	5

These results show that in 2025, the areas that will experience the most significant change will be those ones located upstream, and increasing particularly the changes in the Saltmarsh by 2025. By 2105 the most significant changes predicted are the overall net loss in intertidal area.

4.3.2 Fish Species and Dynamics

4.3.2.1 Introduction

The fish community in Severn Estuary is remarkably rich in composition, comprising over 110 different species of fish in total for the estuary (Department of Energy and Climate Change 2010; Henderson and Bird, 2010; Countryside Council for Wales and Natural England, 2009), and considered of particular relevance for the migratory fish, having the largest number of migratory fish in Britain and providing nursery areas for a wide range of juvenile fish.

From long-term sampling surveys at Hinkley Point in Bridgwater Bay, and Oldbury station, Henderson and Bird (2010) concluded that the number of total species is increasing by about one new species every two years, and the majority of these new species are found to lie in the southern part of the Estuary. Considering a survey of 30 years based on time series abundance, it was deduced that significant changes in the structure of the fish community are at the moment in progress, having recorded recent important increases in abundance. According to Henderson (2007), from 2002 onwards, the rate of increase has been doubled. These relevant levels of change lead to the conclusion that the system is at the moment far from the equilibrium, being in some cases affected by the North Atlantic Oscillation and by the recent water warming. The general increase in fish abundance may improve the water quality and reduce the impact of anthropogenic actions (Henderson and Bird 2010).

4.3.2.2 Species Abundance

Particularly three sites in the Severn Estuary have been used to collect fish species over various decades; these are the Oldbury and Berkeley power stations, located in the upper Severn Estuary, in addition to Hinkley Point at its mouth. Several studies on the fish fauna of the Severn Estuary have been undertaken; one of particular relevance was developed by Claridge et al. (1986) from the Oldbury power station where data on the abundance of all fish species collected at weekly intervals from July 1972 to June 1977. Subsequently, another survey was undertaken by Potter et al. (2001) where the Estuary was sampled with catches of fish at least twice a month from early January 1996 to the late June 1999. This study also compared the data on the fish community in the two surveys. From this analysis it was shown that the abundance of fish at Oldbury was much greater in the 1990s than in the 1970s, principally caused by the increases in the numbers of some marine species, reflecting the notable improvement on the water quality produced in the Severn Estuary between this period of time.

4.3.2.3 Fish Species according to their Life Cycle Characteristics

Fishes corresponding to the different ecological categories defined by Elliot et al. (2007) described in the section 3, have been recovered in the different sites of the estuary. According to Henderson and Bird (2010) some examples of the recovered marine stragglers are the Anchovy (*Engraulis encrasicholus*) or the Mackerel (*Scomber scrombrus*). Regarding the freshwater straglers, these were reported in low numbers at Oldbury station, with the exception of the three-spined stickleback (*Gasterosterus aculeatus*) which was found in significant numbers at Oldbury. Some of the anadromous species included the Sea lamprey (*Petromyzon marinus*), the Salmon (*Salmo salar*), and the Trout (*Salmo trutta*). Being the only catadromous species the European eel (*Anguilla anguilla*). The marine migrant opportunist identified included the Sprat (*Sprattus sprattus*), the Herring (*Clupea *harengus*) and the Cod (*Gadus morhua).* Some examples of marine migrant dependent recovered were the Bass (*Dicentrarchus mustela*), the Sand goby complex (*Pomatoschistus minutes*), and the Dover sole (*Solea solea).* The estuarine resident species identified included the Common goby (*Pomatoschistus microps*), and the Sand smelt (*Atherina boyeri*).

4.3.2.4 Changes in Seasonal and Annual Abundance

All the fish species identified in the Severn Estuary are found to vary in community numbers reflecting regular cycles of abundance that are produced each year. Potter et al. (1997) argued that these consistent cyclical changes at Oldbury are due to the immigration of large groups of juveniles of the different marine species for short periods. There is a major group of fish species whose peak composition and quantity is produced in late summer and autumn, being mainly due to the arrival of new recruits that move to the estuary to feed. This fact points out that the Severn Estuary is a nursery area for many marine fish species. Furthermore, according to Potter et al. (1986) different studies showed that each year regular changes were produced in the abundance of fish species in the Severn Estuary, and these variations were more noticeable particularly in a year when salinities dropped to an unusual low level. During some years, the increases of water temperature have been linked to increases in the abundance of some species as for example the sole, but also with the decline of some others such as the sea snail (Henderson and Bird 2010). However there are other changes in abundance not directly due to singular factors, produced by other phenomena outside the estuary. Potter et al. (2001) concluded that the inter-annual variations in the numbers of particular species in areas located in the southern limit of the Severn

Estuary are considered to be highly correlated with environmental factors. Therefore, in the Severn Estuary the seasonal cycles defined by the fish fauna are well defined and particularly regular; however the inter-annual movements are highly changeable, strongly influenced by various environmental variables.

4.3.2.5 Stability and Change at the Community Level

Henderson and Bird (2010) found that total fish species richness and abundance experienced an increment with the increase of temperature and decreasing salinity. Furthermore Henderson (2007) verified that seawater temperature, salinity and North Atlantic Oscillation have immediate effects on the fish community. It was foreseen that small changes in the inshore water temperature such as an increase of 2 ºC would lead to profound effects, increasing the overall fish species diversity in Bridgwater Bay by about 10%, being mostly all of them marine tourists. Hence, the prediction of the consequences of the fish community in the Severn Estuary under various environmental scenarios is thought to be feasible, as individuals have responded consistently and in a foreseeable form to changes in different parameters (Henderson and Bird 2010).

4.3.2.6 Correlation of the Main Marine Species Recruitment Patterns

Potter et al. (2001) reviewed some surveys developed to test whether or not it is possible to establish correlations between patterns of recruitment of some of the most abundant marine species and between those patterns with salinity and water temperature. The results could not demonstrate any significant interdependence, although the timings of the recruitment processes of these species were correlated (for example if a particular species enter the estuary earlier than normally, the same trend will be adopted by other species). Potter et al. (2001) also obtained a relevant conclusion from the 5-year analysis noted above, which was that while the recruitment strengths and times had a consistent relationship with the mean values for salinity and water temperature, the mean monthly abundances and the times when these occurred were not correlated with those two physical parameters. Although the recruitment patters are not affected by the salinity or temperature, these could partly be associated, to the presence of a salinity gradient.

4.4 Climate Change Impact Studies

4.4.1 Effects on Fishes

The consequences reported of climate change on fish range from increased proportions of oxygen consumption by fishes to changes in migrational patterns in polar seas. According to Roessig et al. (2004), for the comprehension of how the climate change affects fish, various factors should be considered including atmospheric science, physiology and ecology. For example increase of some degrees in the atmospheric temperature will increase the temperature of the water in the oceans and originate relevant hydrologic variations, changing the physical characteristics of the water. Extreme variations in some factors including water temperature, dissolved oxygen or salinity and pH may have severe effects on fish. Furthermore many native organisms currently live close to their tolerance limits, therefore estuarine and coastal systems would show responses earlier to climate changes, such as native species loss and exotic species increases. Fig.4.3, reproduced from Roessig et al. (2004) shows in summary how the variations related to the climate change can impact to fish.

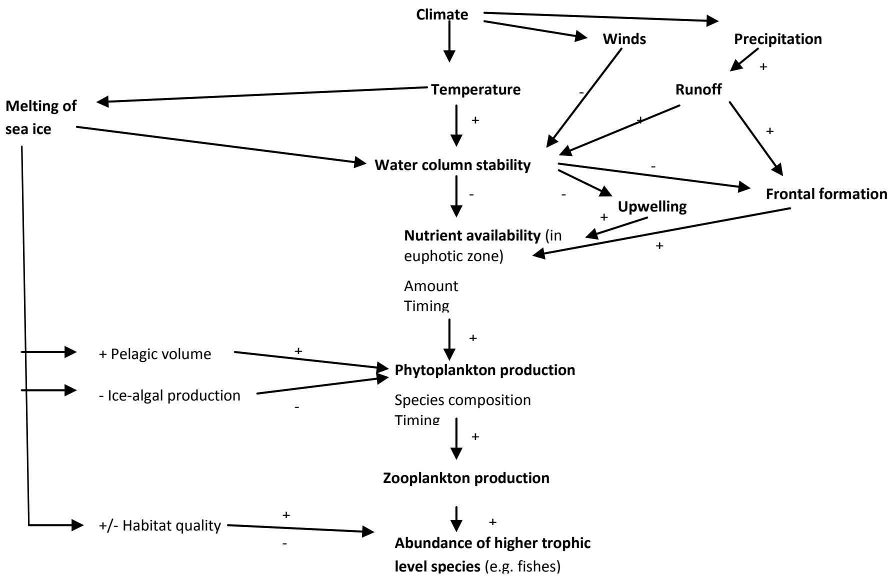

Fig.4.2. *The variable effects of climate on oceanographic processes and production. Signs (+ and – indicate the correlation between any two factors. Reproduced from Roessig et al. (2004)*.

4.4.2 Effects on the Fish Community of the Severn Estuary

As mentioned in the Chapter 3, water temperature and NAOI are considered by various authors to be key variables in the study of the plankton assemblages, which according to the Fig. 4.3 have direct effects on fish. Henderson et al. (2011) examined the effects of climate change on the fish community. The results showed that as average, the temperature of the seawater has increased and as a consequence many species have stayed longer within the estuary, including winter months. The strong correlation of the NAOI, salinity and temperature with individual species abundance was also proven. However some other species have been found to have no relationship detected with any of these three environmental variables. Environmental variables produced notable changes in individual species abundance but numerous aspects of the community structure have been conserved. The core species (which are present every year) were found to be highly stable to environmental variations, while the total species abundance is found to be increasing, mainly due to the increase of seawater temperature (Henderson, 2007). Therefore, changes attributed to recent warming caused particularly instability in the lower abundance species, which showed long term trend of exponential change. In addition, Henderson (2007) suggested that in the future, the changes of NAO, high temperature and salinity may cause a significantly negative combination for the fish fauna, reflecting in recruitment collapse for many species.

4.5 Marine Renewable Schemes

The proposal of harnessing the extreme tidal range through a tidal barrage across the Severn Estuary was first considered various decades ago (Henderson and Bird, 2010). The benefits of extracting tidal power through tidal turbines are undoubted, including the generation of about 5% of the UK's electrical energy consumption, flood defences and transport communications, (Ahmadian et al. 2011). The most feasible scheme to be developed is the Cardiff-Weston barrage, consisting in a 16 km long infrastructure incorporating 246 bulb turbine generators (Xia et al. 2010), (Department of Energy and Climate Change 2010). Although the barrage would have clearly effects on the ecosystem of the Severn Estuary, some of these effects are positive and some others are negative (Boyle, 2004) but generally these are rather uncertain and recognisably need further study. Currently the three possible modes of operation for the Severn Barrage are being considered including ebb generation, flood generation and two-way generation. In the present report only the ebb tide generation way of operating is taken in consideration and the information provided on the predicted effects is therefore based only on these conditions.

4.5.1 Water Quality

Henderson and Bird (2010) predicted that on the water quality the likely consequences of building either a barrage or a lagoon are mainly to have changes in the salinity profile of the estuary, as the barrage would interfere in the water interface by displacing it downwards. Any tidal power scheme in the Severn Estuary would strongly modify its salinity and temperature profiles, therefore even though the way it would affect species abundance is unclear, the distribution of these would surely be affected. Also the concentrations of conservative contaminant elements such as Ni and Cd are thought to increase with the presence of the tidal structure, since salinity controls many other parameters such as metal concentrations, nutrients and dissolved oxygen (through its influence on oxygen solubility). The most likely consequences for the salinity are to experience decreases upstream the barrage. Nevertheless the changes in salinity are predicted to be uncertain and rather negligible, as tidal barrages do not create a significant barrier to tidal flushing (Kadiri et al. 2012).

4.5.2 Sedimentary Effects

The decrease in the magnitude of the tidal currents is predicted to be about 50% (Kadiri et al. 2012) caused by the decrease in the volume of water entering and leaving the system. The reduction of the current velocities both upstream and downstream the array is suggested to cause an increase in the sedimentation rates, leading to decreases in the suspended sediment. The concentration of suspended particles is likely to be reduced from the current conditions of 1200mg/l to 200mg/l (Ahmadian et al. 2009). Kadiri et al. (2012) also argued that locally, in the areas close to the turbines, the water velocities are expected to be high and hence there will not be a significant decrease in suspended sediments. Also, due to the decrease in the volume of water in the estuary, the tidal force on the seabed and the bed shear stress are likely to be reduced. The general decrease of the water velocities is predicted to have also an impact to the vertical mixing, which is likely to decrease and hence the sediment in resuspension will also decrease. But again, in the areas close to the turbines, the mixing is predicted to be enhanced. The combination of some of these effects could lead to change in the environmental parameters in the estuary, such as the increase in the light penetration in the water column (decrease in turbidity) due to the increase in the sedimentation rates and the decrease in the suspended sediment levels. In addition, it has been predicted to have up to 30% of intertidal loss caused by the reduction of the tide force (Kirby 2010). This could lead to the decrease in numbers of benthic invertebrates' community, but at the same time it is predicted that reduced turbidity would have positive consequences on the hard and soft bottom communities, causing an increase in the diversity of suspension-feeding invertebrates (Ahmadian et al. 2009).

The oxygen concentration is particularly a parameter predicted to be altered by the tidal range structures, being the reduction of mixing and flushing processes likely to decrease oxygen levels in the water. However the increase of the light penetration will promote photosynthesis, which will increase the concentration of oxygen in the water. The oxygen concentration could be consumed by the plants that developed it during night time, but being the salinity negatively correlated with oxygen solubility, possible reductions in salinity would enhance the capacity of the water to dissolve and retain oxygen. Kirby (2010) suggested that the combination of the increase in dissolved oxygen concentrations with the high degree of mixing from the flood tide may improve water quality substantially, benefiting particularly the fish population threatened by the low dissolved oxygen levels stated in the Chapter 4.3.2.

4.5.3 Pathogens

There is a reasonable concern about pathogens following the installation of the tidal energy systems that would also increase the residence time of these in the water column and prevent the nutrients in suspension to be flushed out to sea. These microorganisms are derived from sewage and industrial discharges, some of them move with water flow and some others need to be attached to suspended sediments. However the decrease in suspended sediment together with the increase of the sun light penetration with the development of tidal renewable schemes is predicted to decrease the bacteria levels and hence improve the water quality.

4.5.4 Migratory Species and Turbine Injuries

The Department of Energy and Climate Change (2010) suggested that almost all fish species in the Severn Estuary are likely to be negatively affected by the Severn tidal power scheme. Particularly migratory species such as lampreys and shads in addition to marine estuarine species which occur in the estuary regularly have traditionally been declined in population due to the construction of barriers (Henderson and Bird 2010). Only a little is known about the dynamics of migratory fish within the Estuary before moving to the sea or rivers; however it has been suggested that some particular species such as Atlantic salmon and twaite shad could become locally extinct as a consequence of the Severn Barrage.

The main and most significant problem to tackle from the Severn tidal power generation is the fish mortality when those animals pass across the turbines. A few studies found that some species of fish are able to pass through the turbines or sluice gates unharmed, and it is also verified that the proportion of deaths depended on fish species, size and efficiency of the turbine (Henderson and Bird 2010). Turnpenny et al. (2000) carried out a study with small, low-head Francis and Kaplan / propeller turbine designs, estimating pressure fluxes and shear stresses considering available data of salmonid responses to these two variables. It was obtained that shear stress is of relative relevance in small low-head turbines, being the pressure flux substantially more harmful. In addition, injuries related to the runner strike were three times more harmful than those ones related to hydraulic effects (shearing action, pressure effects and cavitation), being highly dependent on the size of the fish and type of turbine (diameter of the runner and number of blades). In addition, Henderson et al. (2010) adapted some data from the Sustainable Development Commission, (2007b), that relates the length of the body of some fishes with their injury rate, showing that adult salmon (1000 mm long) has a rate of injury of 40%; adult European eel (700 mm long), 28%; salmon smolt (150 mm long), 10% and juvenile shad (70 mm long), 53%. According to this data, excluding the juvenile shad, it could be interpreted that the longer the fish body, the larger is the injury rate. However, mortality has been observed for all sizes of fish, smaller fish have a smaller strike rate but a greater mortality rate because the pressure, shear and cavitation factors.

Regarding the tidal power generation turbines, Rulifson and Dadswell (1987) argued that if the barrage does not provide fish passage facilities, migratory fishes must pass through the barrage on flood tides through the sluicegates and freespinning turbines and will use the turbines to pass through the barrage on ebb tides during power generation. One of the possible solutions for passing fish successfully through tidal power installations suggested by Rulifson and Dadswell (1987) is placing gaps in the barrage to allow a percentage of water, and hence migratory adult fish, to pass through the barrage. This implies costs in terms of reduced capability of head of water for electricity generation. In addition, fish guidance methods such as diversion screens, light, bubble curtains or sound have given successful results in some cases. However the main difficulty is the incapacity of juveniles to respond properly in high velocity water conditions particularly occurring in large structures.

5. Habitat Suitability Data Obtaining and Analysis

In this section various parameters influencing fish habitat characteristics will be obtained and examined. Firstly the concept of Habitat Suitability Index will be defined. Subsequently two migrant fish species will be chosen and their suitable values of various environmental variables will be established. The aim of this is to obtain the relationship (curves) with the suitability for their habitat and the different variables and afterwards discuss from maps on the environmental variables how the Suitability Index values could be spatially distributed in the Severn Estuary. A survey undertaken between 1975 and 1977 based on the recording of salinity, temperature and fish species abundance data in 3 spatial locations in the Severn Estuary will be also considered.

5.1 HSI Definition

The Habitat Suitability Index is an indicator of favourable conditions for fish habitat which fluctuates from 0 to 1. This value is related to a range of the chosen environmental variables according to how adequate the range is for the growth, survival and reproduction of the species. Vinagre et al. (2006) related the values of the index with the use of habitat by fish, showed in the Table.5.1. The value of 1 was given to the most suitable conditions, SI of 0.5 was assigned to average favourable conditions, SI of 0.1 was assigned to the conditions where species could occur but occasionally and SI of 0 referred to environmental conditions outside of the range values where species can survive.

Table.5.1.*Definitions of suitability index values (reproduced from Vinagre et al. 2006)*

Suitability index value	Description of habitat use
1	High density or relative abundance in field studies; high growth potential; active preference in behavioural studies
0.5	Common occurrence on average density in field studies; average growth potential
0.1	Rare occurrence or low density in field studies; tolerance documented in field or laboratory studies; little growth potential
0	Little or no occurrence in field studies; mortality may occur in laboratory or field studies; active avoidance in behavioural studies

5.2 Fish Species Selection and Obtaining of Habitat Suitability Data

One of the aims of this project is to give an interpretation of how different scenarios within the Severn Estuary will affect the environmental conditions for the fish habitat. The scenarios that will be considered are mainly two; the Climate Change predictions on the estuary and the development of the marine renewable schemes (Severn Barrage). To carry out this analysis firstly it is required to obtain data on the habitat requisites of the chosen fish species. The chosen fish species should be preferably one of those most affected by alterations on the temperature and salinity, among other variables that will experience variations with the climate change, and also should be migrant species, requiring the estuary in some point of their life cycle. The fish species selected are the Dover sole (*Solea solea*) (MMD), since according to chapter 4.2.3, is one of the most sensitive species to changes in environmental variables (having already shown increases in abundance with rising temperatures). And the second species is the European eel (*Anguilla Anguilla)* since being a catadromous species reaches the estuary as larvae and uses it as a pathway to reach the freshwater. Therefore its habitat will be modified by the marine renewable schemes and also by the climate change.

5.2.1 The Dover Sole

The Dover sole as stated above, is a marine migrant estuarine dependent species (MMD) and one of the most valuable European flatfish in northern Europe. The sole spawning times occur normally during March and April on the Ireland coasts and southern England. From there the pelagic eggs and larvae are brought by currents to estuarine and inshore areas which are used as nursery grounds given their soft bottoms (Claridge and Potter 1986). According to Henderson and Bird (2010) the highest average number of individuals occupying the Severn Estuary occurs between August and September at Hinkley Point. Vinagre et al. (2006) undertook a study where the habitat quality of the Sole was mapped using the Habitat suitability index (HSI) models in the Tagus estuary (Portugal). Based on the habitat affinities of the sole the Table.5.2 was developed, where a range of values of temperature, salinity, depth and different types of sediments in addition to intertidal presence were assigned values between 0 and 1 of the Suitability Index.

Table.5.2. *Definitions of sole suitability index values for abiotic variables (Adapted from Vinagre et al. 2006)*

Environmental Variable	Suitability index value
Sediment	Mud or fine sand = 1
	Sand = 0.5
	Course sand and gravel = 0.1
Depth	D ≤ 10m =1
	10 <D < 14m = 0.5
	D ≥ 14m = 0.1
Temperature	24ºC > T ≥ 16 ºC = 1
	24ºC ≤ T ≤ 26ºC = 0.5
	11ºC ≤ T < 16ºC = 0.5
	26ºC < T ≤ 28ºC = 0.1
	T < 11ºC = 0.1
Salinity	10‰ ≤ S < 33‰ = 1
	7‰< S < 10‰ = 0.5
	S ≥ 33‰ = 0.5
	1‰ ≤ S ≤ 7‰ = 0.1
	S < 1‰ =0
Intertidal presence	Presence =1
	Absence =0

According to the Table.5.2 the preferred habitat for the sole consists in mud or fine sand as bed sediment, water depths up to 10 m, temperate waters (between 24 and 26 ºC and medium-high salinities (from 10 to 33‰).

5.2.2 The European Eel

The European eel is a common and one of the most predominant fish species of many estuaries and rivers in Europe and North Africa, however during the last decades it has declined in abundance mainly due to anthropogenic action such as overfishing, pollution or loss of habitat (Yokouchi et al. 2009). These fish migrate from the Sargasso Sea (central North Atlantic Ocean) by oceanic currents and metamorphose into transparent glass eels when they arrive to the continental shelf. Glass eels enter the Severn Estuary and use the tidal streams to reach the river (White and Knights, 1997). Having a relevant commercial value in Europe the life cycle of the eel is nevertheless not sufficiently understood to establish sustainable management policies (Laffaille et al. 2003). The habitat preferences of the eel change according to the size and age, which makes it difficult to predict the densities and habitat relationships. Laffaille et al. (2003) developed a study with the aim of predicting the spatial distribution of European eel in a small coastal catchment in Brittany (France). To analyse the eel distribution with the habitat characteristics, several parameters were measured such as the distance from the sea, water velocity, substratum granulometry, width, depth and aquatic vegetation. It was found that fish densities were highly dependent on three main parameters: distance from the sea, water depth and flow velocity, and the rest of variables contributed in much smaller proportion. In addition it was obtained that each size of eel showed different patterns of influence, which have been summarized in the Table 5.3.

Table.5.3. *Suitable ranges of different environmental variables, vegetation and substrate preferences for small medium and large eels and optimum ranges of temperature and oxygen concentration summarized from Laffaille et al. 2003 and ACFM (2003)*

Eel size	Distance from the sea	Vegetation Preferences	Substrate Preferences	Preferred depths	Flow velocity	Temperature	Oxygen concentration
<150mm	0 <D< 10km	Medium and high aquatic vegetation density and low riparian vegetation. Avoidance to strong riparian vegetation cover.	Avoidance of silt. Substrate composed by pebbles and boulders.	0-6m	v<0.2, optimum: 0.1-0.2m/s	Optimum: 20ºC < T < 26ºC Minimum: 10ºC, Maximum: 35ºC	Optimum: 5mg/l but able to tolerate up to 2mg/l at 15 ºC
150 < s < 300mm	0 <D< 10km but also up to 20km	Medium and high aquatic vegetation density and low riparian vegetation. Avoidance to strong riparian vegetation cover.	Avoidance of silt. Substrate composed by pebbles and boulders.	0-6m	v<0.2, optimum: 0.1-0.2m/s	Optimum: 20ºC < T < 26ºC Minimum: 10ºC, Maximum: 35ºC	Optimum: 5mg/l and at least should be 2.5mg/l at 21ºC
300 < s < 450mm	D > 10 km	Avoid strong riparian vegetation cover	Avoidance of silt. Substrate composed by sand, gravel, pebbles and boulders	D>6m	v > 0.2 m/s	Optimum: 20ºC < T < 26ºC Minimum: 10ºC, Maximum: 35ºC	Optimum: 5mg/l and at least should be 2.5mg/l at 21ºC
>450mm	D > 10 km	High riparian vegetation cover. Strong avoidance of small riparian vegetation cover	Substrate composed by sand, gravel, pebbles and boulders	D>6m (Very variable)	v > 0.2 m/s	Opt: 20ºC < T < 26ºC but able to tolerate temperatures between 0 and 39ºC	Optimum: 5mg/l and at least should be 2.5mg/l at 21ºC

According to the Table 5.3 small eels have lengths up to 300mm, from 300 to 450 are considered medium and from 450mm are large eels. Salinities were close to 0 in all catches. It was obtained that generally distance from the sea increased with increase of size. Eel distribution showed changes with depth, substratum composition and vegetation. Small eels occur predominantly in shallow habitats with high abundance of aquatic vegetation, while large eels have their highest presence in intermediate to high depth with low to intermediate abundance of aquatic vegetation. Therefore in general, eels migrate to deeper and unvegetated areas as they grow. According to the Advisory Committee on Fishery Management

(2003), the optimum temperature for growth in eel is between 20 and 26 ºC, (below 10ºC the growth stops) being large eels able to tolerate temperatures from 0 to 39ºC. Regarding the oxygen concentration, eels need at least 2.5 mg/l of oxygen at 21 ºC and glass eels can survive at 2mg/l of oxygen at 15ºC. The optimal oxygen concentration is considered to be 5mg/l.

5.3 Data on Fish Occurrence in Spatial Locations

Occurrence data on spatial points in the estuary is very useful since it is possible to deduce that the environmental conditions in these areas (known) match with their affinities. Data on environmental variables in different locations in the Severn Estuary in addition to fish abundance was mainly obtained from Potter et al. (1997) and Potter et al. (1986). The data obtained is based on the recovered numbers of fish species in the power stations of Oldbury, Hinkley Point and Berkeley (Fig. 5.1) from September 1975 to May 1977, (21 months in total) together with temperature and salinity.

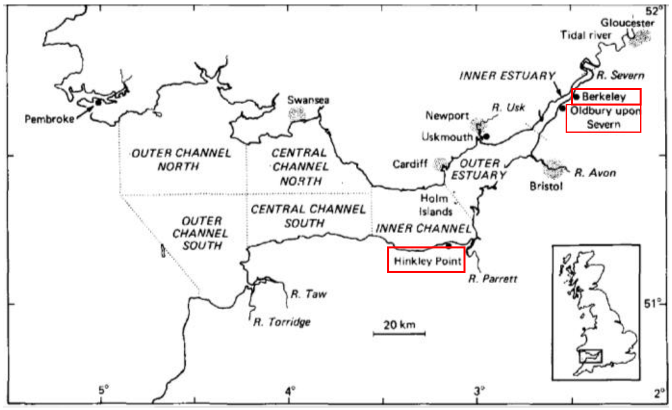

Fig.5.1. *Map showing the location of the power stations in the Severn Estuary. Reproduced from Claridge et al. (1986)*

Fig.5.2 shows the mean temperatures in the estuary during the 21 months and the salinity in the three power stations. The range of optimum salinity conditions of the sole is defined between 10 and 33‰ as stated above, and the only power station where this range is maintained in the whole survey period is Hinkley, this is entirely consistent with the fact that sole presented maximum abundance in this particular location (157 specimens) as showed in Table.5.4. At Oldbury, the sole was the 17th species recorded in the 21 months and hence is not in the list. The eel is present in the top 15 species recorded in all the power stations during the survey period but its occurrence at Berkeley is significantly higher than in the other two locations. Although it is not possible to know the size of the eels recovered at these points, according to their affinities, the high abundance at Berkeley could be related to medium eels (considerable distance to sea).

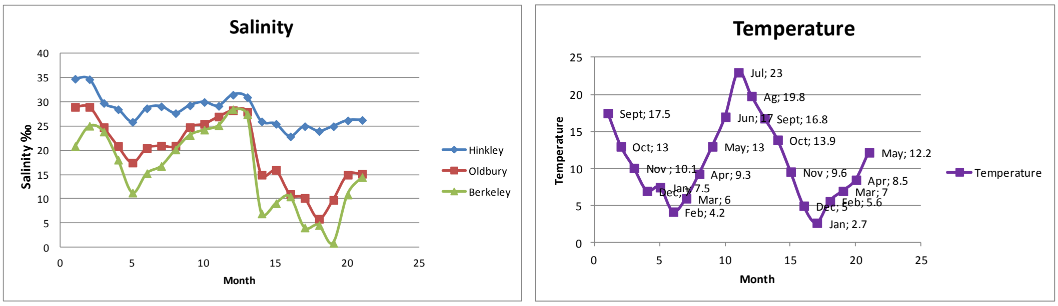

Fig.5.2. *Graph showing the salinities and temperatures recorded from September 1975 to May 1977.* (*Reproduced from Claridge et al. 1986)*

Table.5.4. *15 most abundant species at Oldbury, Berkeley and Hinkley power stations between September 1975 and May 1977. (D: diadromous, E: estuarine, F: freshwater, O: estuarine opportunists, S: marine straggler. Reproduced from Potter et al. (1997).*

Species	Category	Oldbury	%	Species	Category	Berkeley	%	Species	Category	Hinkley	%
Whiting	O	6393	34.7	Flounder	O	1360	23	Whiting	O	714	23.6
Sand goby complex	O	4148	22.5	Whiting	O	1340	22.7	Poor cod	O	362	12
Bass	O	2468	13.4	**European eel**	**D**	**1325**	**22.4**	Flounder	O	210	6.9
Flounder	O	1062	5.8	Thin-lipped grey mullet	O	284	4.8	Thin-lipped grey mullet	O	194	6.4
Thin-lipped grey mullet	O	863	4.7	Sand goby complex	O	243	4.1	Five-bearded rockling	O	188	6.2
Poor cod	O	714	3.9	Sea snail	O	188	3.2	Sea snail	O	170	5.6
Twaite shad	D	701	3.8	Twaite shad	D	145	2.5	Bib	O	165	5.5
Sea snail	O	554	3	Bass	O	137	2.3	**Sole**	**O**	**157**	**5.2**
European eel	**D**	**373**	**2**	Atlantic salmon	D	129	2.2	Bass	O	127	4.2
Herring	O	222	1.2	Poor cod	O	113	1.9	Twaite shad	D	96	3.2
River lamprey	D	132	0.7	Herring	O	85	1.4	Conger eel	S	91	3
Common goby	E	117	0.6	Northern rockling	O	64	1.1	Lumpsucker	S	74	2.4
Sprat	O	109	0.6	Sprat	O	61	1	Pollack	O	61	2
Three-spined stickleback	F	94	0.5	**Sole**	**O**	**58**	**1**	**European eel**	**D**	**46**	**1.5**
Bib	O	89	0.5	Norway Pout	S	48	0.8	Sprat	O	43	1.4

5.4 Data Analysis

5.4.1 Dover Sole

Working with the data obtained on the habitat requirements for the Dover sole, now it is possible to obtain the desired SI curves against various environmental variables. An *Excel* function able to plot the different values of SI that Vinagre et al. (2006) gave to the different ranges of each environmental variable has been designed (based on a conditional function) for each variable. The results derived from the SI function of each variable are shown in the Fig.5.3.

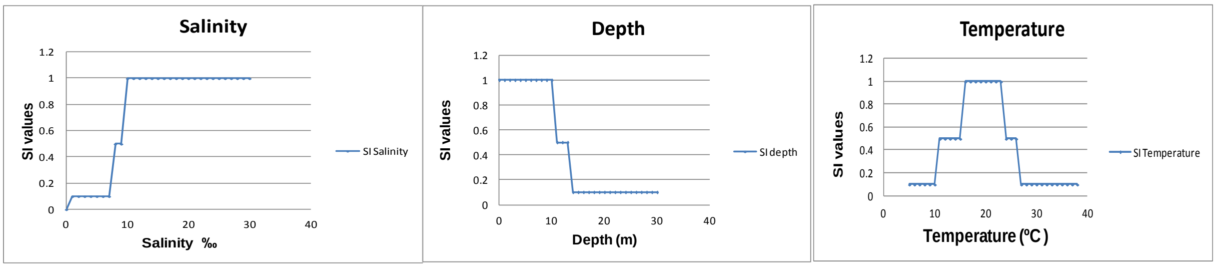

Fig.5.3. *Graphs showing the SI function for the Dover sole which takes values from 0 to 1 with changes in salinity, depth and temperature. Ranges of variables obtained from Vinagre et al. (2006), shown in Table.5.2.*

Fig.5.3 shows how the Suitability Index function takes different values, from 0.1 (unsuitable) to 1 (optimum suitability), with the variation of temperature, salinity and depth. Being a marine estuarine dependent species, the most suitable values of salinity for the sole are from 10 to 33‰ explaining its lower occurrence at Berkeley and Oldbury (Table.5.4). If the salinities are between 10 and 7 ‰, the habitat is still suitable, whereas for values lower than 1‰ the conditions are not suitable in any respect. Regarding the depth, the sole requires shallow habitats for optimum conditions, (i.e. between 0 and 10m) and up to 14 m of water depth the habitat is still reasonably suitable, however for depths higher than 14 m conditions are not adequate. With respect to temperature, the best conditions for the sole are between 16 and 24 ºC being also appropriate temperatures up to 26 ºC or between 11 and 16 ºC. For vales inferior to 11 ºC the habitat is not favourable.

5.4.2 European Eel

Likewise, the data obtained from the European eel habitat requirements specified in the Table.5.3 has been used to create the Suitability Index curves against various environmental variables by the design of *excel* functions that plot different values of SI for specific ranges of the variables. The graphs obtained for the five different variables are shown in the Fig.5.4. In this case the data found was not as precise as for the case of the Dover sole where the given numbers comprising each interval in the different variables were applied. With the eels the ranges of values of some variables are slightly more ambiguous and hence the SI function has been adapted from graphs published on the variables. For example in the case of the temperature, the optimum interval is from 20 to 26ºC (SI=1) and at 10ºC the eels stop their growth in the estuaries or rivers (SI=0). However it was not possible to obtain data on the values in between. Therefore in this case the values of SI 0.5 and 0.1 have been assumed in order to adjust the curve to the obtained information in addition to graphs supporting it. Hence it has been possible to design the desired curve (i.e. similar to SI-temperature curves published for eels).

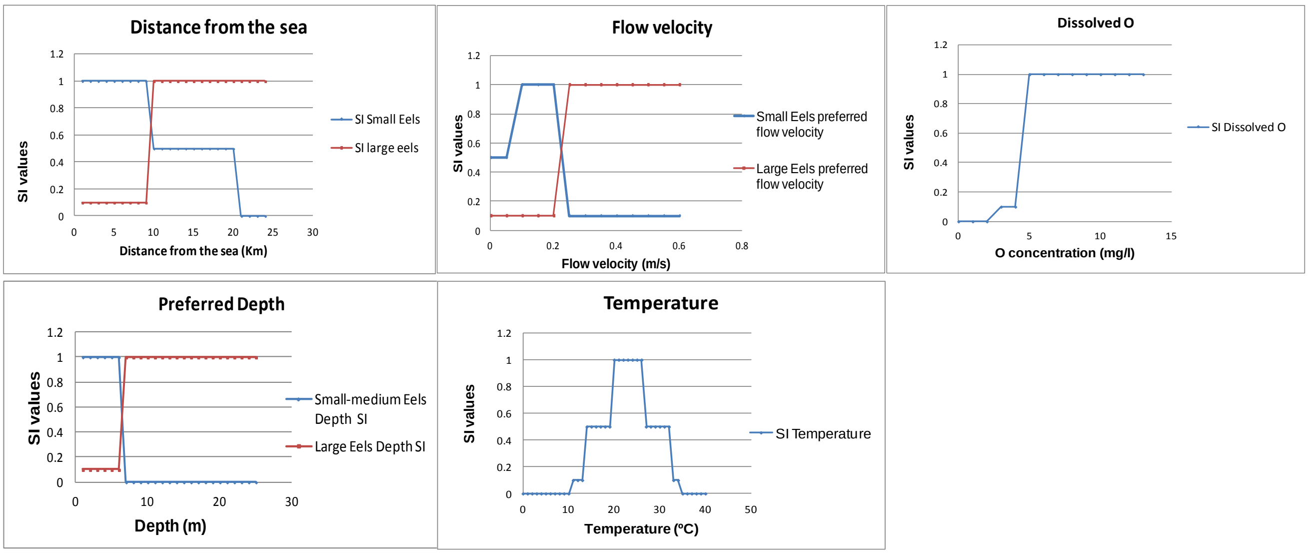

Fig.5.4. *Graphs showing the SI function for the European eel which takes values from 0 to 1 with changes in sea distance, flow velocity, depth, dissolved oxygen and temperature. Ranges of variables adapted from Laffaille et al. 2003 and ACFM (2003).*

Considering the distance from the sea, as noted above, different trends are followed for small and large eels, small eels occur up to 10 km from the sea, and hence their presence is higher in the estuaries than in the rivers, while large eels, as they grow and become robust, they are able to migrate up to the rivers increasing their distance from the sea. In the flow velocity preferences there are also differences between small and large eels. For small eels the optimum velocity is found between 0.1 and 0.2 m/s, being generally adequate from 0.2 m/s downwards. However for large eels the suitable flow velocities are higher than 0.2 m/s, and this is reasonable given that these fish change significantly their physical conditions when they grow and also considering their life cycle it is undoubted that they are able to bear with much higher flow velocities (since they are required to cross at least half Atlantic Ocean). The preferences for water depth are also different with the eel's life stages. Small and medium eels, which are predominantly the ones occupying the Estuary, need shallow waters, up to 6 meters of water depth, while large eels have a very variable range of depths preferably higher than 6 meters. The optimum temperature range for eel's growth is from 20 to 26 Cº being temperatures lower than 14 ºC certainly unsuitable, as well as higher than 30 ºC. The temperatures range can be considered to be the same for all sizes of eels. Likewise the temperature, the dissolved oxygen follows the same pattern for all the eel's life stages, being the optimum concentration about 5 mg of oxygen per litre of water. However, eels are able to live in lower oxygen concentrations, particularly the small ones, which can bear with up to 2 mg/l even though not being their ideal conditions.

6. Distribution of various Physical Variables in the Estuary

6.1 Introduction to the Model

Environmental variables distribution within the Severn Estuary will be obtained from published GIS data and also from maps predicted by the implementation of two numerical models created by the Cardiff University's Hydroenvionmental

Research Centre: the FASTER model (Flow and Solute Transport in Estuaries and Rivers) and the DIVAST model (Depth Integrated Velocities And Solute Transport). According to Falconer and Harpin (2005), The FASTER model is based on a 1-D algorithm that simulates hydrodynamic, solute and sediment transport systems. It consists in the solving of the Saint Venant equations. The DIVAST model consists in a 2-D algorithm obtained by solving the 3-D Reynolds Averaged Navier-Stokes equations (integrated over the depth and hence 2-D) involving the equations of mass and momentum together with the equation of solute transport. These equations are formulated by the finite differences method and solved by an Alternating Direction Implicit scheme. According to Ahmadian et al. (2011) this model also considers the effects of the bottom friction, wind shear and earth's rotation. The main hydraulics equations implemented are (1) and (2) for the x and the y direction respectively.

$$\frac{\partial \xi}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = 0 \tag{1}$$

$$\frac{\partial q_x}{\partial t} + \beta \left[\frac{\partial q_x}{\partial x} + \frac{\partial v q_y}{\partial y}\right] = f q_y - gH\frac{\partial \xi}{\partial x} + \frac{\tau_{xw}}{\rho} - \frac{\tau_{xb}}{\rho} + \varepsilon + \left[2\frac{\partial^2 q_x}{\partial x^2} + \frac{\partial^2 q_x}{\partial y^2} + \frac{\partial^2 q_y}{\partial x \partial y}\right] \tag{2}$$

Where ξ is the water surface elevation for a given datum (m), q_x and q_y are the discharges per unit width in each direction ($m^2 \cdot s^{-1}$), β is the momentum correction factor for non-uniform vertical velocity profile, H is the total water depth (m), f is the coriolis parameter ($rad \cdot s^{-1}$), τ_{xw} and τ_{xb} are respectively the surface and bed shear stress components in the x direction ($N \cdot m^{-2}$) and ε is the depth averaged eddy viscosity. Also the equation of advection-diffusion in 2-D was obtained by the integration of the 3-D equation over the depth and included in the model, so the resultant equation is:

$$\frac{\partial \varphi H}{\partial t} + \frac{\partial \varphi q_x}{\partial x} + \frac{\partial \varphi q_y}{\partial y} - \frac{\partial}{\partial x}\left[HD_{xx}\frac{\partial \phi}{\partial x} + HD_{xy}\frac{\partial \phi}{\partial y}\right] - \frac{\partial}{\partial y}\left[HD_{yx}\frac{\partial \phi}{\partial x} + HD_{yy}\frac{\partial \phi}{\partial y}\right] = H \sum \Phi \tag{3}$$

Where ϕ refers to the depth averaged concentration or temperature and $\sum \Phi$ is the total depth average concentration of the source.

Through these models it is possible to predict the distribution of the water depth and water flow velocity within the Severn Estuary among other aspects. These maps would be obtained from published articles and would be linked to the fish habitat requirements.

6.2 Data from Eco-Hydraulics Models

The distribution of flow velocity and water depth in the Severn Estuary is obtained through the hydraulics models noted above from Ahmadian (2010).

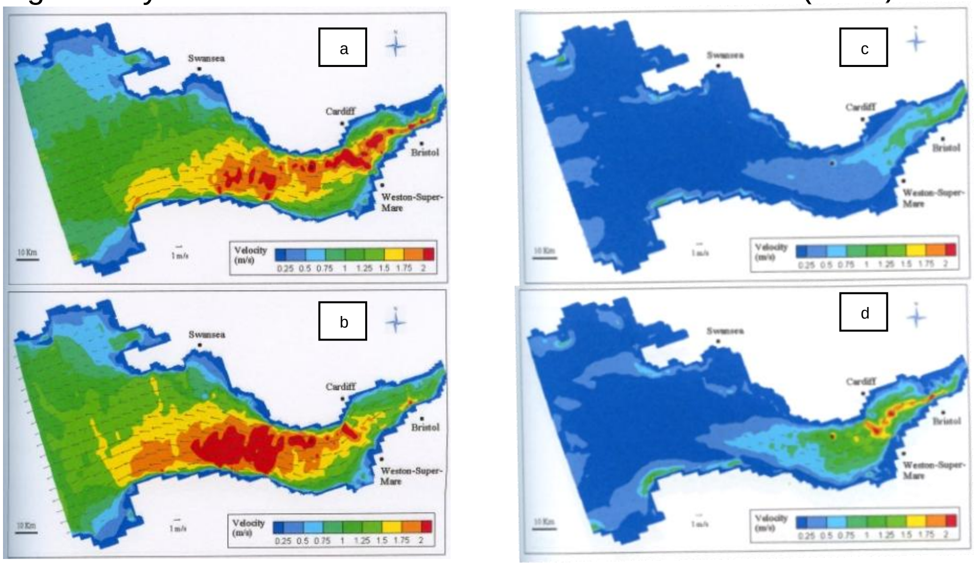

Fig.6.1. *Predicted velocities at mean flood-spring tide (a), mean ebb-spring tide (b), high water-spring tide (c) and low water-spring tide (d), Reproduced from Ahmadian (2010)*

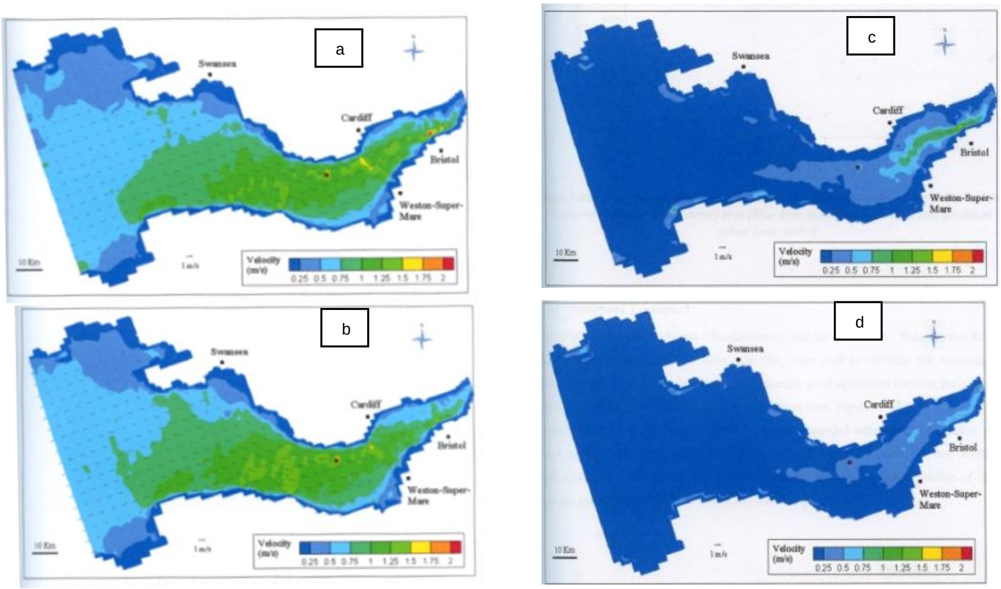

Fig.6.2. *Predicted velocities at mean flood-neap tide (a) and mean ebb-neap tide (b), high water-neap tide (c) and low water-neap tide (d) Reproduced from Ahmadian (2010)*

At Fig.6.1 and Fig.6.2 the velocity distribution in the different phases of the tide are shown. The highest velocities are produced in the central part of the estuary in the upper and lower reaches during the mean flood spring tide and majorly in the inner channel during the mean ebb spring tide; these velocities reach the value of 2 m/s. In the areas closer to the coast the velocity progressively decreases down to 0.25 m/s. During the high water spring tide, velocities between 0.25 and 0.5 m/s dominate the estuary and the channel, being the maximum values of 1.25 m/s. The conditions in the low water spring tide are similar but velocities reach punctually 2 m/s in the inner estuary. At the mean neap flood and ebb tide generally the velocity values are about 1.25 m/s with only a local excess of 1.75 m/s and up to 2 m/s in the inner estuary during the flood. For the high and low water mean neap tide conditions the values of flow velocity 0.25 dominate the channel and almost all the estuary, where the maximum values during the high water are around 1 m/s and 0.75 m/s during the low water conditions.

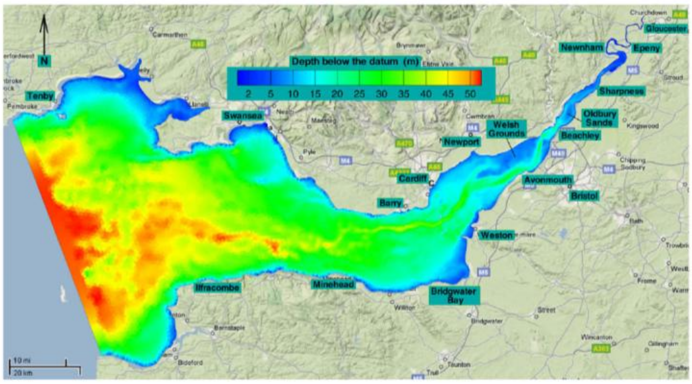

Fig.6.3. *Predicted bathymetry in the Bristol Channel and Severn Estuary. From Xia et al. (2010)*

Fig 6.3 shows the bathymetry of the Severn Estuary and the Bristol Channel. In the upper Severn and in the shores of the estuary the depths are majorly between 2 and 5 meters. In the lower Severn and upper reaches in the estuary the maximum water depths are around 15 and 20 m, being up to 30 m in the central part of the inner estuary. In the mouth of the estuary the depths reach locally 40 m, near the Welsh coast (Barry shore). In the inner channel the dominant water depths are about 30 m being progressively deeper with the decreasing distance to the sea; in the lower regions of the channel the water depths reach the 50 m.

6.3 GIS Data

Data on the bed sediment and the different seabed habitat types in the Severn Estuary is available through the Mapping European Seabed Habitats (MESH) site (online). The GIS data corresponding to the predictive EUNIS (European Nature Information System) habitats map for the MESH study area has been downloaded. This approach was developed considering relevant environmental variables to classify areas into different habitats. Working with these data through the ArcGIS software, a layout with the map integrating different types of habitat for the Severn Estuary has been created. This map provides relevant information that will be used to estimate the distribution of the HSI index, since both the sole and the eel have different bed sediment requirements which certainly restrict their distribution.

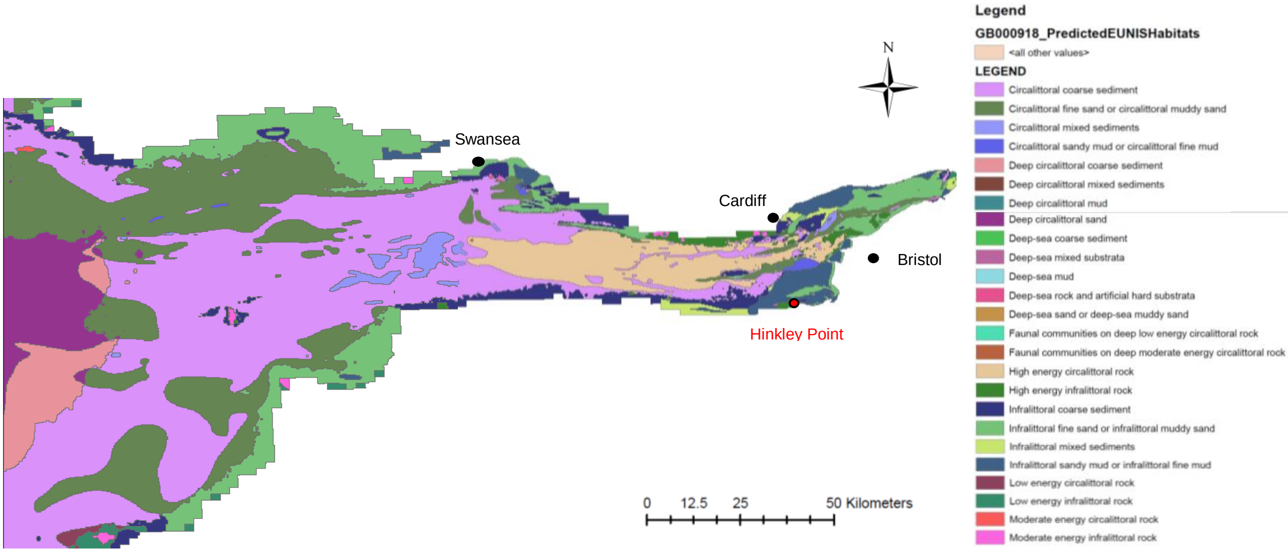

Fig.6.4. *Map of the predicted EUNIS habitat distribution in the Severn Estuary created through the GIS packages published at MESH site.*

In the Fig. 6.4 it could be appreciated that in the upper estuary, the predominant bed sediment is based on fine sand or muddy sand, and in the banks sandy mud or fine mud dominate. In the central part of the estuary high energy rock predominates being alternated in some areas with coarse sediment, and the zones near the shore are composed of a combination between mainly coarse sediment, high energy rock and fine sand or muddy sand. Locally there are accumulations of mixed sediments (in the English side) and moderate energy rock. The outer estuary is dominated by coarse sediment with punctual aggregations of mixed sediments. The two bays located in the estuary's mouth are mainly formed by fine sand or muddy sand.

Also, data from the minimum bottom temperature was used by MESH to develop the digital seabed map of the UK, and this is shown in the Fig.6.5.

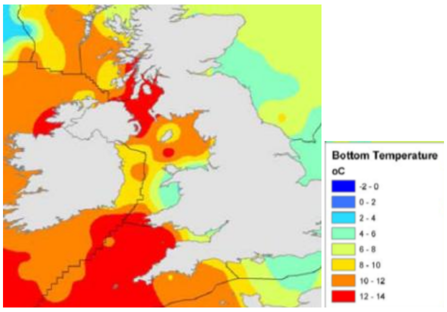

Fig.6.5. *Minimum bottom temperature (Joint Nature Conservation Committee, 2006)*

6.4 Discussion

6.4.1 Present Habitat Conditions in the Severn Estuary

The areas where there is the combination of all optimum values of the environmental variables for the fish species would have a HSI value equal to 1 and the habitat would be entirely ideal. Similarly, the areas where the conditions are overall favourable but not all the environmental variables have optimum values (i.e. the majority of them has optimum values but one or more are not ideal), would have a HSI equal to 0.5. These conditions have been examined for each fish species and digital maps have been created with the approximated habitat areas where the HSI values may be 1 and 0.5. This has been done by downloading a GIS map on the ArcGIS software with the boundaries of the estuary. To this map, the areas where the optimum values of each variable coincided have been mapped and added as a new layer corresponding to HSI = 1, as well as the areas where the majority of the variables was optimum (with some of them slightly different than the most suitable values), which have been assigned a HSI value of 0.5. This has been done for each fish species manually, for the reason that GIS data on all the physical variables of the estuary were not available. Hence, observing the three maps mentioned above, the areas where the maximum water flow velocities were tolerable (particularly for the small eel which has restrictions for the water velocity), the bed sediment and water depths were optimum, and the distance to the sea was adequate, have been identified and mapped for each species as areas of HSI values of 1 and 0.5.

With respect to the sole, the areas where the suitable conditions are fulfilled including shallow temperate waters, mud or muddy fine sand and high-moderate salinity ranges coincide typically in some of the bays located in the lower reaches of the estuary, being the salinity and the water temperature too low in the upper reaches. In Bridgwater Bay the optimum conditions are satisfied, including ranges of salinities between 35 and 22‰, fine sand and sandy mud as bed sediment and water depths between 2 and 10 m. This is consistent with the fact that the numbers of sole recovered in Bridgwater Bay were remarkable. Swansea bay fulfils the salinity and water temperature requirements partially satisfying the optimum bed sediment preferences, being the shores based on muddy sand and the central part of the bay formed by coarse sediment. However in the eastern region of Swansea bay, Port Talbot coast presents very suitable conditions of fine sediment, temperature and salinity for the sole (Fig.6.6). The inner Severn is mainly all formed by fine sediment and hence the suitability of these areas would depend on the temperature of the water and the salinity, which are mainly dependent on the river discharge.

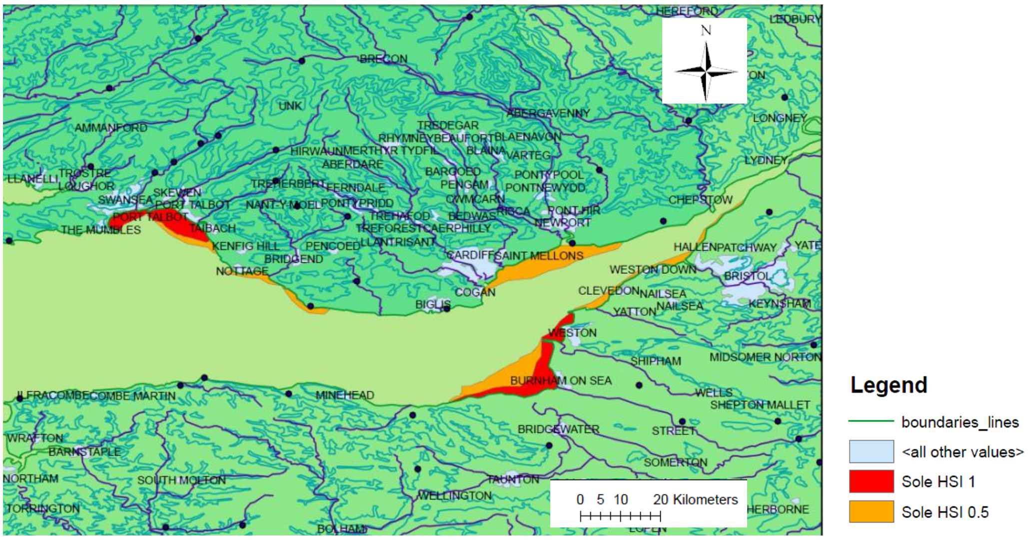

Fig.6.6. *Map showing an approximation of the Habitat Suitability Index distribution values 0.5 and 1 for the sole obtained from the locations where the optimum values of the variables coincided.*

Concerning the eel's habitat, small eel's most favourable areas would be where coarse sediment coincides with low flow velocities, small distances to the sea and ideally warm shallow waters, and this is satisfied in the coast of Porthcawl where the Ogmore (Brigend river) discharges and following the coast eastwards. In this area, as well as in the English coast of the inner channel, the shallow waters located between 10 and 30 kilometres to the sea (therefore also warmer waters), formed by coarse sediment and rather constant velocities around 0.2 m/s create also a suitable habitat for small eels. Another favourable area for small eels would be that located in the central part of Swansea bay, formed by coarse sediment (Fig. 6.7).

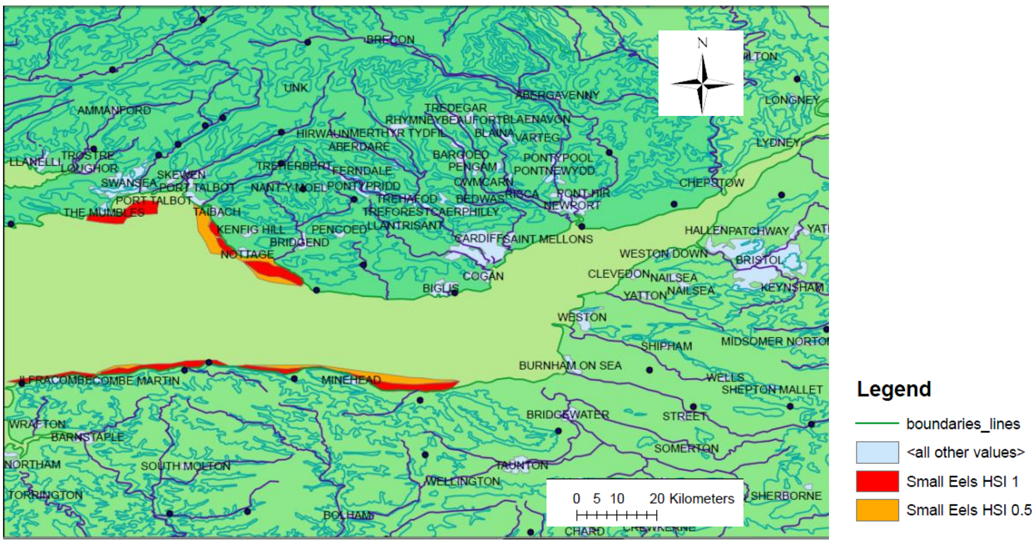

Fig.6.7. *Map showing an approximation of the Habitat Suitability Index distribution values 0.5 and 1 for small eels obtained from the locations where the optimum values of the variables coincided.*

By contrast, large eels' ideal habitat is based on sand and coarse materials as substrate, distances from sea larger than 10 km, water depths higher than 6 m and water flow velocities higher than 0.2 m/s, being generally warmer waters also beneficial but not essential. These conditions are particularly satisfied in the regions between the central areas and the shores, where the substrate is composed by coarse sediment of the estuary, particularly between Bridgwater Bay and Minehead, where the depths are around 15 and 30 m, the mean water flow velocities are around 1 and 1.25 m/s, the distance from the sea is greater than 20 kilometres and the bed sediment is based on coarse materials. Also, another favourable area is identified in the upper reaches of the estuary (Fig.6.8). However the eels as they grow, progressively move up to the rivers, and being also large eels' tolerance ranges wider than these of small eels, the distribution of large eels is more uncertain.

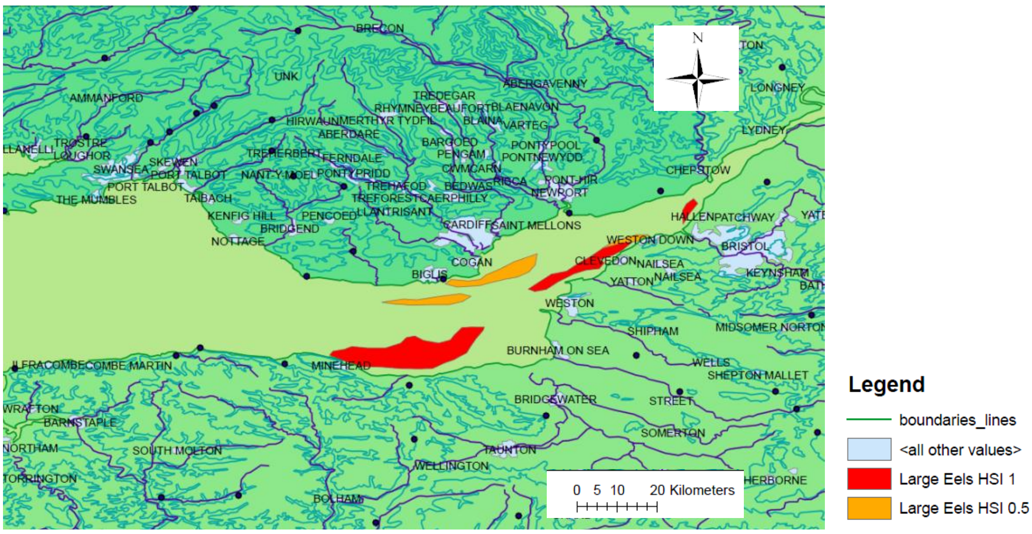

Fig.6.8. *Map showing an approximation of the Habitat Suitability Index distribution values 0.5 and 1 for large eels obtained from the locations where the optimum values of the variables coincided.*

6.4.2 Predicted Habitat Conditions for the Severn Barrage

As noted above in the Chapter 4.3, the development of the Severn Barrage is predicted to have some effects on the physical properties of the estuary. Some of the most important changes predicted affecting the habitat of the two fish species analyzed together with some other relevant considerations made by Kadiri et al. (2012) and Ahmadian et al. (2009) could be summarized as follows:

- Significant decrease in water velocity as shown in Fig.6.9, (reduction of about 50% of the tidal currents) causing an increase of the sedimentation rates.
- Decrease in turbidity will lead to increasing sunlight penetration and overall increase of oxygen dissolved levels.
- Possible, although rather uncertain, decrease in salinity upstream the barrage.
- Reduction in water peak elevations (both upstream and downstream) decreasing up to 2 m upstream, together with a significant increase in low tide levels (Ahmadian et al. 2009)

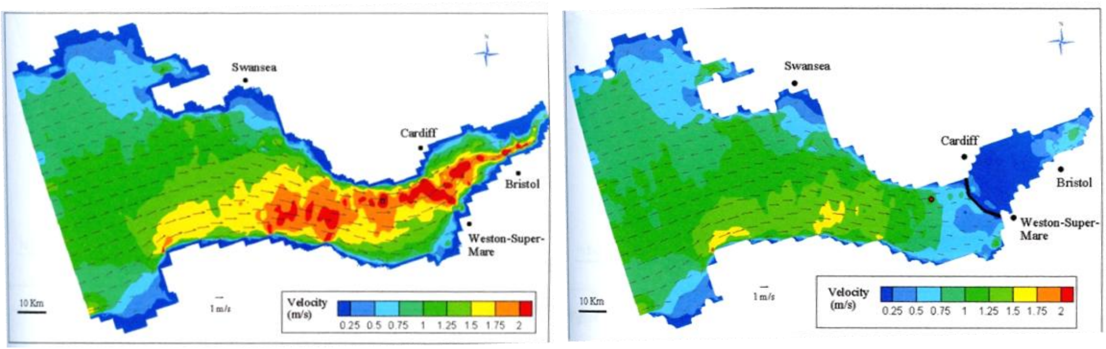

Fig.6.9. *Predicted tidal currents across the estuary at mean flood spring tide, without the barrage, (left) and with the barrage (right). Reproduced from Ahmadian (2010)*

From the above summarized data it is possible to make some relevant considerations about the habitat for the sole and the eel.

Regarding the sole requirements, firstly in respect to the decline in the water velocity, according to the reviewed studies, it is not a particular variable taken into account when examining the sole's habitat; therefore in this case it will not be contemplated. In consideration to the increase in the oxygen levels it undoubtedly would be beneficial for the sole's habitat (as well as for the majority of the fish species), being the Severn Estuary currently remarkably poor in oxygen levels. If there is a reduction in the salinity levels it certainly would not be positive to the sole's habitat, being a marine dependent species its most suitable salinities are between 10 and 33‰. Also being its occurrence currently lower at Oldbury and Berkeley, if salinities further decrease upstream the barrage, it would not be an adequate environment for the sole. Regarding the reduction in the water levels, it recognisably may have a positive impact to the sole's habitat, being its preferred depths lower than 10 m. This parameter would widen the area of the sole habitat where HSI = 1, since water depth is a significant limitation in areas where the suitable salinities and sediment for the sole are given.

Concerning the small eel habitat, the decrease in the water velocities will certainly have a positive impact to their environmental conditions, being particularly beneficial to small and medium eels. From Fig.6.9 it could be observed that upstream the barrage the flow velocities about 0.2 m/s dominate the estuary, being the maximum values about 1.25 m/s. These values are remarkably suitable, since the preferred values for small eels are about 0.2 m/s. Downstream the barrage, where a large proportion of the small eels concentrate, the minimum velocities in their habitat areas would remain rather constant. In relation to the increase in the oxygen levels, this would also be positive for the eels. Although the exact increase in oxygen levels is uncertain, any increase in the oxygen levels would be notably favourable and especially considering that eels have minimum requirements on dissolved oxygen (about 2.5 mg/l). The possible decrease in salinity would not be a decisive fact for the eel in particular, since being a catadromous species has the ability to change its physiology when moving between waters with different salinities. Finally the reduction in water elevations would generally have positive consequences on small and medium eels, being their preferred depths between 0 and 6 m, and hence their suitable habitat conditions could be further extended. Large eels have a very variable range of preferred depths; these are mostly higher than 6m. Therefore if the water elevations decrease it will not be particularly positive for them; however it will not present a relevant change to their habitat.

6.4.3 Predicted Habitat Conditions for the Climate Change

Very little information is published on the climate change effects in estuaries for the reason that precise changes on the environmental variables are still quite uncertain. However the combination of changes in various environmental variables is thought to have adverse overall consequences. Regarding the changes in the water depth, as noted in the section 4.3.1, the mean sea level is found to be rising and in the estuary this is about 5 mm per year. The sea level rise apart from causing habitat losses would have detrimental effects on both the small eel and the sole, being shallow waters particularly suitable for both species. In addition, the consequences of the climate change in the Severn Estuary fish fauna have already been evident as noted in the section 4.1.2. Fish species richness and abundance experienced an increment with the increase of temperature and decreasing salinity, and this explains the fact that the sole increased in numbers in the Severn Estuary during the last decades. According to Henderson and Bird (2010) from data between 1981 and 2008 at Hinkley Point, the sole followed an increasing trend related to the rising water temperature (Fig.6.10)

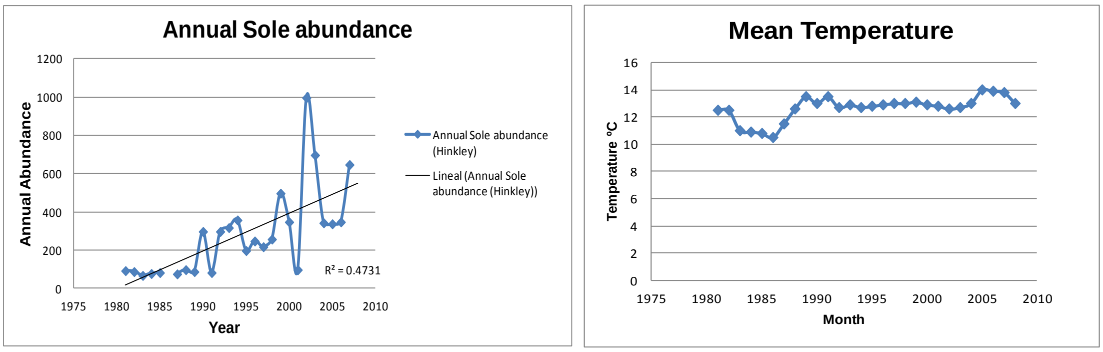

Fig.6.10. *Variation in the total number of sole caught per year at Hinkley point (Bridgwater Bay) and the temperatures recorded each year. (Reproduced from Henderson and Bird 2010)*

Considering the sole habitat requirements, its most favourable range of temperatures is found to be between 16 and 24 ºC and hence if temperature increases a few degrees in the estuary, being the minimum temperatures about 6 ºC and the maximum exceeding 20 ºC, the environment will be more suitable for the sole as it has been shown for the last decades. However, decreases in salinity (due to increased rains and hence river discharge) are in fact unfavourable for this particular species. Therefore even though the sole increased with increasing temperature and decreasing salinity, if salinity further decreases the conditions may become unfavourable for this species and its response would be likely to become the opposite. In regard to the eel, the temperatures for its optimum growth are between 20 and 26 ºC, and hence an increase would also have positive consequences to its habitat. For the eels small changes in salinity are not predicted to represent major changes in their habitat conditions.

7. Conclusions

7.1 Estuary Associated Fish

This report has shown the high complexity of the estuarine associated fish dynamics in different levels such as their ecological guilds and the extensive and rather ambiguous factors influencing the different stages of their life cycle such as their migrations, spawning times or recruitment processes. Fish communities within estuaries are majorly influenced by physical factors, conditioning fish life processes according to their tolerances and affinities. Two major factors have particular relevance in fish assemblages, and these are water temperature and salinity. In addition to these some other factors such as predation and hydrodynamics are found to be particularly important for the recruitment processes success. However the factors influencing seasonal variations in fish communities' composition and abundance are still considerably uncertain.

7.2 Current Fish Habitat in the Severn Estuary

The Severn Estuary with its extraordinary tidal range has been described as a high energy system with vertically mixed temperature and salinity profiles. The high level of turbulence also restricts the system to specific fauna and leads to reduced biodiversity in addition to the presence of some barren areas. The sunlight penetration in the high turbidity phase is inexistent, causing threatening low levels of dissolved oxygen for the fish communities and other organisms. However, the relevance of the estuary as a nursery area for many fish species has also been specified, being a remarkably rich system in composition with around 110 species identified in its waters. The fish community in the Severn Estuary is found to be under continuous changes, increasing in richness by a new species every two years. The variations in the species seasonal movements of this community are regular, strongly sensitive to various environmental variables, and hence significantly predictable. However correlations between recruitment patterns and physical factors cannot be established.

7.3 Habitat Affinities of the Dover Sole and the European Eel

This document has provided various sorts of information on the environmental variables through different means. Firstly from literature review the ranges of suitable values of different environmental variables for the two selected fish species have been obtained. Secondly, the Suitability Index functions for each variable have been designed and adjusted through the Microsoft Office *excel* program. Subsequently, spatial values of the salinity in different locations in the Severn Estuary have been obtained from a long term study. Distribution of the bed sediment in the Severn Estuary and Bristol Channel has been obtained by downloading data on the ArcGIS software and creating a layout map. In addition, data on the water flow velocity and bathymetry has also been acquired from published articles that predicted these maps through the implementation of eco-hydraulics models. Finally the information on the physical conditions in the Severn Estuary and Bristol Channel obtained has been linked to the sole and the eel requirements and hence an estimation of the arrangement of the HSI values 0.5 and 1 has been created.

In summary, the ideal habitat conditions for the Dover sole consist in water depths lower than 10, temperatures between 24 and 16 ºC, salinities between 10 and 33 ‰ and mud or fine sand as bed sediment, (being flow velocity usually not considered for the sole habitat). These conditions are fulfilled in different degrees in some areas according to the distribution of various variables within the estuary. The conclusion is that the optimum suitability areas in the Severn Estuary for the sole are muddy bays and shores with proximity to the sea such as Bridgwater Bay and Port Talbot shore.

The distribution of the European eel has been approximated in the same way as for the sole. Small eels' ideal conditions are based on distance from the sea smaller than 10 km, gravel and other coarse material as bed sediment, water depths lower than 6 m, flow velocities between 0.1 and 0.2 m/s and temperatures between 20 and 26 ºC. These conditions are satisfied in gravely bays and shores, with low distance to the sea, such as Swansea bay or the gravely English shore of the Bristol Channel. By contrast large eels need distances higher than 10 km from the sea, majorly coarse sediment and sand, without avoidance to fine particles as bed sediment, water depths higher than 6 m and velocities higher than 0.2 m/s, for the same range of ideal temperatures as small eels but with wider tolerances. Therefore it could be concluded that large eels' occurrence may be higher in deep gravely high velocity areas such as the central west region of the mouth of the estuary and the gravely upper reaches. However, medium-large eels are highly adaptable to different conditions and therefore their distribution is significantly more uncertain.

7.4 Current Habitat for the Sole and the Eel and Future Changes

It has been shown that the ecosystem of the Severn Estuary has experienced significant improvements particularly during the last decades with substantial ameliorations in the water quality leading to increases in numbers of many fish species. Nevertheless it has been evidenced that either the barrage or the climate change will lead to significant losses of habitat.

The changes that the barrage would induce on the fish habitat conditions could be summarized as the decrease in water flow velocity, that will be particularly suitable for small eels; the decrease of water depths, that will create more favourable conditions for the sole and small eels; increase in oxygen dissolved levels, which will benefit generally all the fish species, and possible decreases in salinity that will not be favourable for the sole but will not represent major negative effects to eels habitat. These conditions are overall positive, however the salinity and temperature profiles will be modified and this would induce changes in the distribution of the species. Moreover only a little is known about the turbine associated injuries which is one of the most relevant matters regarding the interference of the marine renewable schemes on the fish habitat, in addition to the feasible systems for fish to pass through the structure. These aspects are fairly uncertain and therefore also need further consideration.

The climate change involves changes in a wide scope of aspects such as atmospheric science, physiology and ecology. The effects of these changes in estuaries are thought to have particularly negative consequences, being some of the species living currently on the limits of their tolerance ranges. Some of the most certain changes predicted for the Severn Estuary are the increase of the water levels which would cause the loss of significant areas of habitat, in addition to the increase in the water temperature and decrease in salinity. The increase of the water temperature will be beneficial for some species, as it has been reflected with the increase in the numbers of various marine species including the sole during the last decades. However some others such as the sea snail have preferences for colder temperatures and hence this increase in temperatures would have a negative impact to their habitat. In addition the combination of rising temperatures with the decline in salinity will not be beneficial for the marine species in the estuary such as the sole. The increase in the water depth would not be favourable for the sole and neither for the small eels, but will not have negative effects on the large eels' habitat. Therefore the combined effects of changes in various environmental variables is not predicted to have overall favourable consequences on the habitat of the analysed species.

7.5 Suggestions for Further Research

The present report provides a reasonable literature review that may be valuable for the creation of an eco-hydraulics model linking habitat requirements for the Severn Estuary. Recognizably further developing should be based on the integration of the data obtained on the fish HSI to a hydraulics model and obtaining of the spatial distribution of this index in the Severn Estuary in an accurate prediction. To design this type of simulation it is required to modify the codes of the existing hydraulics models by introducing data on the fish habitat suitability, requiring reasonable knowledge of the modelling software. This was implemented by Bockelmann-Evans et al. (2004) in a river restoration study, where the DIVAST model was linked with the macroinvertebrate suitability conditions and hence habitat simulations could be made. Habitat suitability index modelling (HSI) is such a worth tool in ecology which provides useful data for making decisions related to environmental matters (Vinagre et al. 2006). Spatial modelling of the suitability of fish species habitat, and particularly for the sole, has been applied in various studies for different purposes, for example with the aim of monitoring and determining suitable spawning areas (Eastwood et al. 2001) or for the prediction of suitable nursery areas for juveniles (Vinagre et al. 2006), (Maxwell et al. 2009).

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