SCIENCE-BASED TOOLS INFORMING COASTAL MANAGEMENT IN A CHANGING CLIMATE

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Abstract

To better inform decisions associated with coastal management a database of numerical simulations has been generated using publically available data to populate an online decision-support tool (DST). This research is part of the Adaptation and Resilience of Coastal Energy Supply (ARCoES) project that focuses on areas of critical coastal energy infrastructure within the UK, such as nuclear power station locations. This web-based tool has been developed with coastal and energy sector practitioners to produce a system that visualizes plausible future changes in flood hazard to assess when 'tipping points' in a location's management strategy may be required in response to rising sea levels and storms over the next 500 years. Although the main product is focused on vulnerability to flooding, additional research on the natural resilience of shorelines has also been considered in relation to future adaptation strategies. These findings are fed into economic models developed through ARCoES to assess the cost-benefit impacts or real options.

Key words: Flood hazard, shoreline evolution, human intervention, cost-benefit analysis, numerical modelling, Decision support tool (DST)

1. Introduction

Pressures on the coastal zone are increasing in response to urbanization, changing storm climates and sea-level rise (Stevens et al., 2015). To ensure critical coastal infrastructure is resilient in the future, adaptive management (Stive et al., 2013) that responds with the evolving shoreline (Stive et al., 2002) is required. In the UK, shoreline management considers three planning timeframes or 'epochs', the present day (0-20 years), medium-term (20-50 years) and long-term (50-100 years) and four management policy approaches: hold the (defense) line, managed realignment, advance the line and no active intervention. The typical shoreline planning horizon within the UK considers the cost-benefit of a scheme over a 100 years (Hoggart et al., 2014). Management strategies and new schemes are developed and designed based on current understanding of the local coastal processes. An evidence base to underpin the management policy is typically formed from long-term shoreline monitoring programs, modelling studies and new insight from research (Brown et al., 2016). Here we focus on the coastal energy sector, where critical infrastructure needs to be resilient over a 500-year timeframe when considering nuclear new build. This poses a new challenge as climate projections are often made over the 100-year timeframe (e.g., up to 2100AD, IPCC, 2007). Management strategies at sites of critical coastal energy infrastructure must therefore consider vulnerability to changing flood and erosion hazards as a consequence of sea-level rise and storms.

   To make informed decisions plausible model projections and monitoring are required to explore system sensitivities to storm conditions and human intervention (Brown et al., 2016). Through the application of computationally efficient numerical models, sensitivities in coastal response to changing wave and surge conditions can be assessed to gain better understanding of the uncertainty surrounding changing storm conditions. Using sea level projections up to 2500AD (Jevrejeva et al., 2012) also enables the uncertainty in plausible estimates of sea level rise to be evaluated. These ensembles of simulations provide useful information that can be interrogated to inform decisions about alternative management options and can also form the basis of an economic analysis to identify when it is best to implement a new strategy or scheme

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(for more details see, [ARCoES Project - Science in Society](#)).

Tools enabling science-based models to inform coastal management decisions in a changing climate are known as Decision-Support Tools (DSTs) or Decision-Support Systems (DSSs). Here we present model applications and scenarios considered for a DST developed for the UK energy sector as part of the Adaptation and Resilience of Coastal Energy Supply (ARCoES) project (Knight et al., 2015). This approach provides the basis on which ambitious, alternative human interventions can be explored as part of continuing research in a project investigating physical and biological dynamic coastal processes and their role in coastal recovery (BLUEcoast).

2. Methods

A range of science-based models, forced and validated by coastal monitoring systems, have been used to generate a matrix of inundation and sediment pathway scenarios at coastal sites of interest to the UK coastal energy sector. 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 model domain is discretized by a gridded digital elevation model (DEM), resolving the terrain at 5 m resolution to enable efficient runtime. The input data comes from the most recently available airborne laser altimetry (LiDAR) collected by the Environment Agency (EA). The time-varying 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. Future sea-level projections are incorporated into the still water level and are chosen to represent the high-end emission scenarios up to 2500AD (Jevrejeva et al., 2012). Incremental increases in mean sea level are combined with joint-probability storm tide and wave conditions for a range of event severities (Knight et al., 2015) using a storm impact model. To generate the joint wave-water level event joint probability analysis (Hawkes and Gouldby, 1998) has been applied to long-term coastal observations, which have been lengthened with model hindcasts. Wave overwashing or overtopping volumes have been calculated for various defences: hard engineered (SWAB, McCabe et al., 2013; XBeach, Roelvink et al., 2010), sand dune (XBeach) or gravel barrier (XBeach-G, McCall et al., 2015).

The use of XBeach and XBeach-G enables the role of storm-driven morphology to be considered within the impact assessment. These models are applied as 1DH (horizontal) cross-shore profile models for present-day morphologies in addition to hypothetical future morphologies, such as changes in saltmarsh extent, barrier beach morphologies or subtidal bar geometries, to determine potential changes in a system's response to storm impact. The initial profiles 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 defense. An example is shown in Figure 1, where a 1 km spacing decreasing to 50 m at sites of specific interest has been used to generate the flood hazard input. The variability in the beach-barrier system includes an alongshore increase in beach slope in addition to variability in gravel barrier crest elevation. Towards the east of the site, the beach has a more reflective nature whereas in the west it is more dissipative. The dark blue lines represent the region of managed barrier height where the policy is hold the line and the light blue and green lines represent the naturally evolving system. The dashed green profiles (5 and 7) indicate the profiles of lowest crest elevation at the time of the survey.

This exploratory modelling approach is driven by observational data collected by national monitoring programs. These data include the UK tide gauge network, owned and operated by the EA, and WaveNet, a UK network of wave buoys 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. For the UK energy sector, events ranging from typical (1 in 1 year return period) to extreme (1 in 10,000 year condition 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 buoys. To lengthen the datasets, archived data from operational modelling systems can be utilized. The longer the record, the

greater the confidence in the extreme value analysis. This research has used a global wave hindcast, produced in preparation of the European Centre for Medium Range Weather Forecasts (ECMWF, 2016) next reanalysis (ERA5) to lengthen the wave records. These numerical data are validated against existing wave observations prior to use in the analysis. 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 XBeach or XBeach-G simulations and imposed into LISFLOOD-FP (Prime et al., 2016) to generate 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 XBeach or XBeach-G. Although the H_s is kept constant, a JONSWAP (Joint North Sea Wave Observation Project) spectrum is applied to create the 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 run-up levels. For more details on the modelling approach and application please see ARCoES Project - Supporting decision makers.
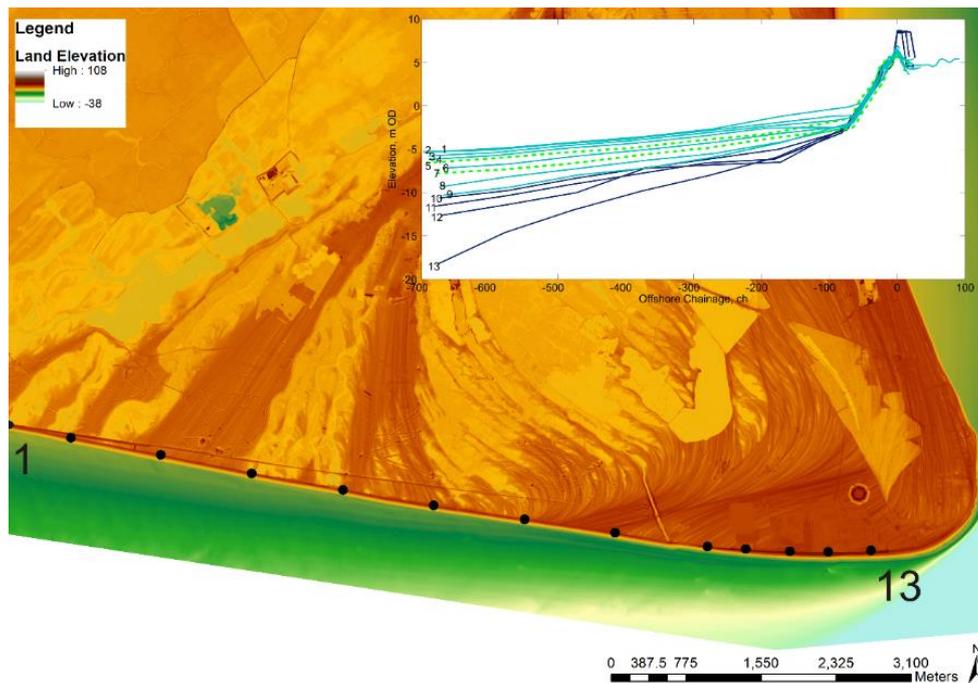

Figure 1. The LISFLOOD-FP model domain used to simulate flood hazard along the southern shore of the Dungeness Foreland, SE UK. The dots indicate where XBeach-G profiles, shown in the inserted panel, provide inflow volumes from wave overwash (Prime et al., 2016)

All modelled data are processed to be visualized within a web-based geospatial DST (Knight et al., 2015). The modelled data is interpreted into a user-friendly useful output, such as spatially varying hazard rating (Surendran et al., 2008) and visualized in open source mapping software (Quantum GIS). Nuclear sites that are licensed by the Office for Nuclear Regulation are overlain in the DST with a polygon that directs the user to the pre-operation or operational safety cases, highlighting that the necessary regulations for safe operations have been met by appropriate risk assessments. The DST then enables the user to explore the vulnerability to flooding for the neighboring coastal zone. Such information is

important for long-term management of access and electricity routes to/from the critical infrastructure. The raster maps form the basis of the web-based geospatial DST (HTTP://arcoes-dst.liverpool.ac.uk), constructed using JavaScripts (Knight et al., 2015). This web-based tool enables the end user to interrogate model results using slider bars (Figure 2). Although the range in storm conditions include storm conditions up to the 1 in 10,000 year event and projected sea-level rise up to 5.5 m, the sliders are linked to storm levels and water levels to explore 'what if' scenarios rather than future timeframes. Such extreme events and sea-level extents are considered due to the operational and post-operational care and maintenance life-cycles associated with nuclear facilities. Due to the uncertainty associated with such long-term projection, the DST considers an extensive range of plausible changes, even those associated with a low probability of occurrence. Base maps of the required infrastructure, such as roads and the electrical grid, can be overlain to identify infrastructure and emergency access routes that could potentially become 'at risk' in a future climate if appropriate measures were not taken to mitigate this risk. The simulated conditions currently apply 'present-day' defenses and coastal characteristics and allow the end user to identify tipping points in the resilience of the current management practices, which are built into the visualization options, to make informed decisions in a timely manner to resource and plan new policies.
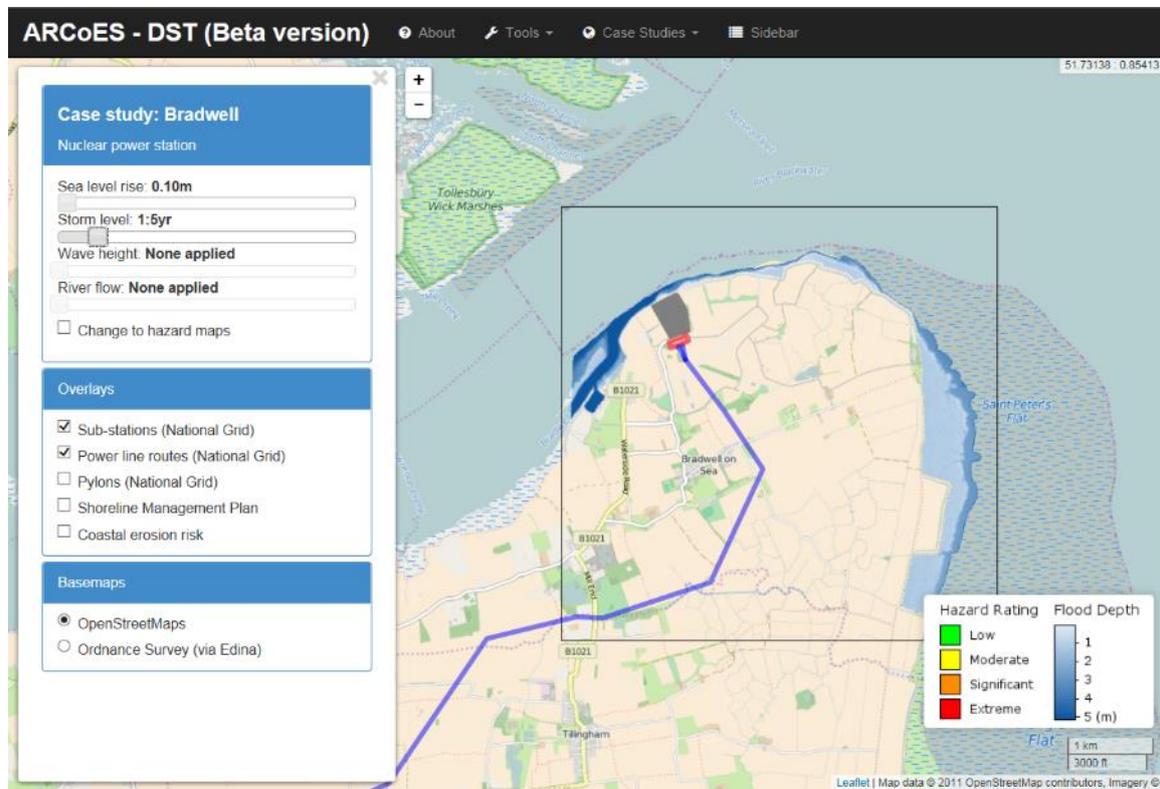

Figure 2. The ARCoES DST, available at http://arcoes-dst.liverpool.ac.uk. Inundation is shown here as a depth map.
The black box indicating the outer bounds of the model domain

In addition to viewing the flood hazard as a standard map of depth and extent, the user can select to view the maps as a hazard rating. Tick box options enable easy toggling between flood depth and hazard rating views. The hazard threshold to people (H) is calculated from the flood depth (d), flood velocity (v) and a debris factor (DF):

$$H = d\,(v + 0.5) + DF \qquad\qquad (1)$$

This classification (Surendran et al., 2008) requires knowledge of the land use to choose an appropriate DF depending on the inundation area (Table 1). The thresholds for each classification are given in Table 2 and

an example for a 1 in 5 year storm event applied with a 0.1 m rise in sea level is shown in Figure 3. As demonstrated when comparing Figure 2 with Figure 3, in some areas there is no hazard to people even when there is inundation. The hazard maps have been adjusted so values are only shown for land elevations above the intertidal. While in the flood depths are available over the intertidal and in locations where deep channels cross the intertidal.

Table 1: Debris factors for different flood depths, velocities and land cover

Depths (d)	Pasture/Arable	Woodland	Urban
0 to 0.25 m	0	0	0
0.25 to 0.75 m	0	0.5	1
$d > 0.75$ m and/or $v > 2$	0.5	1	1

Table 2: Classification of the hazard to people

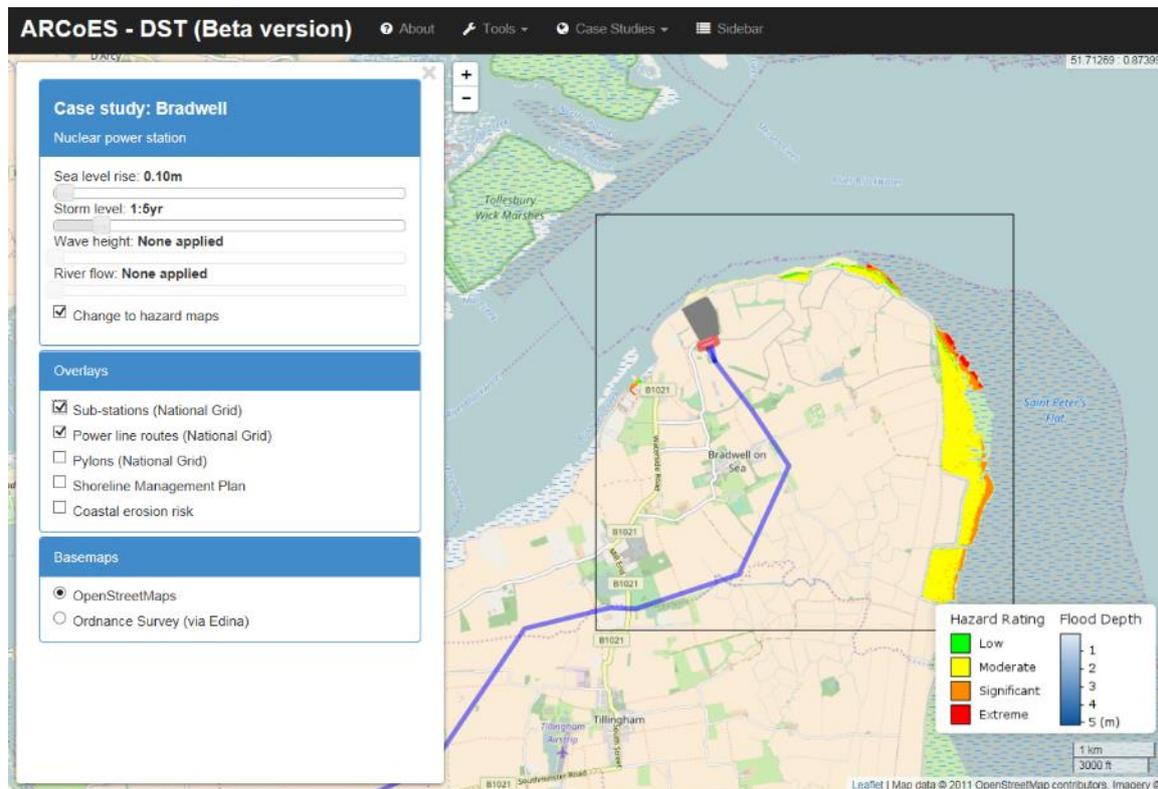| Hazard threshold (H)	Degree	Description
< 0.75	Low	**Caution**: Flood zone with shallow water or deep standing water
0.75 - 1.25	Moderate	**Dangerous for some** (i.e., children): Flood zone with deep or faster flowing water
1.25 - 2.0	Significant	**Dangerous for most people**: Flood zone with deep or fast flowing water
> 2.0	Extreme	**Dangerous for all**: Flood zone with deep or fast flowing water

Figure 3. The ARCoES DST, available at http://arcoes-dst.liverpool.ac.uk. Inundation from the example in Figure 2 is shown here as a hazard to people map. The black box indicating the outer bounds of the model domain

Alongside the model applications that generate the database behind the DST, additional numerical

studies have been performed to understand potential changes in the physical coastal processes that influence the operations of energy infrastructure, as well as the 'natural' coastal protection afforded by beaches and saltmarshes. For example, Delft3D (Lesser et al., 2004) coupled to SWAN (Booij et al, 1999) has been implemented to identify changes in sediment pathways and coastal morphologies under rising sea levels for climates of variable storm frequency. This coastal area model has been applied to the Severn Estuary and the east coast of the UK. The large model domains have required a nested approach to be applied downscaling boundary conditions from operational systems at the kilometer scale to tens of meters at the coast (Fig. 4). Due to the computational expense of these models years that represent a calm (2008/2009) and stormy (2013/2014) winter periods have been hindcast. The models have been validated against tide gauge data using the Brier skill score (Sutherland et al., 2004). Operational model data sets have been used to produce boundary forcing to simulate a July to June annual period, maintaining the continuous winter season. To upscale the annual simulations a morphological factor is applied to simulate a 100-year period. A comparison of the representative stormy climate to the calmer climate enables assessment of how a change in storminess could influence the sedimentation patterns within the region.
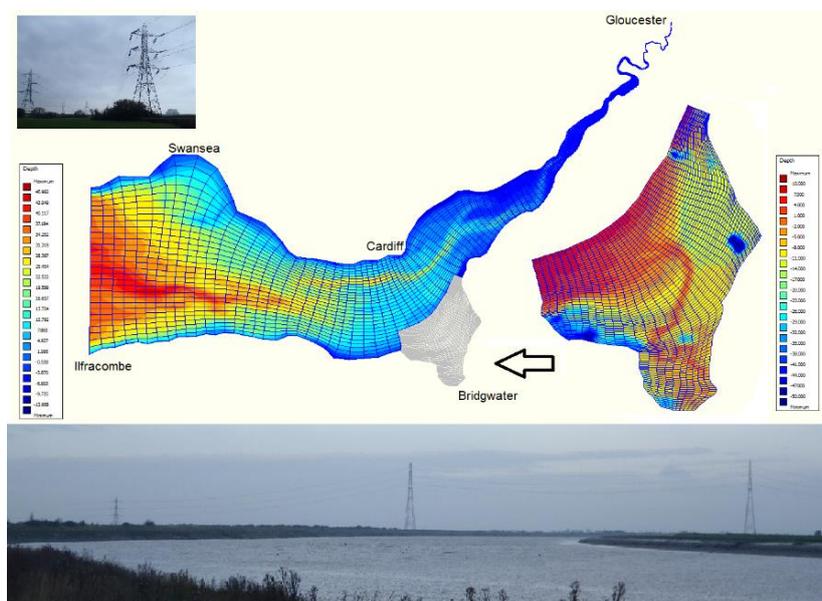

Figure 4. The nested model domain for the Severn Estuary, the high-resolution mesh covers a nuclear new build site and a region where infrastructure (electricity routes) crosses an evolving estuary system

3. **Results**

Different applications of the ARCoES DST are presented to demonstrate the types of information that can be generated for coastal resilience planning purposes. The first example is an application to Hinkley Point, SW England (Figure 5). Here the management policy is hold the line. By selecting a 1 in 250 year storm condition, typical of UK defense standards, we demonstrate the identification of a tipping point in the storm hazard rating under rising sea levels. At this site the flood hazard is in relation to inundation of lower land towards the east. This type of information informs future assessments of hazard to people using access routes or working on the electricity towers. Our second example looks at the long-term resilience of a coastal community. Figure 6 demonstrates an example tipping point in the defense level of a seawall in Fleetwood, northwest England. In this case, a 1 in 250 year storm tide is selected to represent the local design threshold along with a 1 in 100 year wave condition. The change is flood hazard for this combined storm event is assessed for rising sea levels. In many locations coastal schemes have been commissioned at different times and have different designs due to natural variability in flood hazard along the coast. It is seen here that only the north-facing defenses (section 5 and 6) become at risk of wave overtopping under rising sea levels and that the rise in level required to enable wave overtopping is different for each defense section. At this location the inundation has also been visualized in terms of brick courses (Figure 6),

comprising a 6.5 cm brick with 1 cm of mortar (Prime et al., 2015). We show the flood hazard from wave overtopping soon after the point at which increasing sea level enables the waves to overtop both of the vulnerable defenses. This information indicates where mitigation measures such as periscope airbricks could be implemented and where additional flood defenses would be required to maintain the community's resilience to flood hazard under rising sea levels. The brick course maps form a new approach to representing flood maps, which enable easy dissemination of information to coastal managers and local authorities.

Figure 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 250 year storm event and a change in mean sea level from 0.9 m to 1.0 m
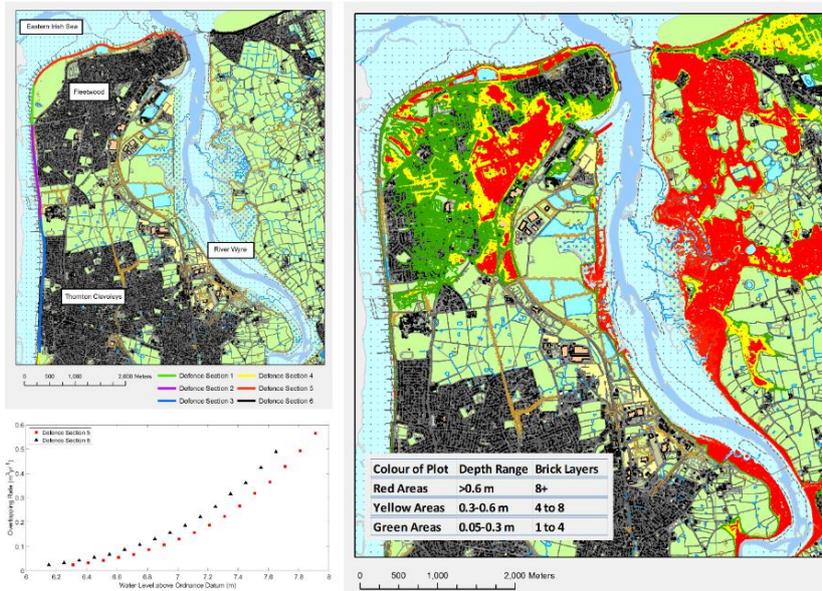
Figure 6. Varying defense sections at Fleetwood, showing the increase in wave overtopping in response to increasing sea level and the inundation for a 1 in 250 year storm tide combined with 1 in 100 year wave conditions and 0.65 m of sea level rise (Prime et al., 2015)

The models used within the DST have also been implemented to explore the impact of tidal lagoons on the potential future flood hazard to adjacent coastal communities and to assess emergency response planning. The ability to use tidal lagoons as both a source of renewable energy, but also as a means of increasing coastal resilience has been assessed by imposing a lagoon as a fixed structure within the LISFLOOD-FP domain (Lyddon et al., 2015). It is suggested that a lagoon with a uniform seawall height of 12.19 m positioned off the north Wirral coast at the mouth of the Mersey estuary, northeast England would reduce future flood risk to the Stanlow oil refinery, positioned up estuary, in terms of both extent and depth under different sea level rise scenarios (Figure 7). Consideration of a lagoon further along the north Wales coastline, however, has been simulated to increase the flood risk to the surrounding low-lying coastline. This numerical approach has also been implemented at Rhyl, north Wales, to assess the flood hazard to people during a seawall breach (representative of a 1 m reduction in crest height for an extreme event that occurred on the 11th December 2013) under future sea level scenarios (Phillips et al., 2017). When considering emergency response the flood hazard rating to

people can be used to assess access and evacuation routes. Figure 8 shows the inundation as a hazard rating for present day sea level and with 0.6 m of sea level rise (representative of the UKCP09 'medium emissions' scenario for 2100).
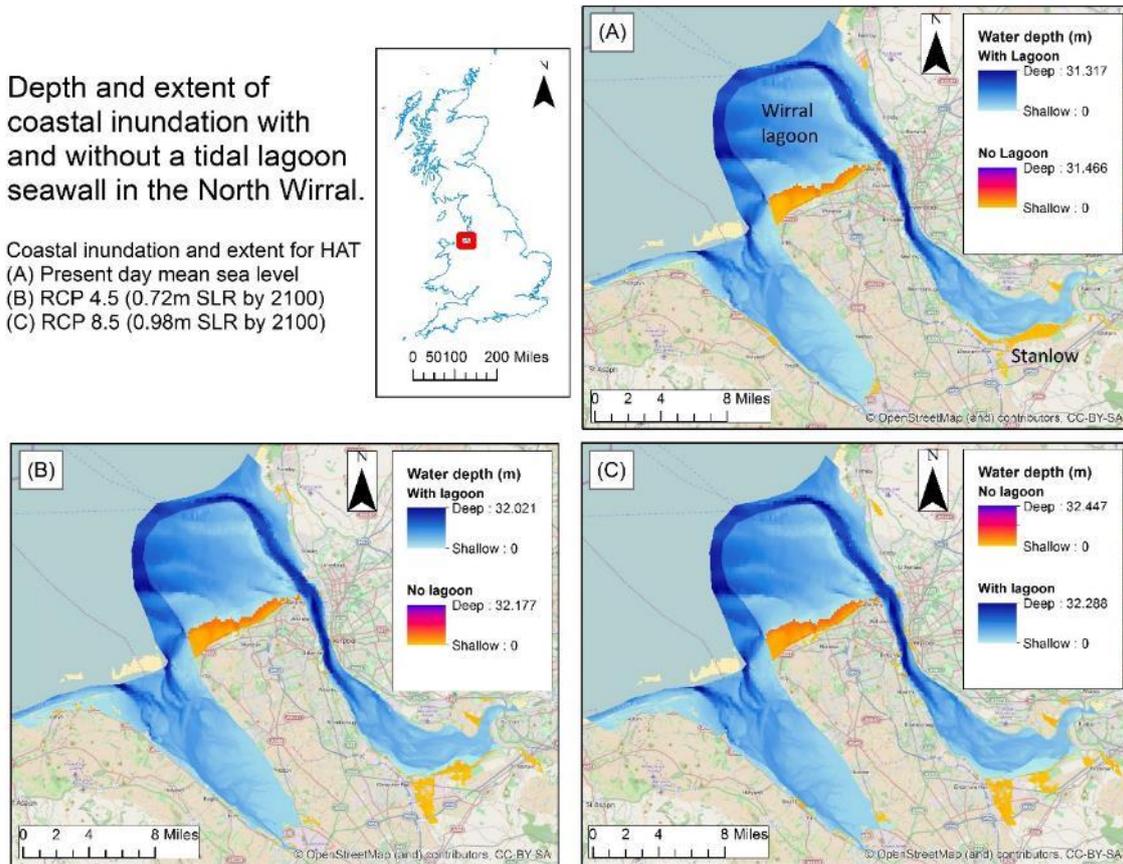

Figure 7. Comparison of inundation with and without a north Wirral tidal lagoon under 3 representative concentration pathways (RCP) (Lyddon et al., 2015)

Figure 8. Rhyl breach scenario showing the change in hazard rating surrounding the ambulance and fire station for present day (left) and future (right) sea levels.

By identifying electrical substations that are vulnerable to future flooding a real options analysis can be applied to identify when the implementation of any resilience measures would be cost-effective. The economic analysis developed within ARCoES includes uncertainty in future sea level rise and

flexibility in managing coastal interventions compared with traditional cost benefit analysis, and produces a more optimal outcome (Prime et al., submitted). This approach combines sea level projections with a real options analysis and takes into consideration inflation, build costs, maintenance costs, cleanup costs and savings in relation to deferring a project. The evaluation is based on the 50th percentile sea level projection and uses the 5th and 95th levels to capture the uncertainty (Figure 9). Although designed for the energy sector such an analysis could be applied for other coastal management needs. The DST is currently setup to provide a simplified estimate of costs calculated from a depth-damage curve for different land uses considering inundation by saltwater. 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 can be planned (Prime et al., 2016). Although designed for the energy sector this DST has been created to be easily upgraded, using open-source components with free licenses. The built-in flexibility therefore makes it transferable for other coastal management applications.
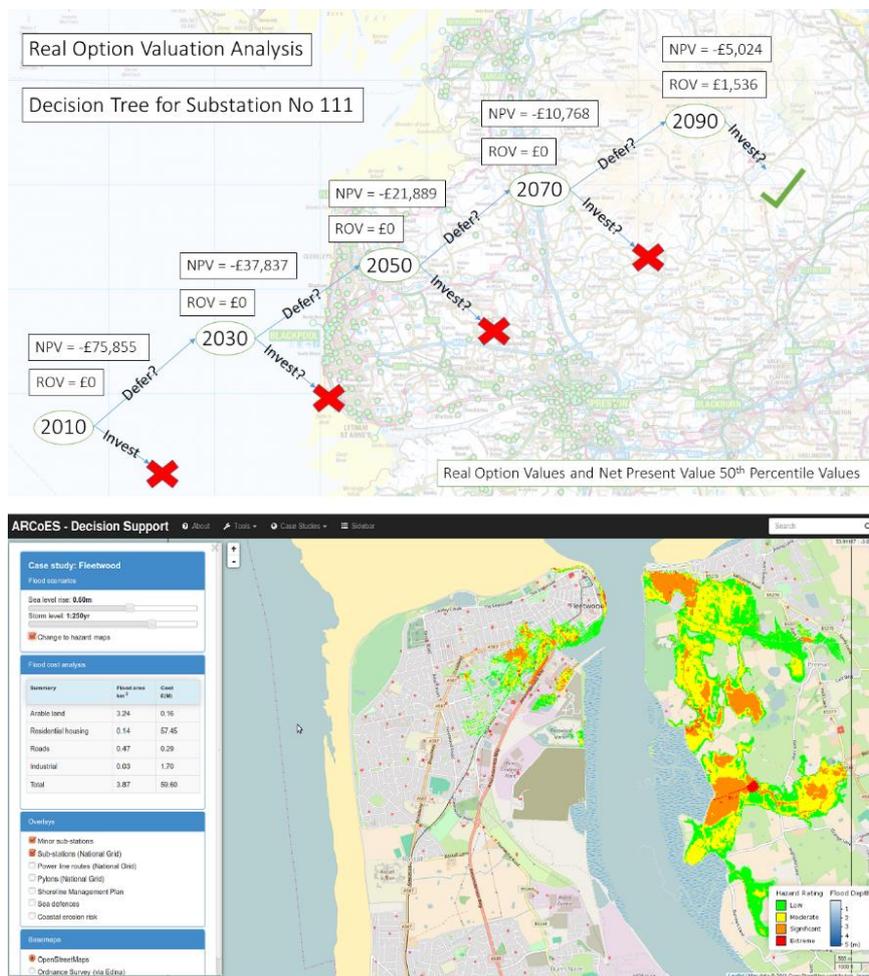

Figure 9. Examples of the real options analysis decision tree for a substation in the northwest England and the DST cost benefit information for Fleetwood, northwest England

Alongside the DST additional numerical studies have also been used to explore long-term evolution and sediment pathways for a limit number of applications due to computation costs and data requirements. Using the year 2008/2009 as an example suspended sediment transport rates for the southeast coast of England have been analyzed for two sediment fractions under different tidal regimes (Figure 10). There results will be reanalyzed under long-term morphological simulations to assess how

the transport pathways could change in the future under the relatively calm winter conditions represented by the chosen year.
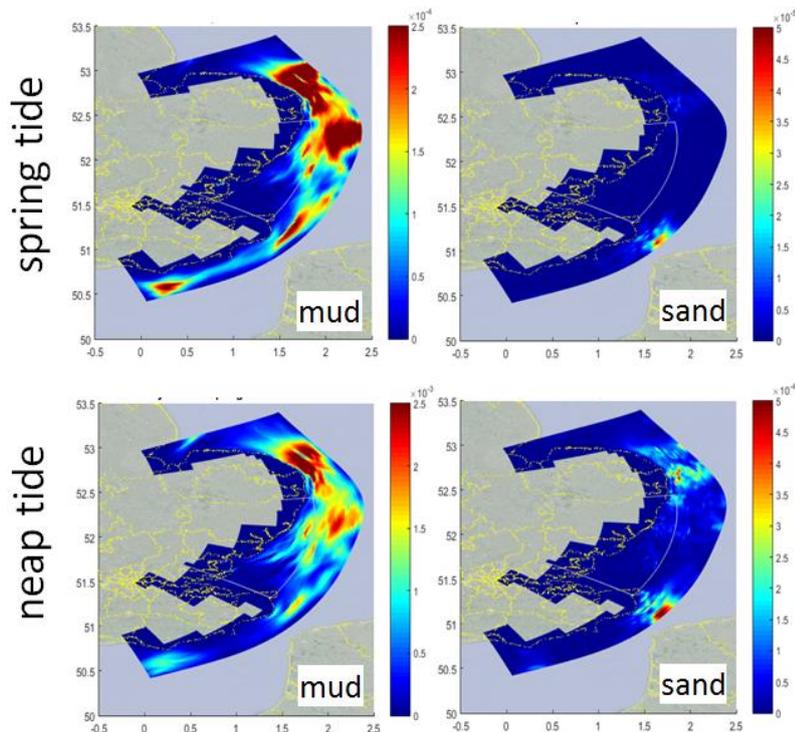

Figure 10. Residual suspended transport (m³/s/m) during a spring and neap cycle in the annual simulation 2013/2014.

4. **Discussion**

The ARCoES DST and parallel numerical and economic studies together 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, thus research directly informs management planning. The current release of the DST uses a static shoreline position, and therefore assesses vulnerability to flooding in the absence of any kind of human intervention or dynamic response of the coast. Continued development at specific sites of interest through BLUEcoast will start to incorporate the role of morphological evolution in modifying the flood hazard through the use of Delft3D into the exploratory modelling. Ways in which a one-line coastal evolution model can be used to update the cross-shore profile of a storm impacts model are also being investigated. This will enable long-term evolution of the shoreline to be incorporated into the short-term simulations of flood and erosion in response to storms to assess changing coastal resilience. The aim of the continued research will be to incorporate human intervention within the DST for specific demonstrator sites (Minsmere and Dungeness). Initial applications have explored the potential impact of beach mega-nourishment on the long-term evolution of a system (Brown et al., 2016), following a similar idea to the Dutch Sand Engine (Stive et al., 2013). In addition to numerical studies (for example the ARCoES Project – Storm chasing) field observations have been used not only for validation purposes, but also to develop our understanding of the coast during extreme events and to assess the environmental hazard from saltmarsh erosion and contaminated sediment redistribution. Observations of radionuclide and heavy metal particles within saltmarsh records can be used to assess past and future movement of these particles and their impact on the environment (for more details see, ARCoES Project – Impacting the Environment). Field observations have also included chasing winter storms and the development of new coastal monitoring techniques using X band radar to collect information that will help understand the sensitivity of the coast (Bird et al., 2017) to then frame the potential impacts of changing storm conditions and sea level rise to ensure coastal infrastructure and communities remain resilient in the

future (for more details see, ARCoES Project – Applying computer models).

5. Conclusions

There is already a good understanding of past and present coastal processes at nuclear locations. However, one of the critical unknowns is future change, which is vital to the operation of existing nuclear sites and in light of nuclear new build. ARCoES is providing new observations and modelling to first explore the future vulnerability to sea-level rise and storms and thence to consider the range of interventions that may be implemented to mitigate this risk The research has shown that coastal nuclear infrastructure within the UK is positioned in resilient locations. The creation of the DST enables maps of flood risk to be accessed by a non-specialist user so that potential future hazards to access and energy routes to and from sites of coastal energy generation can be determined in a timely manner. New scientific insights gained through the component model applications within the ARCoES project are as follows:

- Total estuarine water levels are sensitive to the timing of a surge relative to tidal high water when the phase difference is modified by at least hourly intervals.
- Although a range of water level – wave conditions meet a certain return period threshold, the greatest flood risk under wind sea conditions is posed by both moderate water level and wave conditions when combined, rather than the extremes in either condition (for the swell regime the hazards are greatest and occur under extreme water levels).
- Use of a representative beach profile in a storm impact model can lead to under prediction of wave overtopping hazard if the pre-storm morphology is not smoothed appropriately to account for the event driven evolution.
- Combined river and coastal events have much greater non-linearity in terms of economic impact than in terms of the physical impact.

This improved understanding has provided practice and policy recommendations on building coastal resilience to sea-level rise and storms and is available through the Living With Environmental Change (LWEC) partnership policy and practice notes (Plater and Brown, 2016).

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