# DETERMINING A SUSTAINABLE APPROACH TO MANAGING AN ESTUARY MOUTH – A CASE STUDY

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Estuaries and their floodplains represent locations where significant population, industry and environmental interests exist. Sand spits located at estuary mouths are one factor in influencing both hydrodynamics and geomorphology. As such, their management is important as regards managing both flood and coastal risk, and the evolution of designated flora and fauna. This paper describes a study to develop a way forward for managing Dawlish Warren sand spit, located at the mouth of the Exe Estuary in Devon, UK. Dawlish Warren sand spit is important as it influences geomorphological evolution of the mouth and wider estuary, provides storm sheltering for up to 2,900 properties and national transport infrastructure in the estuary, is an internationally designated Special Area of Conservation (SAC), and influences the wider Exe Estuary Special Protection Area (SPA).

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## OVERVIEW OF EXISTING SITUATION

The Exe Estuary is located in Devon, UK (see Figure 1). It is a spit enclosed drowned river valley (Defra, 2007), which has been subjected to marine inundation caused by a rise in sea level at the end of the most recent glaciation (which ended c. 12,000 years ago). The Exe Estuary has a shoreline length of 40km, channel length of 16km, valley width 2km and a mouth width of 380m. It is classified as macrotidal with a range of 4m, whilst the River Exe (the main tributary) has a mean flow of 23m$^3$/s, and a maximum of 371m$^3$/s. At the mouth of the Exe Estuary, the sand spit of Dawlish Warren covers approximately three quarters of the estuary mouth width, and consequently potentially shelters the estuary from the coastal swell wave climate, as well as influencing the propagation of extreme tide levels. The in-estuary extreme wave climate is consequently limited to significant wave heights of less than 1.1m, with extreme tide levels between 3-4mAOD. The estuary exhibits high tidal velocities through its mouth, with flood/ebb tidal deltas and offshore banks present.

The Exe Estuary has been significantly modified over centuries. In the 12$^{th}$ century the majority of the west bank floodplain was reclaimed, with what was the adjacent mobile sand spit being fixed with seawalls and developed as the town of Exmouth in the 15$^{th}$ century. The mainline railway was built in the 18$^{th}$ century, reinforcing and extending the west bank floodplain reclamation. Dawlish Warren sand spit itself has a long history of being damaged and breached in storm events, with around 13 such events in the last two centuries. In response to this, engineers applied increasingly extensive engineering methods to manage the sand spit, currently including groynes, gabions, rock armouring, concrete revetments and wave recurve walls. The assets managing flood and erosion risk have allowed the development of villages and towns to occur within the floodplains, along with their associated infrastructure. Over the last 50 years the Exe Estuary has also become a heavily designated environment. The mudflats, saltmarsh and wetlands in and around the estuary, and the bird population supported by these, are Ramsar and SPA designated features or sites. Dawlish Warren sand spit itself is designated as a SAC for the physical processes (dune system) and flora and fauna dependent on these.

The management of Dawlish Warren sand spit is therefore of particular importance, as it will influence:

- Flood risk for 2,900 properties in the present day, and up to 7,000 properties by 2110 due to climate change, in the wider Exe Estuary.
- Flood risk to the nationally important mainline railway, as well as regional and local infrastructure.
- Physical environments (both saline and freshwater) that support the Exe Estuary SPA designated features.
- Ecology and physical processes that are designated features of the Dawlish Warren SAC.

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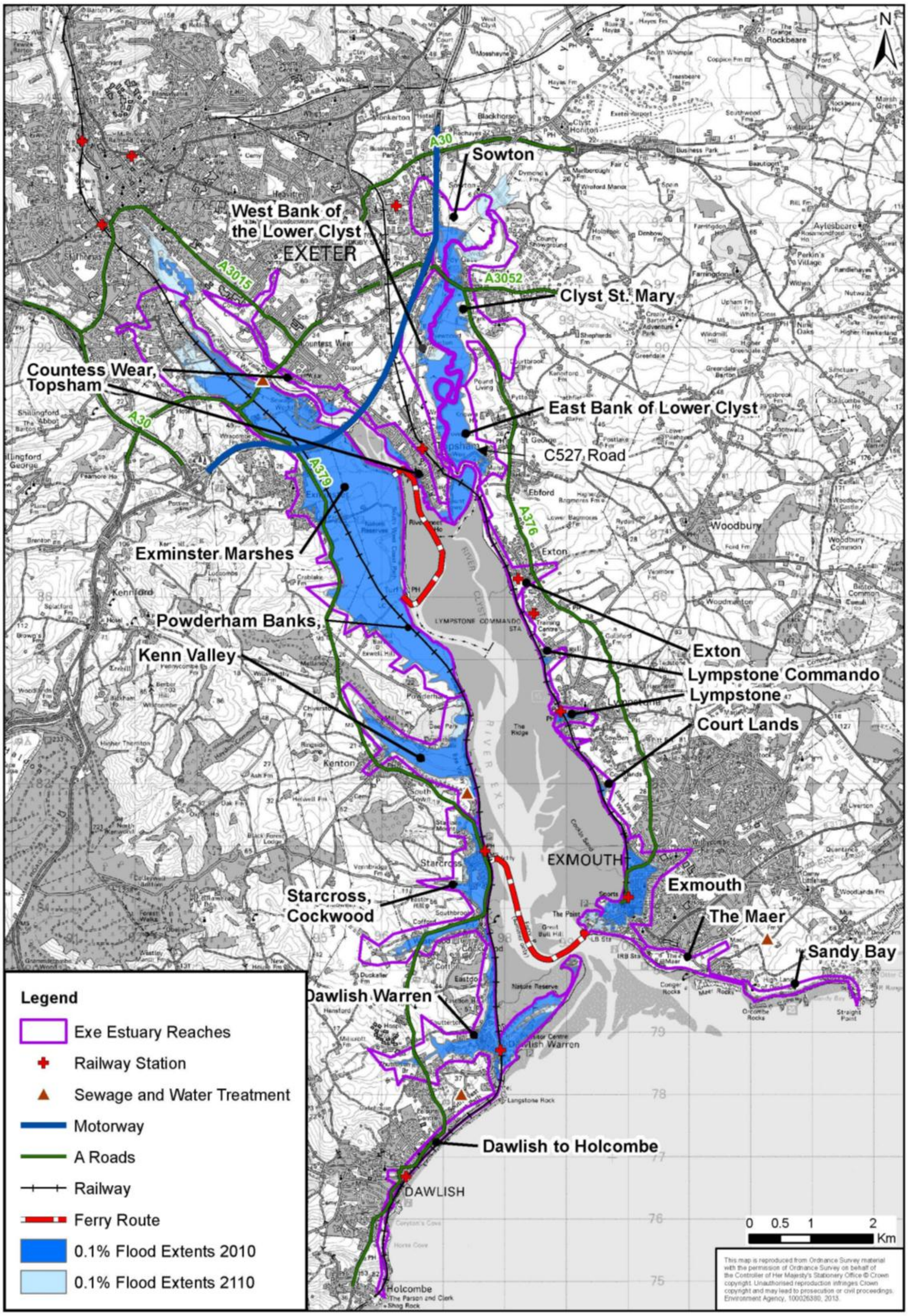


**Figure 1. Overview of the Exe Estuary and its key features.**

## STRATEGIC CONTEXT

The UK applies a hierarchical approach to flood and coastal erosion risk management (FCERM). At the location of interest, the broadest decision-making along the coast and estuaries is assessed within the Exe Catchment Flood Management Plan (CFMP), and the South Devon and Dorset Shoreline

Management Plan (SDAD SMP2), defining policy for managing fluvial flood risk, and coastal flood and erosion risk, respectively. Whilst the Exe CFMP recommended further action in the future to sustain the current level of flood risk, the SDAD SMP2 was not able to clearly define policy for managing coastal risks at Dawlish Warren sand spit (and therefore affecting the wider estuary also), due to the complexity of the sand spits combined SAC, SPA and FCERM functions. As a result the SDAD SMP2 recommended that a strategy study be undertaken to investigate and determine sustainable way forward for FCERM within the Exe Estuary in response to climate change, particularly relating to the future management of Dawlish Warren sand spit. The Exe Estuary FCERM Strategy was recently completed and approved by the UK government, and sets out how flood and coastal risks, and habitat, around the Exe Estuary, in Devon, UK, will be managed over the next 100 years. The technical framework used to understand changes to the physical estuary system, and consequential impacts on the natural and built environment is described below.

## TECHNICAL APPROACH

### Overview and framework

The technical framework was developed to link a wide range of different analyses to give a whole system view, and provide robustness by not relying solely on one technique. A schematic diagram of the framework is given in Figure 2. This is based on the source-pathway-receptor concept, defining the sources of risk (predominantly hydrodynamic and geomorphological), the pathways for the risk to be transferred (mainly overtopping, damage or breach of natural or engineered structures with an FCERM function), and the receptors of risk (such as infrastructure, people, property, flora and fauna). Details of the elements of the technical framework follow.

### Hydrodynamics and geomorphology

The hydrodynamics and geomorphological evolution of the estuary system were investigated and defined by critical review of the white and grey literature, historic trends analysis, and predictive modelling. An extensive literature search found valuable studies and observations (both quantitative and qualitative), including:

- Historic documentary evidence of natural events (storms) and man-made (engineering) interventions from the 12$^{th}$ century onwards, with more detail after the 18$^{th}$ century. This provided qualitative evidence, for example, of the timing and duration of large-scale breaching of the sand spit.
- Recent qualitative observations and expert interpretations of geomorphological linkages between the ebb and flood deltas, beaches, off-shore banks and sub-tidal channels, from the 1960s onwards.

The historic trends analysis collected and quantitatively assessed:

- Ordnance Survey mapping (from 1880s, 1930s, 2000s) and aerial photography (1941, 1946, 1950, 1960, 1969, 1979, 1988, 2000, 2011). These were particularly useful in identifying the extent and location of sand spit breaching; the duration prior to self-healing of breaching; the variation in ebb/flood delta extent over decades; and the transfer of sand waves between the ebb delta and sand spit.
- Bathymetry surveys and charts (1830s, 1890s, 1930s, 1980s, 2000s, 2010s), LiDAR (1998, 2007, 2013) and annual beach profiles (2007 to 2014). These provided data to quantify sediment exchange rates on the order of decades and years.
- Wave buoy and tide gauge monitoring (2007 to 2014), used to confirm the astronomic and extreme wave and tidal climate.

Predictive modelling was undertaken, consisting of coupled two-dimensional hydrodynamic and sediment transport modelling. This was used to transform offshore waves to the near-shore; quantify tidal flow vectors; and indicate quantified bathymetric changes due to sediment transport. All the above studies were used to develop a model of the sediment transport linkages and exchange rates within the estuary system, and an understanding of relative uncertainty of hydrodynamic parameters and geomorphological change, summarized in Figure 3. Salient findings include:

- Visual record of the sand spit breaching in the 1940s, with initial re-attachment within 5 years, and up to 20-30 years for complete regeneration of the distal section. This is shown in Figure 4.
- Ebb delta location and geometry resulting in wave refraction from SW-SE to SW-S, resulting in near total sediment transport from west to east along sand spit.

- Continued erosion of the sand spit, with distal section now also showing signs of erosion due to inlet constriction.
- Continued accretion of the ebb and flood deltas, likely to eventually be limited by fundamental physical constraints.
- Intermittent transferal of large sand volumes from the north of the ebb delta, across to the distal section of the sand spit.
- Lack of aeolian sediment transport across Dawlish Warren sand spit, due to low level and width dry beach width.

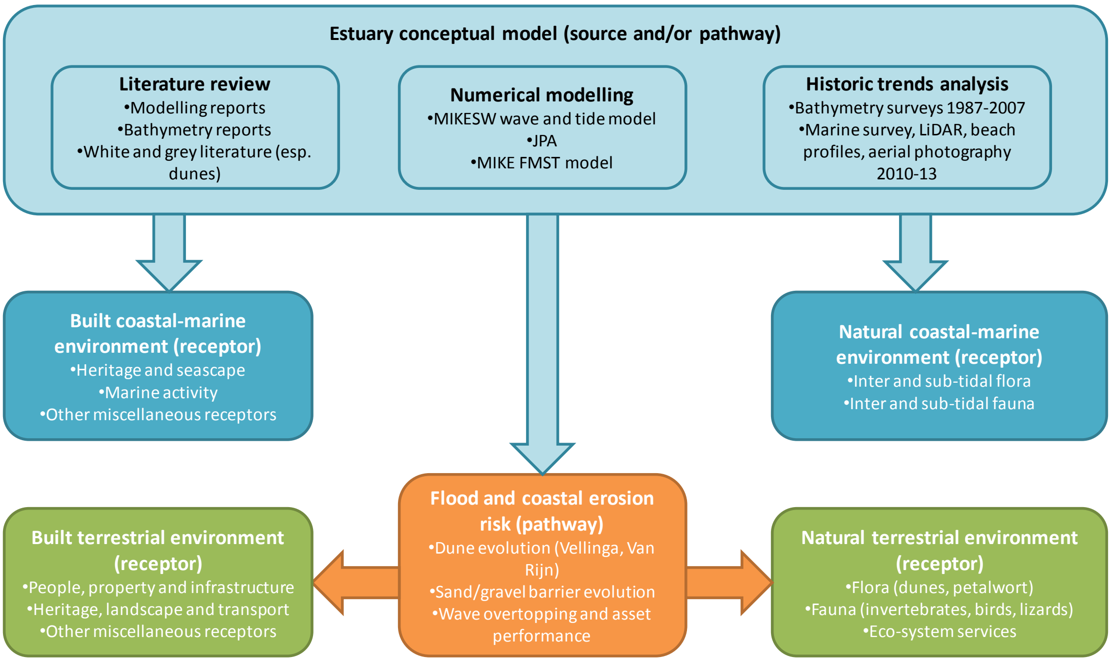


**Figure 2. Schematic diagram of the technical framework.**

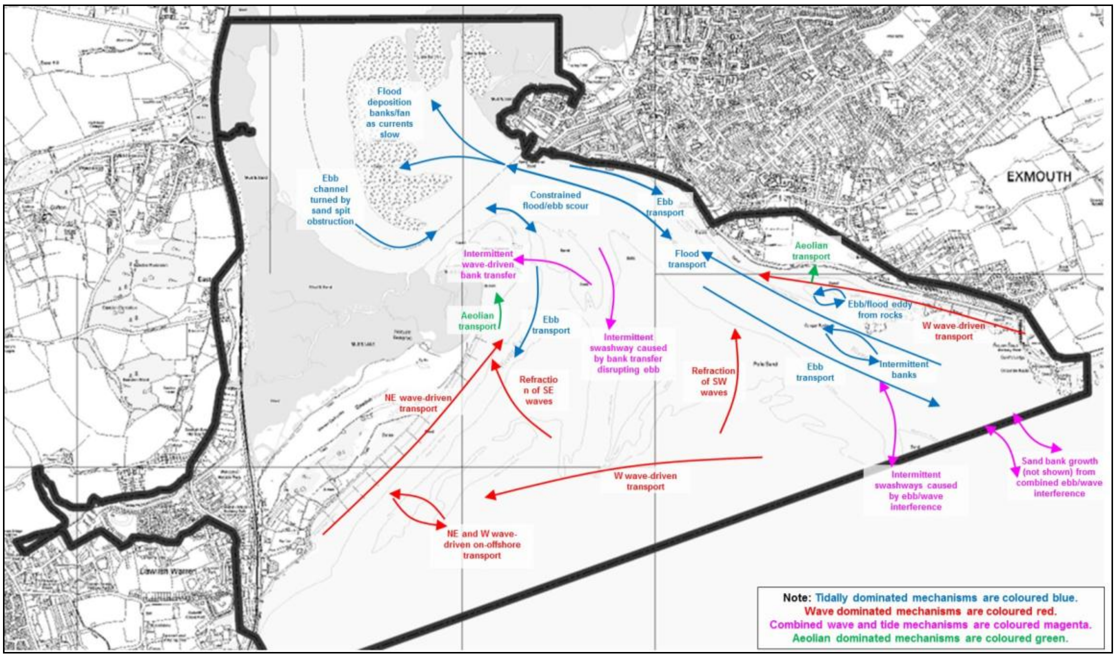


**Figure 3. Graphical representation of sediment linkage and budget model.**

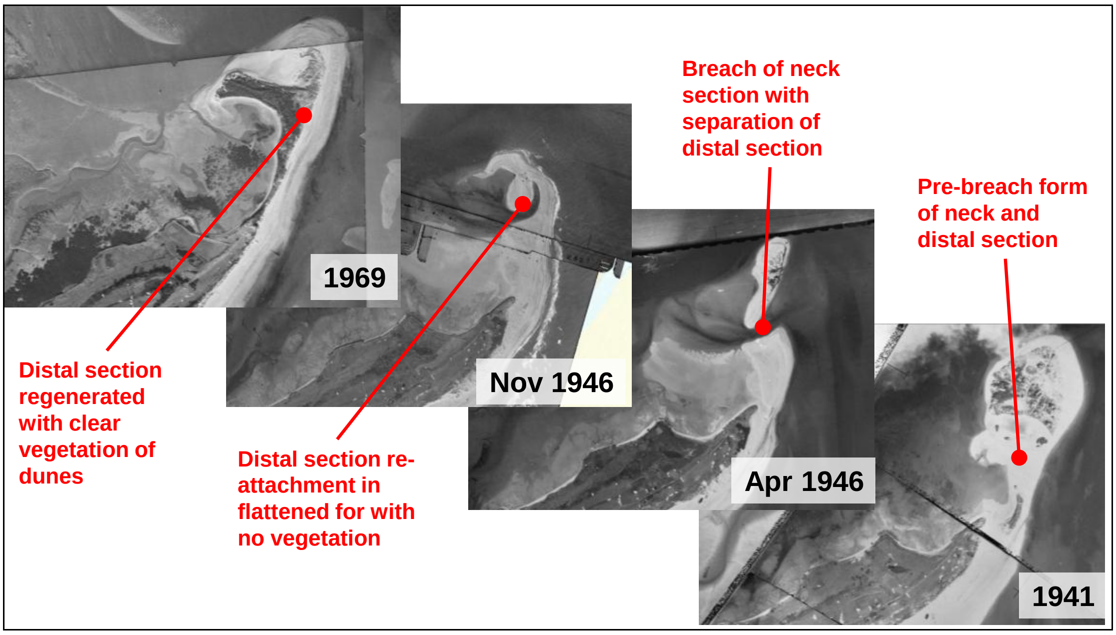


**Figure 4. Historic aerial photography record of sand spit breach, flattening and eventual regeneration.**

**Flooding and coastal erosion**

Analysis of the performance of the beach, dune and FCERM asset system was undertaken using the methods described in Vellinga (1988), Van Rijn (2013) and EC (2007), applying the hydrodynamic and geomorphological inputs described above. The predicted dune recession, based on MHWS as the approximate toe of the dunes and accounting for the cumulative probabilistic impact of 100%-0.1%AEP events, is shown in Figure 5, including the likely eventual transition of the low-lying terrestrial dune slacks in the sand spit to a tidal inlet. The wider evolution of the estuary mouth, drawing also on the hydrodynamic and geomorphological work, is shown in Figure 6.

A particularly stormy period occurred during December 2013 to February 2014. Wave buoy and tide gauge monitoring was present throughout the duration of this period, with pre/post-storm beach and ebb delta surveys also undertaken. The opportunity was therefore taken to determine the extremity of the storms (individually, sequentially, and as joint probability wave-tide events), and compare the response predicted by the conceptual model to that observed in the field. This identified that 20 greater than 100% Annual Exceedance Probability (AEP) events occurred over the three month period. Within this, three particularly extreme events (on 3rd, 5th and 14th February 2014) were observed, with 100-20%AEP high tides (2.84-2.94mAOD) coinciding with 100-5%AEP significant wave heights. In joint probability terms these three events are estimated as having 5-2%AEP, and if the extreme events are simply considered as independent and sequential then overall the three month stormy period would be estimated as 3%AEP. However it should be noted that this simple sequential estimate does not capture the impact of the many near or below 100%AEP events that would have repeatedly caused low level damage to the beach and groynes. A summarized analysis is given in Figure 7.

The observed storm event wave and tidal data was inputted to the analysis of beach and dune erosion. The Vellinga (1988) and Van Rijn (2013) analyses suggested that, without the presence of the existing gabions, the majority of storms would not have caused significant recession (due to the lower extremity of the high tides), but with six storm events (1st, 5th, 18th and 31st January; 3rd and 27th February) predicted to caused dune recession of up to 6m individually. Taking the sequence of storms as a whole, the cumulative dune recession could therefore have been over 20m, enough to cause a temporary breach along the central section of the sand spit. The observed dune recession after the storms was up to 5m along the central section (with gabions present), with the gabions severely damaged.

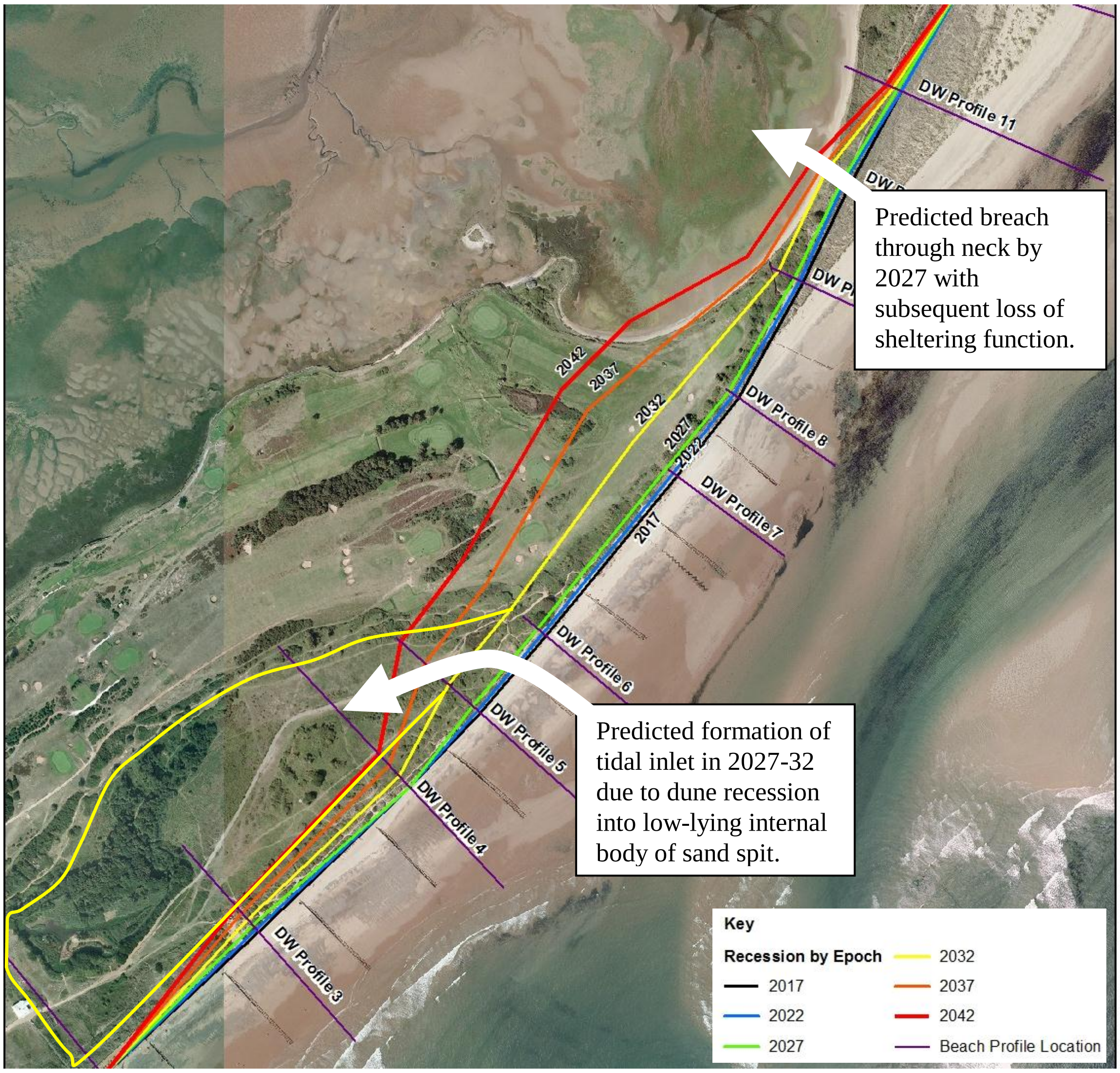


**Figure 5. Predicted dune recession and transition to tidal inlet with no further man-made intervention.**

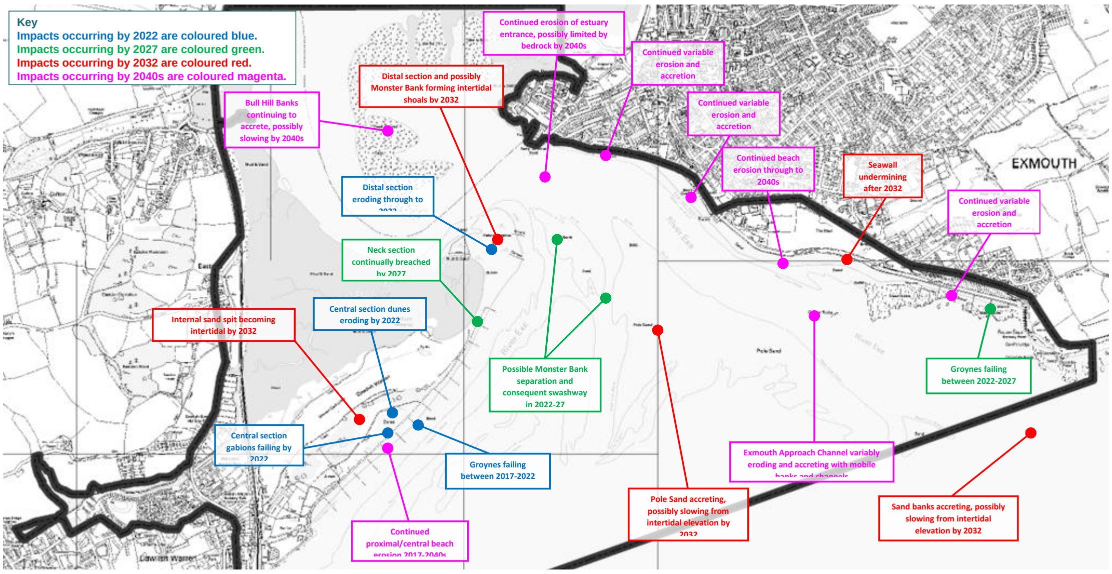


**Figure 6. Predicted estuary mouth evolution with no further man-made intervention.**

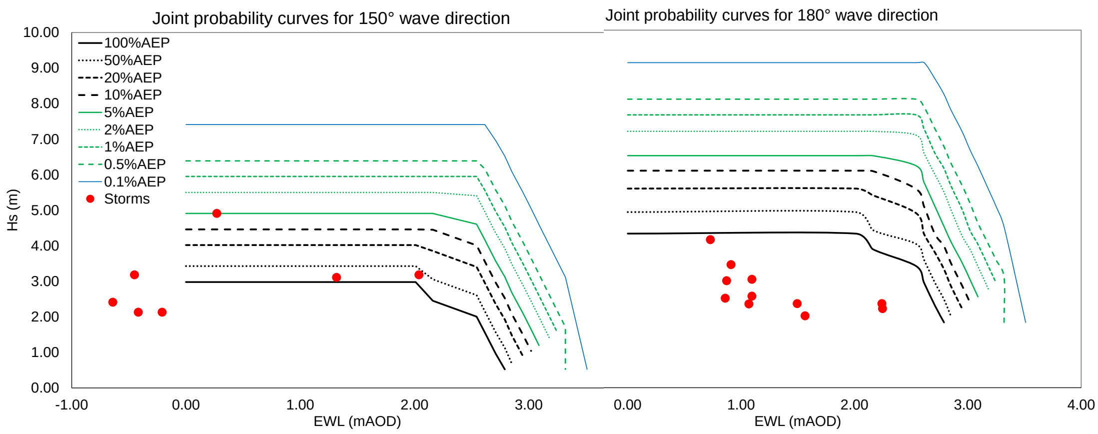


**Figure 7. Estimation of individual storm AEP in relation to wave-tide joint probability curves.**

## Natural and built environment impacts

Analysis of the impacts on the natural and built environment was based on the Strategic Environment Assessment process (expert judgment informed by quantitative analysis) and quantification of economic damages (based on Environment Agency, 2010). Core inputs to the analysis were the FCERM performance of natural and engineering assets, consequent inundation and/or erosion, as well as receptor data (environmental designation features, people, property and infrastructure). The influence of predicted sand spit breaching on the extreme wave and tide climate in the estuary, and the consequent impact on asset performance and economic damage is shown in Figure 8.

The influence on designated features was based on sub-intertidal and terrestrial habitat change as a proxy measure of (for example) bird usage, shown in Figure 9. This was based on:

- Prediction of future estuary bathymetry based on estimated the estuary sediment linkage and budget model (defining vertical and lateral rates of erosion or accretion).
- Prediction of future astronomic tidal levels based on future sea level rise predictions for a range of climate change scenarios.
- Zoning of the present day intertidal habitats using astronomic tide levels (RSPB, 2005). This identified the present day distribution of mudflat, saltmarsh and transitional habitats. The results of this analysis were checked against available habitat mapping and field observations for validity.
- Prediction of future intertidal habitat extent based on the future estuary bathymetry and astronomic tide levels. The results of this analysis were reviewed in light of historic observations, and whether the changes occur within and without the existing SPA, SAC and Ramsar.

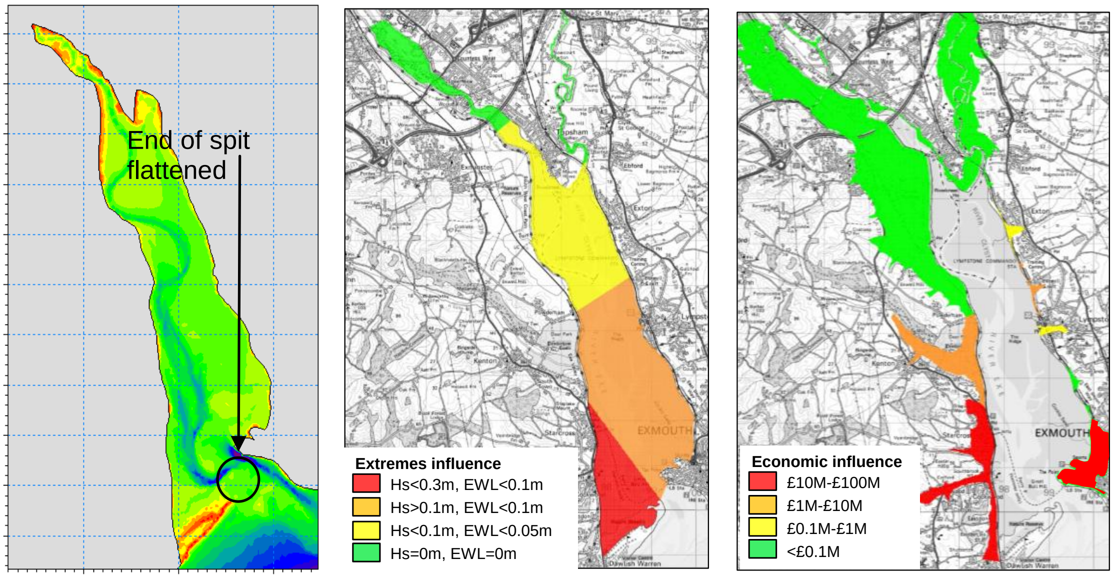


**Figure 8. Influence of sand spit on economics (geomorphology-extremes-economics).**

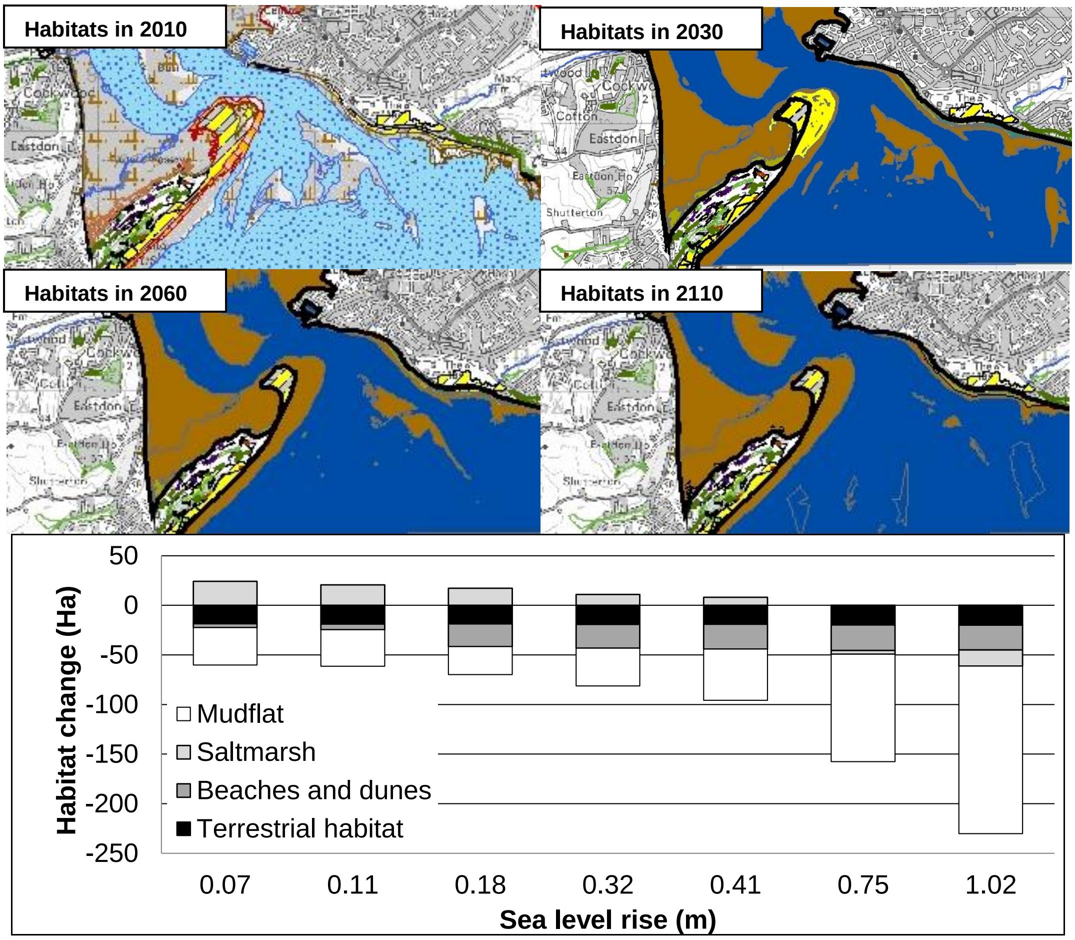


**Figure 9. Influence of climate change on environmental designation (geomorphology-astronomic tides-habitats).**

## SUSTAINABLE MANAGEMENT

### Analysis of management scenarios

The development and verification of the technical framework and its baseline findings provided a powerful holistic tool to investigate the impacts of different future management approaches. Whilst this was undertaken for the whole estuary, the analysis related to management of Dawlish Warren sand spit is focused on herein. A simple representation of the physically viable range of management approaches is given in Figure 10, with description of the environmental and economic impacts included. In summary, there is a clear environmental (legal) driver to remove the gabions and allow natural beach-dune processes to restart. In tension with this, analysis of the relative economic cost for the management approaches highlighted that the optimal timing to accept loss of the sand spit sheltering function and up-engineer the estuary assets (analyzed as up to 0.5m asset raising to withstand the increased wave climate due to loss of sheltering function) would be in the 2040s (this is shown in Figure 11, where the comparative costs of the two approaches cross).

Consideration of the conceptual model understanding indicated that the environmental and economic drivers could both be achieved by:

- Phased removal of the gabion system throughout 2017-2030, with the neck section gabions removed last and replaced with localized buried rock armour. This would enable the sheltering function to continue through to the 2040s, based on a lag between gabion removal and cumulative erosion of the neck section.
- Beach recharge in 2017 and potentially 2030, to increase the dry beach width and height, and restart aeolian transport onto and over the dunes. The beach recharge would also support continuation of the sheltering function. The recharge material would be sourced from the accreting ebb delta, representing a large scale sediment recirculation.
- Construction of a wall/embankment structure in the sand spit body to cut off an internal flood route through to the local village (an existing risk now, and in the future as gabion removal allows the dunes to naturally reform).

### Scheme development and local management

The current scheme outline is given in Figure 12. Further design and licensing work will be undertaken to enable construction in 2017. However, in the interim period between 2014 and 2017, existing risks still need to be managed. The strategic evidence and justification for future management provides a useful guide in this period for how, when and why to respond to storm damage. The storms of December 2013 to February 2014 provided an example of this, where significant damage to the central to neck section gabions and dunes occurred. Rather than the conventional response of repairing the whole length of assets at significant and ineffective cost, the strategic plan focused the response on a) repair to the critical neck section gabions, b) monitoring of the central section gabions and dunes but no action (apart for public health and safety reasons), and c) accelerated construction of the wall/embankment structure across the internal sand spit body, to provide secure, sustainable management of risk to the local village.

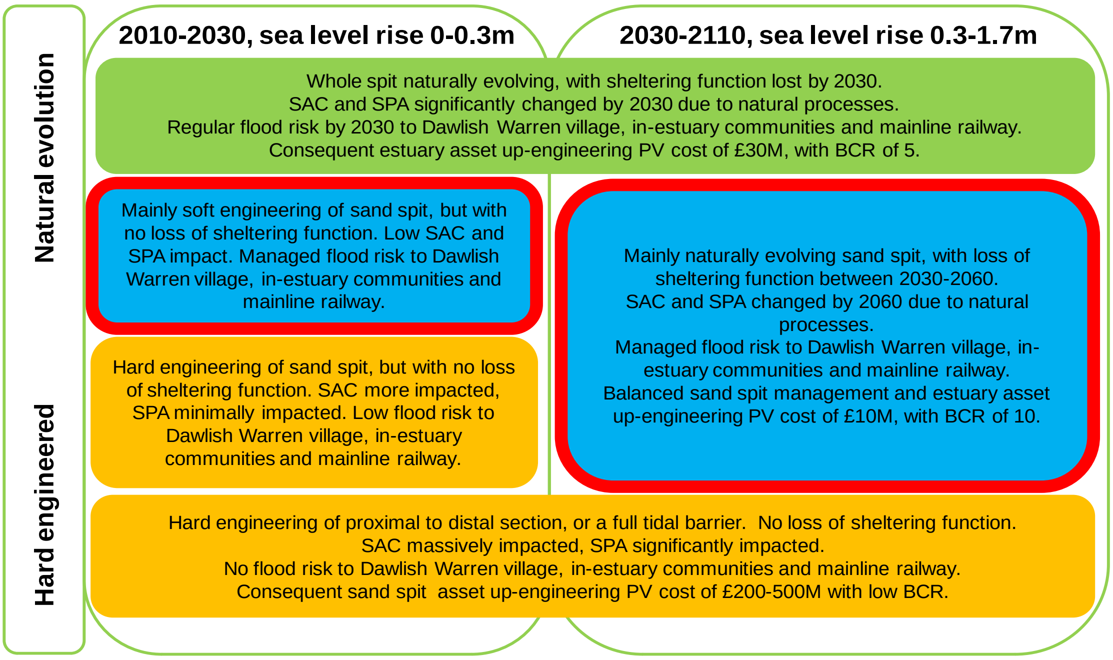


**Figure 10. Physically viable range of future management approaches for Dawlish Warren sand spit.**

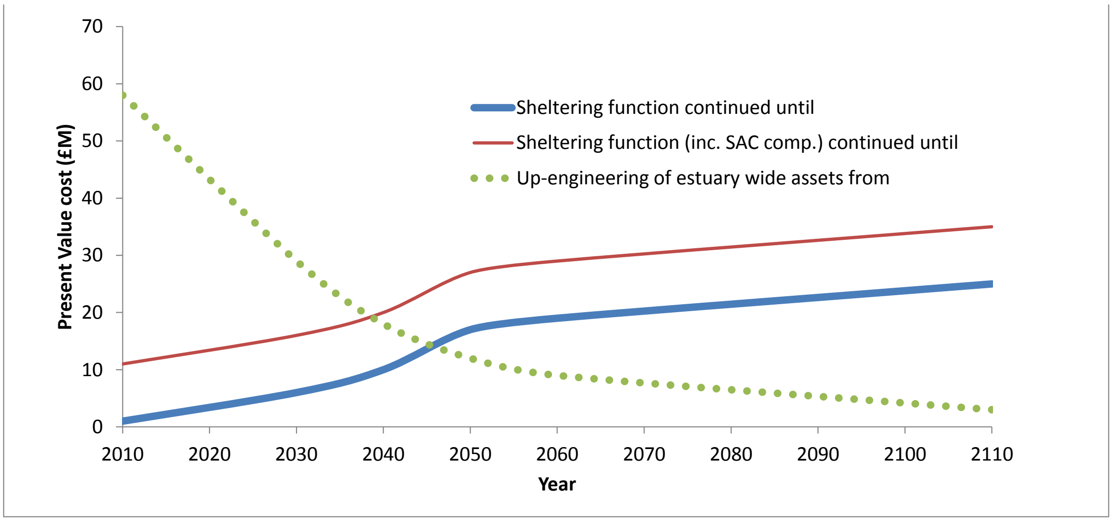


**Figure 11. Optimal timing of transition from sheltering function management to estuary asset up-engineering.**


**Figure 12. Outline of scheme.**

## CONCLUSIONS

The geomorphological model of the estuary mouth and sand spit system has identified the value in developing a wide evidence base to justify changes in management to stakeholders, decision makers and regulators. The model has been used to support a rigorous examination of possible management approaches, enabling informed justification for a more sustainable approach, balancing environmental and economic drivers. The strategic long term management approach has also guided local short term responses to storm events. The overall approach described in this study is applicable to other parts of the world where spits or coastal barriers potentially influence flood and coastal erosion risks.

## ACKNOWLEDGEMENTS

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