APPLICATION OF A NOVEL DECISION SUPPORT SYSTEM TO ASSESS AND MANAGE COASTAL FLOOD RISK IN THE TEIGN ESTUARY, UK

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This paper demonstrates the application of a Decision Support System (DSS) developed for decision makers and stakeholders to manage and raise awareness of coastal flood risk. The DSS is a GIS-based framework that predicts flooding consequences and is structured around the Source Pathway Receptor Consequence (SPRC) model. The DSS draws together points of view from engineering, ecology and socio-economics, allowing the comparative assessment of the consequences of a range of management interventions. The utility of the tool is demonstrated through application to an estuary field site - the Teign estuary in UK. Vulnerability maps, generated by the DSS for pre-set climate scenarios can be used to show their comparative efficacy in changing the consequences of flooding from a range of stakeholder viewpoints. Recently constructed “tidal” defences built within the estuary are shown to be highly effective.

Keywords: THESEUS, Decision Support System, Flood Risk, Risk Assessment, Risk Management.

INTRODUCTION

Understanding of the consequence of management decisions is essential in the context of a changing climate, sea level rise, extreme events, and fluctuations in economies which must be balanced against a desire for sustainable approaches to coastal development and the preservation or enhancement of natural habitats. This work presents the application and demonstration of a Decision Support System (DSS) for created during European framework project: THESEUS “Innovative coastal technologies for safer European coasts in a changing climate”. THESEUS adopted a multidisciplinary approach to improve understanding of the effects of flooding, combining the disciplines of coastal engineering, socio-economics and ecology. The DSS maps the relative risks to a coastal region that arise from coastal management choices and interventions.

The DSS uses open source Geographical Information System (GIS) software to integrate environmental models, databases and assessment tools. Thus, it pulls together physics, engineering, ecology, sociology and economics, deterministic models, experience and discussion-based assumptions to evaluate and represent environmental vulnerabilities, impacts and risks (Zanuttigh et al, 2014).

The tool was developed with eight study sites from across Europe in mind. Here we show its application to one in particular: the Teign Estuary in South Devon, UK (Figure 1). South Devon encompasses both coastal and estuarial environments typifying many of those present elsewhere in Europe. Land use includes industrial, residential, tourism and recreational. There is wide a range of habitats present ranging from exposed rocky and shingle coast to sheltered mud of flooded 'rias'.

Teignmouth and the Teign Estuary

Along the study site runs the railway line that occupies considerable stretches of coastal frontage (Exeter to Dawlish to Teignmouth to Newton Abbot). The railway line has been modified through time to improve the sea wall and to protect the railway from the coastal processes.

The study site also features a range of important and sensitive marine habitats including grazing meadows, saltmarshes, mud flats, rocky and sandy seabeds, together with important biogenic habitats. Intertidal and marsh habitats are important for numerous species of birds, insects and plants. Collectively these habitats support a diverse flora and fauna including rare and endangered species. The estuary also supports commercially important species including oysters, cockles and crabs grazing marshes are important for cattle (Reeve et al, 2012).

The Teign Estuary is approximately 9km in length and less than 1 km wide at its widest Point and is defined as a ria by JNCC (1997). It is one of South Devon’s most valuable assets. The mouth of the Estuary is marked by a permanent spit "the Point", on the north bank at Teignmouth extending southwest, and the red cliffs at Shaldon to the south (Horrillo-Caraballo et al, 2014).

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The spring tidal range is approximately 3.8 m, with a maximum tidal current up to 3.0 m/s, while the tidal current in is relatively weak, at 0.5 m/s. The waves in the area are predominately Atlantic swell from the south-west direction, with yearly mean significant wave height of 2.0 m (max 4.0 m). The corresponding values for 1 in 50 year return period are estimated as 2.7 m (max 5.3 m).

The River Teign arises on Dartmoor at a height of 520m AOD (above Ordinance Datum at Newlyn) and flows in a south-easterly direction towards the Teign Estuary and the sea. The catchment covers an area of 550 km2. The principal sub-catchments are the Rivers Lemon and Bovey and the Aller Brook. The estuary is also influenced by the large river flow. The River Teign flows through a diversity of landscapes and habitats, ranging from open moorland (Dartmoor) to ancient woodland, improved pasture land and broad valleys, before finally meeting its floodplain and the estuary.

Figure 1. (left) Location of the Teign Estuary (red square), South Devon, UK. (right) Teign estuary.

Existing and potential engineered coastal defence structures have a considerable impact on the natural processes in the study site, and in turn, upon the economic, social and environmental systems. One of the major concerns in the study site is the vulnerability of an economically important coastal rail service that runs behind a narrow sea wall below soft cliffs and is frequently disrupted by overtopping under common storm conditions (see Figure 4) and was breached in the winter of 2014. Sea defences in front of Teignmouth town are wider and thus there is a greater capacity for managing overtopping. However on the inside of the estuary, areas with high economic, social or environmental value are at risk of tidal flooding as water levels rise.

METHODOLOGY

SPRC model

The DSS methodology is built upon the Source–Pathway–Receptor–Consequence (SPRC) model. This was initially applied in environmental pollution (Holdgate, 1979) to describe the flow of contaminants from a source (an ocean or river) through a pathway (a coastal protection structure or a beach) to a receptor (flood plain/ urban areas / ecosystems, etc.) The SPRC model has been applied by the UK Environment Agency (HR Wallingford, 2002) for coastal engineering (e.g. FLOODsite, 2009) for representing coastal flood systems and processes that lead to particular flooding consequences (Figure 2).

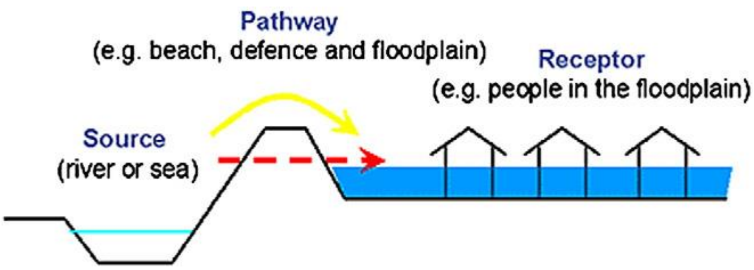

Figure 2. The Source-Pathway-Receptor (SPR) model in flooding analysis (after HR Wallingford, 2002).

Essentially, the SPRC model within the DSS is a conceptual model to combine coastal mitigation and adaptation technologies to promote low-risk at the coast for humans and habitats, integrating the engineering, socio-economic and ecological aspects.

During the THESEUS project the conceptual model was identified and represented for the eight study sites (Narayan et al, 2014; Villatoro et al, 2014) as follows: Sources as waves, tides, storm surge, mean sea level, river discharge, run ups, and others; Pathways as any coastal defence; Receptors as habitats, buildings and infrastructure in general; the Consequence is the change or loss of economic, social and environmental values before and after an extreme event.

Sources are catalogued in two, primary sources as the weather related phenomena that cause flooding, and secondary sources as physical manifestations or consequence, of primary sources, that generate flooding (e.g. waves, surges, rivers). Sources are also catalogued depending on their duration: short term (e.g. storm surge, wind waves, tides, run off), seasonal (e.g. high and low river discharges), and long-term processes (e.g. sea level rise, subsidence). Pathways are the track and processes that are active during the flooding scenario, generally a pathway might be hard and soft coastal defences, infrastructure or a habitat with some coastal protection function. As a rule, there must be at least one pathway between the source and the receptor to follow a consequence (Zanuttigh et al, 2014).

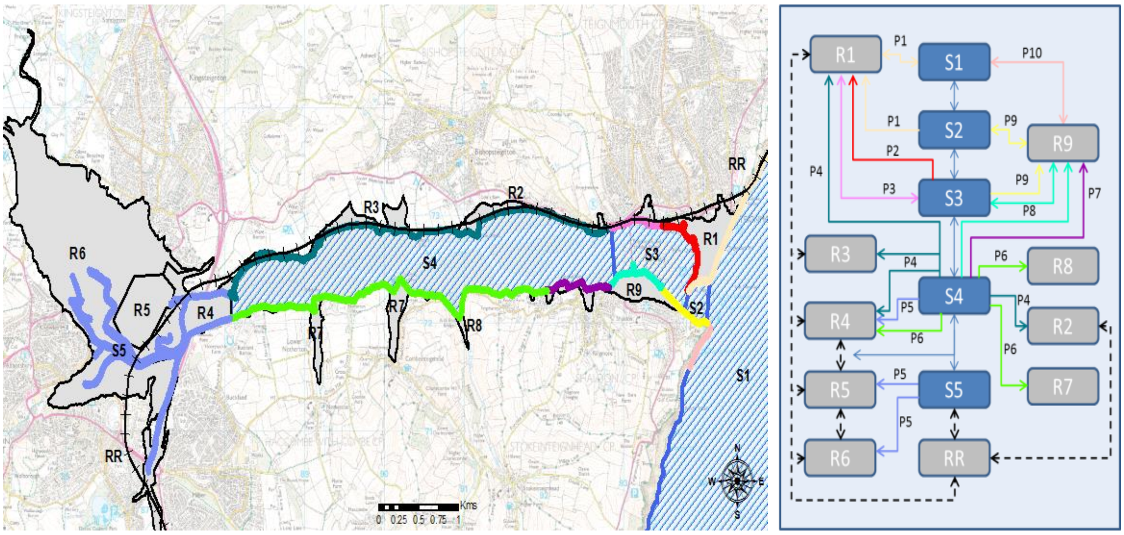

Figure 3. SPRC conceptual model applied to the study site.

Figure 3 shows the SPRC diagram for the Teign Estuary where the geographic distribution of sources, (Sn), pathways (colour coded), and receptors (Rn) are linked in a logical arrangement. The flood areas or receptors are followed by site specific pathways and consequences distributed in a logical configuration (right panel). SPRC maps show usefulness on the basis that they provide additional information to land use and habitat maps (Reeve et al, 2012).

Collation of input data

Wave and climate conditions were modelled and predicted using the software POLCOMS developed by Holt and James (2001) at the Proudman Oceanographic Laboratory, this is a baroclinic 3D model coupled with a wave model ProWAM (Osuna et al. 2004). The model has been calibrated and validated in previous studies (Osuna et al. 2004; Pan et al. 2009a; Pan et al. 2009b; Chen et al. 2010). Wave and surge data were obtained from the POLCOMS/ProWAM model, which was set up with nested grids centred at the study area, present and future wave and surge conditions were modelled for one of the IPCC greenhouse gas emission scenarios: A1B (IPCC AR4 2007) at the study site and using the wind and sea level pressure (SLP) from Max Planck Institute for Meteorology WDCC/CERA database (WDCC 2009).

The next step was to predict the extreme water levels from the numerical model results, Horrillo-Caraballo et al (2012) applied the "bootstrap" method to study the extreme waves under present, mid and long term climate conditions at the Teign Estuary, the study site. Given the time-limited extent of the data sets, bootstrapping was used to re-sample the data and generate confidence limits based on the re-sampled populations following the methods described in Reeve (1996) and Li et al. (2008). These extremes were calculated by fitting the annual maxima to a selection of candidate probability distribution functions, a 1 year lag correlation was calculated to ensure statistical independence within the time series.

Wave and surge climate conditions were generated for present (1970-2009 or 1990’s) and for three predicted scenarios: short (2010-2039 or 2020’s), mid (2040-2069 or 2050’s) and long-term (2070-2099 or 2080’s) scenarios, nonetheless, coastal flooding hazard maps (for different return periods) can be generated and also the short, mid and long-term erosion patterns can be determined from the proposed methodology (Horrillo-Caraballo et al, 2012).

The Decision Support System – structural overview

The DSS adopts a hierarchical structure proceeding from offshore to onshore (coastal systems with multiple sources require special consideration). The predictions are initiated with pre-calculated scenarios comprising water levels, wave climate and other environmental parameters. Based on these values, the overtopping at each pathway can be calculated and a watershed segmentation model is then used to flood the digital elevation model. The extent of the flooding is then used to generate flood hazard maps and damage indicators for the socio-economic and ecological parameters in each receptor.

"Mitigation options" can then be selected to modify the shore line and coastal processes allowing re-calculation and comparison of the hazard maps. The mitigation options that can be considered include: engineering - wave farms, barriers, sea walls, breakwaters; economic - land use, insurance policy; ecological - artificial dunes, biogenic reefs; social - evacuation planning, spatial planning including water storage and changes to infrastructure.

Procedural detail

The DSS requires GIS raster maps and data tables for spatial and temporal characteristics of the environment, socio-economics and habitats. Following Zanuttigh et al (2014), the associated DSS procedure is as follow:

Wave heights are transformed from offshore sources to inshore values accounting for the given tidal level. This calculation also accounts for wave reduction by any seaward coastal defence being considered or other mitigation options that affect wave height. The occurrence and degree of flooding across a pathway into receptors behind the pathway (sea wall, embankment, etc) are determined by the level of storm surge, sea level rise, wave set up and wave run up in relation to the height of the pathway (defence). Erosion of beaches can also be incorporated in the calculations using the simple 1-line model proposed by Miller and Dean (2004). However, this is less relevant at Teignmouth, where the mean water level is close to the sea wall. The GIS-based flood inundation model applies a water overflow method combined with erosion calculations using a watershed segmentation algorithm (Meyer and Beucher, 1990; Soille and Ansoult, 1990). This sequentially floods each pixel lower than and connected to a source of flood water. This specific algorithm can also consider sources of flood water that are finite and time varying.

Coastal ecosystems and/or habitats are considered to be impacted by inundation events within the DSS, through an increase of water levels and flooding depths. Habitats have a vulnerability that depends on duration of these events. The concept of ecosystem vulnerability is linked to that of resilience which can be considered as the speed with which an ecosystem can recover to its initial state. This is embodied in the DSS through the Environmental Vulnerability Index (EVI). This currently considers 10 different types of coastal habitats. For instance, a habitat that can retreat to become additional coastal habitat is more resilient (has a lower EVI) perhaps, than intertidal habitats squeezed between rising water levels and fixed coastal structures. The EVI assessment works as follows: first the impacting sources are identified; habitat types are identified; potential outcomes for these specific habitats in response to the impacts are identified; and finally the EVI index is assessed based on 4 categorical scores (from 0 to 3).

In the THESEUS DSS social vulnerability is modelled from two main viewpoints: 1) damage to critical facilities; 2) expected number of fatalities. Critical facilities are defined as the primary structures and buildings that represent a significant value for society and the normal functioning of a community. Similar to the EVI, the Social vulnerability assessment is based on categorical scores associated with the type of critical facility, flood depth induced-damage, flood duration induced-damage, collateral social damage, life loss and injures. It should be noted that social vulnerability is so complex that no single model can represent the whole spectrum of such vulnerability (Zanuttigh et al, 2014), however the DSS uses such a measure to provide some indication of the relative effect of different mitigations.

The economic consequence of flooding is estimated using an algorithm comprising consideration of land use values, flood depth and flood duration.

The overall coastal risk assessment is performed using a Digital Elevation Model (DEM), that allows consideration of spatial scales typically between 10m to 100km and time scale spans from 1 year to 100 years, the latter commensurate with coastal management timeframes. The overall vulnerability analysis uses a multi-criteria decision making approach. In this the impacts of ecological vulnerability, social vulnerability and economic loss are weighted according to a range of stakeholder viewpoints obtained empirically or through expert judgement. This is presented in the DSS vulnerability maps.

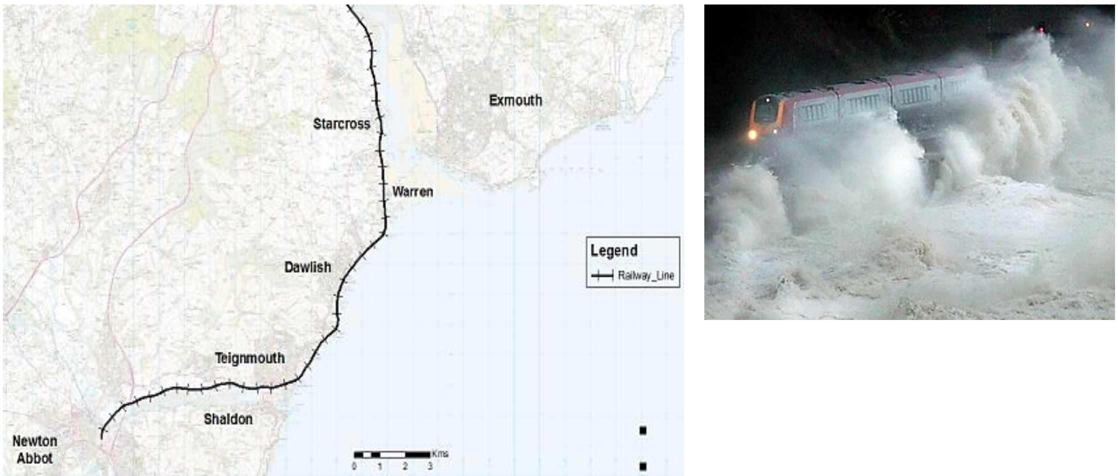

Figure 4. The railway line and sea-wall, an example in the study site.

Figure 5. Flooding Depth: No mitigation options (up) vs All mitigations (down). Close up of detailed maps (right panels), for Mid-term conditions: 2050 yr, Tr 50 yrs.

RESULTS

Here we present some example results focused on prediction for the medium term, in 2050, with a return period of 50 years. The input data (meteomarine climate, economic, social and ecological) is pre-calculated using various analyses outside the DSS, stored as pre-set scenarios.

Figure 4 shows an example of the DSS application, in this case, the railway line and the sea-wall that holds and protects the railway. As mentioned before, the railway line is vulnerable to extreme waves and high water levels during storm conditions, forcing trains to stop and causing major disruptions to the southwest of England, also the flooding impact inside the estuary is of high importance.

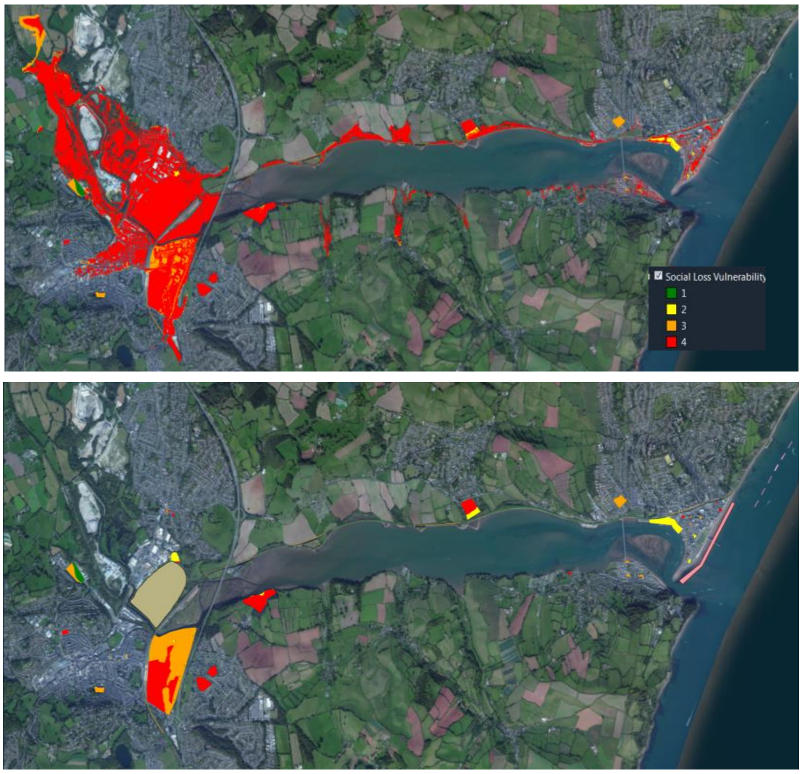

Figure 6. Social Loss vulnerability: No mitigation options (up) vs All mitigations (down). Mid-term conditions: 2050 yr, Tr 50 yrs. Scale: Low (green), Moderate (yellow), Medium (orange) and High (red) risk.

To minimise the consequence (SPRC model) or keep the risk at an acceptable level, the following mitigation options have been implemented in the DSS: two engineering mitigations (submerged breakwaters and increase of height of the railway sea wall), one ecological mitigation (biogenic reef), one spatial planning mitigation (water storage), and an evacuation plan as a social impact mitigation.

There are areas expected to be flooded under severe storminess, most sections of the railway line and railway station suffer from inundation of between 0.5 m to 1 m (Penning-Rowsell et al, 2013), in contrast, other areas (e.g. inside the estuary) are flooded by tidal / storm surges. The railway line option focuses on a re-design of the historic Brunel seawall to mitigate against extreme overtopping although, whilst, in the longer term, abandonment and/ or re-routing of the line on an inland route may become viable. An acceptable mitigation option for the sea wall and railway, given the importance of the tourism industry, would be considered the use of a series of sea facing and land facing orientations of V-shaped rubble mound breakwaters. The aim here is to use the breakwaters to reduce wave height in front of the sea wall and to increase the width of beach. Both of these effects will help to reduce overtopping of the sea wall in this tidal environment and its effect on coastal sedimentation in the lee (Pan et al, 2013). In order to complement the pre-existing sea defences, a recent tidal flood protection scheme was constructed on the estuary side of the spit on which the town sits. This comprised flood walls, community operated flood gates and enhancing the resilience of properties incorporated into the defences, and this has reduced the risk of tidal flooding significantly from a standard of protection of around 1:20 years to 1:1000 years (Penning-Rowsell, et al, 2013). The effectiveness of the DSS is not only on this scheme but also with other mitigation measures (e.g. wave energy converters, bespoke protection, spatial planning, flood storage in sacrificial areas, and managed realignment) that reduce the risk of flooding and erosion in both coast and inside the Teign estuary.

Vulnerability maps

After running the DSS with pre-set scenarios and with/without mitigation measures, output maps can be examined produced for hydraulic vulnerability, flood duration, flood depth, flood velocity, beach retreat, risk assessment, EVI vulnerability, social loss and economic loss.

Figure 5 shows the flooding depth difference with and without mitigation measures. Zanuttigh et al (2014) defined this variable due to flooding velocity and flooding duration as the computation between segments from shore line to onshore or land, depending on flood depth velocity

Figure 6 shows the social vulnerability which is related to the damage of critical facilities and number of fatalities in case of an extreme event. The plots show a significant reduction in social loss when the mitigation measures are activated, practically reducing the damage to the minimum for a mid-term scenario.

Figure 7. EVI vulnerability: No mitigation options (up) vs All mitigations (down). Mid-term conditions: 2050 yr, Tr 50 yrs. Scale: Low (green), Moderate (yellow), Medium (orange) and High (red) risk.

The EVI vulnerability (Figure 7) shows negligible change, particularly in yellow areas. When examined in more detail, the effect of the mitigation measures can be seen (through a change of yellow to green) an improvement of ecological habitat.

For the risk assessment map in Figure 8, the plot in the top shows a do-nothing scenario, indicating a significant flooding impact in all urban areas and habitats adjacent to the estuary, particularly inside and at the end of the estuary, that might end in a considerable loss. When implementing the mitigation options in the DSS, it is clear that there is a risk reduction in urban areas and ecological habitats, as well as for socio-economic conditions, suggesting a necessary and adequate investment in coastal defences along the Teign estuary, improving the railway sea wall and proposed mitigation measures inside the estuary. It worth mention that the current tidal defences already placed at Shaldon and Teignmouth have been integrated in the DSS, even for the do-nothing scenarios.

DISCUSSIONS & CONCLUSIONS

The GIS-based DSS is an interactive computer-based system to help decision-makers (e.g. coastal stakeholders) to rapidly assess local risk level and to make decisions, identifying mitigation measures and reduced impacts, and to organize early warning and evacuation plans. It combines coastal mitigations and adaptation technologies integrating the social and ecological aspects of the flood system within which a diverse range of management options (engineering, social and ecological) can be assessed (Reeve et al, 2012). The DSS proves usefulness for coastal managers and local authorities because it has consistency with the EU policies. Also, it gives a probabilistic approach and multi-scenario analysis to simplify scenarios of all processes.

The DSS has been applied under a medium term scenario with particular environmental / climate conditions. The results indicate at Teignmouth, that when the chosen mitigation options are active, the risk associated to flooding in all the vulnerable areas can be seen to reduce significantly in comparison with the do-nothing scenario (no mitigation options), this is observed for hydraulic, socio-economic and ecological vulnerabilities. The risk assessment is the combination of the above outputs or maps weighted according to experts, stakeholders or normalised scores.

As mentioned above, either scenarios with mitigations or without mitigations, the current tidal defences were included in all pre-calculated data and raster maps and they showed effectiveness, particularly at Shaldon and Teignmouth.

It worth mentioning that the DSS depends on the level of detailed information available for providing the input raster maps in addition to the availability of suitable analyses that provide the pre-set scenarios at a particular study site. Furthermore the DSS does not replace more detailed analysis and investigation of the full consequences of coastal interventions. Nonetheless, it can be seen to provide a useful tool for making rapid comparisons between a range of management choices and a range of stakeholder priorities.

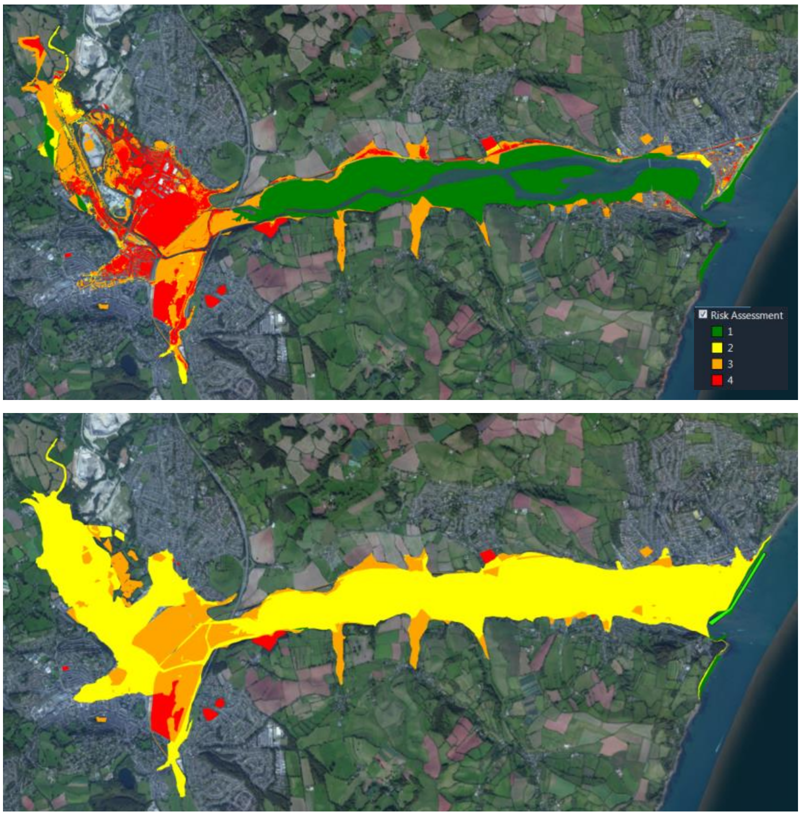

Figure 8. Risk Assessment: No mitigation options (up) vs All mitigations (down). Mid-term conditions: 2050 yr, Tr 50 yrs. Scale: Low (green), Moderate (yellow), Medium (orange) and High (red) risk.

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