A coastal vulnerability assessment for planning climate resilient infrastructure.

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Highlights

- Changing threats to coastal populations and infrastructure are found.
- Features that enable coastal resilience are identified.
- An approach to develop a stakeholder-focussed decision-support tool is presented.
- Physical process understanding and real options analysis are combined.

Abstract

There is a good understanding of past and present coastal processes as a result of coastal monitoring programmes within the UK. However, one of the key challenges for coastal managers in the face of climate change is future coastal change and vulnerability of infrastructure and communities to flooding. Drawing on a vulnerability-led and decision-centric framework (VL-DC) a Decision Support Tool (DST) is developed which, combines new observations and modelling to explore the future vulnerability to sea-level rise and storms for nuclear energy sites in Britain. The combination of these numerical projections within the DST and a Real Options Analysis (ROA) delivers essential support for: (i) improved response to extreme events and (ii) a strategy that builds climate change resilience.

Key words: Decision Support Tool (DST); Real Options Analysis (ROA); Flood hazard modelling; Storm impact monitoring; Human intervention.

1. **Introduction**

Energy security is a fundamental requirement for well-functioning modern societies (Morrissey et al., 2018). Due to its prevalent location in coastal areas, climate change, sea-level rise and extreme events represent significant challenges to the global energy infrastructure and supply chain (Reichl et al., 2013; Morrissey et al., 2018; Prime et al., 2018). The UK Energy Networks Association (ENA) identifies the biggest pressure to be from coastal flooding - if an electrical substation is flooded costs in clean up and repair can be high, and on-going costs from disruption and loss of supply have the potential to add to this significantly (Energy Network Association, 2009). There is already a good understanding of past and present coastal processes, particularly at locations for present and planned nuclear power stations. However, to ensure that coastal populations and the necessary infrastructure required to sustain these populations are resilient in the future, tools that can inform adaptive management are required (Silva et al., 2017; Wadey et al., 2017; Lam et al., 2017). However, this is a complex problem as shoreline resilience to changes in the physical environment varies spatially and temporally in response to factors such as changing beach volume (Castelle et al., 2015), reduction in sediment supply (Guangwei, 2011), and the degradation of coastal wetlands (Lotzel et al., 2006), as well as to human interventions that are socio-economically, politically and culturally determined (Ratter et al., 2016). To be effective, management tools require the capacity to monitor and project a variety of interlinked physical and societal processes including sea-level rise, storm magnitude/frequency relationships, changing sediment budget (Brown et al., 2016) and population change and economic activity (Prime et al., 2018).

Developed for the UK energy sector as part of the Adaptation and Resilience of Coastal Energy Supply (ARCoES) project, this paper presents a web-based geospatial Decision-Support Tool (DST), the ARCoES DST (Fig. 1). Leaflet, an open source Javascript library, is used to construct the DST to enable the end user to interrogate the matrix of model results using slider bars and tick box options to toggle between hazard or inundation maps and overlay different infrastructure or map views (Knight et al., 2015). As described in this paper, the ARCoES DST is used in combination with modelling and monitoring of different coastal environments to better understand future coastal vulnerability. Drawing on the interdisciplinary skills of the ARCoES researchers, the ARCoES DST is combined with an economic framework, Real Options Analysis (ROA), to provide an assessment of when it is most cost-effective to implement a new management approach. From a policy perspective, the data produced by the DST, when combined with a Real Options Framework can be used to initiate discussions with coastal practitioners to identify how future vulnerability to coastal flooding may be mitigated through appropriate and timely intervention and adaptation. Importantly, although the methodology is designed for the nuclear energy sector the DST could also be applied for other coastal management needs.

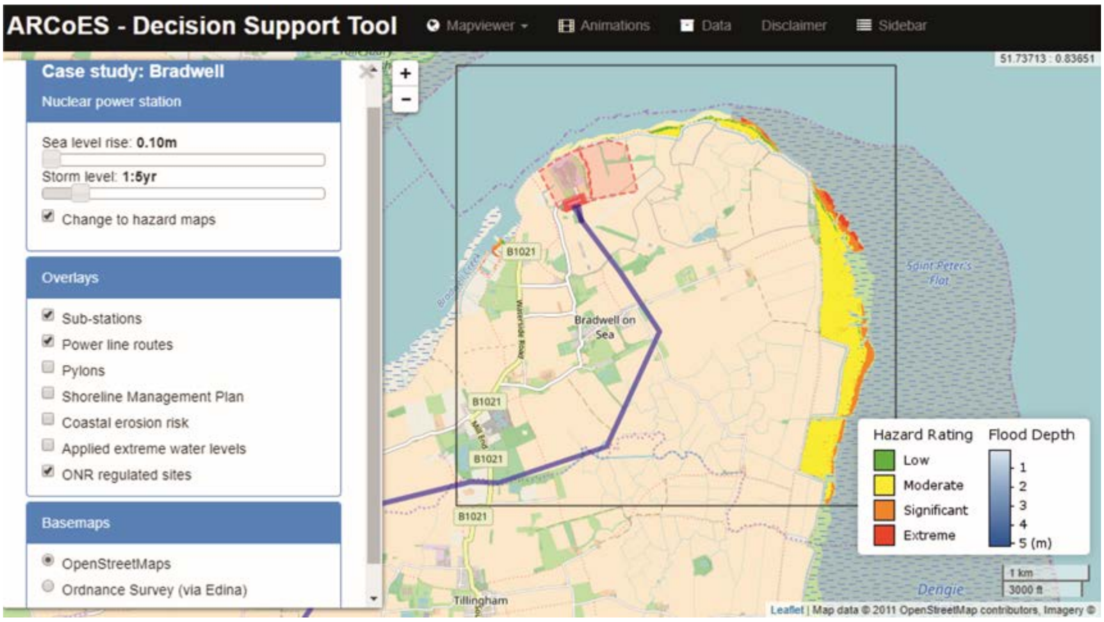

Fig. 1. The ARCoES DST, available at http://arcoes-dst.liverpool.ac.uk/.

Within this context, the aim of this paper is to demonstrate the usefulness of the ARCoES DST in understanding the physical and economic impact of sea-level rise and storms across 4 nuclear energy sites located along the coast of the UK. These sites include Seascale (representing Sellafield in the northwest), Lilstock (representing Hinkley Point in the southwest), Sizewell (in the east), and Bradwell (in the southeast). We also focus on Fleetwood (in the northwest) as an example of its application to a coastal community. The paper continues as follows: the methods used to deliver this holistic assessment are presented in Section 2. In Section 3 a selection of results to demonstrate the application and capabilities of the resulting DST at different sites is provided. The way in which this DST can be used to conceptualize shoreline management requirements to pose questions at a high level for specialized studies to address is discussed in Section 4, before the conclusions about the future resilience of UK coastal energy are drawn in Section 5.

2. Site Descriptions

Although applied to a number of locations, here we focus on five study sites with different coastal geomorphology and hazard exposure. This national application demonstrates the development of a DST for the management needs of an industry with infrastructure in multiple locations rather than in response to site-specific coastal conditions. Each site requires a slightly different model configuration (see Section 3) but uses the same approach.

The coastline at Seascale/Sellafield faces the Irish Sea, the actual location is quite exposed (offshore H_s,10% = 2 m; max H_s =5.7 m; data from British Oceanographic Data Centre (BODC) wave buoy MCMBE-OFF 1974–1976), with a maximum tide range and 1% storm surge height during winter of 7 m and 1 m, respectively. However, the beach morphology fronting the facility is characterised by a reflective high tide gravel/cobble beach with an extremely dissipative sandy intertidal zone. A storm monitored in January 2013 that more or less coincided with spring high tide had therefore insignificant impact on the beach (Almeida et al., 2014).

At Lilstock/Hinkley Point, located in the Bristol Channel, the site is not fully exposed to the Atlantic waves, but wave conditions can be relatively energetic (offshore H_s,10% = 1.8 m; max H_s = 3.7 m; data from BODC wave buoy SEVERNEST A 1979–1981). This is a mega-tidal environment with a maximum tide range of 10.7 m and a 1% storm surge height during winter of 0.8 m. However, in common with Sellafield, the wide and low gradient intertidal zone, here a rocky platform instead of a sandy beach, is extremely dissipative, limiting the wave energy levels impacting the high tide gravel/cobble beach. A storm monitored in December 2013 had therefore very limited morphological impact.

The gravel beach at Sizewell faces the North Sea. Wave conditions are relatively mild (offshore 10% exceedance H_s = 0.6 m; max H_s = 2.2 m; data from BODC wave buoy ALDEBURG 1975–1977) and the maximum tide range and 1% storm surge height during winter are 2.4 m and 1 m, respectively. During the 5-year duration of the ARCoES project, not a single extreme wave event occurred at Sizewell, but some measurements were made during a relatively modest storm event in March

2013. These revealed that the subtidal bar morphology at this site provides significant protection to the high tide gravel beach from large waves and that the main morphological changes occurred due to longshore sediment transport processes. The most significant wave events along the North Sea coast are from the northeast quadrant, but Sizewell is partly sheltered from such storms because the coastline aligns south-southwest to north-northeast, and potentially the most damaging waves for Sizewell are extremely rare storm waves from the southeast. Interestingly, the storm surge event in 2013, and which caused much erosion and flooding along the east coast of England (Wadey et al., 2015), was not an event of significance at Sizewell where H_s at the peak of the storm surge were < 1.5 m.

The Bradwell site is characterised by a narrow gravel coastal plain fronted by the silty tidal flat and is located on the southern bank of the Blackwater estuary. The maximum tide range here is 4.8 m and the 1% winter storm surge is 0.9 m. The site is extremely sheltered and this is demonstrated by the results of a long-term deployment (Oct 2015 –Mar 2016) of pressure sensors at the base of the gravel beach and around low tide level. Mean wave conditions were characterised by H_s = 0.1 m and the most energetic event that occurred during this period had a H_s of 0.45 m.

Observing the physical processes at the sites above has found that they have a low vulnerability to storm impact. Seascale/Sellafield and Lilstock/Hinkley Point are relatively exposed sites, the key aspect limiting their vulnerability to extreme wave events is their highly dissipative intertidal zone (sand at Sellafield and rock at Hinkley Point). The very wide (> 200 m) and low-gradient (< 0.015) surface fronting the high tide gravel/cobble beach and coastal structures at both sites greatly reduces the wave energy levels and wave runup around high tide, and therefore the risk of flooding and erosion, even under the largest offshore waves. Sizewell is sited such that it is not exposed to the most frequent North Sea storm wave conditions from the northeast quadrant. In addition, the low gradient and barred subtidal zone effectively dissipates storm wave energy, and the high and wide inter- and supratidal gravel beach also provides a significant buffer to extreme wave action. The site is perhaps most vulnerable to longer-term coastal dynamics, specifically alongshore redistribution of sand and gravel due to littoral drift. Bradwell is sited in an extremely sheltered location with very limited fetch and potential for wave generation. A low gradient subtidal zone and gravel ridges also fronts the facility, which adds additional protection.

In addition to sites of nuclear infrastructure the ARCoES DST was also developed to assess community vulnerability to coastal hazards. Our example site at Fleetwood, northwest England, is used here to demonstrate how flood hazard management of a community's electricity distribution has to consider the influence of shoreline management plans on the inland flood hazard to electricity substations to ensure the supply is resilient. The coastal conditions at this site include a mega-tidal regime (exceeding 10 m during spring tides), surge events that can reach 2 m and offshore wave conditions that can exceed 5.5 m (Brown et al., 2010). Our study region has a 'hold the line' shoreline management policy to protect the community from flood hazards. Within our study area this policy is implemented by a sea wall, thus understanding when a future 'tipping point' in wave overtopping hazard may occur for the existing scheme under rising sea levels is important.

3. ARCoES DST

There is often a good understanding of past and present coastal processes as a result of coastal monitoring programmes within the UK. However, one of the key challenges for managers in the face of climate change, is future coastal change and vulnerability of infrastructure and communities to flooding. A vulnerability-led and decision-centric framework (VL-DC) (Armstrong et al., 2015), the ARCoES approach combines new observations and modelling to explore the future vulnerability to sea-level rise and storms for nuclear energy sites in Britain. As will be outlined below, the resulting DST provides inundation mapping via LISFLOOD-FP, XBeach, XBeach-G and SWAB modelling. The data are then combined in a ROA framework to provide an assessment of when it is most cost-effective to implement a new management approach.

3.1 Inundation Mapping

Inundation mapping is a key component of the ARCoES DST. While a general overview of the model application is provided here, more detailed studies focusing on individual sites (e.g., Prime et al., 2015a; 2015b; 2016) have considered sensitivity analysis of the model results to ensure the approach is robust for the purpose of the DST. A "soft" coupling approach is adopted where a storm impact model provides the input to an inundation model. Here we use models that are frequently used in flood and erosion risk studies (e.g., Lewis et al., 2013; Phillips et al., 2017; Poate et al., 2016).

LISFLOOD-FP (Bates et al., 2005) has been applied as a coastal inundation model to map depth, extent and velocity of floodwaters for extreme coastal and riverine events under rising sea levels. The horizontal model resolution varies from 20 m to 50 m depending on the size of the domain (which range from sites of critical infrastructure to the regional scale for supply network assessments) to allow efficient computation time and to capture the required level of detail for the management needs. Data on the time-varying storm tide alone, or combined storm tide and wave overwashing or overtopping volumes are used to generate the hazard imposed at the coastal boundary within LISFLOOD-FP, which propagates the floodwater landward across the floodplain. The positioning of the coastal boundary is domain dependent as is the boundary input data. At sites where wave hazard is considered negligible the low water contour is imposed as the coastal boundary and forced by storm tide water levels at 15 minute time intervals. At sites where wave hazard is considered important, through overtopping or overwash, the crest of a defence line (natural or engineered) is set as the coastal boundary and a wave resolving storm impact model is used to provide the (10 minute average) inflow discharge. In all cases the implemented models are run for a tidal cycle starting from low water. The inland model boundary is set some distance from the coast to ensure the flood pathways and area of inundation are generally contained within the domain. The boundary is set to allow through flow so under very extreme events the water is not restricted in a way that will cause it to inaccurately build-up. For the Fleetwood case high river flows have also been imposed as a discharge at the boundary points that cross the river Wyre (see Prime et al., 2015a). This allows the user to explore a range of flood hazard combinations (sea-level rise, coastal storms and high river flow).

At sites with wave hazard, overwashing or overtopping volumes have been calculated for various defences: hard engineered (SWAB, McCabe et al., 2013), sand dune (XBeach, Roelvink et al., 2010) or gravel barrier (XBeach-G, McCall et al., 2014, 2015). The use of the XBeach and XBeach-G models enables the role of storm-driven morphology and features within the cross-shore profile to be considered within the impact assessment. These models are applied as 1DH (horizontal) cross-shore profile models for present-day morphologies within the DST, while hypothetical future morphologies (such as changes in saltmarsh extent, barrier beach morphologies or subtidal bar geometries) are considered in more focused site-specific applications to determine potential changes in a system's response to storm impact (e.g., Prime et al., 2015b). The Shallow Water Boussinesq Model (SWAB) has also been used for a site with a sea wall (Prime et al., 2015a).

Although XBeach and XBeach-G can consider a fixed structure within the profile SWAB has been developed and validated with field observations to account for random wave breaking, impact and overtopping of sea walls (McCabe et al., 2013).

The initial profiles in the 1DH simulations are based on a combination of the latest available bathymetric data and beach profile surveys obtained for the site. The modelled cross-shore profiles have been selected to capture alongshore variability in the present-day coastal defence. At sites of energy infrastructure with a natural defence (gravel barrier or dunes) a 1 km spacing between the profiles with 50 m spacing closer to the nuclear power station is used to capture the alongshore variability in the beach-barrier system (Prime et al., 2016). For sites with sea walls a centrally positioned transect perpendicular to each defence section is chosen to simulate the flood hazard for each of the different defence designs (Prime et al., 2015a). An example set-up is shown in Fig. 2, where the sea wall provides protection to the local community behind. For sites where the 1DH models have been used to incorporate wave impact the wave direction is always assumed to be directly onshore to generate the worst case scenario.

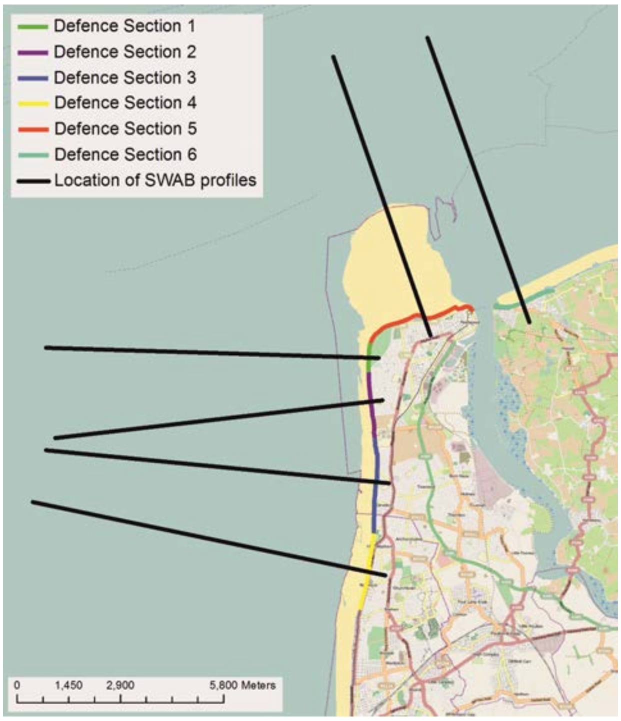

Fig. 2. The LISFLOOD-FP model domain used to simulate flood hazard around the Fylde peninsula, northwest England. SWAB is applied in this example for each cross-section to simulate the wave-water inflow at the defence crest level (Prime et al., 2015a).

Within the ARCoES DST the flood maps were developed using data available to coastal managers. This includes the most recently available airborne laser altimetry (LiDAR) collected by the Environment Agency (EA) and observational data collected by national monitoring programs where available. These data include shoreline profile information collected by the EA or local authorities, the UK tide gauge network record (established in 1953), owned and operated by the EA, and the WaveNet record, a UK network of wave buoys (established in 2002) operated by the Centre for Environment Fisheries and Aquaculture Science (CEFAS). These real-time systems provide a long-term data archive to which a joint probability analysis can be applied to generate wave-water level combinations representative of a range of storm severities. Where observations are not available tidal predictions are obtained from the POLTIPS3 software, available from the national tide sea level facility, and wave data are obtained from long-term (40-year) hindcasts, such as the UK Climate Predictions 09 (UKCP09, Lowe et al., 2009) and the global wave hindcast produced in preparation of the European Centre for Medium Range Weather Forecasts (ECMWF, 2016) next reanalysis (ERA5).

Where observations are limited to within the last decade (e.g., wave monitoring) or where only waves or water levels are monitored, archived data from climate modelling systems can be utilized to lengthen the datasets. The longer the data record the greater the confidence in the extreme value analysis. This research has used the European Centre for Medium-Range Weather Forecasts (ECMWF) 30-year wave ECWAM cycle 41R1 model data to lengthen the wave records. These numerical data are validated against existing wave observations prior to use in the analysis.

For the UK energy sector, events ranging from typical (1 in 1 year return period) to extreme (1 in 10,000 year return period) conditions are considered. The joint probability analysis is performed using JOIN-SEA (Hawkes and Gouldby, 1998). This software uses the generalised Pareto distribution (GPD) model and simultaneous records of significant wave height (H_s) and water level (*WL*) at the time of the observed high water. In most cases the combined observational record covered a period of the order of a decade, the limitation often being related to the deployment of the wave buoy. For each return level a range of wave-water level conditions are generated. These cover conditions that transition from lower *WL* and higher H_s to higher *WL* and lower H_s. The conditions that pose greatest flood hazard along the probability curves are selected from an ensemble of 1DH storm impact simulations that generate a range of inflow conditions to impose into LISFLOOD-FP (Prime et al., 2016). This generates the database of flood maps behind the DST. In this respect, the DST operates as a look-up table.

Once the required wave-water level combination has been ascertained a storm tide is created to force the offshore model boundary. The storm tide comprises a spring tide and a surge curve, available for all UK Class A tide gauge locations from the EA (McMillan et al., 2011). The surge curve is used to scale the tide such that the total high WL reaches the required extreme value. The time-varying water levels are combined with the required wave conditions within the 1DH storm impact model. Although the H_s is kept constant, a JONSWAP (Joint North Sea Wave Observation Project) spectrum is applied to create a time-varying wave field. This approach represents the worst-case scenario as the wave conditions maintain the desired extreme value for the duration of the simulation, a complete tidal cycle. An appropriate peak wave period (T_p) is selected from the wave data for each H_s. At many sites around the UK there is a bimodal wave climate related to the wind sea and swell wave components. For each wave condition the longest T_p associated with each H_s is used to simulate the highest wave runup levels.

Future sea-level projections are incorporated into the still water level of each event to take into consideration sea-level rise and explore future change in the inundation hazard. The projections are chosen to represent the high-end emission scenarios up to 2500AD (Jevrejeva et al., 2012). Incremental increases in mean sea level are considered at 10 cm intervals up to a rise of 2 m and then at 25 cm intervals to a rise of 5.5 m (Knight et al., 2015). The higher resolution is considered for levels representing plausible projections that could occur over the next 100 years, consistent with the long-term shoreline management planning framework. A lower resolution is then applied for the more bespoke longer term (c. 500 year) projections for the energy industry.

3.2 Monitoring

Alongside the numerical applications, storm surveys were performed at three nuclear sites across the UK, including Seascale (representing Sellafield in the northwest), Lilstock (representing Hinkley Point in the southwest) and Sizewell (in the east), as well as a long-term wave gauge deployment at Bradwell (in the southeast). This extreme event monitoring is used to assess the present-day vulnerability and disturbance-recovery behaviours of the sites. In order to compliment short-term survey campaigns that aim to characterise coastal response to storms, a cost-effective method of providing continuous observation of morphological change by automatically mapping large coastal areas has also been developed using a standard marine navigational radar (Bell et al., 2016; Bird et al., 2017a).

3.2.1 Surveys

Storm surveys over a tidal cycle were used to assess the response of different coastal systems and identify features that make them resilient or resistant to storm impact. During an event pre-, during and post-storm topographic data were collected (using a dGPS on a staff pole at low tide) alongside in-situ measurements and remote sensing observations. The in-situ instruments (e.g., Fig. 3) were deployed pre-storm and retrieved after the storm. These included two low water scaffold rigs with pressure transducers and current meters together with five scaffold tubes with pressure transducers deployed alongshore at equal spacing (< 1 km) on the intertidal terrace. These instruments recorded the wave and tide elevations and the current velocities during the storm. Remote sensing techniques included a tower with two video cameras and a second tower with a laser-scanner. The video cameras were positioned to continuously record alongshore variability of wave runup during the storm (Poate et al., 2016). The laser-scanner tower was deployed on the beach face to measure morphological change and swash hydrodynamics along a cross-shore transect throughout the storm (Almeida et al., 2015; Almeida et al., 2017).

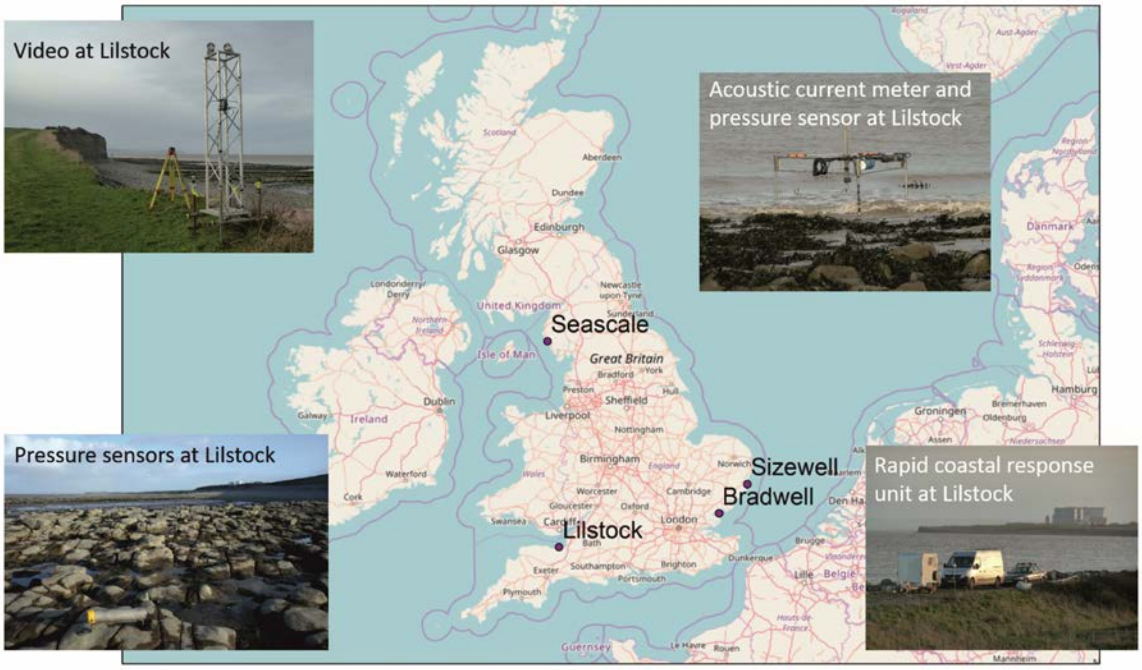

Fig. 3. Location map of the storm survey sites and examples of the instrumented rigs and towers deployed.

3.2.2 Long-term monitoring

A new monitoring technique has been deployed, which uses a radar-imaged sea surface and an accurate record of tidal elevations (such as a nearby tide gauge) as an altimeter to measure tidally-driven water level elevations at each pixel in a radar scan. By knowing the position of the waterline and the tidal elevation a bathymetric survey of the intertidal area can be produced. This methodology was used to observe seasonal changes in morphology over a 3-year period and assess storm impacts on beach volume and intertidal bedforms (Bird et al., 2017a). With the ambition of applying this radar technique to multiple locations a semi-mobile radar survey system has been developed during the ARCoES project by *Marlan Maritime Technologies Ltd*. This system is powered by solar panels and a wind turbine and provides a stable radar tower, CCTV camera and data recorder, enabling coastlines with limited power infrastructure to be monitored effectively. This system continuously monitors beach topography within a few kilometres of the radar for the entire duration of the deployment, which can then potentially update intertidal bathymetry and waterline levels in near real-time. Study sites are shown in Fig. 4.

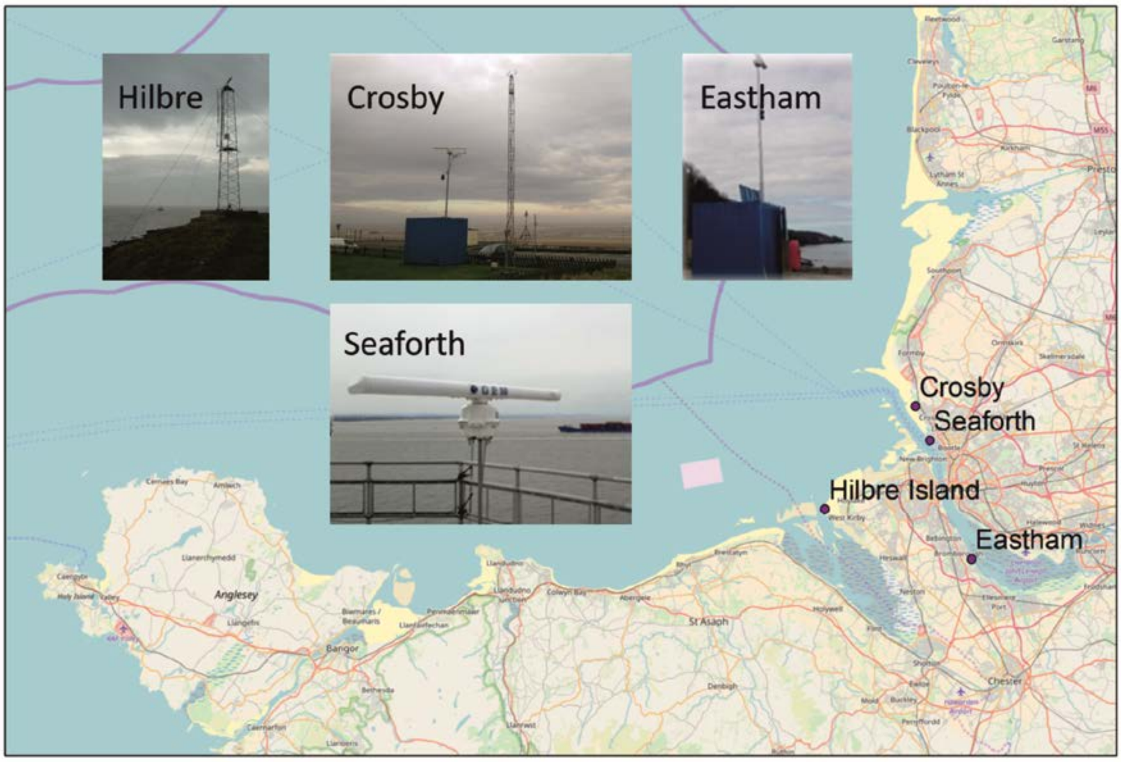

Fig. 4. Location map of the radar monitoring sites and the radar systems deployed.

A previous application to the Dee estuary, northwest England, has demonstrated the capability of the radar to monitor complex geomorphological environments (Bird et al., 2017b). The tidal range in this estuary is in excess of 10 m on high spring tides. The morphology is very complex and includes large areas of intertidal sandflats, subtidal channels, mud banks, saltmarshes and rock outcrops. Using a 2.5 m radar antenna intertidal topography was derived with a 3 m spatial resolution over a 4 km range from the radar. Comparison with LiDAR showed radar-based system was able to derive the major features of the topography including complex channels and bedforms with a vertical accuracy of +/- 20 cm (although limitations with the LiDAR data should also be acknowledged in any error analysis) (Bell et al., 2016). This surveying system therefore provides advanced warning of adverse morphological change, volumetric information on sediment movements (especially useful for monitoring beach nourishment schemes or identifying erosion hotspots), bedform migration and broad-scale indications of a beach system health. Following the development of this rapidly deployable remote-sensing survey platform (Rapidar), planned winter deployments at sites of critical energy infrastructure (2017-18 for Minsmere, E coast UK, and 2018-19 for Dungeness, SE coast UK) will collect data to assess longer-term resilience of these sites. These will also be complemented by additional storm surveys to assess the response of these coastal systems to a winter season. This will help to identify and assess the role of shoreline response and morphological evolution within flood hazard assessments, enabling better understanding of some of the uncertainty surrounding modelled flood maps.

3.2.3 Real Options Approach (ROA)

The financial viability of investment projects or the selection of investment alternatives is typically assessed by cost–benefit analysis. The most widely used method is updating the future cash flows generated by the coastal scheme. This method is often referred as Discounted Cash Flow (DCF). However, it is widely acknowledged that the DCF leads to suboptimal decisions when irreversible investments are subjected to uncertainty (Pringles et al., 2015), such as large-scale infrastructure investment. Parallel to the modelling and monitoring of the physical processes, a Real Options Analysis (ROA) was developed to identify which energy infrastructure will benefit from flood management investment, and the optimal time to invest in this infrastructure (Prime et al., 2018). ROA is an adaptation of financial options analysis applied to valuing of physical or real assets (Pringles et al., 2015). ROA assesses the implied value of flexibility that is embedded in many investment projects. Flexibility acknowledges that investment plans are modified or deferred in response to the arrival of new (though never complete) information or until the uncertainty is fully resolved (Pringles et al., 2015). Using Monte Carlo simulation, the ROA values the options to defer or invest based on a set of pre-defined decision rules and option valuation (see for example Pringles et al., 2015). The analysis provided by the ROA is used to form a cost-benefit decision-support tree.

The next section presents a series of applications of the ARCoES DST to demonstrate the versatility of information that can be generated for planning coastal adaptation to climate change.

3. Results

3.1 ARCoES DST

The examples presented use LISFLOOD-FP (alone) in applications within the Bristol Channel and Severn Estuary, southwest England. At Hinkley Point (Fig. 5) the shoreline management policy is 'hold the line' (HTL Fig. 5a). By selecting a 1 in 200 year storm condition, typical of UK defence standards, we identify a tipping point in the storm hazard rating to people (from low/moderate, Fig. 5a, to significant, Fig. 5b, for road and power line route access) at around 1 m of sea–level rise. At this site the flood hazard occurs due to inundation of lowlands towards the east of the site. This type of information highlights the need to reassess operational strategies in the future, particularly for first responders or workers using access routes or working on the electricity transmission lines.

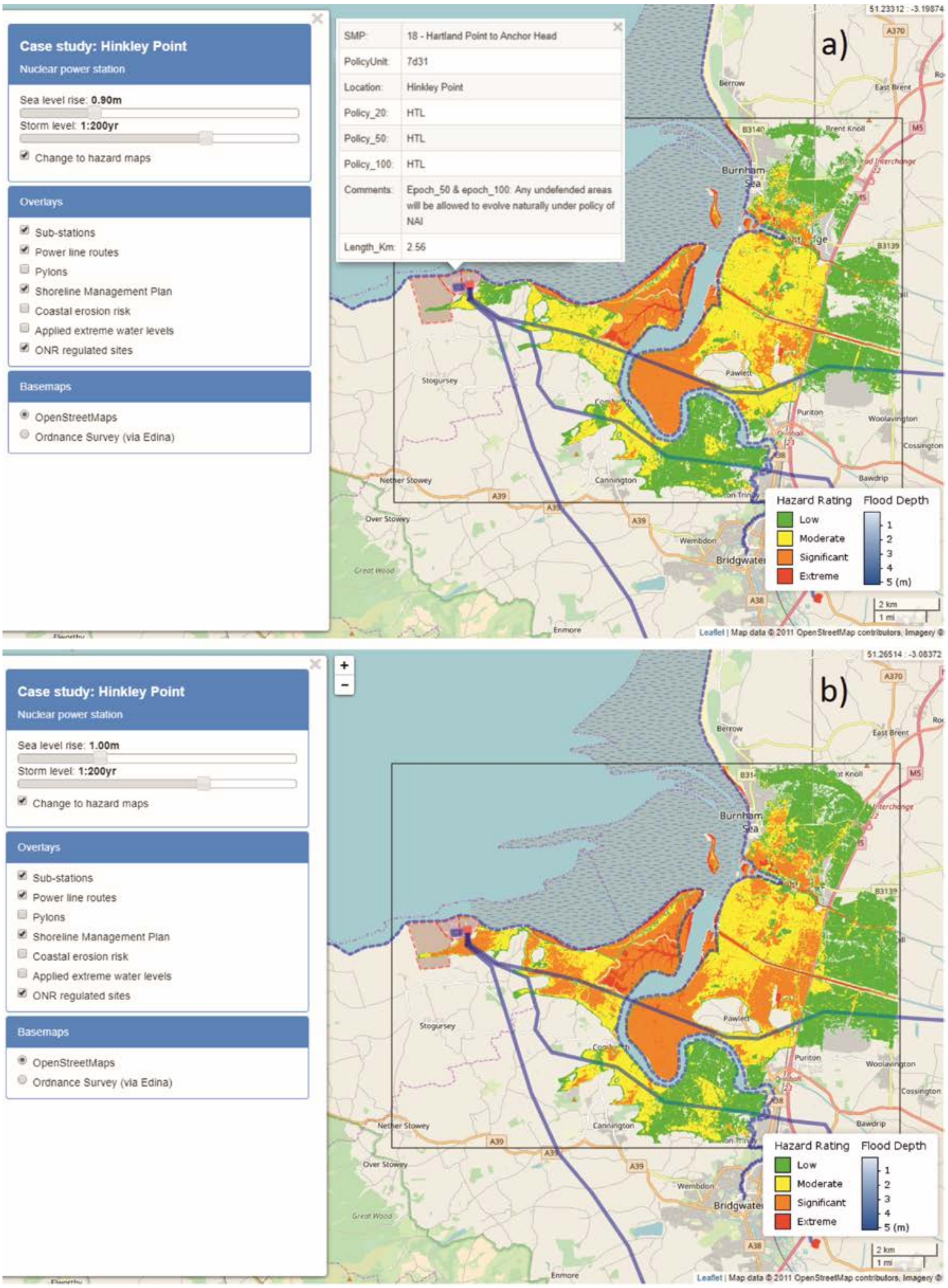

Fig. 5. Hinkley Point, showing a tipping point in the hazard to people from moderate to significant over access and electricity routes for a 1 in 200 year storm event and a change in mean sea level from a) 0.9 m to b) 1.0 m. Panel a also shows a pop-up window displaying the SMP metadata for

a defence section fronting the nuclear power station.

Animations are also available online for incremental sea-level rise and storm return period for certain nuclear power station sites. Fig. 6 shows screen shots of the online animations for the Magnox nuclear power station at Oldbury-on-Severn. The screen shots show increasing sea-level rise and a constant 1:200 year storm level. The base map used for these images in Ordnance Survey (OS, 2014). A 1:200 year storm level under present-day sea level (no increase) results in inundation of agricultural land of less than 1 m. A 1:200 year event, accompanied by 0.2 m sea-level rise results in more extensive inundation. However, the depth of inundation remains up to 1 m. The Oldbury-on-Severn site remains unaffected, as do some residential properties in the towns of Oldbury-on-Severn and Oldbury Naite to the south. Around 0.6 m sea-level rise results in a greater extent of inundation up to 1 m, particularly agricultural land to the southeast of the model domain. Again, the nuclear site remains unaffected as well as some small areas around Oldbury-on-Severn. Widespread inundation results from 1.0 m sea-level rise and low lying inland areas become vulnerable as the flood water propagation is no longer restricted to limited pathways during tidal high water. All transport and access routes within the area are flooded, as well as local amenities, agricultural land and residential properties. These images show how the DST can be used to simulate increasing sea-level rise superimposed on a 1:200 year event and the resulting depth and extent of inundation, and thus identify where the vulnerability to flooding undergoes a step change. This information is simulated with no change to present-day flood defence. It can therefore identify where intervention may be required in the future, showing flood pathways to help inform the optimal locations to invest in defence infrastructure.

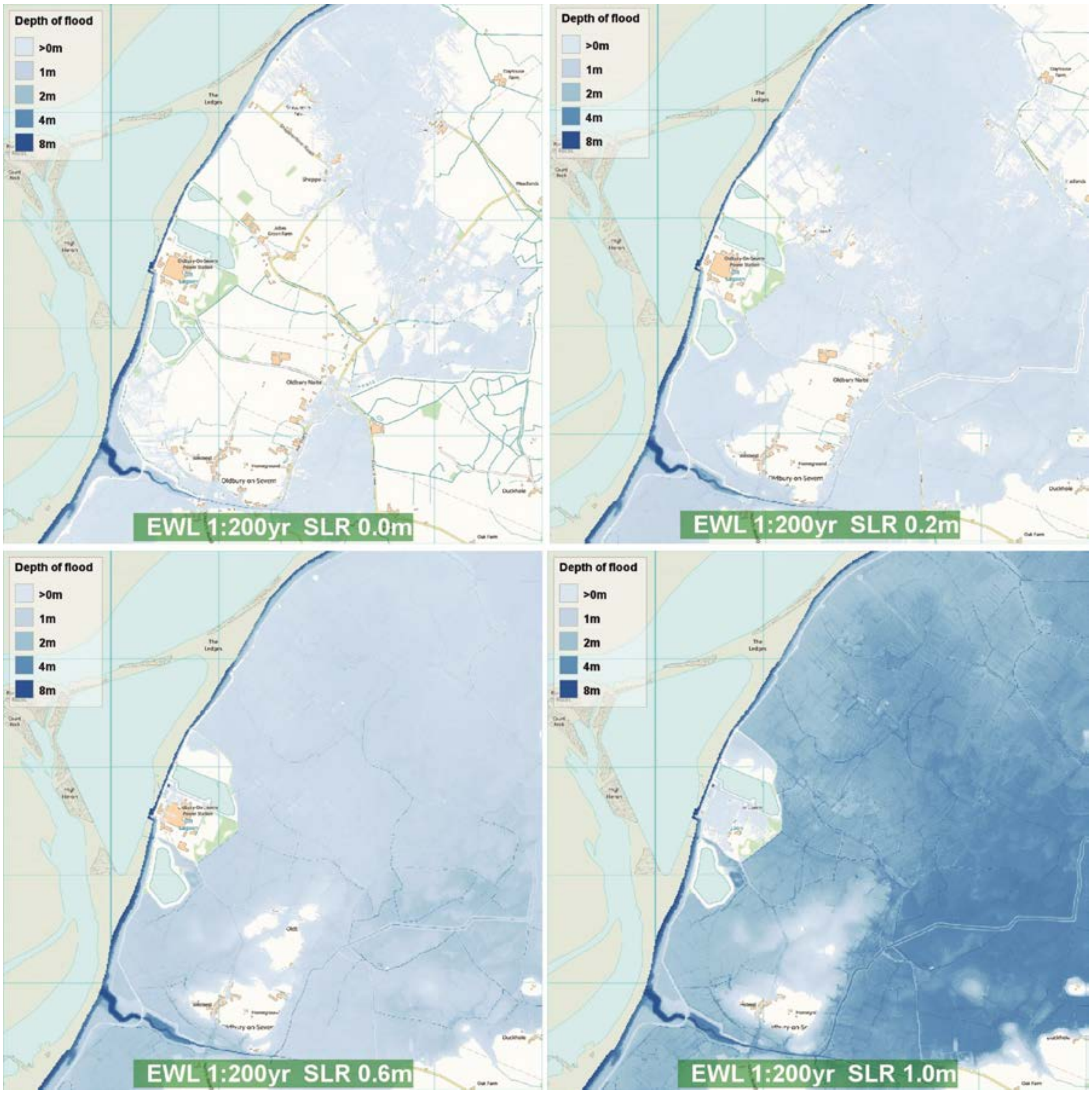

Fig. 6. Animation screen shot of a scenario with a 1:200 year extreme water level (EWL) and 0.0 m, 0.2 m, 0.6 m and 1.0 m sea-level rise (SLR) for the Oldbury model domain.

The DST is currently set-up to provide a simplified estimate of costs calculated from a depth-damage curve for different land uses considering inundation by saltwater (Fig. 7a). The DST displays the flooded area (km^2) and cost (£M) for arable land, residential housing, roads, industry and the total area of inundation for the selected storm event and sea-level value. Using this information appropriate timeframes to implement new management strategies based on the relative costs of flooding and the benefits of implementing resilience measures can be planned (Prime et al., 2015a).

3.2 Real Options Analysis (ROA)

By identifying electricity distribution substations that are vulnerable to future flooding using the DST a ROA can be applied to assess when the implementation of any resilience measures would be cost-effective. The ROA combines the flood hazard exposure maps simulated for the sea-level projections with the economic data associated with the investment decision such as inflation, building costs, maintenance costs, clean-up costs and savings in relation to deferring a project (Prime et al., 2018). Fig. 7b illustrates a classic Net Present Value (NPV) calculation based on the most widely used investment decision tool, Discounted Cash Flow (DCF) analysis. According to DCF-based calculation any substation that has a positive value should go ahead with flood defence investment. However, NPV calculations based on DCF approaches do not value any flexibility in the management process. Using ROA a flexible NPV is also calculated. Based on the more flexible ROA methods, investment in flood defense for substation 111 should only go ahead in 2090.

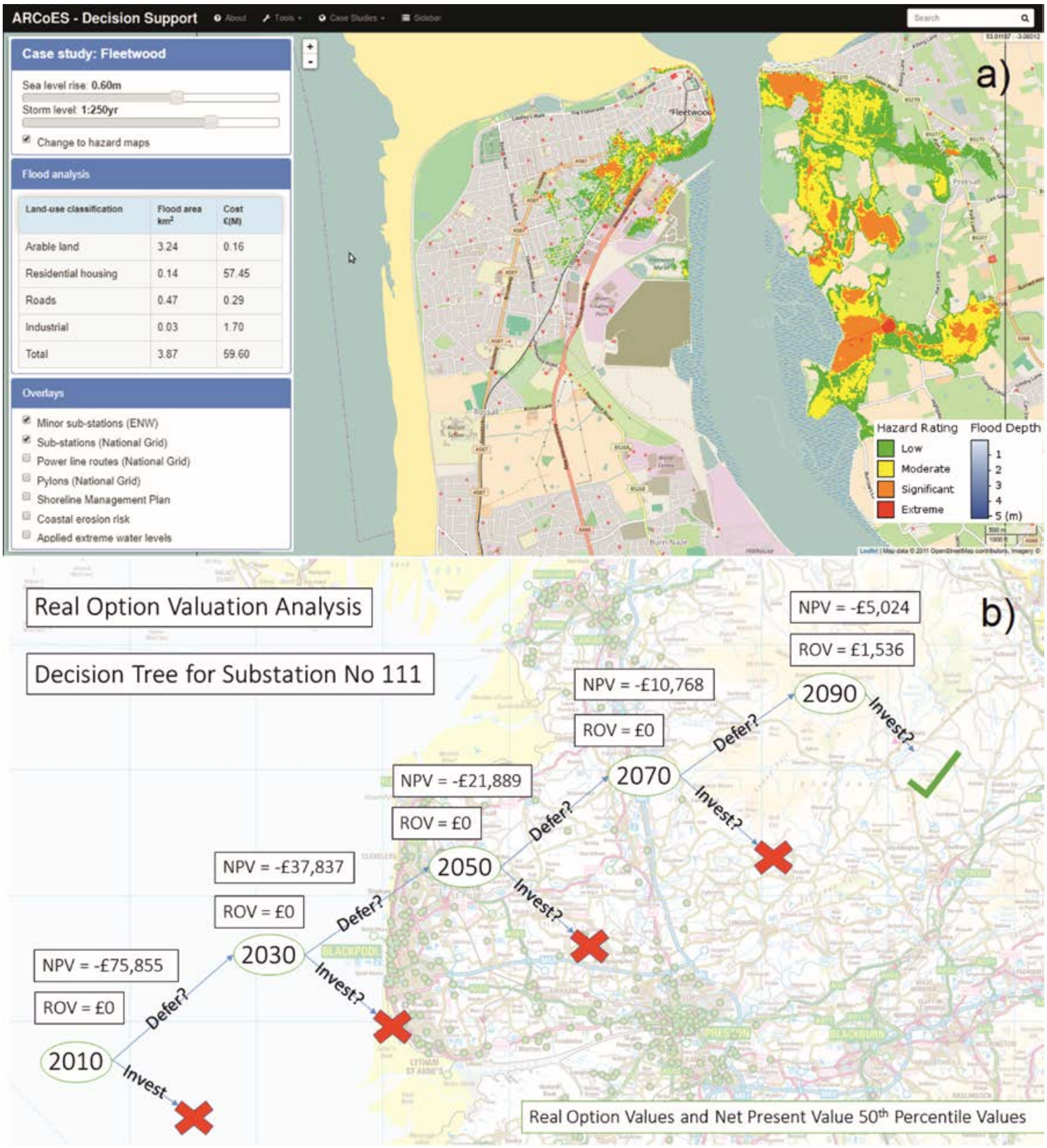

Fig. 7. Examples of a) the DST cost-benefit information for Fleetwood, northwest England, (the red symbols indicating where sub-stations are present) and b) the real options analysis decision tree for a substation in the northwest England.

3.3 Monitoring

While the DST explores future scenarios identifying when tipping points in flood hazard for the current management practice occur and the ROA enables assessment of when it is most cost-effective to implement a new management approach, observations inform us of the present-day disturbance-recovery behaviours of coastal environments (cf. Almeida et al., 2015). The ARCoES project found that all four nuclear power station sites that were observed (see Section 2) currently experience limited vulnerability to extreme storm events due to the combination of their siting and geomorphology, as well as any site-specific interventions required as part of their pre-operational and operational safety cases as a requirement of their licencing approval.

From this understanding we can cast the coastal flooding and erosion risk to nuclear power station into a Source – Pathway – Receptor framework (Narayan et al., 2012; Sayers et al., 2002) and make two general statements. Firstly, all nuclear power station locations have limited potential for the occurrence of extreme wave conditions (i.e., Source) due to their siting. At the same time, the sites have a common morphology (i.e., Pathway), characterised by a reflective and permeable gravel/cobble high tide beach fronted by a wide and low gradient dissipative feature. This ensures that even if the site experiences extreme wave energy levels, potential damage to the nuclear power station site (i.e., Receptor) due to flooding and erosion would be limited. With uncertainty surrounding the consequence of climate change and sea-level rise (the Source) at the coast, monitoring of the morphology (Pathway) is recommended, using techniques such as Rapidar, to provide early warning to trigger a review of the current management strategy to maintain the required standard of protection (to the Receptor). Through understanding of the present-day processes, critical evolution within the system can be identified for consideration in sensitivity modelling using the models that make up the DST. One example would be the update and exploration of time-evolving beach profiles within the numerical approach that generates the hazard maps. Such studies continued study will highlight areas for continued development within the DST.

4. Conclusions

The ARCoES DST and parallel ROA presented in this paper provide a resource that can be used to initiate discussions with coastal practitioners to identify how future vulnerability to coastal flooding may be mitigated through appropriate and timely intervention and adaptation. Such a forum for dialogue is required to improve the transfer of knowledge between costal researchers and decision-makers, to enable science based evidence to underpin choices made when setting new coastal management strategies. The DST enables maps of potential flooding, and associated costs, from increments of sea-level rise and storm magnitude to be explored by a wide range of users to identify key locations and ‘tipping points’ where and when the increased vulnerability to flooding challenges current operations, emergency plans and long-term management strategy. When combined with understanding gained from present day observations informed monitoring programmes to support management decisions can be put in place and site inspections can be focused on assessing geomorphic change that has the potential to change a sites vulnerability to storm impact. The detailed understanding of the local processes also allows the limitations of the 'static' morphology within the DST to be put in context thought the identification of how uncertainty within the mapped results could occur. A key area for expansion of the ARCoES framework would be to incorporate shoreline evolution within the projections of future coastal flood hazard. By using freely accessible models and mapping systems within the DST continued development can be facilitated, enabling incorporation of such information in the future.

Within a policy context, project outputs have already provided practice and policy recommendations for national and regional decision-makers on building coastal resilience to sea-level rise and storms (please see the Living With Environmental Change (LWEC) partnership policy and practice notes, Plater and Brown, 2016). In this respect, the DST and associated resources provide a framework for engagement and dialogue across research and stakeholder communities for the co-production of future plans (e.g., Armstrong et al., 2015). Over the longer term, the DST provides energy infrastructure stakeholders with a roadmap for planned investments that address resilience to future change in sea level and extreme events. This would include measures such as the relocation of substations, raising transformers and other hardware above ground, and replacing ageing assets (e.g. circuit breakers) that may be more sensitive to water. The DST therefore delivers essential support for: (i) improved response to extreme events and (ii) a strategy that builds climate change resilience. Both offer the consumer greater confidence in the constancy of energy supply and an awareness that their money is being spent effectively in combating present and future risks from flooding.

Finally, the ARCoES DST platform is an effective example of inter-disciplinary collaboration across physical, natural, and social sciences on one axis, and across research, energy and infrastructure sectors, coastal management authorities, environmental regulators, and coastal communities on another. Interactive dissemination of the DST has revealed its value in discussions that centre on: (i) future changes in coastal geomorphology and how this may be managed to promote 'natural' coastal resilience, (ii) engagement of stakeholders with projections of flooding due to sea-level rise and other forcing factors, and uncertainties therein; and (iii) interventions that mitigate impacts in an appropriate (according to location and scale of challenge), timely and cost-effective way. The DST is therefore presented as a resource for framing dialogue and exploring solutions, rather than providing simplistic answers out of context. Rather than this being viewed in negative terms by decision makers, the DST has been received positively as providing a focus for the sharing of knowledge, perspectives and priorities.

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