CONTENTS

1 DRIVERS

This theme considers the physical processes responsible for sea-level change on the Severn Estuary. Drivers are divided into climatic and non-climatic factors that influence sea level on short and long timescales. They combine to determine the frequency and magnitude of extreme water levels.

a) Slow and incremental change

The impacts of sea-level change may be slow and incremental, for example through gradual erosion of salt marsh by 'average' sea conditions, or by **event-driven change**.

b) Event-driven change

The impacts of sea-level change may be event-driven or 'catastrophic', for example flood inundation by short-term extreme water levels caused by storm **surges** or **tsunamis**. **Slow and incremental change** may also occur.

1.1 Climatic drivers

a) Natural cycles and variability

A number of natural factors alter the radiative balance of our planet, which in turn causes the climate to change. These include influences that occur on Earth (**internal forcings**) and those that are external to it (**external forcings**). Natural cycles and variability cause SLC on short timescales (for example the **frequency & intensity of storms**), medium timescales (e.g. the **NAO** and El Nino Southern Oscillation [1]) and long timescales (e.g. **glacio-eustacy: large ice sheets**). They also force local sea levels indirectly, by influencing **geology**.

b) External forcings

The Earth's climate naturally varies according to the amount of radiation emitted from the sun (solar variation) and changes in the Earth's axis and orbit around the sun (Milankovitch Cycles)[1].

c) Internal forcings

The Earth's climate naturally varies according to atmospheric factors (e.g. changes in gas concentrations in the atmosphere), oceanographic factors (e.g. changes in ocean currents) and terrestrial factors (e.g. volcanism, orogeny[2] and changes in albedo[3]) [2].

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[1] Milakovitch cycles are orbital changes that drive ice age cycles: obliquity (Earth's axial tilt), precession (Earth's wobble on its axis) and eccentricity (shape of Earth's orbit around the sun).

[2] Orogeny is mountain building

[3] Reflectivity of the Earth's surface

d) NAO (North Atlantic Oscillation)

The North Atlantic Oscillation (NAO) describes fluctuations in the atmospheric pressure difference at sea level between the Azores high and the Icelandic low pressure systems. It controls the strength and direction of winds and storm tracks over the North Atlantic, and therefore has a large impact upon the weather over the British Isles. The NAO has two phases; positive and negative. In positive NAO winters the UK experiences wetter, stormier conditions. Negative NAO winters are calmer, drier and cooler. The two stormiest periods for which there are reliable records (1920s and 1990s) coincide with a sustained positive NAO index, while the calmest decade (1960s) experienced the most negative NAO [3-5]. Wave heights are particularly sensitive to the NAO on western coasts of the UK [6].

The NAO has been found to correlate with windiness, **waves**, **surges** mean sea level [6-11], and coastal **morphological change** as a function of these [12, 13]. Future changes in the NAO will be important, and may systematically affect **storm typology and track** on the Estuary [Harry]. However, there has been little overall observed trend in the NAO over the last 50 years [3], and future changes to the NAO in response to **ACC** are uncertain [6, 8, 14]. As the climate warms, sea level pressure is projected to increase over mid-latitudes and decrease over high latitudes, and many models project a positive trend in the NAO index as a result [15, 16]. The situation is complex though, and this could cause a poleward shift of storm tracks, leading to *fewer* storms in mid-latitude regions [15]. There is little consensus at present.

e) ACC (anthropogenic climate change)

Anthropogenic climate change (ACC) describes the secular change in the Earth's average atmospheric and surface temperature due to human activities, principally **greenhouse gas emissions**. The rate and extent of future ACC is unknown. However, a mean warming of around 1.3^{o}C above pre-industrial levels is estimated from the combustion of fossil fuels by existing infrastructure alone between 2010 and 2060 [17], so warming can be expected to exceed this as world population and energy use increase. It is increasingly recognised that global temperatures may rise by as much as 4^{o}C by 2100 [18, 19].

As the world continues to warm, mean global SLR is inevitable [20] through **thermosteric SLC**, **glacio-eustacy** and **changes in atmospheric surface pressure and ocean circulation.**

ACC feeds into the influence diagram in a number of ways in addition to causing SLR. Notably, ACC may change weathering processes, **precipitation**, temperature and **storms** [21], which will together affect *relative* sea level. It also contributes to **socio-economic vulnerability** [22] and **physical vulnerability**.

1.2 Non-climatic drivers

a) Planetary forcings: lunar cycles

Tides are the main cause of day-to-day changes in sea level on the Severn Estuary. Although tides can be predicted many years into the future [23], they are not constant: tidal heights vary significantly from year to year due to the way in which the Moon orbits the earth (the 18.61 year lunar nodal cycle and the 8.85 year lunar perigee cycle) [24]. In estuaries with large tidal ranges such as the Severn, the tidal range changes by an order of magnitude greater than the rate of mean SLR [Frank].

b) Geology

Over geological timescales, sea levels are determined by the ways in which plate tectonics configure the earth's crust. Local earthquakes can cause particularly dramatic SLC on short timescales. However, whilst moderate earthquakes (around 5M_L[4]) are 'relatively common' in South Wales [25], the intraplate tectonic setting of the UK means that it is not vulnerable to very large local earthquakes (a maximum earthquake for the UK is postulated to be 6.2 M_L [26]). The estuary is vulnerable to (relatively small) **tsunamis** generated by greater magnitude geological events occurring far from the Estuary, for example aerial and submarine landslides, and undersea earthquakes [27]. The Severn Estuary is also affected by **isostatic subsidence** [28], which significantly contributes to mean SLR over long timescales. Sea levels also fluctuate due to **sediment compaction** [20], and through the long term evolution of the Severn Estuary's geomorphology.

1.3 Greenhouse gas emissions

Concentrations of greenhouses gases in the atmosphere are increasing, primarily through the burning of fossil fuels such as coal and gas [29]. This is decreasing the amount of thermal radiation that can escape into space and is leading to **anthropogenic climate change (ACC).**

1.4 Extreme sea levels

The coast of the Severn Estuary will be most acutely affected not through *mean* SLR but through the frequency and amplitude of *extreme* sea levels, which are a function of local short-term changes combined with longer term trends. Local sea levels show much more variation than global mean sea levels because although the volume of water in the oceans is nearly constant, its distribution is not [30].

The study of extreme sea levels also has larger uncertainties than the uncertainties involved in understanding and predicting global sea level [31], and although mean sea levels are rising, there is some debate between experts [Claire, Harry] over whether *extreme* sea levels are actually increasing on the Severn Estuary and how they will change in future. Data from four sites in the Bristol Channel and Severn Estuary showed a trend of *decreasing* maximum sea levels and *increasing* minimum levels from 1993-2007 [9]. However, due to the additive nature of sea-level, even if there are no changes in extreme events such as surges and waves, increased MSL will result in more frequent extreme high waters and flooding unless the incidence of such events substantially *decreases* [32, 33]. Thus, the main agent of future changes in extreme levels is projected to be rising sea levels rather than changes to **waves** and **surges** [34].

The frequency and magnitude of extreme sea levels determine impacts at the coast. Extreme water levels can be defined as infrequent occurrences 'at the high and low end of the range of values of a particular variable' [15]. By their very nature, they are uncommon and are therefore difficult to predict. Furthermore, many are the result of a number of combined factors or **concurrent events**, so linking an event to a single, specific cause is problematic [15].

[4] Local magnitude on the Richter Scale.

a) Concurrent events

Extreme sea levels are sometimes caused by one factor alone (e.g. **tsunamis**), but on the Severn Estuary tend to be most acute when they are the product of concurrent events. This means that joint probabilities (the probability that two or more events will occur at the same time) are important. Some events tend to occur together; for example the risk of flooding is increased when extreme **surges** coincide with high river flow, both of which can result from the passing of a mid-latitude cyclone [35]. Likewise, spring tides are largest in spring and autumn, which are often stormy periods. However, some events actually suppress others (e.g. large surges rarely occur close to high tide [36]). Extreme sea levels on the Severn Estuary currently have long return periods on account of the number of factors that need to combine to produce very high water levels [Andrew], but these return periods are expected to decrease as mean sea levels rise.

1.4.1 Long term sea level variability & trends

Long timescale SLC happens on global, regional and local levels, and impacts are a response to both relative (local) SLC and eustatic (global) SLC [31]. The Severn Estuary has a history of long-term sea level variability, which continues today. Records show that average sea level on the Estuary is gradually rising [37], and has been throughout the Holocene[5], with fluctuations superimposed onto this upward trend [38]. Sea levels are expected to continue to rise throughout the coming centuries. The factors contributing to long term mean SLR are outlined in this section.

a) Halosteric SLC

Halosteric SLC is caused by changes in the volume of water due to its salt content. Its contribution to overall global SLC is only about 1% of the total SLR budget, but on a regional level halosteric contributions can be as important as thermosteric contributions. I am not aware of any work that has assessed current or future halosteric contributions to SLC on the Severn Estuary.

b) Isostatic subsidence

Uplift and subsidence describe increased or decreased elevation of the land. They can be natural or human-induced, slow or fast [20], and future trends are likely to depend on socio-economic scenarios; for example human induced subsidence is more likely under some population/emission scenarios than others [20].

The Severn Estuary has experienced substantial subsidence due to glacial isostatic adjustment (GIA) [28]. GIA occurs as the Earth's crust rebounds when large masses of ice are removed and water is redistributed in the ocean basins [39], and has caused a complex pattern of subsidence and uplift across the UK since the last glacial [40]. During the past four thousand years, GIA has caused the inner Bristol Channel/Severn Estuary shoreline to subside at an estimated rate of around 0.76mm/yr [28], a trend that is expected to continue over the next 100 years [41]. For its draft management policies, the Severn Estuary SMP2 assumes a current vertical land movement of -0.5mm/yr [41].

When compared to future climate-induced changes in sea level, changes due to subsidence are probably not a big factor on the Severn [Jack]. On long timescales, it is a different matter. For example, by the year 3000, London (which is sinking faster than the Severn) is projected to sink by around 2m regardless of climate change [42].

[5] The Holocene is the current interglacial period; the geological epoch that began around 11,700 years ago and continues today.

c) Changes in hydrological cycle

Global sea levels can be modified by changes in the hydrological cycle (e.g. groundwater depletion or impoundment of water in reservoirs) [20], but its contribution is small or compensated for by other contributions [20]. On a local scale however, changes in the hydrological cycle can have significant impacts on relative sea levels. For example, river run-off can cause sea level fluctuations and may contribute to UK SLC in sheltered systems such as estuaries [43].

d) Thermosteric SLC

Thermosteric SLC (or thermal expansion) is caused by the change in water volume due to temperature change[6]. The process is still happening in response to the last ice age and represents a 'commitment to SLR' [44]. Thermosteric SLR is the dominant contribution to modelled sea-level change for future scenarios (with ice melt a close second) [20], although this is in part due to gaps in knowledge regarding ice-sheet dynamics.

e) Sediment compaction

Sea levels can be affected by the amount of sediment being supplied to an area and the degree to which the sediment is reduced in volume as it is compacted over time. It is typical of Holocene sequences on North European coasts [45] and is probably causing localised subsidence in parts of the Severn Estuary [46]. Research suggests that sediment compaction in large estuarine systems in the southwest of the UK can occur on the order of 0.7mm to 1.0mm per year [47], but rates for the Severn Estuary are unknown.

f) Changes in Geoid

Changes in the Geoid (the Earth's gravitational field mapped over its surface) affect the regional distribution of relative sea level. The large ice sheets of Greenland and Antarctica have so much mass that their gravitational pull causes raised relative water levels around them. The melting of such ice sheets causes a redistribution of this water, thus raising it elsewhere [20, 48]. The impacts of these processes on the Severn Estuary would depend which ice sheets melted (northern or southern hemisphere), and by how much.

g) Changes in atmospheric surface pressure & ocean circulation

Sea levels can change due to variations in ocean and atmospheric circulation, on short-medium timescales. Decadal variations in sea level have been attributed to changes in the Beaufort Gyre, an Arctic wind-driven ocean current [49], and teleconnection systems such as El Nino/La Nina and the **NAO**. NAO variations are particularly important for the Severn Estuary region (see **NAO**).

Future regional sea-level changes due to variations in ocean and atmospheric circulation are uncertain [40, 50]. However, they can be much greater than the global trend [15] so are an important consideration in addition to global averages. For example, although an 'abrupt transition' of the North Atlantic thermohaline circulation before 2100 is 'very unlikely' (probability <10%), such a transition could accelerate SLR [51, 52].

[6] As water molecules get warmer, they gain more energy, move about more and therefore become more spread out. This causes the volume of water to increase.

1.4.1.1 Glacio-eustacy

a) Glacio-eustacy: small glaciers and ice caps

Glacio-eustacy is caused by changes in the amount of water held in the cryosphere[7]. In the IPCC 4th Assessment Report (AR4) [51], the second largest contribution to projected mean global SLR was from glaciers and small ice caps (with the largest contribution of around 66% attributable to thermal expansion). SLR contributions from large ice sheets were small because changes in ice sheet flow were lacking in the published literature. The contribution to global mean SLC from small glaciers and ice-caps between 2003-2010 has been calculated from satellite data to be 0.41 ± 0.08mm yr^{-1} [53].

b) Glacio-eustacy: large ice sheets

Glacio-eustacy is caused by changes in the amount of water held in the cryosphere. The response of large ice sheets to warming constitutes the biggest uncertainty in the range of future climate–induced SLR [54]. Research since the publication of AR4 [29] shows that the contributions are already significant and that the decline in polar ice sheet mass is now accelerating [e.g. 55, 56]. Research suggests that the contribution to global SLR from ice sheets has nearly doubled since around 2003 [57], and tide-gauge and satellite observations show that sea level is already rising at or above the fastest rate proposed by AR4 [58]. The contribution to global mean SLC from Greenland and Antarctic ice sheets between 2003-2010 has been calculated from satellite data to be 1.06 ± 0.19mm yr^{-1} [53]. Possible causes of future ice-sheet collapse are readjustments continuing from the last glacial maximum, more recent climate change, or through internal flow instabilities [59]. Recent research indicates that warm currents are causing basal melting of Antarctic ice-sheets, leading to ice sheet thinning and rising sea levels [60]. This means that a lot of ice can be lost without the summers being warm enough to cause the snow on-top of the glaciers to melt.

While it is very unlikely that the major ice sheets of Greenland and Antarctica will melt in the near future [61], collapse of the Greenland Ice Sheet and the *West* Antarctic Ice Sheet (WAIS) in around 300 years is conceivable [62]. If these three ice sheets *were* to melt, the results would be catastrophic: the total volume of ice on Earth is equivalent to more than 60m SLR [58, 63], most of it held in the Greenland and Antarctic ice sheets. It is estimated that the Greenland Ice Sheet holds around 7m and the WAIS around 5m [64], with the East Antarctic Ice sheet accounting for the rest. During the Pliocene around 3 million years ago, atmospheric CO_2 concentrations were about the same as today and the sea level is thought to have been 15 to 25m higher than present [58, 65].

1.4.2 Short term SLC

It is the combination of short-term variations combined with longer term changes that cause extreme sea levels at a given location. Some short term changes, such as tides, can be accurately predicted many years in advance, but many are difficult to predict. The nodes in this section document the factors that cause short term changes in sea level.

[7] The portion of the Earth's surface where water is frozen, including snow, ice and permafrost.

1.4.2.1 Non-climatic causes of short-term SLC

a) Tides

The Severn Estuary is dominated by tidal processes. It has the second highest tides in the world, with an average mean tidal range of 6.5m at neaps and 12.3m on springs [66]. Tidal range increases further up the estuary, and high spring tides reach as far as Tewkesbury when river flows are low [38]. The Estuary's high tidal range is caused by a combination of factors: an uninterrupted tidal setting for North Atlantic tidal wave propagation, amplification of the wave as it is constrained and converges in the Estuary, and a resonance[8] effect due to its distance from the Atlantic amphidrome[9] [41, 67]. The tidal curve is complicated by geomorphological constrictions and the partial impoundment of the ebb spring tide by the flood spring tide [41].

b) Severn bore

Large spring **tides** commonly lead to the formation of a tidal bore that propagates up the Severn at a height of up to 2m [68]. The wave is formed as the water is funnelled into the narrowing and shallowing channel as the tide rises. Flooding can result when the bore causes overtopping where soils are already saturated, as it did in February 2009 [41], but the bore does not pose a major flood risk [Matt]. This is in part because high freshwater levels in the upper estuary due to heavy **precipitation** events decrease the height of the bore, counteracting the potential flood risk [41].

c) Tsunamis

Tsunamis are long-periodicity, long wavelength ocean waves caused by displacement of water by events such as earthquakes, volcanic eruptions, mass movements or asteroid impacts. They can travel at speeds of up to 600mph (965km/hr) over hundreds of miles of open sea before they hit land [69]. Their increased wavelength results in larger run-up values than for waves with an equivalent height generated by other means [70].

There is debate amongst experts regarding whether the devastating 1607 floods on the Severn Estuary may have been caused by a tsunami [71-73], but historical accounts indicate it was more likely caused by a storm surge [74]. Irrespective of whether the 1607 flood was caused by a tsunami or storm surge, tsunamis have probably affected the UK coastline in the past [27, 70, 75, 76] and an event on the scale of the 1755 Lisbon earthquake, which is believed to have caused waves of up to 3m in Cornwall [77], has the potential to once again threaten the coast of the UK [77, 78]. The tsunami risk for the Severn Estuary is therefore a "small but unquantifiable hazard" [74], which could be increased by ACC through increased incidence of mass movements [79]. A potential maximum tsunami height of 1-2m, with local run-up effects of up to 4m has been suggested for the Bristol Channel area [27].

1.4.2.2 Climatic causes of short-term SLC

Heavy **precipitation** events, **storms** and **surges** cause short term SLC on the Severn Estuary. The frequency and magnitude of these may change with **ACC** (see below), and any or all of them may combine with raised mean sea levels to exacerbate risks to the coast.

[8] Resonance is the tendency for greater oscillation.

[9] An amphidrome is a point of almost no vertical tidal movement.

a) Storms

Storms are the main agents of change at the coast, with their effects moderated by mean sea levels [33]. The Severn Estuary is particularly vulnerable to Atlantic storms because of its **topography and coastal configuration**, orientation with respect to prevailing winds, and tidal setting, which together enhance **surge** heights from storms tracking east and north-eastward [80, 81].

The Severn Estuary has a long history of damaging storm events [80, 82, 83], and future storminess (intensity, frequency and location of storms) will be very important [20]. However, it is very uncertain if and how storminess will change [10, 84-86][Jack]. There is much variation in the historical record; for example there was a trend of increased storms in the 1960s-90s, but this was within existing variation and did not exceeded the storminess of the 1920s [85].

An increase in storminess could cause **morphological change** and **inundation**. It could also alter estuarine organic matter inputs, phytoplankton and fish populations, salinity and oxygen levels, and biogeochemical processes, all of which can significantly impact the overall **ecology** of estuaries [87].

b) Precipitation

Although the whole of the Severn Estuary is dominated by tidal processes, fluvial influence becomes appreciable further up the Estuary, north of The Noose at Awre, Gloucestershire [88]. The Severn Estuary has one of the largest catchments in the UK, and is vulnerable to increased water input from the land as well as from the sea, and future rainfall trends will be an important factor determining the relative water level in the estuary.

Heavy precipitation events can occur in both summer and winter, and can combine with high sea levels to exacerbate risks of flooding on the estuary. Heavy rainfall was reported in a number of historic flood events on the estuary, but not all [Claire].

UK fluvial flooding due to heavy precipitation events is expected to increase in future [85, 89], and there has been an increase in heavy winter precipitation events on the Severn Estuary since the 1960s [90]. Rainfall is expected to become more seasonal with ACC, with more rainfall in winter and less in summer [91]. However, future *increases* in summer rainfall are also possible [91]. Future fluvial flooding will also be affected by **environmental management and land use** changes.

c) Surges

Storm surges are temporary increases in sea level caused by low pressure and the force of strong winds over water. The Severn Estuary is particularly vulnerable to surges because of its orientation and due to its **topography and coastal configuration**. There is debate over where on the Estuary is most exposed to surges. It may be that the surge level builds as it travels up the estuary [Matt] and thus threatens the upper reaches more, or that the surge amplitude reduces as water spills out onto the floodplain as it travels [James], thus affecting the lower reaches more.

Thanks to the Severn Estuary's massive tidal range, only extremely large surges or those that occur near high tide have the potential to cause flooding. For example, even a 3m surge would not exceed the mean high water level if it occurred at low or mid tide. The largest recorded surge event on the Severn Estuary was a positive surge of 3.54m, recorded in March 1947 at Avonmouth, but fortunately it occurred at low water on a neap tide, so large scale flooding did not occur [37]. This was a far larger surge than the 1.45m surge of 1981, which occurred closer to high tide and caused extensive flooding along the north Somerset coast [90].

Interactions between **tides** and surges are a very important consideration on the Estuary. Surges rarely occur at high tide and instead tend to cluster on the rising tide, with a second, less dominant mode on the falling tide [36]. However, although the largest surges don't tend to occur at the top of the tide, big surges can still occur near high tide [Claire]. Tide-surge interactions are sensitive to small changes in tidal phase, so if SLR affects **tides** on the Severn Estuary, it may have knock-on effects on surge levels [36]. Modelling suggests that decreased tidal range may increase the risks of surge residuals arriving near high water [36].

The Environment Agency [92] use tidal records and the skew surge joint probability method (SSJPM, which takes into account tide-surge interactions), to provide closely-spaced design sea level values around the UK coastline. They calculate that the 10,000 year (tide plus surge) return level for Avonmouth is currently 9.89mOD (metres above ordnance datum). This is the largest in the UK [92]. For comparison, the 1 year return level is 8.16mOD.

Potential changes in the frequency and height of storm surges are very important for future risk. Some studies suggest that surge levels may increase [93], perhaps by more than 0.8 mm/yr for the 50-yr skew surge[10] return level [40]. However, there is little consensus as to what future changes in surges might be [32, 94]. Uncertainties arise from: the science and methodology used to estimate the response of the climate system to greenhouse gases; future greenhouse gas emissions themselves; the modelled surge trend; the present-day surge baseline; future mean sea level; and natural climate variability [40, 94]. The lack of a strong historical trend [e.g. 11] compounds the issue.

d) Waves

The wave climate of the Severn Estuary is strongly seasonal, with the highest risk of extreme wave heights throughout autumn and winter, but there is a lot of inter-annual variability [95]. The wave climate mainly comprises swell waves from the Atlantic Ocean and locally generated wind waves [38], but the situation is complex, and exposure depends on **location within the Estuary**, and how waves are affected by local currents [Frank]. Wind waves generated within the inner estuary have a short fetch unless they are aligned south-west to north-east (the alignment of the inner estuary), and sand banks often act as natural breakwaters [38]. These factors mean that significant wave heights[11] in the inner estuary are much reduced, decreasing from more than 3m in the Bristol Channel to less than 1m in the upper reaches of the Estuary [88].

Waves are a powerful erosive force, and can cause flooding through overtopping and defence failure. Any future **changes in wave characteristics** on the Severn Estuary will therefore be an important risk factor. Wave climate trends due to climate change are uncertain [20], and there is currently no consensus on future storm and wave climate in the UK [10, 34, 85], despite a lot of work in the area.

Having said this, as SLR increases water depth at the coast, larger waves may approach the shore [10, 96] and research suggests that SLR has already exacerbated the impacts of storms during the past century [9]. **NAO** trends will be important, because the annual mean significant wave height is positively correlated with annual NAO index [Andrew]. Future changes in wind and wave *direction* might be more significant than changes in wave height [97], and may also be expected with strengthening NAO [Hurrel 1995, cited in 6]. Such changes in wave direction could alter coastal **erosion** patterns [6] [98]. Longer term changes could occur with a shift in **storm typology and tracks**, but this seems unlikely [Frank].

[10] Skew surge is the difference between the predicted high tide level and the highest observed tide level.

[11] Significant wave height is the average wave height of the top third largest waves.

e) Storm typology & track

The type of storm and the track it takes determines its impact on the coast. Two broad synoptic patterns cause storm damage on the Estuary [Andrew]. Evidence suggests that a westerly storm track causes a modest surge residual, while the highest surges may be caused by complex meteorological conditions featuring an enclosed circulation over the estuary with local forcings perhaps even causing a dampening of tide-surge interactions, leading to higher surge levels [82, 99].

Storm typology is affected by **time** of year. The major storm season is October-January [35], with winter storms often accompanied by high winds and heavy seas posing **coastal flooding** risks. However, summer storms featuring thundery rain also pose a threat through **fluvial flooding**, and although projections are for more rainfall in winter and less in summer [91], future *increases* in summer rainfall are also possible [91].

f) Meteotsunamis

Meteotsunamis are unanticipated 'long-period waves that possess tsunami characteristics but are meteorological in origin, although they are not storm surges' [100]. They can be caused by a number of factors including the passage of hurricanes, sudden changes in atmospheric pressure and wave superposition[12] [100]. They may have affected the Severn Estuary in the past [100], but are not currently accounted for in coastal defence planning. Further research would be necessary to assess the extent to which they may threaten the Severn Estuary coastline in future. Future trends may be affected by many of the same processes governing future trends in **storms**.

1.5 Unknowns

'Future events may not be drawn from the restricted list of those we have learned are possible; we should expect to go on being surprised' [Herman Kahn, 1967, cited by 101]. There are elements of the future we simply cannot anticipate, such as unexpected discrete events, discontinuities in long-term trends, and sudden emergence into political consciousness of new information [Brooks, 1986, cited in 101].

1.6 Other climatic and non-climatic factors

Many international dimensions of climate change may have indirect effects on people living around the Severn Estuary. These include changes in global agricultural practices and productivity, international instability, disruption of supply chains by more frequent coastal disasters, security threats due to forced migration, and a decline in UK prestige if developed countries are blamed for disasters attributed (rightly or wrongly) to ACC [102, 103].

More locally, ACC may cause **changes in species' diversity, distribution & structure**. For example, increased CO_2 levels may have a fertilising effect upon harmful algal blooms [104]. Increased

[12] Wave superposition is when overlapping waves combine to form a larger wave.

temperatures may affect nitrogen fixation and denitrification, oxygen and carbonate solubility, viral pestilence, pH and levels of photosynthesis in estuaries [104].

Finally, there are a number of very unlikely but physically plausible extreme events that pose risks to the Severn Estuary. These include a shift in climate regime caused by a mega volcano eruption, a return to ice age conditions due to a shut-down of the Atlantic Meridional Overturning Circulation (AMOC)[13], or a change in the River Severn's course from a meandering one to a braided one as a result of changes in runoff [105].

Regardless of whether any of these issues are more or less important than SLC, they may interact to affect processes, impacts and vulnerabilities to SLC. For example, direct local impacts of very hot and cold weather, drought etc (e.g. on health and infrastructure) may exacerbate deprivation and increase peoples' **vulnerability** to flood risks [Sandra].

2 PHYSICAL IMPACTS

This section summarises potential impacts of SLC on the Severn Estuary's hydrological, ecological and morphological environment. Some are immediate, like flooding, submergence and saltwater incursion into surface water. Others such as wetland loss and changes in water tables are lagged. Some impacts are linked to others by pathways.

> ***"When sea level rises, all the processes that operate around the coast change" [106]***

a) Recovery?

On short timescales, storms can cause dramatic shoreline responses, from which the coast may self adjust [13]. However, under conditions of SLC and **ACC**, full recovery may not occur. What constitutes a 'recovery' on the Severn Estuary is difficult to define due to ongoing **estuary retreat / rollover**.

b) Slow and incremental or event-driven

Physical impacts of SLC will have knock-on impacts for ecosystems, people and the built environment. These impacts may be slow and incremental, for example through the gradual **blight** of an area as people begin to find insurance purchasing difficult. Or they may be event-driven, for example loss of life during an extreme flood event.

[13] Large scale ocean circulation driven by density currents. Part of the 'great ocean conveyor'.

2.1 Pathways

Pathways are major routes by which some impacts of SLC affect other systems. They include inundation, pollution, landscape changes and impacts on water resources and drainage.

a) Overtopping/failure of natural & engineered defences

Flooding may occur through overtopping or defence failure. There is debate over which process will be dominant as sea levels rise [Claire, Matt, Roxy]. During the period up until 2020, when the SLR is an expected 3.5mm per year, 'only isolated lengths of the tidal defences are at any significant risk of failure' [107], but this risk will increase over time as defences deteriorate and sea levels rise, unless defences are maintained and improved.

b) Inundation (permanent/temporary)

Flood inundation is expected to be a major problem as sea levels rise [Jack]. This refers to the flooding of land not previously covered by water, and can constitute a permanent or temporary state.

c) Pollution

Pollution from water treatment works, landfill sites and contaminated land (of which there are significant areas around the estuary [108]) may become an increasing issue as sea levels rise. Incidents may be event driven or chronic. For example, event-driven pollution may occur when coastal landfill sites are flooded or when pollutants are mobilised by storm runoff during heavy **precipitation** events (current waste infrastructures are not equipped to handle very big storms) [Bob]. Chronic pollution may occur as heavy metals and toxins are washed or leached from polluted land such as that around Avonmouth; or settled-out pollutants may be remobilised due to **erosion** of sediments containing waste [Frank]. Pollution incidents can be expected to negatively impact **habitats**, finances (e.g. through **cost of recovery**), **leisure** and **health** (e.g. through drinking water contamination).

d) Landscape changes

An increase or decrease in land area, or a change in the physical make-up of an area, small or large, e.g. a change in slope or surface facies may result from sea-level change itself, or by measures taken in response to it e.g. building **coastal defences**.

e) Impacts on water resources

Groundwater and surface water resources may be impacted by salt water intrusion and/or by increased tidal influence within coastal areas, increasing the salinity within estuaries [109]. See **groundwater flooding** and **surface water flooding** for more information. The compromising of water filtration and provision may impact **health** and **wellbeing**.

2.2 Hydrological change

SLC may impact upon hydrology through a variety of means, including changes in tidal regimes, surge and wave characteristics, and by causing saltwater intrusion into freshwater environments.

a) Changes in tidal regime & curve

The tidal range on the Severn Estuary shows variance over short timescales [Harry], but SLR may cause more pervasive changes in tidal regime and curve on the Severn Estuary [110]. An increase in tidal range would exacerbate the impacts of SLR [Jack], whilst significant decreases in tidal range could expose the coast to more acute **erosion** by concentrating wave action over a smaller area.

SLR can change tidal regimes by 10-20% [74] but it is unknown how the tidal range on the Severn Estuary may change in response to SLR. The most likely change is for a decrease in tidal amplitudes, as indicated by paleaotidal research, observations and modelling studies [111-113]. Some evidence suggests that tidal range has *increased* on the Severn Estuary as sea levels have risen [110]. However, the tidal wedge appears to be migrating up the estuary, meaning tidal amplitudes are *decreasing* on the outer estuary [114].

It seems more likely that tidal range will stay the same or *decrease* as sea levels rise, because the tidal regime on the estuary is already at or near resonance (Jack) [115]. Large decreases in tidal amplitude are modelled for a SLR of 2m[14] in the resonant Bristol Channel and Gulf of St. Malo [113], while other areas show increases in tidal range. Greater changes are modelled for spring tides than in neaps and M2[15] tides [113], with spring tides modelled to decrease in amplitude by 43cm at Newport under a 2m SLR scenario. The scale of any decrease in tidal range would likely be less than the rate of SLR [Jack]. More significant changes in tidal regime would be expected with the implementation of a **barrage** [116].

Processes are complex and act over long timescales, making projections problematic. Furthermore, because tidal propagation on the Estuary is controlled by the estuary's morphology, **morphological change** may have more impact on tides than changes in water depth might. Morphological feedbacks may mean the current range is maintained [Frank].

b) Changes in surge characteristics

Changes in water depth and **tidal range** may impact **surges** and tide-surge interactions (see **surges** for more information).

c) Changes in wave characteristics

Both short term SLC (i.e. raised water levels during a storm **surge**) and long term SLC (i.e. mean SLR caused by climate change) may lead to increased wave heights at the coast [Bob, Frank] and research suggests that SLR has already exacerbated the impacts of storms during the past century [9]. However, there is much uncertainty in predictions of how the wave climate might actually change [41]. SLR will increase fetch and thus wave generating capacity and wave heights [41], and as SLR increases water depth at the coast, larger waves may approach the shore [10, 96]. Future changes in wind and wave *direction* might be more significant than changes in wave height [97], and may be expected with strengthening **NAO** [Hurrel 1995, cited in 6]. Such changes in wave direction could alter coastal **erosion** patterns [6] [98]. **Changes in tidal regime and curve** may alter the fetch over which wind waves are produced.

[14] In this study (Pickering et al 2011) 2m SLR was chosen for model runs to represent an upper limit of SLR during the 21st century and a low to middle scenario for 2200.

[15] The largest constituent of the tide in most locations, the M2 component is caused by the gravitational pull of the moon.

2.2.1 Saltwater intrusion & waterlogging

a) Saltwater intrusion into rivers & changes in saltwater wedge

As sea levels rise, the saltwater wedge may move further up the Severn, increasing salinity and affecting river ecology. Changes in **precipitation** may interact with these processes. For example with a predicted decrease in summer precipitation, summer flow levels on the Severn may reduce by up to 50% [117], exacerbating saltwater intrusion.

b) Saltwater intrusion into groundwater

Salt water intrusion is the 'encroachment of saline water into fresh ground water regions in coastal aquifer settings' [118]. SLR is expected to cause the mixing zone between fresh and saline water to migrate inland [118], causing **ecological change**, **impacts on water resources** [e.g. 119] and impacts on **land use** e.g. agriculture, forestry and aquaculture through decline in soil and water quality [103]. Although SLR may affect groundwater locally [120] it is unlikely to be a big issue at present because 'only aquifers with very low hydraulic gradients are more vulnerable to sea-level rise [than to groundwater extraction] and these regions will be impacted by saltwater inundation before saltwater intrusion' [121].

2.2.2 Flooding: changes in frequency/magnitude/likelihoods

Together with habitat loss, flooding is the main risk facing the Severn Estuary from SLC [Jack]. Flooding is already the most common natural hazard in Europe [122], and climate change is increasing this risk [123]. Flooding can occur through slow inundation or through short timescale extreme events. It might be that areas already flooded occasionally or for short periods of time become flooded more often or for a longer duration [Roxy].

Estuaries are particularly vulnerable to flooding because they are exposed from the coast and from rivers as well as from surface water and groundwater. Estuarine flooding tends to occur when some or all of these factors combine [124], reducing total floodwater storage and compounding the overall flood risk. It is not fully understood how the different sources of flood risk combine and interact [125], but mechanisms include the reduction of storage capacity on coastal floodplains when rhynes (drainage ditches) are at capacity due to high rainfall [Claire].

a) Surface water flooding

Surface water flooding occurs when rainfall overwhelms drainage capacity. It is more difficult to model, predict and map than coastal and fluvial flooding, but may become more of a problem on the Severn Estuary in future [Daisy], especially with **environmental management and land use** change such as increasing use of impermeable materials in urban areas [Sandra] and changing farming practices [Matt]. Surface water flooding is more of a problem in Wales than **groundwater flooding** due to the underlying geology having a low capacity for water storage [Sandra]. The Summer 2007 floods in the UK were mostly the result of surface water flooding [126].

b) Groundwater flooding

Groundwater flooding occurs when the groundwater level rises above surface water level. It is not a significant problem in Wales, where the underlying rock type is relatively impermeable [Sandra], but in future may be exacerbated by SLR, which could decrease the elevation difference between freshwater and seawater, thus slowing gravity drainage [127]. This is especially a problem where water tables have been raised due to increased **precipitation** [128], or where sea levels are increased due to storm **surges** or high **tides** (**tide locking**). Groundwater flooding is primarily driven by long duration extreme precipitation (months) but can also be exacerbated by intense short duration events [128].

c) <u>Coastal flooding</u>

Coastal floods are a consequence of a set of factors including storm **surges**, high **tides**, **waves**, changes in **sediment supply**, **topography and coastal configuration**, **coastal defences** (condition, nature, strength and height) [83, 105] and mean sea levels. A number of severe coastal flooding events have affected the Severn Estuary in the past, including the 1607 flood that extended about 40km along both banks of the Bristol Channel to a depth of 2-3m [73], flooded more than 500km^2 and killed more than 2000 people [71].

As the mean sea level rises, the return period for a given coastal flood level is reduced [23]. Coastal flood risk in the UK is expected to increase in proportion to fluvial flood risk as Sea levels rise [123]. In the Severn Estuary, flood damage is expected to increase even under a 'local stewardship' emissions scenario [117]. Particular areas at coastal flood risk include Kingston Seymour, Brean, and the Berrow peninsula from Burnham upwards [James].

d) <u>Fluvial flooding</u>

A number of severe fluvial flood events have affected the Severn Estuary in the past, including the major Gloucester floods in 2007, which were caused by excessive rainfall [129] leading to surface water and fluvial flooding.

There is an obvious and direct link between climate-induced SLR and coastal flooding: as sea levels rise the return period for a given flood level is reduced [23]. However, the links between climate change and flooding caused by rainfall are less definite, and there is a lot of uncertainty in the modelling of such events [130]. Fluvial flood processes are driven by a complex set of factors, and thus the impacts of climate change are also likely to be complex. For example, climate change is expected to cause changes in precipitation and therefore runoff. But it is also predicted to cause changes in temperature, which will affect evapotranspiration and soil moisture, which also affect runoff [105]. In turn, catchment runoff is affected by **environmental management and land use** e.g. catchment management, urban planning and agriculture, while **river conditions** such as river morphology, ecology and sediment supply impact upon flood conveyance, routing and storage [105].

Notwithstanding these uncertainties, a number of studies suggest that there will be an increase in fluvial flooding in future [e.g. 122, 131], and although attributing any given event to climate change is problematic, recent research has linked increased rainfall and flood risk to greenhouse gas contributions [132, 133]. Future predictions of ACC for the Severn Estuary suggest that there could be a 20% increase in river flows [107] due to higher autumn/winter precipitation by the end of this century [90]. In coastal areas such as the Severn Estuary the threat of fluvial flooding will be exacerbated by SLR; for example many flood events occurred in the coastal segments of rivers at high tide during the UK autumn/winter floods of 2000/2001 [32].

e) <u>Tide locking</u>

Tide locking occurs when drainage of fluvial or surface floodwaters is impeded by high tide, causing a 'backwater effect' or 'backwater flooding'. It is a major factor in flood risk on the Severn Estuary [107], and although there are some measures such as valves in place to avoid it, these are limited by funding [Matt]. It is difficult to say what the impacts of tide locking will be in future [James], but it is likely to increase under conditions of SLR [107]. It may be made worse by a **barrage**, which would hold the low tide at a higher level [James], thus increasing the **fluvial flood** risk.

2.3 Morphological change

SLC leads to morphological change through alterations in **erosion** and **accretion** patterns, which lead to changes at many scales both above and below the waterline. The rate and extent of change will be controlled by the rate of SLC, storminess (particularly changes in storm tracks) [7], **sediment supply**, **river conditions**, soil moisture and weathering [22], temperature changes, rainfall [Sandra], and **NAO** trends [7, 134], all of which may be affected by **ACC**, and thus also depend on **greenhouse gas emissions** scenarios and **mitigation** measures. The main driver of change on a short timescale is **storminess**, while **SLC** drives longer term trends [135].

a) Sediment supply

Any future changes in sediment supply will impact upon **erosion** and **accretion** in the estuary. Coasts with a positive **sediment budget** may not erode [106]. For example marshes may be able to maintain their vertical accumulation rates under conditions of SLR if incoming suspended sediment concentrations are high enough [136]. Therefore, if the sediment supply were to increase in future, for example due to increased runoff, it could counteract increased erosive potential of **storms**.

Future changes in sediment supply are unknown; they will depend largely on changes in **precipitation**, **land use** and **agricultural practices**. However, unless a **barrage** is built, sediment supply both from on land and at sea is unlikely to change much, and changes would likely act on longer timescales than changes in sea level and **storminess** [Frank].

b) Changes in biochemical cycling

The amount and type of sediments in the estuary affects biochemical cycling and thus impacts upon food chains and can cause **ecological change**. The estuary is understudied in this respect, but work is ongoing into the impacts of ACC on biochemical cycling in the Estuary [Bob].

c) Changes in the supratidal environment

The supratidal environment is the coastal zone normally not submerged during high tides. This zone will become inundated more often or permanently as sea levels rise, and may be expected to migrate inland provided it is not impeded by **coastal squeeze**.

d) Changes in the subtidal environment

The subtidal environment is the coastal zone that is normally submerged at low tide. It is expected to change as sea levels rise and the estuary responds by widening and deepening [41]. Reefs and sandbanks are expected to shift, but their behaviour is uncertain [38].

e) <u>Changes in the intertidal environment</u>

The Severn Estuary is an 'important location for salt marsh, a resource that is in decline throughout Europe and across the UK' [123].

The intertidal environment is the zone between high and low tide, and includes various environments including beaches and marshes. While SLR is likely to intensify the **erosion** of beaches [135, 137, 138], the largest areas at risk in the Severn Estuary are mudflats, sand flats and salt marsh [38, 139].

The maintenance of intertidal surface elevations in estuaries is a dynamic process, governed by periodic erosion by storm **waves** and subsequent recovery via **sediment deposition** [33]. Future trends will therefore depend on the rate of **SLC**, changes in **storms** and **sediment supply**. If the rate of SLR is too fast, the marshes will drown; but if change is slow enough, and enough sediment is supplied, the marshes may vertically accrete fast enough to maintain their relative elevation [140]. The critical rate of SLC that an estuary can experience before it can no longer maintain equilibrium morphology varies between estuaries, and is dependent on **sediment supply**, sediment transport, and **management and land use** [141].

Salt marsh extent is already showing a declining trend in England and Wales [142]. A net loss in intertidal habitat is projected on the Severn Estuary during the period 2005-2105, with the largest changes expected in the inner estuary [38]. There is a projected loss of 7% of intertidal areas compared to the 2005 baseline area by 2055, and 11% by 2105 [38].

Changes in the intertidal environment can affect changes in other coastal features by altering **sediment supply** to other coastal systems. Also see **coastal squeeze**.

f) <u>Erosion</u>

Coastal erosion is a natural process whereby wind, **waves** and **tides** wear away the coastline [143]. Patterns of erosion and **accretion** depend on a number of factors including coastal **geology & geomorphology**, connectivity with other coastal systems, **environmental management & land use**, **storminess**, and **river conditions** (how the river moves the sediment) [144][Bob].

Although erosion is not as big an issue as flooding in the UK generally and on the Severn Estuary in particular [Jack, James] [32], future trends will be an important risk factor. Though there is much variability in accretion and erosion on the Estuary over short [38], and long [80] timescales, studies show a long term trend of erosion [12, 38] consistent with southern UK trends [145]. This is expected to worsen in future [105]. ACC may lead to increased mass movements in the upper reaches of the Severn catchment [Matt, Sandra] and along coastal cliffs [21]. But the main impacts are expected to be felt in intertidal mudflats and sand flats, salt marsh, grassland and the subtidal environment [38].

Areas at risk from shoreline erosion on the southern coast of the estuary include Porlock Bay, Blue Anchor Bay, Sand Bay, and the coast between Hinkley Point and Weston-Super-Mare (excluding Brean Down) [146]. Areas showing erosional trends on the north side of the estuary include Penarth Head, Cardiff Flats, Wentlooge Levels, parts of the Caldicot coastline and Cone Pill (near Lydney) [41].

g) <u>Accretion</u>

Accretion is the process of accumulation of material in an environment. Patterns of **erosion** and accretion depend on **sediment supply** (e.g. due to **environmental management & land use**), tidal patterns, runoff, **geology & geomorphology**, connectivity with other coastal systems, **storminess**, and **river conditions** (how the river moves the sediment) [144][Bob]. Changes in these factors will affect patterns of erosion and accretion, and thus will control the evolution of the coastal zone as sea levels rise.

h) Estuary retreat / rollover

In a process termed 'rollover', Pethick [147] predicts that with a SLR of 6mm/yr, estuaries will migrate landwards at a rate of around 10m/yr in order to maintain their position within the coastal energy gradient. There is evidence that this may be occurring on the Severn Estuary [38, 114] as a response to SLR. The process happens over long timescales and will only be possible if there is room to migrate (else **coastal squeeze** will occur), and if sediments are available.

i) Carbon & heavy metal sequestration / release

Salt marshes provide an important ecosystem service through heavy metal and **carbon sequestration** [142]. Disturbance of these ecosystems (e.g. through **erosion**) may cause carbon release, thus further contributing to **ACC**.

j) Coastal squeeze

Coastal squeeze is the process by which coastal habitats are trapped between a rising sea and a fixed landward boundary such as a **flood defence**, and are thus reduced in quantity or quality. Coastal squeeze is occurring in many European estuaries and leading to a loss of intertidal area [148]. It is expected to be a major impact of SLC on the Severn Estuary [Frank] [38, 149], with a projected decline of intertidal areas as a result, unless **managed realignment** is implemented on a large scale. However, current shoreline management strategies around the estuary feature widespread defence maintenance and improvements (the 'Hold The Line' approach) [109, 150], so losses of intertidal habitat through coastal squeeze are expected. Such coastal squeeze will expose flood defences to increased damage as they lose protective salt marsh fronting [107].

2.4 Ecological change

'The natural environment is vulnerable to both extreme weather events and incremental environmental change' [151]

The Severn Estuary is a biologically important area. The SMP2 study area[16] includes 7 Natura 2000 sites, over 50 Sites of Special Scientific Interest, 4 National Nature Reserves and one Area of Outstanding Natural Beauty [109]. There are also a number of designations (see **Environmental management and land use**). Some of these designated sites (SAC, SPA, Ramsar) are expected to experience long term detrimental changes in habitat, particularly in intertidal habitats that are vulnerable to **coastal squeeze** [38]. The Estuary contains the largest aggregation of salt marsh habitat in the south and south-west [108], which is particularly important for bird feeding, roosts, fish feeding grounds [Frank], and as natural **coastal defences**.

[16] The area covered by the Severn Estuary's Second Shoreline Management Plan.

Ecological change may occur either through direct habitat loss or through changes in species diversity, distribution and structure. Change may be driven by a number of factors, including physical loss of land through **inundation** and **erosion**, alterations in the interaction between freshwater and seawater, altered river flows and sedimentation patterns [152].

a) Habitat loss

Habitat loss on the Severn Estuary is a central concern for experts, and is viewed as one of the two greatest threats of SLC on the estuary, the other being **flooding** [Jack]. Loss may occur through flooding and/or **erosion**. Habitat loss may lead to extensive changes in **species diversity, distribution and structure**.

b) Changes to species diversity, distribution & structure

As well as changes in habitat *extent*, SLC may also lead to changes in habitat types, structures and distributions. Firstly, increasing estuarine salinity will likely affect ecology [119], and will tend to displace existing coastal plants and animal communities inland, consistent with an **estuary retreat/roll-over** process. Changes in freshwater runoff are likely to cause changes in the physical mixing properties of estuaries, which in turn may also impact upon estuarine ecology. There is already evidence that the fish community in Bridgewater Bay is responding to changes in seawater temperature, salinity and the **NAO**, and that future changes may lead to the collapse of some species [153].

Changes in coastal **storms** could alter **sediment supply**, organic matter inputs, phytoplankton and fisheries populations, salinity and oxygen levels, and cause **changes in biogeochemical cycling** in estuaries, all of which could significantly impact upon estuaries' overall ecology [87].

Ecological changes also result as knock-on impacts of **socio-economic responses**, such as **adaptation** measures. For example, recent research shows that coastal salt marshes created by **managed realignment** have different community compositions to those that they replace [154].

Changes in species distribution and structure can have both positive and negative impacts on local ecosystems [Sandra]. Some species may benefit from climatic changes on the Estuary, for instance the Honeycomb worm *Sabellaria alveolata*, which is currently at its northern most range in the UK, could extent this range as waters warm [108].

3 SOCIO-ECONOMIC IMPACTS

This theme outlines the impacts of sea-level change on people by means of social, built environment and ecological changes. It is not divided into sections because there is a high degree of overlap between nodes. Instead, it is organised through three broad pathways of impacts: people, built environment and ecosystems, and loosely grouped into three clusters: personal & community wellbeing, business and industry, and government.

The main impacts are expected to result from flooding, as only a few isolated areas in the Estuary are at high risk of erosion [James]. These impacts range from inconvenience to injury and death. The devastating impacts of such events were illustrated during the summer of 2007 when large swathes of the UK were flooded. The event killed 13 people, necessitated the rescue of 7000 people, and caused

55,000 properties to be flooded (48,000 households and 7,000 businesses) [155]. The floods also cost the insurance industry £3 billion [155].

Pathways

The 'People' pathway summarises impacts on people, be it individuals, communities or stakeholders. The 'built environment' pathway summarises impacts on the built environment, including housing and infrastructure. The 'ecosystems' pathway essentially describes **ecosystem services**, which we tend to undervalue and are often difficult to calculate [Frank], but are increasingly recognised for their importance [142].

Clusters

The government cluster links direct and indirect impacts on government. For example a flood event may directly damage governmental infrastructures, or may affect peoples' trust in governmental policies. Nodes related to the government cluster are: cost of **recovery, bailouts, impacts on peoples' trust in government**, and links with **personal and community wellbeing** (for example changes in funding for community projects due to top slicing of funds for flood defences or flood recovery operations).

The personal and community wellbeing (or 'quality of life'), cluster encompasses a wide range of factors that together reference a general 'level of living'. Factors include access to healthcare and recreation, economic and environmental welfare [156]. Related nodes include direct impacts on **health**, disruption to **services**, **displacement** and **decreased availability and increased cost of insurance**.

The business and industry cluster summarises impacts on the business sector. ACC does not necessarily pose 'new' risks for the business sector, but a change in existing risks and/or opportunities [151]. Businesses can be affected directly or indirectly from SLC. For example, flooding can damage a business' property or goods, have **impacts on logistics and supply chains**, or prevent customers, employees or suppliers reaching the business. Many of these impacts are likely to be caused by **disruption or damage to infrastructure** around the Severn Estuary, of which there are significant assets including ports, power stations and transport networks.

Research indicates that businesses are insufficiently prepared to manage High-impact, Low probability (HILP) crises [157] such as a major flood. It is calculated that due to the 'just-in-time' global economy, the UK could manage at most a week after a major disruption, and that the impacts would not be limited to the local area [157].

a) Cost of recovery

Clean-up and recovery operations after a flood can cost individuals, businesses and governments vast sums of money. Flood costs for Wales are expected to increase from around £70 million now to £1000 million under the 2080 'National Enterprise' scenario [117].

b) Bailouts

Government bailouts may be necessary after a major flood event, particularly with **decreased availability and increased cost of insurance** for individuals [Daisy].

c) Top-slicing of funds from other departments

Money for insurance **bailouts**, emergencies, clean-up operations and **flood defences** may be top-sliced from other services, impacting upon sectors such as health care and education [Sandra].

d) Impacts on peoples' trust in government

Peoples' trust in government can be affected by how they perceive action on various socio-economic responses to SLC. For example, how a local government responds to a flood risk, or implements food security or **managed realignment** policies [Frank].

e) Increased/decreased sense of community

Community bonds can be strengthened as people pull together during extreme events such as floods, but they can also be damaged by **blight**, outward migration and land-use conflicts.

f) Direct & indirect impacts upon health: death, injury, disease, mental health

Cold related deaths may substantially decline due to **ACC** [22]. However, increased flooding is likely to have severe impacts on peoples' health, for example through pollution incidents [106], mould induced health effects [22] and waterborne disease [151]. Health can also be affected through not being able to access healthcare during/after a flood event [Sandra], and through mental trauma. Psychological stress and mental health issues are common during and after flood events, and may occur due to trauma, loss of house and inheritance, and not being able to reach open spaces [Sandra]. Health impacts can last for a long time after flood waters recede [22, 158] and have economic consequences [106].

Although UK floods are associated with few direct deaths [158], largely because of improvements in communication, warning and forecasting [Roxy], mass loss of life still remains a possibility. Indeed, with ACC 'the risk of major disasters caused by severe winter gales and coastal flooding is likely to increase significantly' especially in the event of a major sea defence breach [22].

g) Inconvenience

Inconvenience includes that caused by travel disruption and difficulty accessing services and leisure spaces, for example during a flood event.

h) Disruption to education, recreation, social care & essential services

Flood events may cause disruption to many service infrastructures including schools, recreation facilities and essential services such as police and social care. Damage to these services or to the transport networks that connect them could have welfare implications [Sandra].

i) Homes & property damage

The Severn Estuary is home to over 1 million people [108], with high concentrations of housing in areas such as Bristol, Cardiff, Newport and Gloucester. Flood damage to homes and personal property is a major cause of psychological stress and mental health issues.

j) Disruption /damage to infrastructure: transport networks & ports, IT networks, communications, water supplies, waste facilities (landfill, sewerage, collections), drainage networks, energy (production, distribution, renewable potential)

The Severn Estuary's flood plains include £14 billion of important infrastructure [37], and a lot of new infrastructure is still being built on floodplains. Key infrastructure around the Severn Estuary includes: 18 telephone exchanges, 20 water and sewage treatment works, 139 schools, 25 railway stations, 538 electricity sub-stations, 7 hospitals, 43 emergency response centres and 122 care homes [159]. The Severn Railway Tunnel, major transmission lines across the Gwent and Somerset Levels, and docks at Avonmouth, Portbury, Portishead, Lydney, Newport and Gloucester are also situated within the SMP2 area[17] [159].

SLC may affect such infrastructures through permanent or temporary inundation, scouring [151] and impacts on drainage. It might be that infrastructure that's only designed to cope with inundation for a short period of time is flooded more often [Roxy] or that infrastructure that is not designed to be flooded at all is inundated. Impacts upon key infrastructures in one area often have knock-on impacts elsewhere, for example through **disruption to supply chains** and **impacts on logistics**.

Transport networks and ports

The Somerset Levels have some of the most threatened transport infrastructure in the UK, with much of the M5 and a main railway route below 5m elevation. The northern banks of the estuary are also highly threatened: for example the railway and motorway near Caldicot are low-lying, and part of the Severn rail tunnel lies within 2300m of coastal defences [88]. The impacts of fluvial floods, sea-level rise and storms are 'priority topic areas' for UK railways, together with heat-related risks from climate change [160]. Transport disruption can cause a variety of knock-on economic and social impacts, ranging from people not being able to visit friends or family, or not being able to get to work or to hospital, through to police and ambulance services being impeded. Longer term disruption can occur where transport infrastructures are permanently relocated. Damage to some of the Severn Estuary's transport infrastructure may have knock-on impacts for coastal defences because railways and motorways act as defences in a number of locations, for example the train line at Lydney in Gloucestershire [37].

IT networks & Communications

Damage to IT infrastructure and phone lines could have implications for personal and business communications, and for essential services such as police and hospitals, with knock-on social implications [Sandra].

Water supplies, waste facilities and drainage networks

Damage to water, waste and drainage infrastructure may cause widespread disruption around the Estuary. Water supplies could be affected by pollution incidents due to flood events, or by salt-water incursion. Flooding of landfill sites can cause pollution incidents and/or gradual leaching of harmful substances, while flooding of sewage systems can cause disease outbreaks and pollution incidents. Waste services may also be affected through the disruption of collection and operations during events. Impeded drainage can depreciate the economic viability of agricultural land.

Energy infrastructures

[17] The area covered by the Severn Estuary's Second Shoreline Management Plan.

SLC may impact energy in a number of ways. Firstly, it may mean that renewable potential is altered. For example the energy potential of a barrage will change with SLC, trends in **storminess** and **changes in tidal regime and curve**. Secondly, flood events could affect energy distribution networks through erosion and/or flood inundation of distribution infrastructure. There are a number of sub-stations and distribution pylons on low-lying land around the estuary, some of which have flooded in the past and could flood more regularly or more severely with SLC. Thirdly, a number of power stations around the estuary may be directly impacted by flooding and erosion. These include commissioned nuclear power sites at Oldbury and Hinkley Point (B), one decommissioned site at Berkeley, and another at Hinkley A. According to the International Atomic Energy Agency (IAEA), **ACC** poses a number of potential impacts upon the safe operation of nuclear power plants [161], one of the main hazards being SLC [IAEA 2003, cited in 161]. Coastal reactors are affected by inundation (permanent or episodic) and erosion. The expected main effects of flooding include damage to safety-related structures and systems, damage to the structure and foundations of the plant, and disruption of communication and transport networks [162]. According to Kopytko and Perkins [161], several safety issues repeatedly occur during storm events, including the failure of alarm systems. Flooding can also increase the dispersion of radioactive material after an accident [162].

Hinkley and Oldbury are currently both at low risk of flooding [70], with risks mainly posed by wave overtopping and extreme rainfall events rather than still water levels, which have been taken into account when designing the plants' substantial sea defences. Hinkley has already been affected by extreme events: during the 1981 flood, a power failure affected the tide gauge at Hinkley Point, 'presumably associated with the flooding of parts of the power station' [82, citing personal communication with Wessex Water Authority], and Hinkley A was flooded by a storm surge during construction in 1962 [163]. The flood risk to such energy infrastructures is expected to increase by the 2080s [Defra, cited by 164]. Rising sea levels will not only threaten commissioned power stations, but also decommissioned sites such as Berkeley, where rising sea levels will make decommissioning, recovery and movement of nuclear waste difficult and expensive [David Crichton, cited in 164].

Impacts upon energy supplies can be expected to impact people living far from the area. Knock-on impacts include disruption to power for schools, hospitals, sewerage systems and businesses.

k) Increased risk of nuclear accident

The major earthquake that caused a nuclear accident at the Fukushima nuclear plant in March 2011 raised questions over whether UK nuclear reactors could suffer the same fate if they were subjected to a major flood event. The Office for Nuclear Regulation concluded that they 'see no reason for curtailing the operation of nuclear power plants or other nuclear facilities in the UK' [70] though raised sea levels, increased storminess and/or a tsunami would increase the risk of accident to Hinkley and Oldbury.

l) Rising energy costs

Extreme events that damage energy infrastructures may cause increases in personal and business energy costs as energy providers have to protect such infrastructures from further damage.

m) Jobs

Jobs can be affected on both long and short timescales. Firstly, flood events can prevent employees reaching their place of work. Secondly, the closure or relocation of business can lead to job losses and resultant personal and community wide impacts (see also **blight**). Staff can be affected by not being able to get to and from work during and after flood events, which can have knock-on impacts for personal wellbeing and business performance.

n) Economic Cost

A large amount of capital is at risk from flooding in the Severn Estuary [107]. The economic impacts of SLC on the Severn Estuary will be direct and indirect, and are likely to be felt at the national and regional scales (e.g. coastal defence spending, payment of compensation after flood events), regional scale (e.g. impacts upon tourism), local scale (businesses, local authorities) and personal scale (insurance premiums, loss or damage to land, possessions, house values and livelihoods). For example, the present value damage associated with flood inundation under a No Active Intervention scenario is £6 billion [159], and insured losses from a repeat of the 1703 storm[18] today in the UK would be an estimated £10 billion [165].

o) Displacement

Displacement may be of individuals, businesses/services or communities, and may be voluntary or involuntary, long or short term. Up to 35,000 people may have to be evacuated from South Wales during an extreme event [Daisy], and tens of thousands of properties are also threatened on the English side of the Estuary [James]. Environment Agency flood maps illustrate the large areas at risk of fluvial and coastal flooding around the Estuary [166].

p) Blight

'Because the issue of SLR is so widely known, disinvestment from coastal areas may be triggered even without disasters actually occurring' [106].

Blight describes the decline of an area due to economic downturns, disinvestment and out-migration. Blight can occur due to business and community **displacement** or through the avoidance of threatened areas. Blight can be economic, social or planning based, and can include higher insurance premiums, disinvestment, loss of peoples' sense of quality of life, and being unable to sell homes [22]. Blight can become a cycle, where disinvestment or lack of new investment impacts on the social sector through the loss of investment into services, or where lack of information leads to rumours among communities and businesses (especially regarding areas at risk of flooding/erosion)[22]. The closure or relocation of businesses not only leads to job losses, but can affect the local community through the loss of amenities and morale.

q) Decreased availability & increased cost of insurance

ACC will mainly impact the insurance industry through extreme events, of which flooding makes up a significant proportion [167]. For the last five years, the Statement of Principles, a 'gentlemen's agreement' between the government and insurance companies, has meant that that the government agreed to provide flood defences and insurers agreed to provide flood cover as standard. However, this is shortly to change when the Statement of Principles is due to end in June 2013, on account of defence funding being cut [168]. Insurance cover is likely to decrease while premiums are likely to rise and may become unaffordable for some [Daisy]. Where insurance provision is not available or fails,

[18] The 'Great Storm' of 1703 caused widespread destruction throughout the southwest of the UK, including extensive flooding and loss of life around the Severn Estuary.

governments may have to provide **bailouts** [Daisy], which will have knock-on impacts for other **services** due to **top-slicing of funds from other departments** [Sandra].

r) Impacts on logistics & supply chains

Flood events may disrupt the transportation of goods [Sandra], suppressing business output [151] and negatively impacting industries both close to the Severn Estuary and far from it.

s) Opportunities for new products & services

Some new and existing businesses may benefit from SLC, for example through the exploitation of new markets and through employment in **coastal defence** construction and maintenance.

t) Changes in distribution and density of aggregates

Dredging, predominantly for construction use, has been a significant activity in the Severn Estuary for around 100 years, with around 1 million tons currently dredged per year from sands in the outer and middle estuary [169]. Changes in **storminess**, **tides**, **erosion and accretion** may lead to changes in the distribution and density of such aggregates, thus affecting the aggregate industry.

u) Impacts on agriculture & food security

'At the local level, flooding or coastal erosion can be a significant risk to agriculture' [151].

Fully 69% of the SMP2 area has agricultural land use, mostly of Grade 3[19] quality [159]. Agriculture may be affected through the loss of or damage to land (through **flooding** or **erosion, saltwater intrusion or water logging**) during extreme events, or through **managed realignment** schemes. It might be that fields already flooded occasionally or for short periods of time become flooded more often or for a longer duration, making them more difficult to farm [Roxy] or forcing crop changes.

Other ACC-and non-ACC factors such as foot and mouth or crop disease may be more of a risk to food security than loss of land around the Severn Estuary due to SLC [Bob]. Whatever is the cause of impacts on agriculture, they will likely have knock-on impacts on other sectors such as farmland **ecology**, and **personal and community wellbeing**.

v) Impacts on shipping & ports

SLR is likely to increase the vulnerability of port operations to **flooding**, while changes in wind speeds and **storminess** could mean altered loads, route changes and shipping restrictions [34]. Ship navigation may also be affected by changes in **sediment regime** and **changes in the subtidal environment,** and different types of vessels are likely to be impacted in different ways. See also **disruption /damage to infrastructure** and **impacts on fisheries**.

w) Impacts on fisheries

Changes in the subtidal environment and **changes in the intertidal environment** may affect fish populations, and fisheries may suffer from more intense **storms**, affecting the number of days in which a vessel can/cannot go to sea [22]. There is evidence that climate change is already affecting fish

[19] Grade 3 = good to moderate quality agricultural land.

populations on the estuary, and that it will continue to do so in future [153]. For more information see **changes to species diversity, distribution and structure**.

x) Impacts on cultural environment & heritage

The Severn Estuary has one of the richest and most varied archaeological landscapes in the UK, including Mesolithic footprints, Iron Age villages and Mediaeval Fish Traps [108]. Such coastal historic assets are already being affected by **ACC** and this is expected to worsen [170].

y) Increased/decreased recreation & tourism

A number of regions in the Severn Estuary and wider Bristol Channel have high tourist potential [108, 171, 172]. Major tourist attractions around the Estuary include Bristol, Cardiff, Barry Island, Weston-Super-Mare, the Severn Way Walk, Slimbridge Wildfowl and Wetlands Trust and the Newport Wetlands [108]. Recreational activities include sailing, bird watching, fishing and sightseeing.

If UK temperatures increase as predicted, tourism could increase in the UK [34, 173], which is likely to lead to increased tourist revenues, new infrastructure and increased employment. It could also exert increased pressure on the coast, coastal environments and coastal communities. Conversely, increased coastal **erosion** or the loss of land due to **managed realignment** schemes may cause a *decline* in tourism [174], having the opposite effect.

On short timescales, recreation may be impacted when flood events affect access to friends and family and open spaces, or cause water contamination in places of leisure [Sandra]. This node also includes the impacts of sea-level change and responses to sea-level change (e.g. flood defence construction) on visual amenity.

z) Ecosystem Services

Ecosystem services are resources and processes provided by natural environment, from which humans benefit [175]. Examples include: natural coastal defences provided by intertidal habitats [142], water provision and filtration from river courses and carbon sequestration from salt marshes. Damage to these environments therefore has both ecological and economic implications. See **impacts on water resources**, **flood defences** and **carbon & heavy metal sequestration/release** for more information.

4 SOCIO-ECONOMIC VULNERABILITY & PHYSICAL VULNERABILITY

'Trends in exposure and vulnerability are major drivers of changes in disaster risk' [176]

Vulnerability can be described as the degree to which a system is susceptible to, and can cope with change. It is like a filter or a moderator for the drivers and pathways, controlling how much impact they have. Vulnerability is a function of exposure, sensitivity and adaptive capacity [44]. For clarity, it is here divided into exposure, physical sensitivity and adaptive capacity, socio-economic sensitivity and socio-economic responses (covering adaptation and mitigative responses, and the drivers that dictate the capacity to respond).

5 EXPOSURE

Exposure is the degree to which the system is exposed to drivers. Exposure varies in space and time.

a) Location within the estuary

Exposure varies over space because some areas are more exposed to risks due to their geology, topography, aspect and exposure to certain storm tracks and wind directions. So while the risk of tidal flooding affects the whole of the estuary, some sections of the estuary are threatened by further flood risks, depending where they are [Frank, James]. Wave overtopping is a problem in the outer estuary, while the greatest flood risk in the uppermost reaches of the estuary (e.g. around Gloucester) is from high river flows [37] and tidal currents [41]. This spatial heterogeneity makes prediction and adaptation complicated, but means that one event is unlikely to devastate the whole of the estuary.

Much of the coastline (except between Brean Down and Portishead) is protected from swell waves due to the change in alignment between the Bristol Channel and the Severn Estuary [38]. Wind waves generated within the inner estuary have a short fetch unless they are aligned south-west to north-east (the alignment of the inner estuary), and sand banks often act as natural breakwaters [38]. These factors mean that significant wave heights[20] in the inner estuary are much reduced, decreasing from more than 3m in the Bristol Channel to less than 1m in the upper reaches of the Estuary [88]. Waves are important up until around Severn Beach [James]. Beyond this, erosion is less of an issue. As well as spatial heterogeneity in natural protection, there is variation in the amount and quality of protection through **flood defences**.

b) Time

Exposure varies over time. On a daily timescale for example, the Estuary is resilient to change at low tide, whilst just a small surge can cause flooding at high tides. Furthermore, the same high water event may not produce flooding on both sides of the estuary due to tides being different on north and south coasts at a given time [Claire]. On a slightly longer timescale, **storm typology & track** is affected by time of year, and on longer timescales still, the **lunar nodal cycle** and natural variability affect vulnerabilities throughout the Estuary.

[20] Significant wave height is the average wave height of the top third largest waves.

6 PHYSICAL SENSITIVITY & ADAPTIVE CAPACITY

Physical sensitivity describes the degree to which the physical system is affected (positively or adversely) by SLC, and adaptive capacity describes the ability of the system to adjust. These factors combine with exposure to determine the overall physical vulnerability of the system. Some factors make the Severn Estuary particularly sensitive to flooding, such as its large catchment size, coastal configuration and topography. However, factors such as its high tidal range afford it some resilience.

a) Rate of change

The rate of SLC is likely to be as important, if not more important, than the scale of SLC. For example, if change is slow, intertidal habitats may adapt. If SLR is too fast, they may drown [140]. For example, although sediment supply may increase through changes in land use or rainfall, local erosion and flooding may happen more quickly than coastal habitats can recover.

b) Environmental management and land use

Environmental management and land use includes conservation, agricultural practices, catchment management and urban planning. Such measures can be short or long term, positive or negative, and they impact upon many other factors within the **Physical Sensitivity and Adaptive Capacity** theme. A number of nature conservation designations apply to the Severn Estuary. The main designations are summarised in the table below [after 177]. The SMP2 study area also includes 7 Natura 2000 sites, 4 National Nature Reserves and one Area of Outstanding Natural Beauty [109].

Designation	Brief description
Site of Special Scientific Interest (SSSI)	On the Severn Estuary, this is an area of land notified by English Nature or the Countryside Council for Wales under the Wildlife and Countryside Act 1981 as being of special nature conservation interest (biological, geological or geomorphological).
Special Protection Area (SPA)	An area of land designated under the European Council Directive on the Conservation of Wild Birds.
Ramsar Site	International wetlands designation
Special Area of Conservation (SAC)	An area of land designated under the European Council Directive on the Conservation of Natural Habitats and of Wild Flora and Fauna.

Table I: Key designations in place on the Severn Estuary

A major impact of environmental management and land use is upon **catchment characteristics** and runoff. For example, the weight of farming machinery and the way in which fields are ploughed have a large impact on how much water and sediment enter rivers. Future trends in farming practices are therefore important. It seems most likely that future changes will *decrease* the amount of runoff and sediment reaching rivers rather than increase them because upland farmers are currently encouraged to engage in practices that make the flood hydrograph[21] longer [Frank]. This would mean that with regards to changes in **sediment supply**, an increased landward sediment source is unlikely [Frank].

[21] A flood hydrograph shows how a river's discharge responds to a period of heavy rainfall, showing rate of flow against time.

Other environmental management and land use practices that affect physical sensitivity and adaptive capacity include: water management by the Environment Agency (clearing drainage courses etc); and a move towards Sustainable Drainage Systems (SuDS), designed to reduce the impact of developments on surface water drainage; and coastal defence measures, which can have knock-on impacts on **erosion** and deposition/**accretion** patterns.

6.1 Morphological factors

a) Sediment

Sediment budgets, as well as the quality and mobility of available sediments, influence the sensitivity of the coastal zone by affecting the amount of net **erosion/accretion** and **species diversity, distribution and structure**.

There is a limited supply of sediment into the Estuary [Frank]. Most of the fine sediment comes from river catchments, with a negligible supply from seaward, while sands seem to have an immediate western origin [178]. Although sediment supply is limited, huge quantities of sediment are mobilised with each tide, and the strong currents prevent suspended sediment from accumulating [41].

Construction of the 2nd Severn Crossing caused sandbanks to change position, which indicates that the estuary's sediment regime may be sensitive to perturbations [Frank]. The future erosion/accretion of the Severn Estuary coastline depends on how much sediment is supplied to the system, and thus **changes in sediment supply** will control future trends. Changes in soil conditions are a significant threat from **ACC** in Wales [179]

b) Geology & geomorphology

The Severn Estuary is composed of a variety of morphological units [41]. The underlying geology is sedimentary, with a number of hard rock outcrops that constrain the system and help to maintain the estuary's characteristic funnel shape [41]. Upstream of a line between Lavernock Point and Breen Down, the bedrock floor of the estuary is covered with mud, sand and gravel; below this parting zone the bedrock is exposed [108]. Major sand deposits and banks are found in the central estuary. Some of the near-shore sandbanks provide a degree of protection from wave attack; and thus the dredging of **aggregates** is closely monitored [108]. The coastal zone consists of sandy beaches and dunes on the Atlantic facing coast, muddy tributary estuaries, and muddy intertidal foreshores with relatively limited salt marsh for the Estuary's total area [41]. A clay belt (natural levee laid down by historical flood events) runs down each side of the estuary, with very low-lying plains landward of it [Claire, James].

c) Topography

The topography of the Estuary is largely low-lying floodplain, consisting of much historically reclaimed land, particularly at the Gwent and Somerset Levels. About 120km^2 of the Somerset Levels are at or below sea level [73] and some regions, particularly the Somerset Levels, have experienced subsidence due to peat shrinkage [Allen 2000, cited in 12]. The topography and bathymetry of the Estuary play important roles in its physical sensitivity by influencing **surge** heights and flood wave and tsunami propagation. Thus, if SLC affects these, **changes in wave characteristics** and **changes in surge characteristics** may result.

d) Coastal configuration

The dimensions of the Bristol Channel are very favourable to the amplification of ocean waves, including tides [74]. The coastal configuration and orientation of the estuary also means it is exposed to strong prevailing winds, which are funnelled up the estuary [James]. Surge heights are also increased due to this funnelling effect: as the channel narrows, it focuses the incoming tidal wave, increasing its amplitude and creating high current velocities [41].

6.2 Ecological factors

Impacts will depend upon the sensitivity and adaptability of ecosystems and individual species, and upon ecological corridors and connectivity. Natural adaptive capacity can be enhanced by people, for example by removing barriers to migration and undertaking **managed realignment**. It can of course also be reduced by inappropriate management or land use practices.

a) Keystone species

Where migration is not blocked, and the rates of SLR are not greater than the rate of communities' capacity to adapt, estuarine plant and animal communities may persist. However, if changes adversely affect keystone species, this may have sweeping community level changes [104]. Keystone species are species that play a unique and crucial role in the ecosystem. Therefore, how ACC and SLC impact these species will affect how the rest of the ecosystem responds. One possible keystone species candidate on the Severn Estuary is the ragworm *Hediste diversicolor,* which is important in the functioning of the sediment system [180].

Together with keystone species, a number of 'significant species' have been identified as 'priorities for action' according to factors such as whether they are endemic to the UK, whether they are declining and/or threatened, whether they are highly characteristic of the area, and whether they are popular with the public [177]. Significant species include: birds such as Bewick's Swan *Cygnus columbianus bewikii* and Dunlin *Caldris aplina*; fish such as River lamprey *Lampetra fluviatilis* and Eel *Anguila anguila*; invertebrates such as the Honeycomb worm *Sabellaria alveolata* and Estuarine barnacle *Balanus improvisus*; and plants such as Corn parsley *Petroselinum segetum* and Eelgrasses *Zostera angustifolia* and *Z.noltii* [177].

b) CO_2 fertilisation

Carbon dioxide fertilisation is the stimulation of plant photosynthesis due to elevated CO_2 concentrations (see **ACC**), leading to enhanced productivity and/or efficiency [64]. CO_2 fertilisation of salt marshes, for example, may improve their resilience and adaptability to change.

c) Species diversity, distribution & structure

The diversity, distribution and structure of habitats affect their sensitivity and capacity to adapt to change. For example, weeds, pests and diseases can reduce the resilience of 'natural' and farmed land. Changes in species, changes in migration patterns and increases in invasive species are significant threats from **ACC** in Wales [179].

d) Species interdependencies

Ecological impacts at the subtidal and intertidal levels may have knock-on impacts up the food chain. Interdependencies may not all be known.

e) Ecological corridors

Species that are more adaptable to new environments or have wider ranges may be able to shift their distribution with ACC and SLC. However, this depends on whether there are ecological corridors and transitional habitats to allow them to move to new habitats [Sandra].

6.3 Hydrological factors

The hydrodynamics of the estuary are partly a function of its geographical setting [41] in relation to weather systems and other landmasses, and partly a function of morphological factors such as the shape of the estuary and its catchment characteristics.

6.3.1 Marine

a) Surge characteristics

There may be a resonant phenomenon with surges as there is with tides, where a surge builds up as it propagates up the estuary [Jack], meaning surges in the estuary may be higher than they would be out on the open coast. Note, due to tide-surge interactions large surges do not tend to occur at high tide (see **surges**).

b) Wave characteristics

The orientation of the estuary means that the outer estuary is far more exposed to swell waves than the inner estuary. Swell waves from the Atlantic decrease in height as they travel up the estuary [41]. Wind waves are more important once the estuary's orientation changes from west-east to southwest-northeast, but decline in height as the estuary narrows and fetch distance decreases [41]. The width of the estuary itself provides for a relatively large fetch for wind-generated waves [Frank] a fetch that is much greater at high tide than at low tide [41].

c) Tides

The Severn Estuary's large tidal range affords a degree of protection from extreme events. The state of the tide has a large influence on the physical vulnerability of the estuary. When the tide is low, extreme water levels caused by for example a storm surge or **tsunami** would be very unlikely to raise water levels above bank or defence levels (James). Only extremely large surges or those that occur near high tide have the potential to cause flooding. For example, the largest recorded surge event on the Severn Estuary was a positive surge of 3.54m, recorded in March 1947 at Avonmouth [37], but fortunately it occurred at low water on a neap tide, so large scale flooding did not occur (ibid). Tides also affect **wave characteristics** [41] by significantly affecting the amount of water in the estuary. The dynamical nature of the tides also means that inundation is different depending on **location within the estuary**.

d) Flood or ebb tidal dominance

Whether an estuary is flood or ebb tidal dominant may influence trends in **erosion and accretion**, with flood dominance being more conducive to accretion [141, 145]. The Severn Estuary is considered to be ebb dominant near the mouth and flood dominant upstream, with the switch located near Avonmouth [41].

6.3.2 Fluvial

a) Catchment characteristics

Catchment shape and size control volume and delivery of runoff[22]. Catchment shape controls the nature of the flood hydrograph[23], and changes in shape can alter the hydrograph and consequential flood risk. For example, set back or managed realignment can reduce the height of the flood hydrograph by holding more water in the floodplain, reducing the flood risk.

At 21,590km² [108] The Severn Estuary has one of the largest river catchments in the UK [131], with catchments of a number of rivers (e.g. the Usk, Avon, Taff and Wye) discharging into the estuary on both the North and South sides [41]. This large catchment means that heavy **precipitation** concentrated in a small locale is unlikely to have a major impact on the estuary as a whole, but that events over large geographical areas can be particularly severe. The Estuary's catchment regions have very different characteristics; for example the short and steep catchments of the Welsh valleys (e.g. River Taff) contrast with far gentler gradients on the Somerset Levels (e.g. River Brue) on the English side, meaning characteristic flood hydrographs are different.

There is limited groundwater resource potential due to underlying lithology [108]. The distribution of water is therefore dominated by surface flow processes, principally from rivers and man-made watercourses [108].

b) River conditions

River conditions such as morphology, ecology and **sediment supply** impact upon flood conveyance, routing and storage [105], and affect how the river moves sediment [Bob]. These in turn affect the **flushing time** of the system and the **erosion and accretion** of sediment. Reductions in river flows are a significant threat from **ACC** in Wales [179].

c) Flushing time

Flushing time is the turnover time for freshwater in an estuary, i.e. the time needed to drain a volume of water passing through the system. The Severn Estuary is a slowly flushed system, with a flushing time of approximately 200 days [68]. Slowly flushed estuaries may be less vulnerable to river flow and surge peaks occurring simultaneously [35]. However, they also hold pollutants for longer, meaning increased exposure and susceptibility to **pollution**, eutrophication and algal blooms, which can be harmful to the ecosystem [104] and thus affect **ecological factors**. Faster flushing times can result from increased run-off, meaning **precipitation** trends and **catchment characteristics** are important.

[22] Runoff is the water leaving a drainage area (precipitation minus water lost by evaporation). It is a function of many factors including catchment characteristics and land use, duration and intensity or precipitation.

[23] A flood hydrograph shows how a river's discharge responds to a period of heavy rainfall, showing rate of flow against time.

7 SOCIO-ECONOMIC VULNERABILITY

The extent to which people are affected by SLC (socio-economic vulnerability) is determined by how sensitive people are to change (socio-economic sensitivity) and how they respond (socio-economic responses). The two factors are considered separately, but many aspects are closely linked.

8 SOCIO-ECONOMIC SENSITIVITY

> ***'Coastal impacts of climate change are likely to be significant and ...certain individuals, groups and communities within coastal areas may have a reduced capacity to adapt to some of these impacts' [22].***

The socio-economic sensitivity theme is composed of factors that influence the degree to which people are affected by change. Together with exposure and socio-economic responses, it determines overall socio-economic vulnerability. The theme is not divided into sections because there is a high degree of overlap between nodes. Instead, it is organised into two clusters: personal sensitivity and community/societal sensitivity. Although the nodes give an idea of the factors that tend to affect a person or community's sensitivity to change, vulnerability is increasingly recognised as highly dependent on context. For example, elderly people are often seen as vulnerable, but it is often factors such as health problems, low income or living in isolation that makes them vulnerable, not their age [22]. Similarly, while research suggests that coastal communities may be particularly hard hit by climate change, not all of them are equally vulnerable.

a) <u>Age</u>

Rural areas around the Severn Estuary have high (and growing) percentages of older citizens, while this percentage has decreased in cities [181]. Elderly people tend to be more vulnerable to change [Sandra] [22], and are less likely to access information and support due to poor IT skills, no access to the internet or a lack of trust in people from outside of the community [22]. These factors contribute to a lack of awareness of the impacts of **ACC** among the elderly [22], and thus a reduced capacity to adapt. Older people are also at higher risk of drowning; for example the majority of deaths in the 1953 East Coast 'Big Flood' were of elderly people [158].

b) <u>Ethnicity</u>

Recent immigrants are particularly sensitive to change due to language barriers, cultural differences [22] and low engagement with information [Sandra], making raising awareness difficult [22].

c) <u>Gender</u>

Males are more vulnerable to dying in floods than females, probably due to risk-taking behaviour [182].

d) <u>Mobility</u>

People with low mobility are more sensitive to flood events [Sandra].

e) Transience

Transient populations in deprived coastal towns may have low awareness of (or be less able to understand) risks and associated **adaptation** measures [Sandra].

f) Income

Coastal flood risk is not evenly distributed among the population in terms of socio-economic status [158]. Although the risk of fluvial flooding is spread relatively evenly across income groups, the people most at risk of coastal flooding in England are those on lower incomes [22, 183] and many disadvantaged groups in the UK live near the coast [22]. A number of urban areas on the Estuary have high levels of deprivation, including Gloucester, Weston-Super-Mare, Burnham, Newport and Cardiff [109]. People on low incomes are more vulnerable as they are unable to buy themselves out of risky areas, and are less likely to be able to afford **insurance** [Sandra]. They are less likely than others to have the necessary **resources**, **knowledge** and ability to choose where they live [22].

A cycle of coastal deprivation (seasonality, low wages, cheap housing and transience) can place high costs on local authorities and other service providers [22], thus impacting **institutional drivers** of responses. Finally, social justice issues also feed into social **resource drivers** of responses, through the cost-benefit analysis (CBA) of measures such as **flood defences**.

g) Insurance availability & take-up

People with flood **insurance** are less sensitive to flood events. However, SLC (together with policy changes) is likely to lead to **decreased availability and increased cost of insurance**. Insurance take-up depends on **income** [Sandra] and therefore may become prohibitively expensive for many [Daisy], increasing the sensitivity of those who are no longer covered.

h) Knowledge

"People don't necessarily know how to cope with even small flooding events" [Roxy].

Peoples' knowledge, awareness, past experiences and access to information may affect their responses and ability to cope with SLC. Education, awareness and warning also appear to be key in preventing flood deaths [182]. The value of local knowledge should not be underestimated [184].

i) Isolation

Physically and socially isolated people and communities can experience heightened sensitivity to SLC. There tend to be a higher proportion of lone people with fewer support networks in cities than in the countryside [Sandra], and hard to reach communities such as those permanently living in caravan parks are often less likely to be engaged in flood risk response activities [22]. Closer communities tend to have less of a problem in obtaining volunteer help for clean-up and repair operations after flood events [185].

j) Health

People with existing physical or mental health problems tend to be more sensitive to the impacts of climate change [22].

k) Provision & design of services & infrastructure (including defences)

The provision of services and infrastructure influences the extent to which people are prepared for and affected by a flood event. The provision of **flood defences** is an obvious factor, with people living in protected areas being less vulnerable, provided the defences hold. Building types and layouts also affect the magnitude of flood losses per unit area [105], and the structure of service networks determines whether a flood has consequences far beyond the area directly inundated [105].

l) Population density and distribution

Figures show slight increases in population figures across all Severn Estuary local authority areas between 2001 and 2010 [108], especially in major cities [186]. There are approximately 80,000 residential and 10,000 non residential properties in over 550 km^2 of tidal floodplain around the Estuary, much of which is concentrated in the major urban areas [107] including Cardiff, Bristol, Gloucester, Newport and Weston Super Mare. There are also hundreds of isolated properties [James]. Due to the nature of the floodplain, particularly in Somerset, lots of threatened people live a long way inland so do not realise that they are at risk [James].

New dwellings continue to be built on floodplains in the southwest of the UK [187] despite rising flood risks, and a number of major developments are currently planned or underway on lowland areas around the Severn Estuary [181]. Indeed, development on the floodplain grew at a faster rate than elsewhere in England in the ten years prior to 2012 [188]. Current and future planning policies will be a key determinant of future socio-economic vulnerability (see **Institutional drivers: government & policy**).

m) Heterogeneity of economic sectors

Regions focusing on one economic sector can be more sensitive to change than more heterogeneous systems. On the scale of the whole estuary, the Severn Estuary has heterogeneous sectors including primary, secondary and tertiary industries. On local scales however, sectors can be more homogenous, for example in coastal towns that rely heavily on tourism.

n) Economic climate

The economic climate is the general condition or 'mood' of the regional or global economy. It controls how much money is available to governments, businesses and individuals, and influences a number of nodes in the model, including **institutional drivers**, **resource drivers**, **environmental management** and **insurance availability and take-up**.

9 SOCIO-ECONOMIC RESPONSES

Adaptive capacity refers to the level at which an individual, community or country can adapt to change, and is a function of a combination of factors such as their attitude and finances [189]. The ways in which humans are responding or might respond to SLC on the Severn Estuary are here termed socio-economic responses. They include mitigation, adaptation and geoengineering responses; the choice and execution of which are determined by response drivers.

9.1 Response drivers

A number of different elements must come together for a response to occur, and there are many drivers of and barriers to these responses [190]. The choice and effectiveness of any given response depends on a number of drivers: institutional, resource, process and social. The choice of which response is 'best' is not an easy one; some decision makers see adaptation as futile and believe SLR will have a big impact, while others think that low rises in sea level will mean adaptation is possible and effective [44]. The most appropriate response is likely to be a combination of mitigation and adaptation [31, 106].

a) Decisions & Conflict

Conflicts can arise when response decisions are made. A prime example is the conflicts that arise from **managed realignment** proposals, which often result in the loss of valuable agricultural land.

b) Institutional drivers: government & policy

A number of different people are responsible for managing flood risk: land owner/developer, local planning authorities, regional planning bodies and the Environment Agency [191]. This can cause problems. For instance, when a seawall in Bridgewater collapsed, there were debates as to who's wall it was and thus who was responsible for fixing it [192]. But generally, there is a widespread view amongst the public that it is the government's job to protect them from flood risk [Daisy][106]. This means government policies and investments will be instrumental in deciding what options are chosen, how they are implemented and who will benefit from them. There is however 'uncertainty over how the planning and flood risk management systems will interact in future' [125].

Institutional drivers operate on a variety of different scales, from local (e.g. management of a drainage ditch) to international (e.g. mitigation or geoengineering agreements). Institutional drivers can be explicit, such as funding decisions for flood defences, or more subtle, for example Health and Safety Executive regulations for ploughing up and down hillsides, which is safer for farmers but increases runoff [Matt].

On national scales, priorities such as food security, planning objectives and environmental protection affect decisions such as whether to allow building on a floodplain, or whether to implement a hard engineering or **managed realignment** scheme. For example, Planning Policy Statement 25 (PPS25) states that construction can proceed in flood risk areas if not appropriate to build in less risky zones [191]. It has been argued that this "build and protect" approach will leave a legacy of rising costs of protection and flood damage with ACC [188]. National government policies may also contribute to **decreased availability and increased cost of insurance**.

Currently, the coalition government's localism agenda is leading to devolution of responsibility to local authorities and communities [22], and Defra is changing how it funds projects and some will require local funding. (see **flood defences: hard structures**).

Devolutionary processes have greatly impacted the institutional framework for climate change risk management. For example, Wales now has its own Environment Agency (EA Wales), and its own National Strategy for Flood and Coastal Erosion Risk Management (FCERM) [193]. Local Authorities also have different responsibilities on the English and Welsh sides of the Estuary with respect to coastal protection (see Table II). The table below summarises the groups involved in managing flood and coastal erosion risks on the English and Welsh sides of the Severn Estuary, as set out in the respective National Strategies for FCERM.

	National flood and coastal erosion risk management strategy for England [194]	National Strategy for Flood and Coastal Erosion Risk Management in Wales [193]
Government	Responsibility for setting out FCERM, led by Defra	Overall responsibility for all matters relating to flooding and coastal erosion
Environment Agency	Strategic overview of sources of flooding and erosion, delivery of management activities (e.g. defences), and provision of flood warnings (in partnership with the Met Office)	Operational responsibilities in relation to flooding and erosion. Oversight responsibilities in relation to all FCERM. Also lead initiatives such as Flood Awareness Wales
Local Authorities	Development of local flood risk management strategies, particularly to alleviate flooding from surface water, groundwater and ordinary watercourses	Responsible for 'local flood risks' including from surface water, groundwater and ordinary watercourses
Internal Drainage Boards	A function in managing the risks of flooding from ordinary watercourses such as drainage channels and streams	Powers to undertake work to secure drainage and water level management e.g. flood defence works on ordinary watercourses
Water and sewerage companies	Managing their own assets or structures where the structure forms part of a FCERM system and to reduce the risk of flooding from their activities	Making the appropriate arrangements of drainage. Primary responsibility for floods from water and sewerage systems
District councils	A function in managing the risks of flooding from ordinary watercourses such as drainage channels and streams	(District councils have local authority responsibilities for areas with no unitary authority)
Riparian land owners	A function in managing the risks of flooding from ordinary watercourses such as drainage channels and streams	(Not referred to in the Strategy)
Highways authorities and other organisations	Management of their own structures where they form part of a FCERM structure	(Local authorities act as highways authorities)

Table II: groups involved in managing flood and coastal erosion risks on the English and Welsh sides of the Severn Estuary, as set out in the respective National Strategies for FCERM

While flood risk on the Severn Estuary (including flood defences, maintenance of river channels, provision of flood risk maps, flood forecasts and warnings, and promotion flood awareness) is managed mainly by the Environment Agency (England and Wales), local authorities also have influence and are heavily involved in the Severn Estuary Shoreline Management Plans. Local authorities also indirectly influence the choice and effectiveness of responses through, for instance, the location of services.

The Severn Estuary Partnership (SEP) is an example of a successful integrated coastal management project [195], aiming to bring all of the relevant Severn Estuary groups together. It was set up in 1995 as an independent, estuary-wide non-statutory initiative and is led by local authorities and statutory agencies to work across all sectors for the management of the estuary. Its roles include acting as a co-ordinating body, promoting stakeholder involvement, and facilitating effective communication across and between individuals and organisations [196]. All of the councils, authorities and agencies will have their part to play as the estuary responds to ACC and its impacts.

c) Resource drivers: human, social, financial & physical

> ***"In wealthy countries, we have the economic means [for coastal defence], if we so choose to use them. But that does mean that we're not spending money on hospitals. There is a resource allocation question" [Jack]***

Socio-economic responses depend on the resources available for such responses. These include technological options, physical resources, human capital (e.g. education level), social capital (trust, norms, networks) and information management (e.g. is the relevant information about the risks available to the relevant people?) [197]. Financial resources can be particularly important, with cost-benefit analysis (CBA) being a major tool for decision makers in the context of **flood defences**. This driver acts over a variety of scales. For example, some individuals are more able to adapt due to higher levels of social justice, and therefore have reduced **personal sensitivity**. On a larger scale, local authorities are currently having difficulty recruiting and keeping appropriately qualified flood risk staff [125] due to financial resources, thus increasing **community/societal sensitivity**.

d) Social drivers: public attitudes, awareness & expectations

Public attitudes and expectations determine both personal and governmental preferences for socio-economic responses, and there are a number of social barriers to adaptation. Firstly, people's perceptions affect how they personally respond to risks such as ACC, SLC and flooding. There is a wealth of literature about public attitudes towards risk [e.g. 198, 199] and the topic will here only be touched upon, by way of a few examples. For instance, people often resist evacuation because they don't believe the risk event is going to happen or they do not detect the risk signal [200]. Indeed, it is wrong to assume that people respond to threats with 'adaptive coping strategies' rather than maladaptive ones, or simply with denial [201]. People employ a number of cognitive strategies to avoid accepting unpleasant futures [202], including denial, reinterpretation of the threat and unrealistic optimism [203]. In addition to such cognitive barriers to adaptation, there are plenty of more tangible ones: including a lack of awareness of impacts (particularly among the **elderly**), a lack of trust in government, conflicting information in the media and confusing information from government [22].

Secondly, attitudes affect adaptation and mitigation on a societal level. For example public reluctance to accept adaptation measures like **managed realignment** can prevent such measures from going ahead. Such opposition has been suggested to stem from a lack of environmental awareness and individualistic pursuit, the public's 'inherent conservativism about the coast', inadequate information and lack of involvement in the decision-making process [32]. But it is a complex and nuanced issue involving trust, historic contexts and social complexities [Frank].

e) Process drivers: understanding, uncertainty & time frames

> ***'A variety of psychological, social and institutional barriers to adaptation are exacerbated by uncertainty and long timeframes, with the danger of immobilising decision-makers' [201].***

SLR is one of the least well understood impacts of ACC [204], and our inadequate understanding of the response of sea level to increasing **greenhouse gas emissions** is constraining government and local adaptation decisions [31].

Uncertainties in processes arise from many sources, including: climate modelling (models are a representation of reality and cannot include all of the intricate complexities of the climate system), **natural variability**, the prediction of future emissions (which are in turn dictated by uncertain societal, technological and economic factors), downscaling data from global to local scales, extreme scenarios prediction, **thresholds, time lags and feedbacks** within the climate system.

The *consequences* of sea level rise also remain uncertain and contested due to uncertainties in the future success or failure of **socio-economic responses** [106]. It is also difficult to quantify and monetise many of the risks, for example to **ecosystem services**. This means that using CBA to choose the best response is difficult, and perhaps misguided. Timeframes are important. For example, planners are interested in 100 or more years, but many sectors are very short-termist. For instance, political cycles work on 4 year cycles, and small businesses tend to work on very short timescales. On such short timescales, issues such as economic crises are seen as more important than SLC.

Uncertainty increases over longer timescales because uncertainties increase with time due to the chaotic nature of the climate system and unknowns such as emissions scenarios.

9.2 Mitigation

So far in the UK, the main focus in tackling climate change has been mitigation, i.e. attempting to reduce **greenhouse gas emissions** [189]. Mitigation includes personal measures to reduce energy use and wider scale measures like renewable energy production (e.g. with a **barrage**). There is disagreement on the scale of emissions cuts required to avoid 'dangerous' climate change [205], with some analyses indicating that cuts of around 80% by 2050 [205], or a roughly linear decline to zero emissions by 2200 [42] are necessary.

a) Barrage

"The Severn Barrage clearly would be a PHENOMENAL influence" [Jack]

Ideas for a Severn Barrage have existed since the 19th Century, and the Severn Barrage Committee was set up in 1925. Popularity has waxed and waned since then: the Committee's 1933 proposal for a barrage generating 800 MW was shelved due to the outbreak of World War II, and serious consideration of the concept only re-emerged with the onset of the oil crisis in 1973. The barrage idea again became very popular with the UK government's proposed target of 15% energy consumption from renewable sources by 2020 [206], but was rejected by the British Government in October 2010, following the Severn Tidal Power Feasibility Study [207]. It was rejected mainly on the grounds of economic feasibility, but there was major opposition from organisations such as the RSPB on environmental grounds. Barrage proposals hit the headlines again in 2012 when shadow Welsh secretary Peter Hain publically supported the project. However, a recent report by a House of Commons Select Committee concluded that Hafren Power, the company behind the latest proposals, have 'failed to overcome the serious environmental concerns' associated with the project and that further research is needed [208].

A number of renewable energy options for the Severn have been put forward, but a barrage from the Vale of Glamorgan to Somerset is the most popular. Such a barrage would provide an estimated 5% of the UK's current electricity demand and create around a thousand jobs [207]. It would also change many of the processes operating on the Severn Estuary. For example, it should reduce the risk of **coastal flooding**, but could increase **fluvial flooding** by holding the low tide level higher, thus increasing **tide locking** [James]. It would cause extensive **ecological change**, particularly the loss of salt marsh and mudflat habitats. A barrage would lead to significant changes in the sediment regime by causing much of the suspended sediment to drop out into the channel [Frank]. A barrage could also affect processes far from the Severn Estuary, perhaps even increasing flood risks in North Wales [James]. Finally, as well as its physical impacts, a barrage would affect other stakeholders and existing investments. For example, it could impact upon existing power stations' access to estuary water [67].

9.3 Adaptation

'Even with strong international action on mitigation, past and present emissions mean that the climate will continue to change and the UK will need to respond' [189].

A commitment to SLC [209] means that adaptation is necessary. Adaptation can be defined as 'the planned or unplanned, reactive or anticipatory, successful or unsuccessful response of a system to a change in its environment' [197]. It can be long or short term, anticipatory or reactive, large scale or small scale.

In the context of coasts, adaptation is a social, political and economic process as well as a technical one. People have been adapting to changes in the coastal zone (including sea-level changes) ever since they moved to coast [197]. This historical experience is important because accelerated SLR is likely to modify existing problems rather than create new ones [197]. In the past, our response to flooding has tended to be reactive (only occur after the impacts are observed) rather than proactive/anticipatory (implemented before the impacts are observed) [210]. However, a proactive response would now be prudent considering the 'large potential impacts of sea-level rise, the less certain threat from other climate change factors such as storminess, and the continued development of the world's coastal zones' [210]. Some decisions can be more reactive than others. For example, ports may respond to what's happened over the last few decades [Jack], whilst integrated coastal zone management probably cannot.

a) Maladaptation

Maladaptation is where adaptation measures increase risks rather than reduce them. It can include increasing **greenhouse gas emissions** (e.g. through the use of air conditioning to adapt to warmer climates), disproportionately burdening the most vulnerable people, reducing incentives for other adaptation, or setting paths that limit future choices [211]. Some adaptive actions may be initially effective but turn out to be maladaptive later [190]. For example, coastal protection designed for a +2^{o}C world may be overcome in a +4^{o}C world [18]. The risks of maladaptation are reduced by improved **understanding** and predictions, and a flexible approach to adaptation measures. 'Low-regrets' measures are those that provide benefits under a range of future scenarios [176]. They include early warning systems, risk communications and sustainable land management [176].

9.3.1 Reactive adaptation

Reactive adaptation takes place in response to impacts rather than before the impacts are observed [197].

a) Unplanned retreat

Unplanned retreat is where people retreat from the coastline in response to an extreme event. Such relocation occurred at the village of Hallsands in Devon, which was destroyed by a storm after offshore dredging depleted the beach.

b) Market responses

Market responses, including changes in insurance premiums and house prices, can have impacts upon **business & industry**, **personal & community wellbeing**, and **government** systems.

c) 'Quick fix' defences

Quick fix defences typically involve the use of sandbags or temporary defences to protect vulnerable properties.

d) Compensation & Disaster relief

Disaster relief during and after an event, and compensation for losses incurred, affect the overall **cost of recovery** of a flood.

9.3.2 Anticipatory adaptation

Anticipatory adaptation takes place before impacts are observed rather than in response to them [197]. Anticipatory adaptation can range from short term personal coping measures such as the storage of emergency food supplies, through to the relocation of towns and cities. Measures can be categorised into **planned retreat**, **protection** and **accommodation**. Many such measures are already in place on the estuary, with much of the land highly managed for flood risk through the use of flat valves, drainage ditches and **flood defences**. People living in areas with more protection are likely to have lower **socio-economic vulnerability**.

9.3.2.1 Planned retreat

Planned retreat is where humans pull back from the coast via land-use planning and development control [44]. It includes **managed realignment** on a variety of scales, and the total **relocation of towns and cities** in the most extreme cases.

a) Managed realignment

Managed realignment (or managed retreat) is where an area not previously exposed to flooding is allowed to flood through the removal of defence structures. Schemes can range from relatively small scale pockets through to the removal of all defences, which would be unrealistic on the Severn Estuary [Frank] due to the sheer amount of land and property currently protected.

Realignment is already underway at Steart in Somerset [212] and is proposed for areas around Lydney, Awre, Slimbridge, Brean Down and Middle Hope during the 21st century [37, 150, 213]. These schemes should create habitats to replace those lost through **coastal squeeze**. However, recent research shows that coastal salt marshes created by managed realignment are not equivalent to those that they replace, and therefore do not satisfy requirements of the EU Habitats Directive[24] [154].

Managed realignment is difficult in many places on the Severn Estuary due to its topography and high concentrations of costly investments at the coast. It is also often very unpopular with local residents, and there is conflict between managed realignment and food security. Food security is already high on the national agenda, and may become more so in future, for example for climate change **mitigation** (reductions in food miles). These issues combine with a fashion for public consultation, localism, a focus on victims and institutional inertia to hamper managed realignment schemes [214]. Currently, most realignment is proposed for the English side of the estuary rather than in Wales, which causes further tensions [James].

b) Relocation of towns and cities

If global average sea temperatures rise by 4°C rather than 1°C or 2°C, adaptation may have to be more extreme, for example the relocation of cities rather than **flood defences** or **managed realignment** measures [18].

9.3.2.2 Flood defences

We don't *have* to retreat, even with high SLR [Jack]. While protection comes at a significant cost, analyses suggest that in densely populated areas protection costs are much less than the impacts they help to avoid [54]. The future of flood defence on the Severn Estuary will have a major impact on future flood risk. Decisions will be value judgements as to what is worth protecting, and will inevitably cause conflict.

a) Hard structures

'Current levels of investment in flood defences and uptake rates of protection measures for individual properties will not keep pace with the increasing risks of flooding. Climate change could almost double the number of properties at significant risk of flooding by 2035 unless there is additional action' [188].

Hard defences include sea walls, groynes and breakwaters. On the Severn Estuary, some **infrastructure** structures also act as 'accidental' defences, particularly the national railway line near Caldicot, and the M5 motorway, which runs down the southern edge of the Estuary. Hard defences tend to perform two functions: protecting the coast from **erosion** and reducing the likelihood of **flooding** [70].

The 'vast majority' of the Severn Estuary coastline is currently protected by coastal defences, some of which date back to Roman times [123]. Flood defences have been getting progressively better since the end of the 1700s, meaning flood incidence has decreased [Claire]. Coastal defence work is ongoing; for example a tidal barrier is planned for the River Parrett in Somerset [192].

An increasing risk of overtopping and/or breaching of such defences is expected due to deterioration with time as well as the effects of SLR. However, during the period up until 2020, when SLR is an expected 3.5mm per year, 'only isolated lengths of the tidal defences are at any significant risk of

[24] The EU Habitats Directive, together with the Birds Directive, forms the cornerstone of Europe's nature conservation policy. A network of protected sites, including the Severn Estuary, protects hundreds of species and habitats of European importance.

failure' [107], and the Severn Estuary's defences are generally in good condition (though some would be of concern [Matt]). It should be noted that Severn Estuary defences have not recently been tested by a major event.

All of the existing flood defences around the Severn Estuary would have failed by 2060 if they are not maintained [88, 215]. This would mean much of the low-lying land around the estuary flooding several times a year [88], which would render current land uses difficult to maintain [37]. The worst-case scenario would see approximately 1000km² inundated, with 198,000 properties directly affected and widespread ecological degradation [88]. This should of course not happen, because the Environment Agency makes constant improvements to estuary defences. However, defence spending has been cut by the Coalition government and the defence funding climate is changing [168].

As central government spending for maintaining and improving current flood levels is reduced, Defra is changing how it funds projects, meaning some will require 'significant additional funding being secured locally' [125]. Rather than depending on the cost-benefit ratio, it depends on the ratio of benefits to central spending. So projects with low CB ratios that attract funding are more likely to go ahead than those with higher CB ratios that have not attracted local funding [125].

Defences impact upon many other nodes in the system. Firstly through resource allocation: government money spent on defences is money not spent on other services, and flood defence works are translated to public pockets through taxes. Secondly, the coast of the Severn Estuary is a connected system, so a defence in one place impacts processes in another, shifting **erosion** patterns and flood wave transmission. Finally, while coastal defence developments can protect people from risk, they can also lead to a false sense of security.

b) Soft defences

Soft defences include beach nourishment and the rehabilitation of natural coastal protection such as salt marshes and sand dunes. The implementation of **managed realignment** schemes can provide such soft defences through protecting or recreating salt marsh habitats.

9.3.2.3 Accommodation

Accommodation is where natural processes are allowed to occur and human impacts are minimised by adjusting their use of the coastal zone [44]. Measures include education, insurance and increasing the resilience of designs and investments.

a) Education & awareness

Education and awareness operate at a number of scales to reduce vulnerability to SLC. On a personal level for instance, people can be educated to not eat any food contaminated with flood waters. Work is ongoing to raise awareness of flood risks in around the Estuary, for example the Welly Boot Tour run by Environment Agency Wales, with funding from the Welsh Assembly. On a stakeholder level, building practices can be improved to increase resilience to flood events (such as installing plugs half way up the wall rather than in the skirting boards). On a governmental level, raising risk awareness can inform better management decisions.

b) Prediction, emergency planning & warning

Emergency plans have been set up around the Estuary, for example community flood plans and refuges have been set up in Wales. However, it is questionable whether the procedures could cope with the large number of people who may be affected by an extreme event on the Severn Estuary [Daisy].

The POL storm surge model run at the Met Office's Flood Forecasting Centre provides surge forecasts for 35 sites around the UK coastline, including sites in the Severn Estuary, for the Environment Agency [216]. They are used, together with data from the National Tide Gauge Network for coastal flood warnings in England and Wales [216]. The storm tide warning service has however had some accuracy issues in the estuary [Matt].

c) Insurance

Flood insurance is a means of sharing the burden of the cost of flood damage across populations and through time [217]. But flood insurance provision is changing due to new environmental uncertainties arising from climate change, policy makers becoming more capable of spatially differentiating risks, and pressures to limit public commitments to flood defences [218]. This means that a **decreased availability and increased cost of insurance** is expected around the Severn Estuary [Daisy].

d) Increased flexibility & resilience of designs, structures, services & investments

This node refers to methods of increasing the range of sea levels that a coastal system can withstand. They include measures to reverse trends that increase vulnerability (e.g. only allowing hospitals to be built in low-risk areas) and measures to increase flexibility of vulnerable managed systems by allowing midterm adjustments and re-appraisals (e.g. the All Wales Coastal Path, which has been flexibly routed to accommodate coastal changes [Roxy]). Planners need to plan a long way ahead because many of today's designs and investments will be expected to still be here in a few hundred years time [Roxy]. On a personal scale, people can increase the resilience of their own properties by installing floodboards etc.

9.4 Geoengineering

Geoengineering is 'deliberate large-scale intervention in the Earth's climate system, in order to moderate global warming' [219]. Modelling by Moore et al [220] examined the impacts of five geoengineering approaches to mitigating SLR: stratospheric aerosol injection[25], mirrors in space, afforestation, biochar[26], and bioenergy with carbon sequestration. Their results suggest that the 'least risky and most desirable way of limiting sea-level rise is bioenergy with carbon sequestration', although aerosol injection and space mirrors could also limit or reduce sea levels if they were to reduce insolation at a fast enough rate [220]. Geoengineering is seen by many as very much a last resort: much is unknown about wider impacts of such approaches, and the implementation of geoengineering could have wide-ranging direct and/or indirect impacts on numerous Severn Estuary processes.

9.5 Do nothing/wait and see

[25] Stratospheric aerosol injection is the injection of small particles into the stratosphere to reduce the amount of solar radiation entering the lower atmosphere.

[26] Biochar is a method of sequestering carbon from the atmosphere and storing it as charcoal.

Timing is an important factor in all **socio-economic responses**. Planners may decide to do nothing, or monitor and actively respond when more information is available [Jack].

10 Thresholds, time lags and feedbacks

A number of thresholds, time lags and feedbacks operate with regard to SLC processes and impacts on the Severn Estuary.

A threshold is a condition marking the transition from one state to another. For example, **ACC** passing key (but uncertain) thresholds for irreversible breakdown of the Greenland Ice Sheet and the West Antarctic Ice Sheet could lead to a commitment of SLR of 13-15m over many centuries [106]. Thresholds are also important in adaptation decisions. For example, coastal protection may be viable up to a SLR Of 50cm, but managed retreat more viable for 60cm. There are also thresholds with how much (e.g. flooding) people can put up with before they respond.

A time lag is a length of time separating two correlated physical phenomena. For example, thermal inertia of the deep ocean means that SLR will continue long after climate forcings have ceased [106]. And modelling suggests that 'the majority of SLR from Greenland dynamics *during the past decade* [emphasis added] is yet to come' [221]. Some models show a 1m commitment to SLR even if climate change was stabilised immediately and all major ice sheet deglaciation avoided [209]. There is also inertia in many of the systems in the **vulnerability** theme. For example, building regulations don't currently state that plugs have to be high up on walls. Such a regulation would take a while to filter through the system because construction employees would need to be trained, supply lines would need to be set up and markets would need to be established [Sandra].

Feedbacks are where changes in one condition cause a response that leads to further change in the initial condition. Negative feedbacks can lead to self-equilibrium, while positive feedbacks can lead to snowballing effects. The numerous feedback mechanisms in the climate system include releases of methane (a powerful greenhouse gas) from surface waters as ice melts [222] contributing to further warming, and increased warming caused by the reduction of surface albedo through extensive permanent inundation [223].

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