PRESENT AND FUTURE CONDITIONS FROM PLYMOUTH SOUND TO EXE ESTUARY

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1. INTRODUCTION

The Plymouth Sound to Exe Estuary site is located in southwest England, see Figure 1a, encompassing a 100 km stretch of coastline bordered by the English Channel. The site is one of the most diverse coastal settings in Europe and incorporates a range of habitats from exposed rocky and shingle coast to sheltered mud of flooded valleys or 'rias' together with densely populated urbanised and industrial zones of Plymouth Sound, Torbay and Exeter.

(a) Plymouth Sound to Exe Estuary

(b) Exe and Teign Estuaries (c) Teign Estuary

Figure 1. Study site – Plymouth Sound to Exe Estuary

Within the study site, we focus first at the medium scale on the Exe Estuary to Teign Estuary section (Figure 1b), and then in detail on the Teign Estuary itself (Figure 1c). A major modifier of the coastline is the railway line running from Exeter St Davids to Teignmouth in 1846 and later extended to Newton Abbot. It has since become part of the mainline rail network linking the southwest to London, and beyond. The railway line occupies considerable stretches of coastal frontage (Exeter to

Dawlish to Teignmouth to Newton Abbot), and Network Rail (runs, maintains and develops Britain's tracks) has responsibility for the sea defences along those sections that protect the railway infrastructure. Coastal defence work to protect the railway line has had an impact on coastal processes. Pressures also include physical disturbance, for example by trampling, dredging, fishing, land reclamation and adjacent coastal development through the construction of sea defences, as well as the potential for changes in the hydrological regime. Teignmouth is an historic port on the mouth of the Teign estuary lying along a stretch of red sandstone coast.

The study site also features a range of important and sensitive marine habitats including grazing meadows, saltmarshes, mud flats, rocky and sandy seabeds, sand dunes (at Dawlish Warren) and other important biogenic habitats.

Within the adjoining coastline are Slapton Ley (to the east of Kingsbridge), Torbay and the Exe Estuary. **The Exe Estuary** is a RAMSAR site (wetland of international importance) Site of Special Scientific Interest, a Site of Special Protection (EC Birds Directive). Sea grass and mussel beds, present throughout the area are important habitats and potential ecosystem engineers which stabilise the substratum and provide an important source of organic matter, and a surface for attachment by other species. **Slapton Ley** is a lagoon separated from the sea by a shingle beach, known as Slapton Sands. It is the largest natural freshwater lake in South West England. The site is a National Nature Reserve and a Site of Special Scientific Interest. The main trunk road (A379) between the Ley and the sea runs along the shingle ridge. About 5 years ago is was damaged by storm action and realigned. The ridge itself is a fragile shingle beach constantly being re-shaped by the sea.

2. Data and Methods

2.1. Overview

The methodology adopted for this study is based on the Source-Pathway-Receptor-Consequence (S-P-R-C) approach. Each element of the coastal area system needs to be defined at an appropriate level of detail.

The S-P-R-C model (See Figure 2) is, essentially, a simple conceptual model for representing systems and processes that lead to a particular consequence. For a risk to arise, there must be hazard that consists of a 'source' or initiator event (i.e. high water levels); a 'receptor' (e.g. properties in the flood plain); and a pathway between the source and the receptor (i.e. flood routes such as defences).

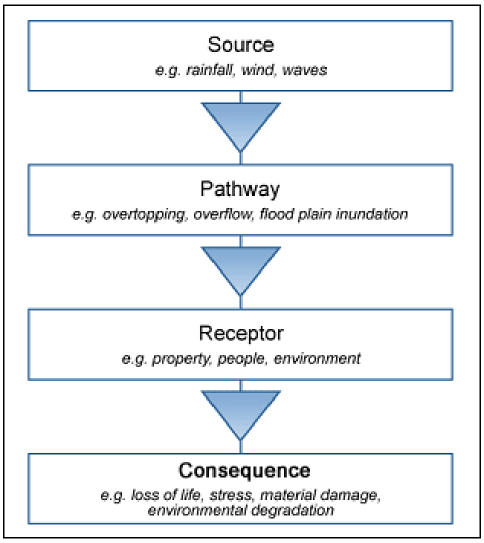

Figure 2.Source-Pathway-Receptor-Consequence Conceptual model (Flow diagram)

Each element of the coastal area system needs to be defined at an appropriate level of detail. As an example, it may be necessary to define:

- Sources (waves, water levels, beach levels)
- Pathways (structure geometry, material, condition)
- Receptors (land elevation, land use)
- Consequences (flood depth, duration, damage to structures, people and property)

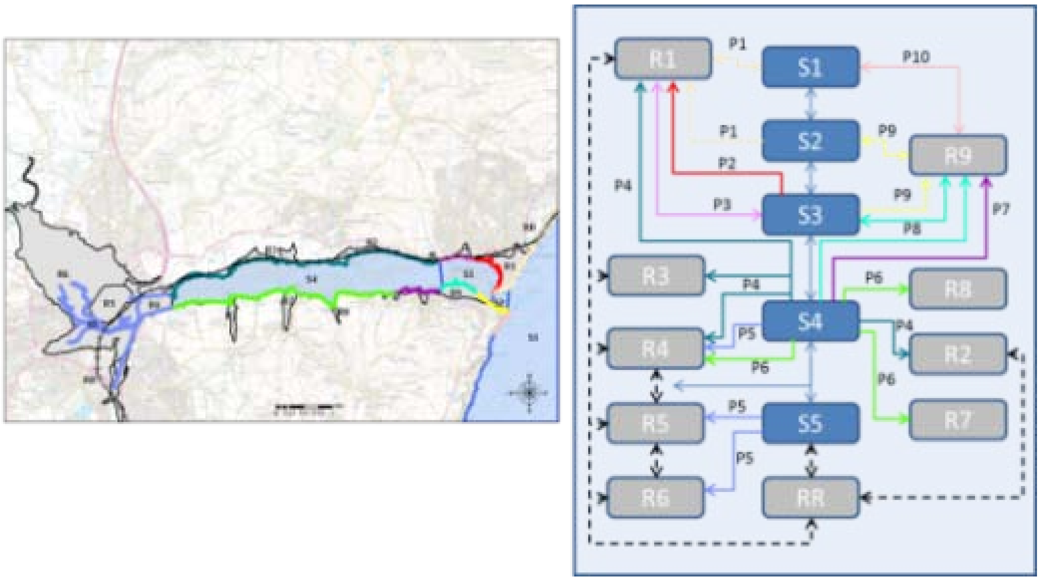

Figure 3.S-P-R-C diagram for the Teign Estuary

The range of information to undertake such a study on an area the size of this site at anything more than a cursory level is immense. Thus we have adopted an approach recommended by the industry. That is, we use a nested approach, starting with a basic level of information at the whole site scale, introducing more detail at the medium scale and further detail at the smallest scale. Consequently the S-P-R-C analysis for this site is at three levels. Due to the large area and relatively small coastal plains focus is on the detailed levels (see Figures 3).

2.2. SOURCES

Prediction of the source variables is a logical start and a necessary prerequisite for all detection and flood forecasting methods in coastal areas. The assessment of the wave and water level conditions near the coast – wave heights, wave periods, wave directions and water levels near the shoreline – is essential for the estimation of flood characteristics. From these, extreme values of water level, wave conditions and combinations of these can be determined through established statistical analysis techniques. The extreme conditions are then used in shoreline response and flood inundation models to describe the pathways of erosion and flooding. The calculation of extreme values of wave heights (+ corresponding periods) and water levels for this site for the present, 2020, 2050 and 2080 have been described in ID1.11.

2.3. PATHWAYS

In this study site, the pathways will be primarily sea defences, dunes, and embankments. Along the coast, and certainly within the estuaries, the defence type and construction can vary over very short distances. Information on crest levels, condition, age, beach mobility and so on is available from the UK Environment Agency. Potential pathways have been identified in the S-P-R-C diagrams. The most likely pathways have been identified by combining information on the structures with the source information. That is, for example, where there is a long reach of defences protecting an area, the defence, when considered as a single unit, will only be as strong as its weakest element.

2.4. RECEPTORS

Figure 4 shows the land-use maps at local scale extracted from the European Environment Agency's CORINE database and linked to the local background mapping. Receptor regions have been identified on the basis of land use (from the CORINE database) and limited, where appropriate, by applying topographic and extreme water level information. That is, for example, properties within a defined land use area which are above the extreme water level are excluded from the receptor.

Figure 4. Land-use map at the local scale

2.5. CONSEQUENCES

This is the stage where the flood areas are combined with socio-economic and ecological information to define damage or benefits in terms of financial measures.

2.6. FLOOD ASSESSMENT

Flooding at the coast arises from one or more processes. These are: overflow (water level greater than the crest level); overtopping (waves breaking and running over the crest of the defence); breach (the combination of wave and water level loading causing a defence to fail, resulting in a lowering of the crest and thus initiating overtopping and/or overflow; toe failure (the foreshore level lowering beyond a level that compromises the structural stability of the defence, leading to collapse and then subsequently breaching). Overflow discharges can be estimated using weir discharge formulae or numerical models. Overtopping can be estimated using recent guidelines, such as EurOtop (2007). Existing methods to estimate overtopping of beaches and dunes are much more limited. Breaching and toe failure are more difficult and uncertain to predict.

The main problem associated with estimating the flooding potential corresponding to a given probability is assessing the contribution of each component (ie. tide, surge and waves). There are two main options to estimate water levels:

- To directly estimate it from existing time series of water levels;
- To estimate it by analysing the integrated contribution of each component.

When time series do not exist or they are too short to be used to estimate a reliable extreme distribution, alternative techniques must be employed. These are essentially hybrid methods, (eg. Reeve & Burgess 1994; Meadowcroft 1995a,b; Environment Agency 2000), which attempt to estimate extreme conditions on the basis of marginal distributions of water levels and waves or, in the absence of even this level of information, estimating extreme levels on the basis of engineering judgement and historical records. Some examples of this type of approach are given below.

- **FOR WAVES:**

1. If Only H available, use annual maxima and compute extremes;
   - Take corresponding T from assumption that wave steepness = 1/18.
2. If wind records only, use hindcasting to find H, T and direction;
   - Select worst direction sector, compute extremes as in 1.

- **FOR WATER LEVELS:**

3. If annual maxima only available, compute extremes;
4. If time series of water levels, select annual maxima and follow (3);
5. If surge only available, compute annual maxima and extremes

- **FOR BEACH LEVELS:**

6. If profiles exist, calculate annual minima levels near structure, compute extremes;
7. If not, use qualitative information plus engineering judgement to assess beach variability and level of risk of toe failure.

- **OVERFLOW**

Overflow occurs when the water level exceeds the crest level of the defence. The hazard may then be estimated by:

- The probability of failure can be computed from the extreme water level distribution as 1 – F_{WL}(ECL); where ECL is the effective crest level.

- **OVERTOPPING**

Overtopping volume can be estimated as follows:

- Define the 20, 100, 200 and 1000 year events, (in terms of water level, H and T – assuming normal wave attack), calculate overtopping under these conditions using EurOtop guidance.

- From time series of water levels and waves a time series of overtopping rates may be constructed for each defence length, (using EurOtop guidance). Annual maxima are selected from this series and a distribution function fitted to these. The probability of failure is then 1 – FQ(Qth).

- **FLOOD VOLUMES AND EXTENT**

To determine flood volumes and extent differentiation needs to be made between cases where there is or isn't structural damage. Various different cases are outlined below – together with the means of estimating flood volumes:

1. Overflow – no structural damage
   - Water level-ECL gives the head. This is used in an appropriate weir equation (sharp-crested for thin sea wall, broad crested for wide embankment) to determine flow, q.
   - Volume = q x defence length x storm duration
   - Spread volume over receptor, accounting for variations in elevation. If the resulting water level in receptor > extreme sea level reduce flood area so there is equality
2. Overtopping – no structural damage
   - Volume = Q x defence length x storm duration
   - Spread volume over receptor as above
3. Toe failure
   - Flood area = area inundated with imposed extreme water level

Flood depths are determined from the flood area at a resolution equal to the grid resolution of DTM/DEM as the difference between the static water level and the terrain level.

Storm duration – CIRIA/CUR (1991) suggests 16 hour growth, 3 hour peak and 16 hour decline is typical. A duration of 3 hours is recommended but may be treated as a 'calibration' parameter.

3. RESULTS

3.1. FUTURE CLIMATE FLOODING MAPS

The projected sea level rise recommended in the Planning Policy Statement 25 – PPS25 (DCLG, 2010) study were used in this report.

Table 1 shows the extreme sea level for different climate change scenarios combining the projected net sea-level rise from year 2010 to 2100 based on the PPS25 and the projected sea-level rise for the Teign Estuary area.

Table 1. Extreme sea-level (in metres) for the different scenarios and return periods in the area of Teignmouth

Return Period (years)	Climate scenarios for sea-level rise			
	Present (1970-1999)	Short-term (2010-2039)	Mid-term (2040-2069)	Long-term (2070-2099)
20	2.955	3.008	3.248	3.593
100	3.157	3.210	3.450	3.795
200	3.244	3.297	3.537	3.882
1000	3.444	3.497	3.737	4.082

The flooding maps obtained using the data in Table 1 were generated using a Geographic Information System software (ARCGIS) combining the information from LiDAR and topographical data obtained from the Plymouth Coastal Observatory (http://www.channelcoast.org) and from the DIGIMAP (EDINA, 2011). The flooding surface was generated using the toolboxes and a flood simulation model (Kwan, 2011).

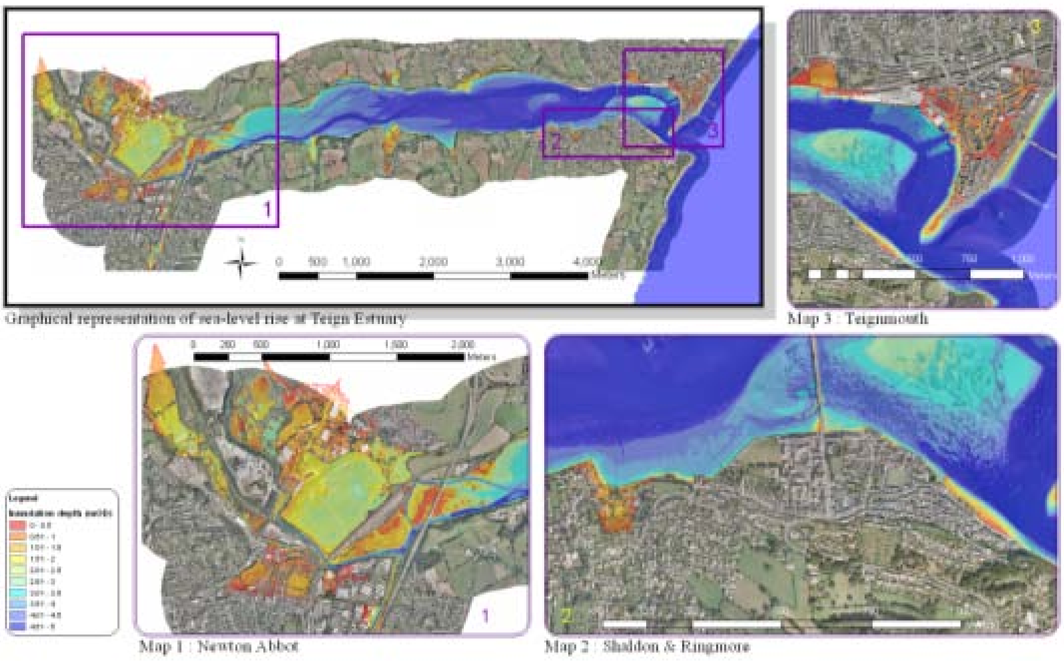

Figure 5. Flood simulation for sea-level rise scenario Mid-term scenario (1/1000 yr).

According to the study of the flooding scenarios, Teignmouth is found to be subject to a tidal flood risk for a return period as low as 1/20 year under the Present sea-level rise scenario. However, the flooding situation is relatively mild as compared with Shaldon and Ringmore. As mentioned before, Teignmouth is a small port but its importance lies in the fact that the main railway line runs through it. The simulation results identified that the railway line is subject to the risk of coastal flooding in the section running from the north of the Old Quay in Teignmouth to the west of Shaldon Bridge. Although the flood depth is only around 0.5 m – 1.0 m and would only happen in the long-term scenarios, the disruption of the rail services by the breach of the seawall will inevitably cause economic losses and inconvenience to the passengers.

Examining the future scenarios shows that flooding would not occur until a 1/1000 return period high water in the mid-term scenario. Figure 5 shows clearly that flooding will first occurs in Ringmore.

For the long-term scenarios, flooding at Shaldon and Ringmore occurs in long-term scenarios 1/200 and 1/1000. Water levels in this area could be as high as 2 to 3 metres which will inevitably cause serious economic losses in the area.

3.2. Future climate erosion analysis

In this case, the erosion and accretion in the Teignmouth area would maintain similar as in the present conditions. This is mostly due to the wave direction conditions in the climate scenarios, which are shown in Figure 6, are sustaining the same directions as in the present conditions.

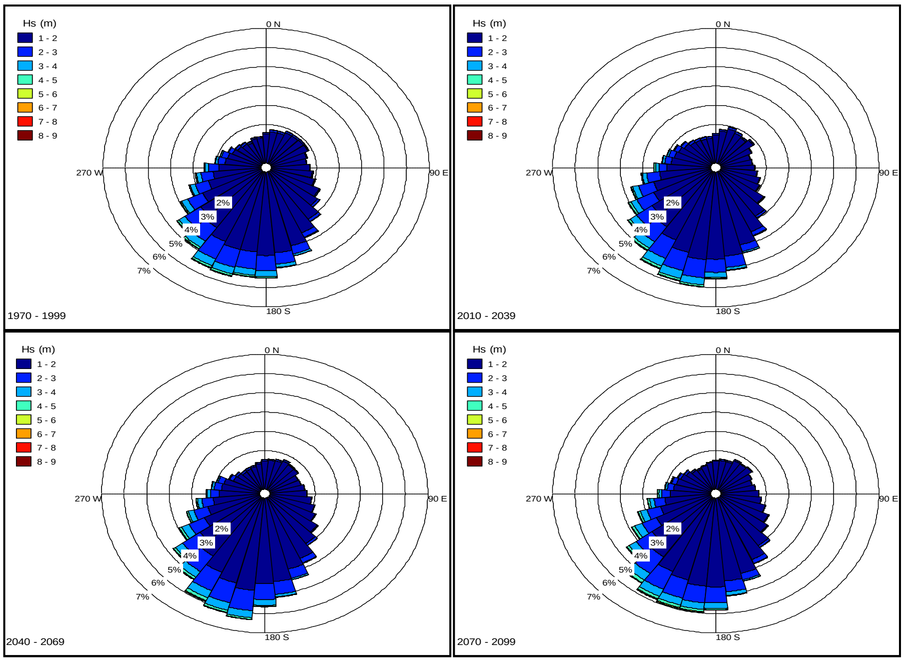

Figure 6.Exmouth wave roses for the different climate scenarios (Present, short-term, medium-term and long-term).

Figure 6 shows the wave roses for the area of Teignmouth and Exmouth for the different scenarios (present, short-term, medium term and long-term as defined in the OD1.3).

Taking into account for the wave roses detailed in Figure 6, the areas in the Teignmouth estuary that suffer erosion or accretion in the present conditions will continue suffering erosion or accretion during the climate scenarios. That is to say that the areas that are eroded or accreted in the present conditions will be eroded or accreted during the future condition in a lesser or a greater degree than the ones that they are suffering in the present condition.

For this reason the erosion maps and accretion maps for the future conditions will look similar to the ones for the present conditions (Figure 7).

Figure 7. Erosion and accretion maps for present and future conditions.

3.3. Present and future overtopping analysis

3.3.1. Overtopping inside the estuary

A storm wind of approximately 25 – 30 m/s will be used to determine the overtopping effect over the Teignmouth estuary. And the fetch will take account of the area where the overtopping is calculated. For each receptor the fetch taken into account will be the larger that can affect this receptor and the level of the structure will be taken as the lowest in that receptor with their respective crest elevation. For representative tides, the common use is 10% -20% higher than mean tidal range (Latteux, 1995, Oliveira et al., 2006). A similar formula to calculate the tide elevation to that in the latter studies has been used here:

Representative tide range = $(2/3)*(R_S – R_N) + R_N$

where R_S is spring tide range and R_N is neap tide range.

For each case of the short-term, medium term and long-term scenarios, the SLR will be added to the tide elevation and the surge depending of the return period used for the calculation of the overtopping. The tide elevation for the area of the Teignmouth estuary and the Teignmouth approaches are tabulated on the Table 2.

Table 2. Tide elevation for the area of Teignmouth

Location	Tide Elevation (mOD)
Teignmouth (approaches)	1.67
Teignmouth (New Quay)	1.73

For overtopping calculation, the surges will be added to each of the cases of the climate change scenarios (short-, mid- and long-term). The first case considered, will be in the estuary, and taking into account each receptor according to figure 8.

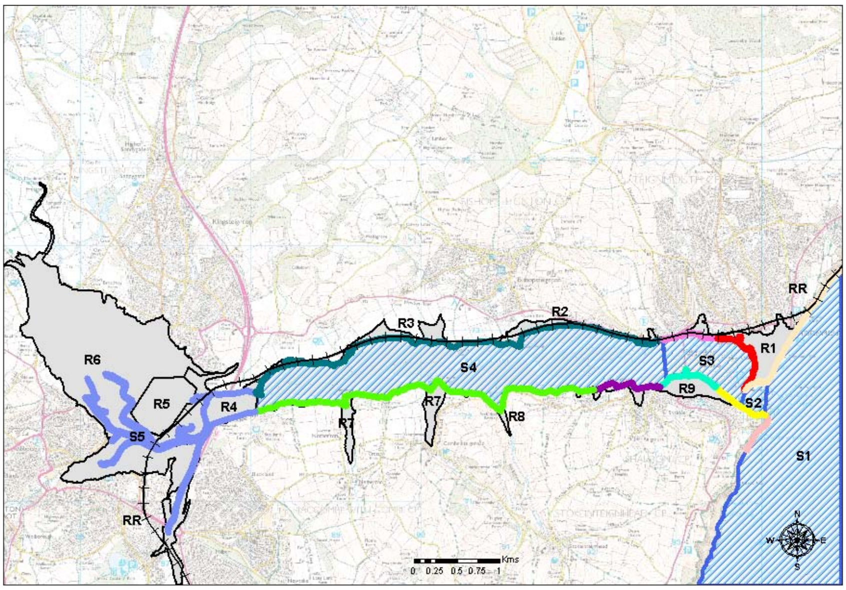

Figure 8. Sources, pathways and receptors in Teignmouth estuary.

Table 3 summarises the values that will be taken to determine the overtopping over the receptors in the estuary. The tide elevation considered for the Teignmouth - New Quay (inside the estuary) is 1.73 mOD. This value includes tide elevation, maximum surge and sea-level rise. The sea-level rises are 0.053m, 0.2925m and 0.6375 for the short-, medium- and long-term scenarios respectively.

Table 3. Predicted water levels at Teignmouth for overtopping calculation

Return Period (years)	Climate scenarios for sea-level rise (m)			
	Present (1970-1999)	Short-term (2010-2039)	Mid-term (2040-2069)	Long-term (2070-2099)
20	2.866	2.919	3.1585	3.5035
100	3.089	3.142	3.3815	3.7265
200	3.184	3.237	3.4765	3.8215
1000	3.405	3.458	3.6975	4.0425

The Eurotop manual (Eurotop, 2007) was used to calculate the overtopping in the different areas of the Teign estuary and the open sea in part of the railway line which is most susceptible to flooding.

Table 4 shows the overtopping volumes calculated for the mid-term conditions. The data of the coastal defences (crest levels and asset lengths) were obtained from the database of the Plymouth Coastal Observatory.

Table 4. Overtopping Volumes (Mid-term conditions, 2040-2069)

Receptor	Fetch (km)	Wave height (m)	Wave Period (s)	Crest Level (m)	Asset Length (m)	Overtopping volume (m^3)			
						1:20	1:100	1:200	1:1000
R1	5.91	0.70	3.1	2.79	170.4	N/A	N/A	N/A	N/A
R2	4.28	0.65	2.9	4.05	1366.8	27397	66722	97558	236139
R3	4.15	0.64	2.9	4.12	692.7	9636	23842	35072	86063
R7	1.53	0.50	2.3	2.76	76.4	N/A	N/A	N/A	N/A
R7	3.79	0.63	2.8	2.93	239.0	N/A	N/A	N/A	N/A
R8	2.25	0.56	2.5	2.30	348.6	N/A	N/A	N/A	N/A
R8	3.48	0.62	2.8	2.46	636.7	N/A	N/A	N/A	N/A
R9	3.24	0.61	2.7	2.61	237.8	N/A	N/A	N/A	N/A
R9	3.68	0.63	2.8	3.82	107.7	4841	12153	17986	44777

According to the results, there are places that are already overflowed before the overtopping occurs. In this case the table entry is recorded as N/A. As it is expected the volumes increase with the scenarios. Generally the areas flooded in the present conditions are located near the Port in

Teignmouth and other areas at the end of the river catchments, such as Receptor 7 (R7) and Receptor 8 (R8).

3.3.2. Overtopping in the railway area (Teignmouth – Receptors R1 and RR)

Wave overtopping occurs for a combined occurrence of extreme water levels and extreme *w*ave heights and therefore it is dependent on the joint probability of water levels and wave height.

The overtopping calculated for the area of the railway is limited by the depth in front of the structure. That is to say that whatever the wave height is, the depth will limit the wave that will break in front of the structure. For this reason, the wave in front of the structure will depend on the water level.

Isolines on Figure 9 represent the events of wave height and surge having a joint return period of 2, 5, 10, 20, 50, 100, 200, 500, 1000 and 2000 years. These figures are created using the marginal extremes for each of the variables. CIRIA (1996) gives a detailed description of the method.

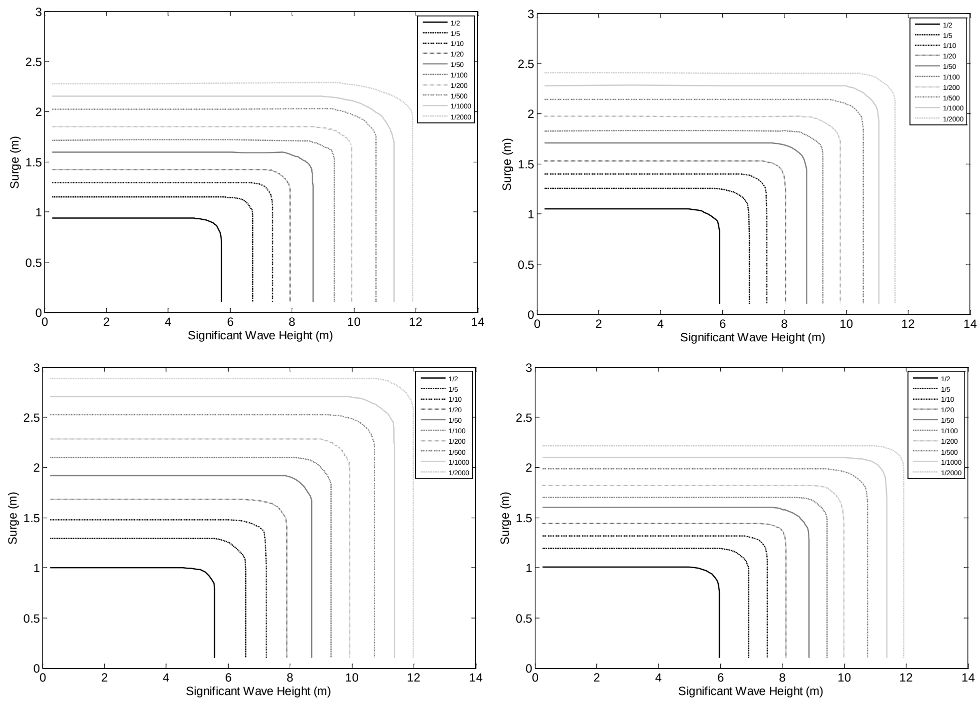

Figure 9. Joint probabilities for climate change scenarios with lines representing return periods. Present (top left), short-term (top right), mid-term (bottom left), long-term (bottom right).

Table 5 shows the values of the water level at Teignmouth according to UKHO (2009), the significant wave height and the surge for each one of the scenarios (present, short-, mid-, and long-term). Table 6 is created using Figure 9.

Table 5. Values for the calculation of the overtopping volumes

Return Period	# of cases	Present			Short-term			Mid-term			Long-term		
		WL (m)	Hs (m)	Zt (m)	WL (m)	Hs (m)	Zt (m)	WL (m)	Hs (m)	Zt (m)	WL (m)	Hs (m)	Zt (m)
20	1	1.73	3.5	0.80	1.73	2.0	0.65	1.73	2.0	0.90	1.73	2.0	0.80
	2	1.73	6.0	1.05	1.73	9.6	0.75	1.73	6.5	1.08	1.73	7.9	1.20
	3	1.73	10.0	0.90	1.73	8.5	0.25	1.73	6.0	0.40	1.73	6.0	0.25
100	1	1.73	4.0	1.65	1.73	3.0	1.85	1.73	4.0	2.05	1.73	1.0	1.65
	2	1.73	8.7	1.55	1.73	9.0	1.70	1.73	9.0	2.00	1.73	9.2	1.57
	3	1.73	9.3	0.35	1.73	9.3	0.5	1.73	9.3	0.50	1.73	9.5	0.35
200	1	1.73	3.5	1.85	1.73	2.0	1.95	1.73	2.0	2.30	1.73	2.5	1.83
	2	1.73	9.5	1.75	1.73	9.5	1.88	1.73	9.6	2.20	1.73	9.7	1.75
	3	1.73	9.9	0.30	1.73	9.8	0.52	1.73	9.9	0.30	1.73	10.0	0.40
1000	1	1.73	2.0	2.20	1.73	2.0	2.14	1.73	2.5	2.57	1.73	1.5	2.12
	2	1.73	10.7	2.00	1.73	10.8	2.07	1.73	10.7	2.70	1.73	11.0	2.05
	3	1.73	11.3	0.25	1.73	11.1	0.30	1.73	11.3	0.30	1.73	11.3	0.35

Table 6 shows the overtopping volumes for each of the conditions (Present, Short-, Mid- and Long-term). Table 6 is tables are calculated using the EUROTOP Manual (EUROTOP, 2007) and following the empirical method (probabilistic approach). The overtopping values on the table are considered as the instantaneous overtopping, times storm duration, times the asset length.

According to Table 6, all cases in each scenario present overtopping. The volumes calculated increase with the scenarios, as it is expected. The table results show that different combinations of wave height and surge (with the same joint exceedence return period) produce different overtopping rates. The wave height/surge level combinations with the highest surge levels have low waves so rarely overtop. The combinations with the highest offshore wave heights have depth-limited waves at the structure toe but low water depths. Another combination has relatively high (possibly depth-limited) waves and a higher surge and gives the highest overtopping rate for a given offshore wave return period.

Table 6. Overtopping Volumes (Long-term conditions, 2070-2099)

Crest Level : 4.94 mOD		Toe Level: 1.01 mOD			
Asset Length: 266.6 m					
Return Period	**# of cases**	**EWL + surge (m)**	**Wave height (m)**	**Freeboard (m)**	**Overtopping volume (m^3)**
20	**1**	2.53	1.19	2.41	2419
	2	2.93	1.50	2.01	20333
	3	1.98	0.76	2.96	13170
100	**1**	3.38	1.85	1.56	101339
	2	3.3	1.79	1.64	79785
	3	2.08	0.83	2.86	812
200	**1**	3.56	1.99	1.38	166886
	2	3.48	1.93	1.46	135309
	3	2.13	0.87	2.81	1025
1000	**1**	3.85	2.22	1.09	332888
	2	3.78	2.16	1.16	283436
	3	2.08	0.83	2.86	849

3.4. Present and future Habitat Teign Estuary

The map shown (Figure 10) displays the habitat types for all habitats found within the 5m contour (terrestrial, intertidal and sub-tidal communities). The 5m contour represents the worst case scenario of sea-level rise in connection with storm events, as such all these communities are vulnerable. ID1.4 and ID1.12 discuss the vulnerability of these systems to storm or flooding events.

Through sea level rise it is anticipated that one community will be converted to another for example:

- Intertidal mudflats will convert to sub-tidal communities
- Sand banks will convert to sub-tidal communities
- Shingle banks will convert to sub-tidal communities
- Salt marsh will convert to Mudflats
- Terrestrial communists such as grasslands, meadows and woodlands would be converted to salt marsh.
- Estuarine transition zones will shift further inland into current freshwater channels

There will be an interaction between sea level rise and topography which also needs to be considered when judging the size of the area where habitat change will take place, Figure 11 below schematically outlines this.

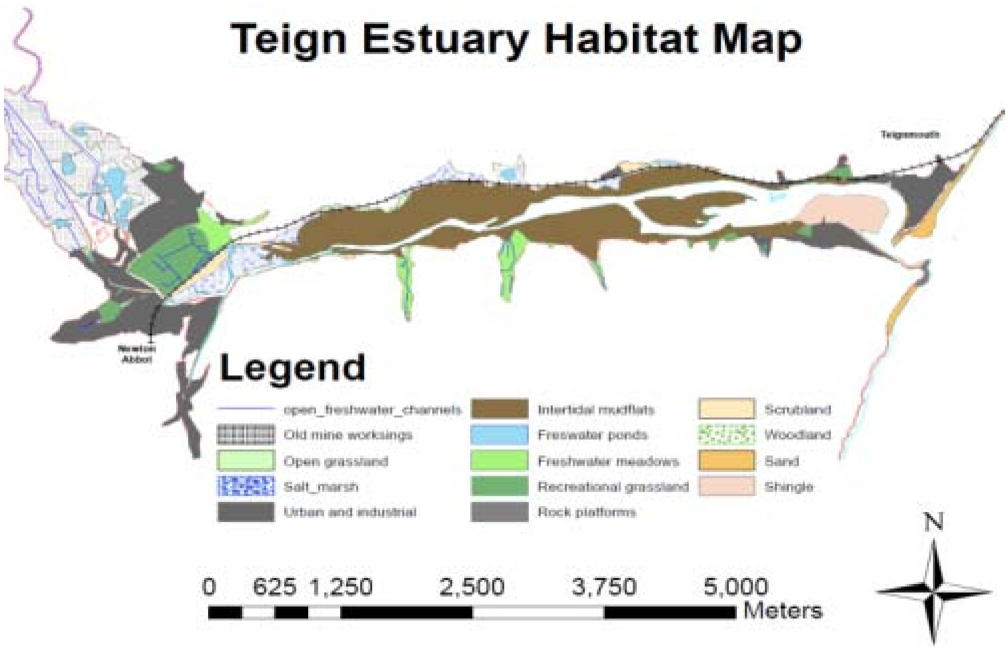

Figure 10. Teign Estuary habitat map.

Sections A, B and C represent different hypothetical habitat types. Scenario 1 shows no change in area for each habitat type under an elevated sea level. Scenario 2 shows that the area for all habitat types is reduced under an elevated sea level. Scenario 3 shows that the area of habitat type C is increased under elevated an elevated sea level.

3.5. Socio-economic impacts

According to the interviews conducted by the Middlesex University (Penning-Rowsell and Parker, 2011), they concluded the following about the lessons learned from the business interviewed:

- Structural solutions are preferred instead of resilience measures by those at risk of flooding. Resilience is seen as ‘second best’, too costly and an inconvenience
- It is important to explain the businesses at risk, what are the advantages of resilience measures which may be less well understood.
- Corporate businesses often adopt generic business resilience measures which coincidentally also serve as useful flood resilience measures (e.g. JIT, Loyalty Cards, IT back-up)

- Knowledge of physical flood resilience measures is limited to measures such as flood gates: opportunities exist for businesses to introduce more flood resilience measures

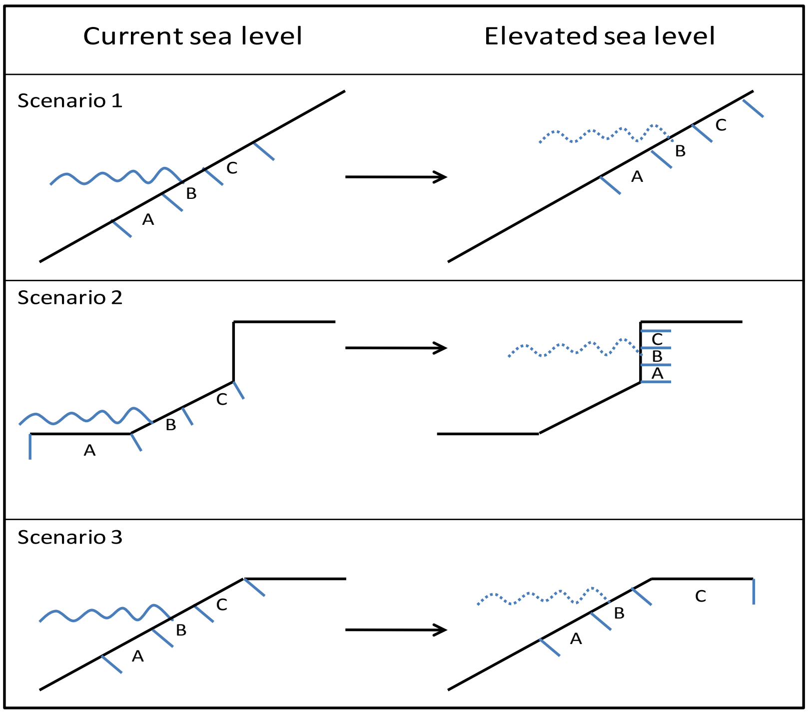

Figure 11. Schematic diagram showing the interaction between sea level rise and topography and the potential implications for habitat types

4. SUMMARY AND CONCLUSIONS

A Source-Pathway-Receptor-Consequence analysis has been performed for the Plymouth to Exe Estuary site. This has followed a nested approach, focusing on the Exe to Teignmouth estuaries plus intervening coastline at the medium scale and on the Teign Estuary at the most detailed scale. Sources, pathways and receptors have been identified and assessed. Information for the sources was derived from tide gauges at Plymouth and Weymouth, (operating as part of the national UK tide gauge network), simulated surge and wave conditions derived from running POLCOMS over a 30 year time slices. Pathway information was obtained from a variety of sources but largely from the UK Environment Agency databases. This provided crest levels and qualitative descriptions of the defence type and foreshore condition. The quality of this dataset was the main constraint on the sophistication of the risk assessment that was possible to apply. Receptors were defined on the basis of land use obtained from the CORINE database, publically available terrain elevation data and defence type. Strenuous attempts have been made to obtain better information on pathways.

Should this become available while the mapping for the future scenarios is being prepared then the more sophisticated methods described above can be adopted to define the maps.

5. References

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