Project Information	
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Deliverable information	
Deliverable number	5.1
Deliverable title	Prototype sea level planning and scenario visualization tool
Description	Development of a prototype data-driven modelling and visualisation tool to be tested with selected stakeholders. The prototype will be used to create a roadmap for visualising data leading to better coastal resilience decisions in the management of future sea level rise. The deliverable will include a brief report.
Work Package number	5
Work Package title	Coastal Resilience and Operational Services Demonstrator
Lead beneficiary	ARUP
Lead authors	Michael Dobson
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Comments	A presentation with embedded videos showing the prototype functionality is available upon request

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1. Executive Summary

As part of Work Package (WP) 5, “Coastal resilience and operational services demonstrator”, task 5.1.3 “Data-driven modelling and visualization for sea level guidance”, aims to improve decision making for flood risk management in the coastal zone. The primary aim is to improve understanding of how the deep uncertainty over climate change induced sea level rise can impact decision making at the early stages of the process. The deliverable 5.1, “Prototype sea level planning and scenario visualization tool” has explored this problem and delivered a visualisation prototype. During project inception, the team identified that the core problem in making informed decisions with Sea Level Rise (SLR) was that the large variation in potential future scenarios was not considered due to the complexity of the processes and calculations required to translate each physical scenario into societal impacts; it did not get through to the economic decisions. The challenge therefore was to provide a full picture of the scientific predictions and associated uncertainty within the economic decision making framework.

To tackle the challenge, a case study location was required. Previous experience within the team pointed to Hull on the East Coast of the UK as an ideal location. Built largely on low lying land on the coast, and with an excess of 100,000 properties at risk from coastal flooding, Hull faces some real challenges in how it can understand, respond to and adapt to increasing coastal flood risk with SLR into the future. The team has good links to the main risk management authority responsible for managing coastal flood risk in Hull, the Environment Agency (EA). This presented an ideal opportunity to combine a case study with targeted stakeholder engagement with the EA, and the possibility of filling some data gaps.

During the initial scoping stage of this task, a series of workshops were held between Arup, National Oceanography Centre (NOC), University of Cambridge (UCAM) and CADA Consulting (CADA). In the workshops, the problem was broken down into distinct phases and a workflow was produced to deliver the modelling and visualisation prototype, with actions assigned to Arup, UCAM and CADA. The basic premise of the proposed prototype was to visualise the economic damage resulting from a large set of SLR flood risk scenarios. This required a correspondingly large set of simulations to generate the flood risk data and, potentially, a prohibitive amount of computational expense to estimate the associated economic losses. With the aim of providing a full representation of the scientific uncertainty in the predicted damage, the aim was to reduce the detail in the engineering calculations, which translate the environmental conditions into building level flood impacts, and also the economic calculations that turn flood impacts into damage estimates. This was the alternative to reducing the number of SLR scenarios to be visualised. During this scoping stage, a concept User Interface (UI) was also developed.

The modelling process can be summarised in 3 steps:

1) Specifying nearshore hydrodynamic conditions (still water level, storm surge profile, wave conditions).

2) Calculating the pathway of water onto the land through overflow and wave overtopping of high ground or defences.

3) Determining how the flood water spreads on land.

This was a significant undertaking and a core element of the task. UCAM developed an approach to bring together all elements in a streamlined model workflow. The aim of the approach is for this workflow to be replicable in alternative locations. However, only the case study location has been modelled within the scope of this project.

Alongside the development of the modelling approach, a visualisation prototype was designed and built to receive, process and visualise the modelling outputs. The modelling method results in a very complex set of data focussed on a wide range of “scenarios”. The scenarios are created by three primary sources of uncertainty:

1. Emissions scenario (e.g. RCP4.5)
2. Model uncertainty for sea level rise predictions within a given emissions scenario (e.g. 50th percentile)
3. The multiple wave possibilities combined with the storm and tide extreme still water level combination

The final dimension is the geographical distribution of the flooding; where does the flooding occur and what localised damage is it causing? The spatial calculation grid was simplified but still contained 1000 hexagonal regions to cover the flood extent within Hull.

Altogether, this results in thousands of potential scenarios across 80 years and a thousand geographical points, all requiring an economic damage calculation. The sheer volume of data creates a challenge; how can the user understand the data and how can it be used to inform decisions on the impact of sea level rise? This issue has been resolved through the creation of a visualisation prototype which is a web-based interface to the data, allowing the user to easily select a scenario and, importantly, rapidly change the scenario and compare to other scenarios. In this way the user can immerse themselves in the data and get a feel for how decisions on the originating uncertainty levels (items 1 to 3 above) alter the overall flooding in the region, its distribution and the resulting economic impact.

It was important to achieve sufficiently fast functionality of the visualisation prototype as significant delays between scenario changes would quickly lose the interest of the user and limit the potential for interactive data exploration. To achieve this, the calculations were pre-processed before uploading a static data set to the visualisation prototype. This allowed the incorporation of two different ways to view the data. A single scenario view where the impacts of the chosen scenario inputs can be examined with maps, graphs and metrics. Then a two scenario option where different inputs can be compared alongside each other to understand how certain changes in the physical inputs manifest in the impacts.

Initial stakeholder feedback from the Environment Agency on the visualisation protype was positive and included acknowledging:

- the value in this approach as it explains uncertainty and helps people to understand their own appetite for risk.
- This is a good means of visualising sea level change since people often struggle to understand this in a meaningful way.
- It is useful to see how a change in one small parameter can affect a whole city
- Different stakeholders will want the information at different scales

The future development of this modelling approach and visualisation prototype may consider the following:

- The balance of modelling accuracy with speed of processing according to the location and user needs
- The incorporation of quick defence raising assessments

- Enhanced economic calculations (more detail and or wider economic metrics), again balancing the needs for more information with speed of processing
- Different methods of visualisation, such as 3D, depending on the stakeholder and user needs
- Robustness and testing of the calculations in readiness for commercialisation

This task has proven that the prototype sea level planning and scenario visualization tool is a viable prospective means of communicating the high degree of uncertainty that is inherent in current projections of sea level extremes Future commercialisation depends on follow-on funding to implement the recommended development work. The task consortium plans to continue engagement with existing stakeholders to explore use cases and funding opportunities to refine the prototype in respect of the Humber case study area. At the same time, the task consortium is keen to identify other potential beneficiaries and funding bodies (port operators, coastal communities, insurers, planning authorities etc), who might support the enhancement of the prototype to a commercial standard in other geographical areas.

2. Background

2.1. Scientific Justification

Flood Risk Management (FRM) in the coastal zone requires consideration of a range of hazards from the sea and their impacts inland, typically focusing on urbanised areas of population in need of protection. The current approach to assessment of risk of coastal inundation typically considers a range of extreme events, each with return periods and establishes an annualised risk. This annualised risk is projected into the future taking account of changing risk with sea level rise (SLR), and an optimum level of protection is established by comparing reduced risk from interventions with the costs of those interventions.

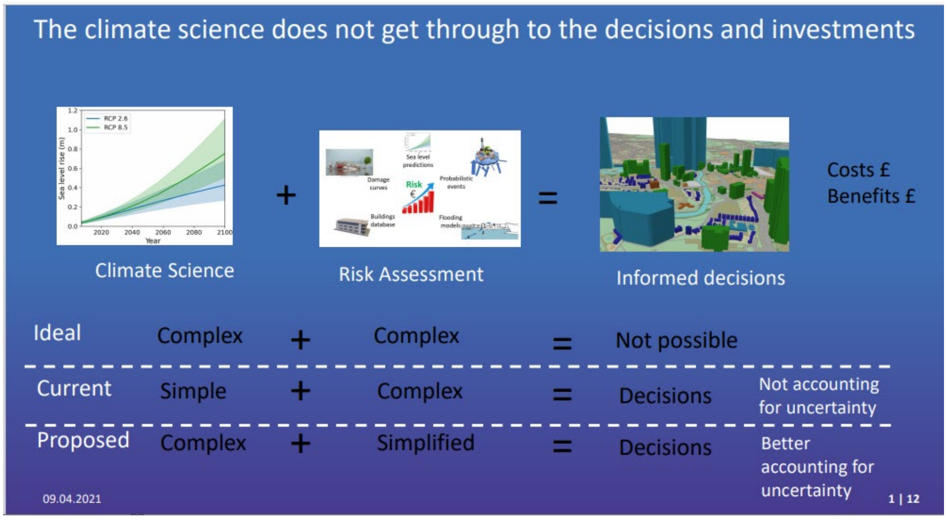
However, this risk-based process is relatively complex, involving several analytical steps:

- complex hydrodynamic and hydraulic modelling of the hazards (modelling the impact of sea levels, waves and storms to understand how they flood inland)
- economic modelling of the flood impacts on inland receptors (homes, businesses and other assets)
- option development including engineering (where and how to build measures to deal with flood hazards), costing (what will those measures cost) and performance (modelling how effective those measures will be in reducing the impacts of flooding)

This complexity means that the processing, time and cost of analysis are prohibitively large. Organisations who have the responsibility for managing coastal flood risk have limited time and budgets, which means that efficiencies have to be found in the risk assessment process. This generally has a direct impact on the number of Sea Level Rise possibilities that are considered. For example, in the UK, typically the process will focus on the medium estimates for Sea Level Rise, with the upper and lower bounds addressed with sensitivity testing near the end of the process.

This does not provide a robust understanding of the extent to which investment decisions are sensitive to the choice of Sea Level Rise scenario. The initial decision to select the main Sea Level Rise projection therefore carries a risk that it will lead to a sub-optimal conclusion, for example, in the case that the extreme modelling scenarios are close to a cliff edge effect. With the high degree of uncertainty present in current sea level rise projections, a more robust approach is required to bring more of the SLR science through to decision makers.

This task aims to address this problem and develop a new streamlined approach to modelling the interactions between sea level hazards, economic activity and risk, bringing more science through the risk assessment process, resulting in better informed decision making and investment planning. This is illustrated in figure 1.



The climate science does not get through to the decisions and investments

Climate Science + Risk Assessment = Informed decisions

Costs £
Benefits £

Ideal Complex + Complex = Not possible

Current Simple + Complex = Decisions Not accounting for uncertainty

Proposed Complex + Simplified = Decisions Better accounting for uncertainty

09.04.2021

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Fig 1 . Overview of the problem and proposed improvement

2.2. Humber Case Study – City of Hull

Geographical Context

Situated on the banks of the River Humber estuary on the East Coast of the UK, with a population of 258,000, Hull is the largest city in the county of East Yorkshire. The river Hull runs through the centre of the city, discharging into the estuary through the Humber Tidal Surge Barrier; the river is tidally dominated within the city. The city is very low lying, with the River Hull flowing in a high level perched river channel above the surrounding land; this provides a hydraulic barrier splitting Hull into two distinct flood risk areas. Typical ground levels within the city of Hull are between 1.2 to 2.2m below the mean high water spring tide level, and around 1.7 to 2.7m below the water level in the river during high spring tides. Hull has the highest number of properties at risk of flooding (140,000) in a single urban area outside of London (in the UK).

The River Hull catchment covers approximately 980 square kilometres with the Yorkshire Wolds to the west and north and the Humber Estuary to the south. Fluvial flood flows can be fed from the chalk aquifers of the Yorkshire Wolds as well as the runoff from other parts of the catchment. Following heavy rainfall, the river can remain in fluvial flood conditions for days and weeks, rather than for a matter of hours, due to the influence of groundwater flow.

The River Hull is navigable, with historic right of navigation between the Humber and Driffield. The river is used daily by commercial shipping either side of high tide.

The Humber Estuary is internationally important for wildlife. It is designated as a Special Area of Conservation (SAC) and a Special Protection Area (SPA) under the Habitats Regulations. It is also an internationally important wetland under the Ramsar Convention. These designations form a European Marine Site (EMS).

Social and economic Context

A large proportion of the Hull flood risk area is classed as deprived, with 53% of residential properties classified in the most deprived group nationally. Hull is in the top 10 index of relative decline for UK cities; in terms of the average growth rate of employment and output in % between 1981 and 2011, Hull was lowest in the country. However, the city has attracted significant national and European investment in recent years, including major investment in the city's infrastructure which is stimulating growth. Hull was the UK City of Culture (2017).

Hull still remains an important economic centre for the Humber region and the north of England, with significant international import and export through the ABP ports complex. Many of the economic activities in the Humber region have important links with wider supply chains, both in the Humber region and the rest of the UK. As well as containers, ferry travel and roro (roll on, roll off) shipping, the ports at Hull specialise in handling forest products and a range of bulk commodities. There is a strong presence in the chemical market through BP which has a facility at Saltend. Hull is also home to the UK's first fully-enclosed cargo-handling facility for weather-sensitive cargoes such as steel. It is the focus of the Humber's burgeoning renewable energy sector, including a wind turbine blade manufacturing, assembly and servicing facility at Alexandra Dock.

History of Flooding

Hull has been impacted by three significant tidal flood events in the past 65 years, most recently in the December 2013 tidal surge when 264 properties were flooded due to overtopping of the existing tidal defences.

However, flood risk in the city is not limited to tidal flooding from the Humber, Hull is at risk from several flood sources, including fluvial (River Hull) and pluvial (storm water drainage and sewerage capacity). The urban areas of Hull have been flooded from the River Hull, Holderness Drain, Beverley & Barmston Drain and their tributaries, pluvial events.

Some of the recent significant flood events are listed in table 1 below.

Date of Event	Description
January 1953	Extreme tidal surge caused catastrophic flooding to coastal areas around the Humber, including the city of Hull.
September 1969	Tidal surge caused flooding to 855 houses, 490 commercial and 177 industrial properties within the City of Hull.
April 1980	The risk of tidal flooding was reduced by the construction of the Hull Tidal Surge Barrier (TSB) which was commissioned in April 1980.
November 2000	Significant fluvial flooding from the River Hull and engineered land drainage systems from a long duration rainfall event caused flooding to properties and land upstream of Hull.
June 2007	Extreme rainfall causing widespread surface water and sewer flooding to the city and rural areas. A total of 8,657 residential and 1,300 commercial properties in Hull were primarily affected. Including

Date of Event	Description
	the wider East Riding of Yorkshire Council area a further 6,000 properties and 12,334 Ha of land were flooded. There was no recorded flooding of property from the rivers during this event.
2009/10	The Hull TSB has recently undergone an extensive mechanical and electrical refurbishment.
December 2013	Significant ingress of flood waters occurred into the English Street area and flows spread into the city centre and as far as Hessle Road to the west, flood damage to 115 businesses and 149 residential properties has been recorded. Tidal levels in Hull peaked at 5.8m above Ordnance Datum (as recorded at the Hull Tidal Surge Barrier).

Table 1 Recent significant flood events

Governance

The area of Hull at risk from flooding falls largely within the Kingston Upon Hull administrative boundary, also referred to as Hull City Council (CC), as seen in figure 2, although there is some overlap with the wider East Riding of Yorkshire area where flood risk extends beyond the city boundary. However, the Environment Agency has the responsibility for leading on tidal flood risk in Hull. The Environment Agency also leads on the flood risk from the River Hull, however, Hull CC lead on surface water flooding issues. The regional water company, Yorkshire water, also have a key role in water drainage and sewerage.

Fig 2 . Governance in the region around Hull

Tidal flood risk along the Humber frontage defences within Hull is being addressed by the Humber Hull Frontages project, led by the Environment Agency. This project considers options to maintain and improve tidal flood risk protection now and against sea level rise. Tidal flood risk at two specific locations on the frontage (Hessle and Paull) is being considered separately by East Riding of Yorkshire Council.

There is an over-arching strategy for tidal flood risk for the entire Humber estuary, Humber 2100+, which is also being delivered by the Environment Agency. The city of Hull is the largest flood risk area in terms of properties within this strategy, split into East Hull and West Hull by the river.

The Environment Agency has been consulted as a key stakeholder on EuroSea.

Existing Tidal Flood Risk Protection

Hull is protected from extreme tidal flooding by an existing 10.3km length of formal flood defence walls and embankments that run along the Humber frontage. The Standard of Protection (SoP) of the frontage varies from 1:5 (20%) to over 1:100 (1%) annual chance of flooding.

The City is protected from flooding from the River Hull with approximately 18km of constructed defences. Although the height of defences is sufficient to protect against almost any flood (with the Tidal Surge Barrier in place), their condition is poor and studies have found there is a risk of breach along their length due to the poor condition (the Environment Agency project River Hull Defences PAR has examined this risk and has proposed defence improvements to address it). Should the Tidal Surge Barrier fail, the river defences could overtop from tidal flooding and would almost certainly breach.

Sea Level Rise

Sea level rise will reduce the standard of protection (SOP) of most of the existing tidal defences to less than 1:5 (20% annual chance) by around 2040. This is based on the mid-range of the current UK sea level rise projections (based on the IPCC projections and referred to as the “change factor” in Environment Agency guidance). The SoP would continue to decline between 2040 and 2115 as sea level rises, which would significantly increase flood risk to Hull. It is therefore important to understand the future possibilities with Sea Level Rise in Hull.

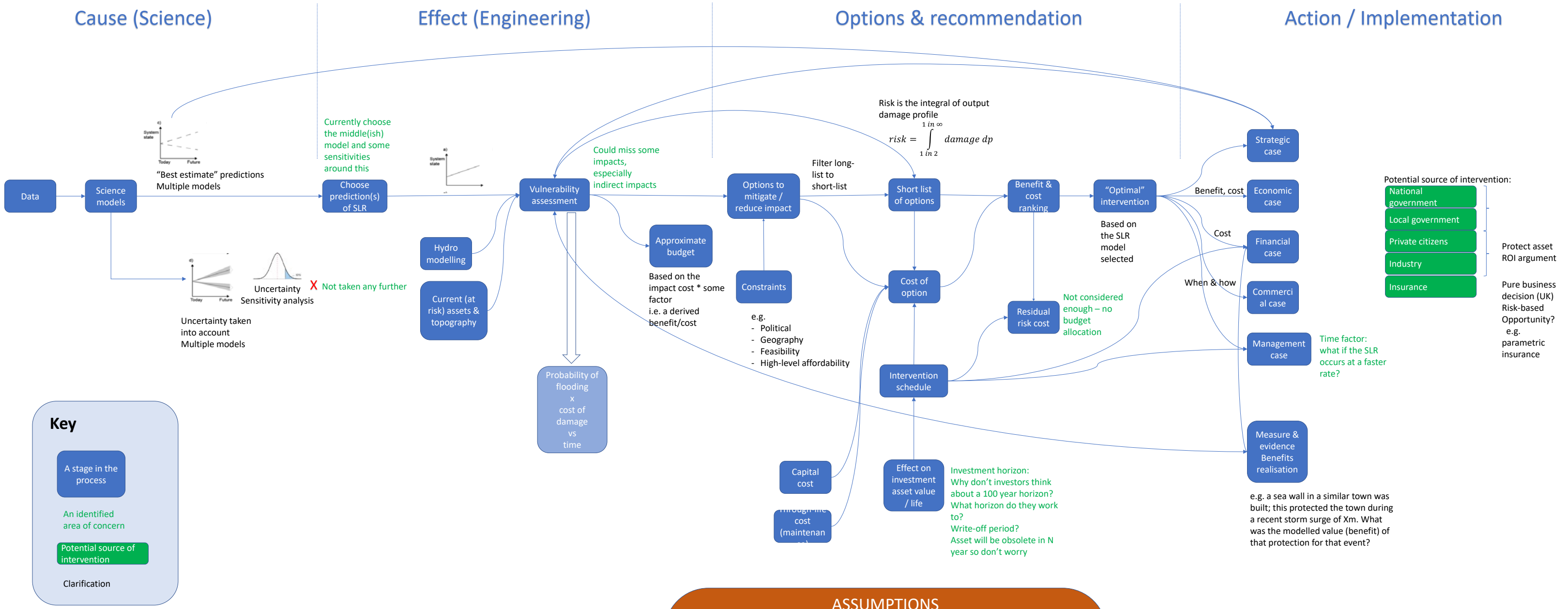
3. Prototype sea level planning and scenario visualization tool (the “Visualisation Prototype”)

3.1. Initial Scoping Stage

Problem scoping Session

The first stage of EuroSea task 5.1.3 involved a problem scoping session by the Arup, UCAM and NOC teams. Figure 3 below shows how the problem was broken out into distinct phases which would eventually inform the design of the approach to modelling and the design of the visualisation prototype.

Fig 3 . Initial Problem definition



ASSUMPTIONS

This is a programme run by NOC where the main objectives are creating better measurements to support the science, and communicating that science to inform decision making. Therefore the science needs to be at the core of what we propose.

We should avoid thinking too much about non-scientific arguments in isolation, for example different (re-)insurance mechanisms. However, an economic sensitivity argument that hinges on uncertainty in the predicted sea level rises would be acceptable.

Notes:
- We can't challenge the science
- The science is regularly changing

Hypothesis:
- Including uncertainty will result in a more stable recommendation (less sensitive to changing science advice) and therefore be used as part of the case

Potential objectives for this contract:

CHALLENGE FROM SCIENCE PERSPECTIVE

S: Science is not informing decision making well enough. The science is the best available information; we need to believe it and need to keep up with it.

C: We believe better decisions would be made if the science/evidence ended up in the business case. This isn't helped by the fact that the (detailed) science recommendations are continuously changing.

Q: How do we get science further down the chain and get it listened to?

A: Move the science to the right a bit – in the engineering column. A good start would be to maintain the uncertainty bounds when generating the impact assessments.

CHALLENGE FROM INVESTMENT PERSPECTIVE

S: The business case to spend more on flood risk/resilience is not strong enough to do any more.

C: The science community believe that sea level rise will happen and the current protection, future provision & planning/budgeting are insufficient.

Q: What do we need to do to change the investment business case (where the outcome might not be "more of the same")?

A: ????!!!!????

2-day Brainstorming workshop

During a 2-day workshop, Arup and UCAM reviewed the existing UK flood risk appraisal process and refined the problem definition. A concept definition of scope for the modelling approach and the visualisation prototype was drafted along with a draft workplan for the split of research and development activities between partners.

During the workshop, a concept design for the visualisation prototype User Interface (UI) was created as shown in figure 4 below.

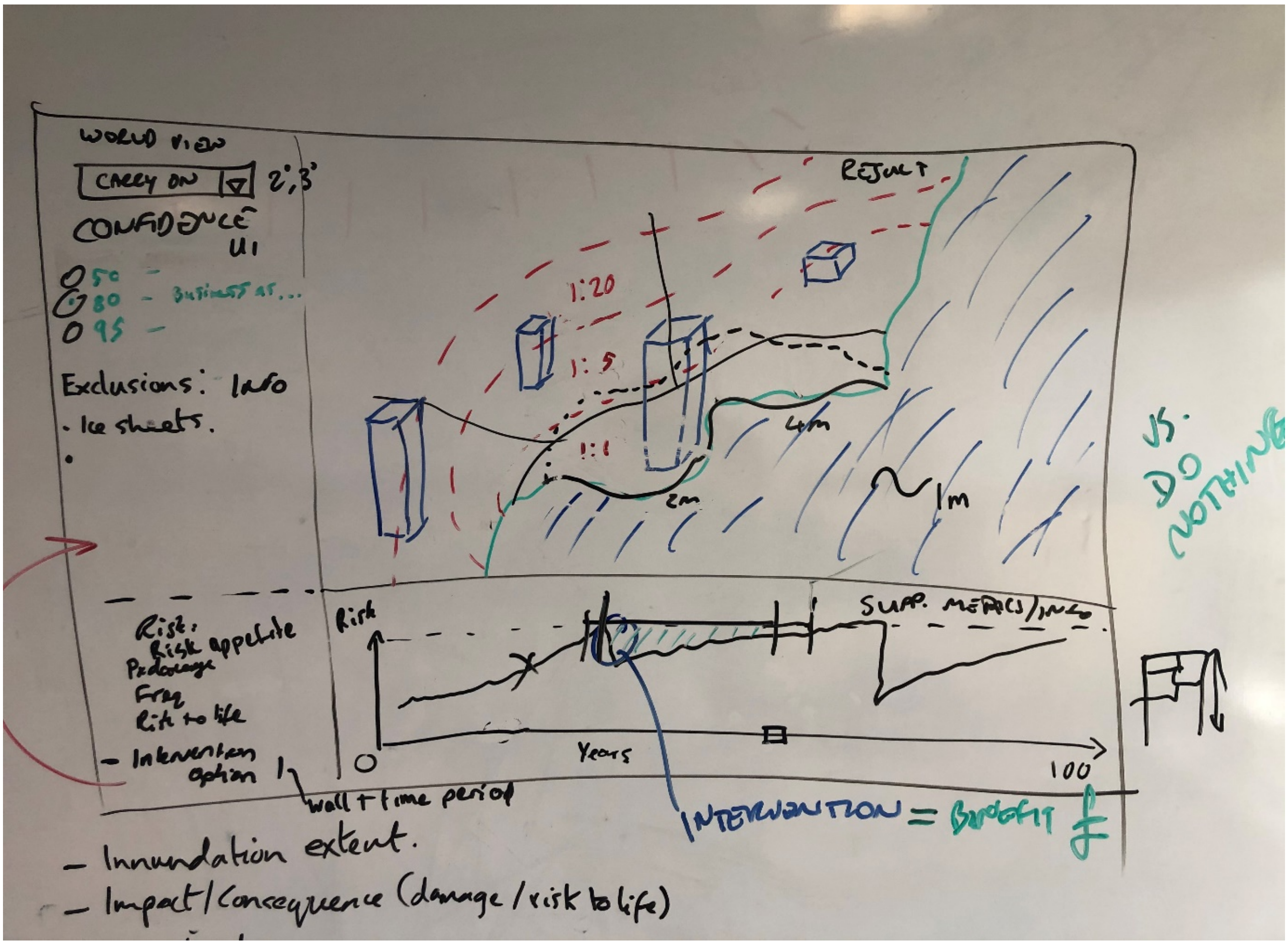


Fig 4 .User Interface (UI) concept design.

3.2. Visualisation Prototype outline

Following the workshops, a high-level description of the data flow was produced. Figure 5 below shows how the data flows from the climate science (sea level projections, waves and extreme storms), through hydraulic and hydrodynamic modelling, collectively the “physical inputs”, to the economic impact model and finally into the visualisation prototype. Further detail on each element is explained in the following sections of the report.

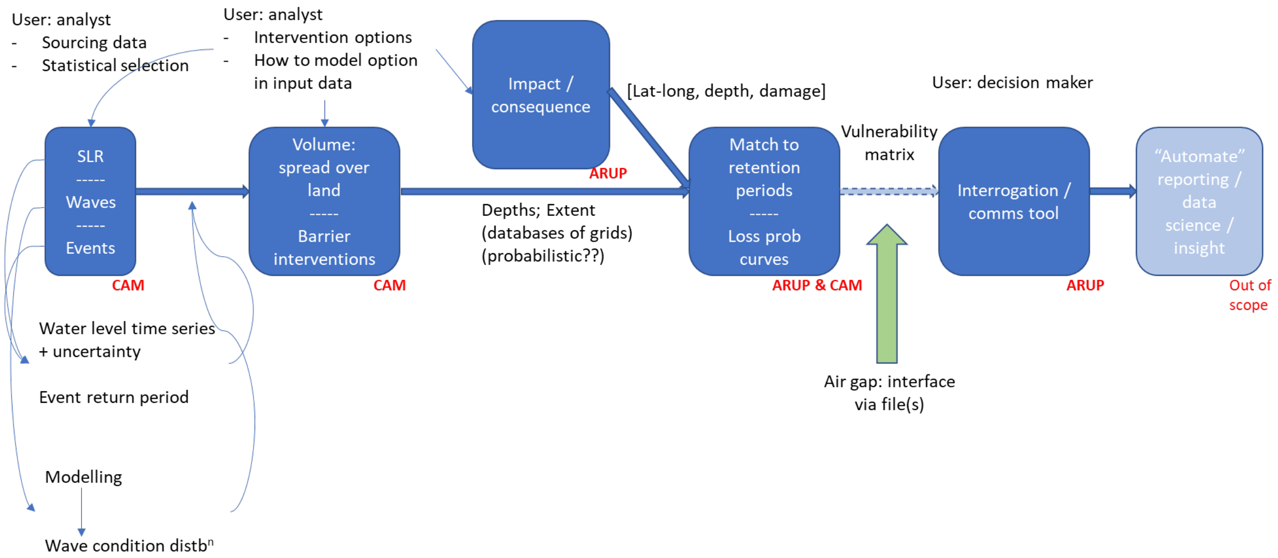


Fig 5 . Data flow for modelling and Visualisation Prototype.

3.3. Generation of Input Data

Modelling the Physical Impacts

Overview

A framework has been developed to model the physical hazard from sea level rise. This takes a high-level approach that allows uncertainty in sea level rise predictions to be propagated through to feed economic damage calculations using a probabilistic approach. This methodology aims to streamline the modelling process by optimising performance and reducing complexity in the modelling process such that a large number of model runs can be produced quickly. The framework is also designed to be adaptable for easy application in new locations.

The modelling of the physical flood hazard takes a three-step approach (Figure 6). This involves:

1) Collating the range of potential nearshore hydrodynamics.

2) Calculating the pathway of water onto the land through overflow and wave overtopping of high ground or defences.

3) Determining how the flood water spreads on land.

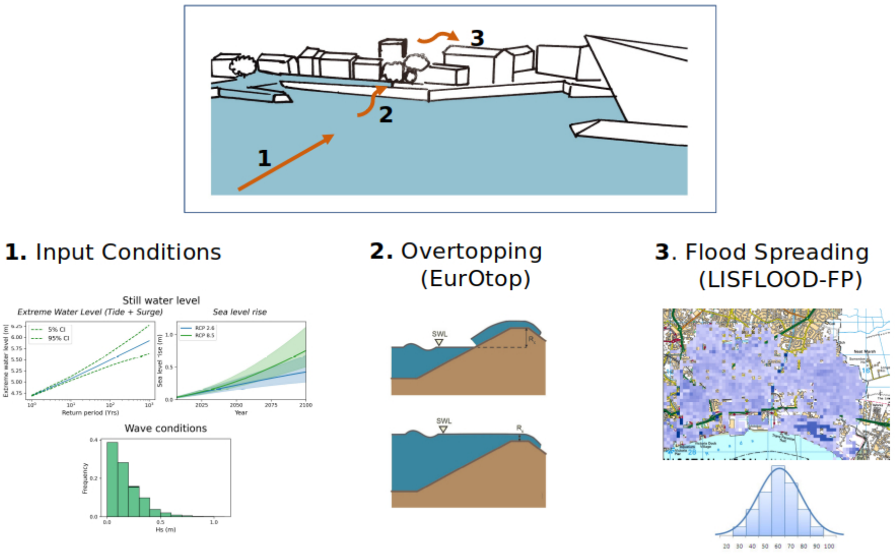


Fig 6 . Overview of the physical hazard modelling framework.

Input conditions

In order to run the framework probabilistically, the full range of potential hydrodynamic conditions at the site needs to be determined. Whether flooding will, or will not, occur is dependent on the nearshore still water level and wave conditions for any given event. The still water level defines the water level elevation in the absence of waves, it is comprised of the water level due to the tide, storm surge and sea level rise. Waves will then act on top of this still water level generating shorter term water level oscillations.

The input conditions for the Hull case study were collated from pre-existing datasets:

Future sea level rise projections, are provided around the UK at a 12km resolution by the marine UK Climate Projections 2018 (UKCP18) (Palmer et al., 2018). These projections use future emission scenarios from the IPCC's 5th Assessment Report (IPCC AR5). Future climate predictions are based on 3 scenarios (referred to as Representative Concentration Pathways (RCP) which give a range of potential climate outcomes based on different assumptions of future economic, social and environmental changes. RCP2.6 can be viewed as a low emissions scenario, where future CO_2 emissions are reduced; RCP4.5 represents an intermediate pathway; and RCP8.5 a high emissions scenario. For each scenario, UKCP18 provides sea level projections to 2100 with the associated uncertainty distribution (given as 5th,10th,30th,33rd,50th, 67th,70th,90th, and 95th percentiles). For the Hull case study the sea level projections are extracted at the Immingham tide gauge location, as this is the furthest into the Humber data is available for.

Extreme sea levels as a result of storm surges play a significant role in flooding on the east coast of the UK. Extreme water levels above the current conditions (where SLR = 0) are expressed as the probability of still water levels being reached. The Environment Agency carried out detailed extreme water levels for the Humber Estuary in 2014 (EA, 2014), where still water level projections are provided at 7 sites over the Hull frontage, from Hessle to Salt End, for return periods of 1 in 1, 10, 50, 100, 200, 500, and 1000 years.

Wave conditions within the Humber were collated from existing data sources to avoid any extra modelling. The range and probability distribution of wave height, period and direction have been back calculated from an ABPmer joint probability analysis report for the Humber (ABPmer, 2007). Wave heights and direction are randomly selected based on the probability of occurrence, and the wave period selected from a linear regression of the wave height and period relationship. Four spatial data points from the report cover the Hull frontage at Salt End, Alexandra Dock, Albert Bridge Dock, and Hessle Haven. At all 4 locations wave conditions are dominated by small wind waves, which are thought to be locally generated as they have small wave periods.

A matrix of input conditions were generated from these datasets, incorporating:

- The full range of sea level rise scenarios, including variation between emissions scenarios and uncertainty over predicted rise for a given scenario.
- Transient augmentation of the still water level due to storm surges.
- A range of extreme wave conditions, selected based on the probability of occurrence of the wave height.

Overflow and overtopping

The pathway of water onto land occurs as a result of overflow, where the still water level is greater than the coastal defence crest level, and wave overtopping where waves interact with a coastal defence leading to water discharging on the landward side. The wave overtopping and overflow calculations were based on the EurOTop 2018 manual (Van der Meer et al., 2018). This methodology uses empirical formula to calculate overtopping discharge in units of m^3/s per m width of coastal defence.

The EurOtop formulae require as input the water level time series and wave conditions, as well as the coastal defence features, including type of defence (i.e. embankment/vertical wall), direction relative to wave impact, shape of the defence and features. These coastal defence properties were generated in this application with information on location of defences and parameterisation of the transect from a cross-section of its elevation. The coastal defence properties were extracted through an automated process to ensure that the framework is easily adaptable to new case study locations.

Detailed coastal defence information is available in Hull through the Environment Agency Spatial Flood Defences dataset (EA, 2021). New coastal defence sections were generated from this database by merging neighbouring sections with similar properties; defence sections were separated at points where the angle between two parts of a defence deviated by > 20°. For each new coastal defence section, a representative transect was taken perpendicular to the defence, and the defence features (e.g. toe height, defence face slope) are extracted from the Environment agency DTM LIDAR (2017-2018, the latest available), https://data.gov.uk/dataset/f0db0249-f17b-4036-9e65-309148c97ce4/national-lidar-programme .

Flood spreading

The spreading of the flood water once it reaches the landward side of the coastal defence was calculated using the flood model LISFLOOD-FP model (Bates & De Roo, 2000). LISFLOOD-FP is a raster-based inundation model; it was ideal for the purposes of this study as it allows a range of model complexity.

The extent of the inundation model was selected as the administrative areas of Kingston Upon Hull and the town of Hessle, adjacent to Hull. A raster topographic grid file was created from LIDAR DTM data with a spatial resolution of 100 m, to allow a fast model run time (< 1 second). The overflow and overtopping discharge timeseries at each coastal defence section were set as point source boundary conditions for each model run. Output was in the form of the maximum water level for each grid cell. Maximum water levels were then spatial averaged onto the planning viewer hexagonal grid which has a resolution of 400 m.

Validation of Results

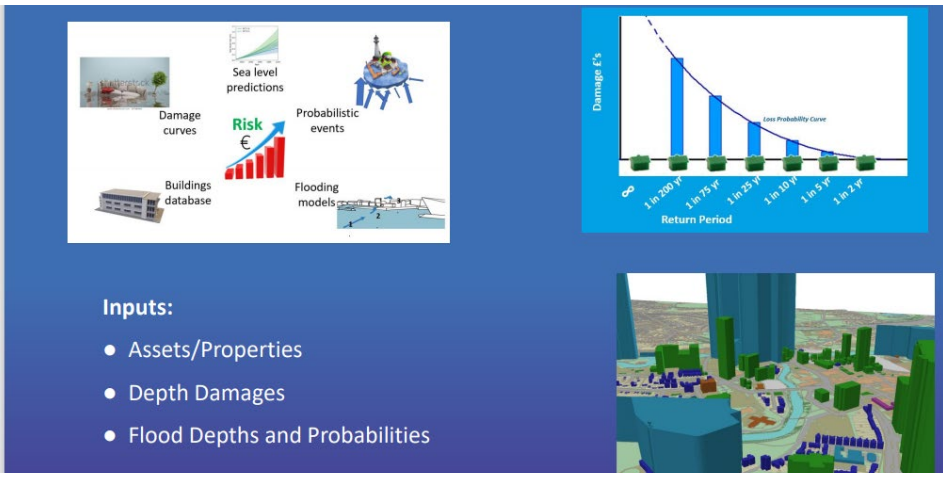
The aim of EuroSea task 5.1.3 was not to accurately model the impacts of Sea Level Rise on flood risk to the case study location (Hull). Instead, the aim was to test what can be modelled in terms of number of model iterations and parameters in order to feed a visual tool to communicate uncertainty. However, it is important for future development to understand how the modelling approach performed against more traditional deterministic modelling. With this in mind, the modelling lead at UCAM carried out a stakeholder feedback meeting with the Arup modelling lead on the Humber Hull Frontage project. This allowed some subjective feedback to be given on model output comparisons for some selected similar scenarios. This feedback is reflected in the recommendations section. No improvements have been made at this point following the feedback and this will be addressed in future developments.

The Economic Impact Model

In order to generate economic impacts from the flood levels produced from the flood spreading, a simple depth-damage economic model was produced. This model takes receptor data (houses, businesses etc), depth damage data (receptor types, damages per type for varying depth) and combines with flood depths to calculate economic damages.

The annual chance of each flood depth is then used to produce an annualised economic risk which is converted into a present value equivalent over the duration of the analysis. The calculation is deliberately simplistic, only considering direct economic damages such as building fabric, possessions and machinery and cleanup costs. For the case study, the receptor data was obtained from our stakeholder the Environment Agency and the depth damage data was from the UK Multi Coloured Manual produced by the Flood Hazard Research Centre (FHRC), which Arup hold a licence for. Keeping the calculation simple allowed for multiple economic calculations for the probability distribution of modelled flood depths.

The calculation could be expanded by adding in less direct economic impacts such as emergency services costs, loss of business stocks, distribution to transport and local economies and risks to life. However, this would have to be balanced with the increased demand of processing and the desire to understand the full range of Sea Level Rise uncertainty. This is for consideration in future developments.



Inputs:

- Assets/Properties
- Depth Damages
- Flood Depths and Probabilities

Fig 7 . Illustration of economic impact model.

3.4. Visualisation Prototype design and build

Philosophy

The method described above results in a very complex set of data focussed on a wide range of “scenarios”. The scenarios are created by three primary sources of uncertainty:

4. Emissions scenario (e.g. RCP4.5)
5. Model uncertainty for sea level rise predictions within a given emissions scenario (e.g. 50th percentile)
6. The multiple wave possibilities combined with the storm and tide extreme still water level combination

For a selected combination of items 1 & 2, extreme events can be generated with a range of return periods, i.e. the frequency you would expect a flood event to re-occur, for example a “1 in 10 year” return period means you would expect that degree of flooding to occur with an average annual chance of 1 in 10.

The scenarios evolve over time as the sea level rise predictions evolve and so there is also a time dimension where the user can consider the impact during any decade between now and 2100.

The final dimension is the geographical distribution of the flooding; where does the flooding occur and what localised damage is it causing? The calculation grid contains over 1000 hexagonal regions which allow the spatial distribution of expected damage to be examined between scenarios and along timelines (e.g. how sensitive is flood risk in this area in relation to the emissions scenario or how will it change across decades for a given scenario?).

This results in thousands of potential scenarios across 80 years and a thousand geographical points, initiated by feasible hydrodynamic inputs and resulting in the associated economic impact. This has not been achieved to this degree before, to our knowledge. The sheer volume of data creates a challenge; how can the user understand the data and how can it be used to inform decisions on the impact of sea level rise?

This issue has been resolved through the creation of a visualisation prototype which is a web-based interface to the data, allowing the user to easily select a scenario and, importantly, rapidly change the scenario and directly compare to other scenarios. In this way the user can immerse themselves in the data and get a feel for how decisions on the originating uncertainty levels (items 1 to 3 above) alter the overall flooding in the region, its distribution and the resulting economic impact. The metrics of flood levels and economic impact are presented using methods that laypersons and decision makers are familiar with, namely maps and time series charts respectively.

The hope is that by using the visualisation prototype, the user will gain an in-depth, intuitive understanding of the sensitivity of predicted outcomes to model uncertainty and allow them to make an informed decision regarding what scenarios should feed into their more detailed subsequent analysis.

Design

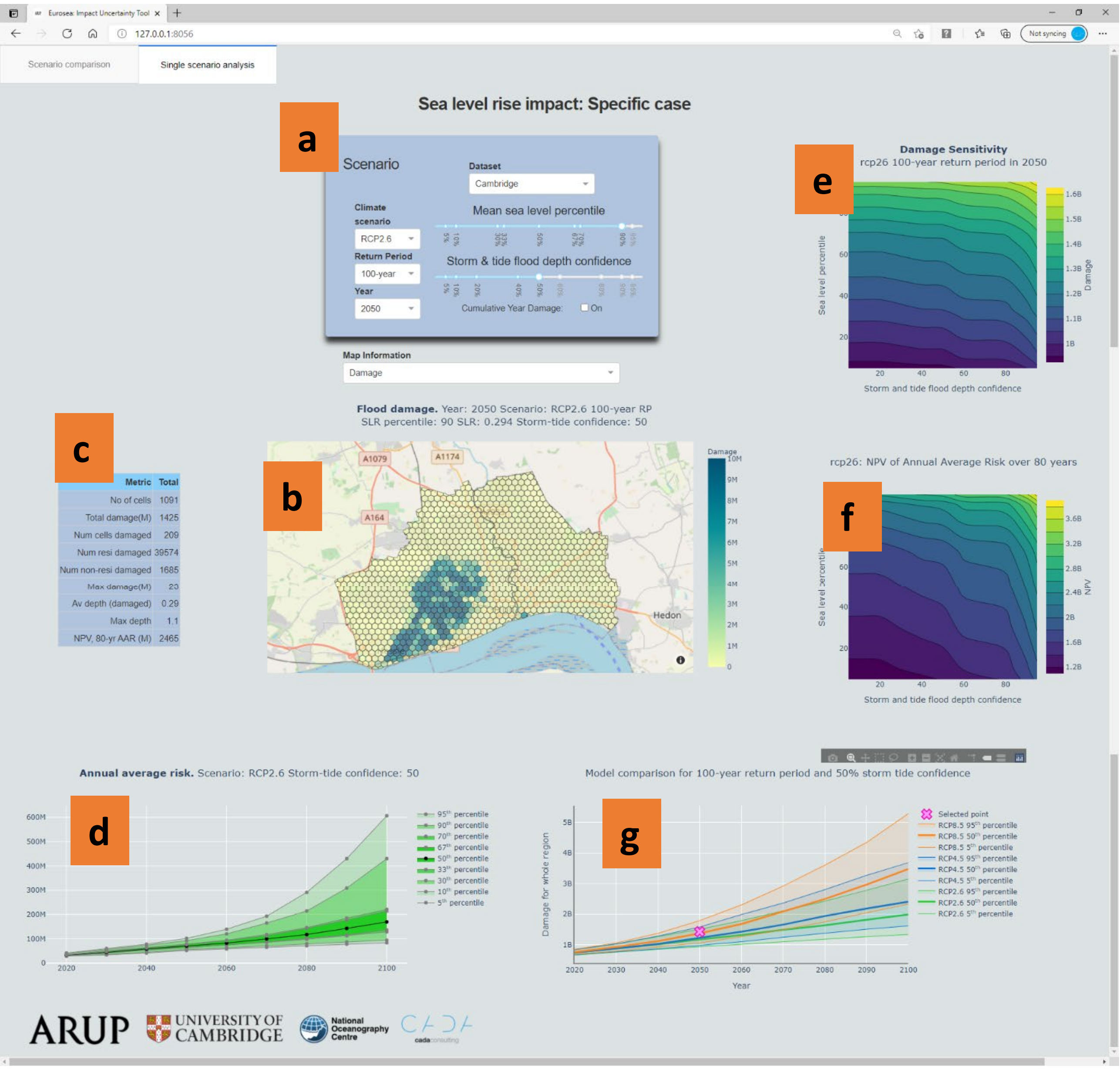
The visualisation prototype has two main methods of display and interrogation:

1. **Single scenario**: this allows the user to look at one scenario and provides detailed metrics associated with that scenario. The user can easily change the scenario and see how the metrics are updated.

2. **Two-scenario comparison**: this allows the user to directly compare two scenarios for the same dataset or compare two different datasets. Again, the user can rapidly switch between scenarios to get a feel for the sensitivities.

Each page provides a set of plots and images which are intended to be useful to a decision maker or interested stakeholder. They demonstrate a selection of potential presentational techniques to promote further discussion for any future implementation.

Single Scenario



Sea level rise impact: Specific case

Scenario

Dataset: Cambridge

Climate scenario: RCP2.6

Return Period: 100-year

Year: 2050

Cumulative Year Damage: ☐ On

Map Information: Damage

Flood damage. Year: 2050 Scenario: RCP2.6 100-year RP
SLR percentile: 90 SLR: 0.294 Storm-tide confidence: 50

Metric	Total
No of cells	1091
Total damage(M)	1425
Num cells damaged	209
Num resi damaged	39574
Num non-resi damaged	1685
Max damage(M)	20
Av depth (damaged)	0.29
Max depth	1.1
NPV, 80-yr AAR (M)	2465

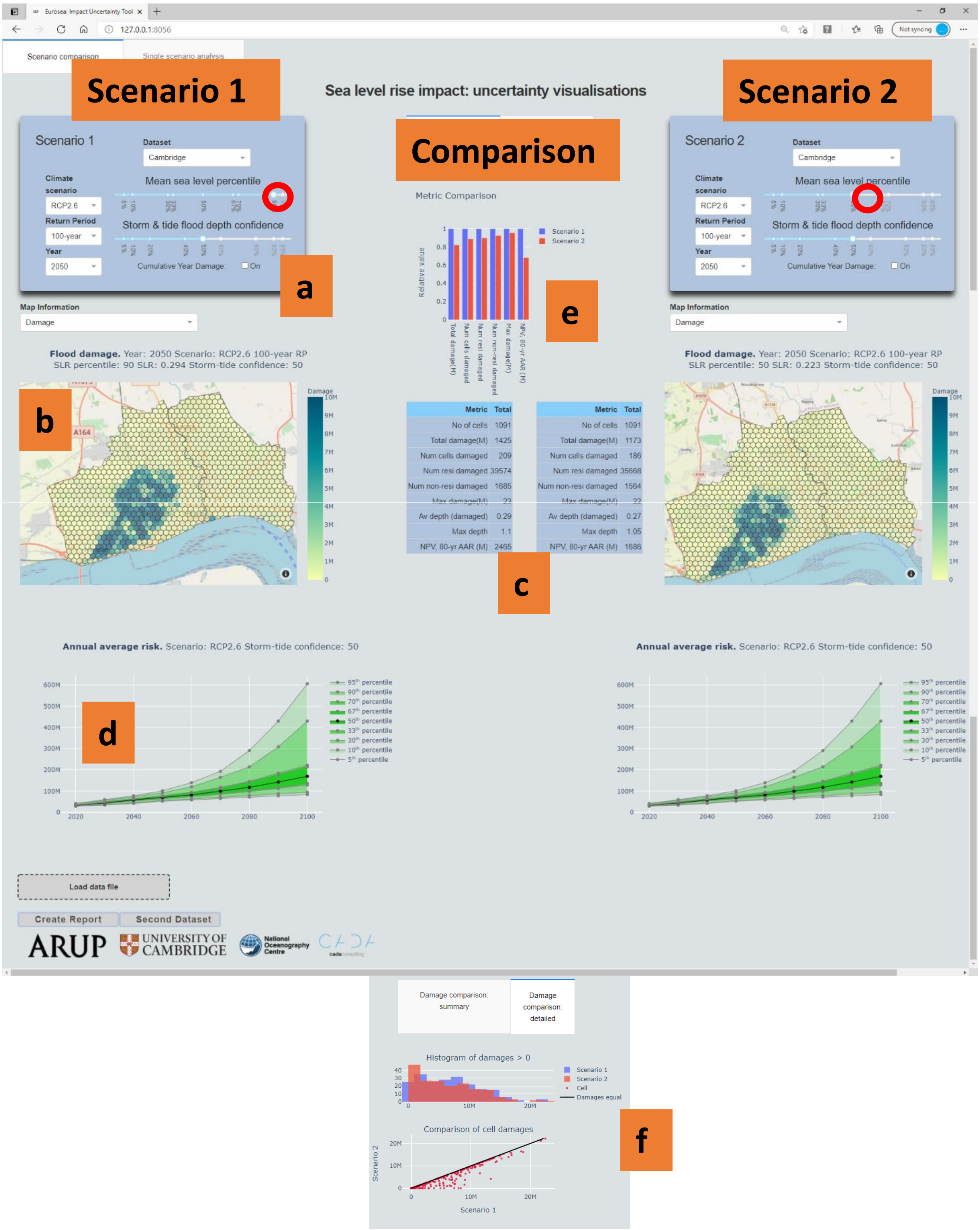
Figure 8: A screenshot of the visualisation prototype for a single scenario, in this case sea level model RCP4.5 at the 90th percentile with the best estimate (50%) storm & tide flood depth confidence at a 100-year return period in 2050. A description is provided below using the orange block letters as reference points.

Single scenario mode functionality:

a. Set the scenario. Use the drop-down lists and sliders to select the scenario to be presented.
b. Map of the region. A visual representation of the data for the selected scenario. The user can choose to show:
    - Flood depth
    - Economic damage
    - Elevation
    - Population density

   In addition, the cursor hover-over functionality provides further information, including:
    - Number of buildings affected (residential and non-residential)
    - Socio-economic descriptor for the region
c. A summary table of key metrics for the whole region and (if selected) sub-region.
d. A time series plot of the average annual risk for the whole region, for the given scenario and each of the sea level rise confidence intervals.
e. A contour plot of the effect of the sea level rise and storm-tide uncertainties on resulting total damage across the region for the chosen scenario.
f. A contour plot of the effect of the sea level rise and storm-tide uncertainties on the Net Present Value of the average annual risk across the region for the chosen scenario.
g. A time series plot of selected extreme cases of sea level rise confidence values for the three sea level rise models, to get a feel for the sensitivity to model selection.

Two-Scenario Comparison



Sea level rise impact: uncertainty visualisations

Scenario 1

Dataset: Cambridge
Climate scenario: RCP2.6
Return Period: 100-year
Year: 2050
Cumulative Year Damage: ☐ On
Map Information: Damage

Flood damage. Year: 2050 Scenario: RCP2.6 100-year RP
SLR percentile: 90 SLR: 0.294 Storm-tide confidence: 50

Annual average risk. Scenario: RCP2.6 Storm-tide confidence: 50

Scenario 2

Dataset: Cambridge
Climate scenario: RCP2.6
Return Period: 100-year
Year: 2050
Cumulative Year Damage: ☐ On
Map Information: Damage

Flood damage. Year: 2050 Scenario: RCP2.6 100-year RP
SLR percentile: 50 SLR: 0.223 Storm-tide confidence: 50

Annual average risk. Scenario: RCP2.6 Storm-tide confidence: 50

Metric	Total
No of cells	1091
Total damage(M)	1425
Num cells damaged	209
Num resi damaged	39574
Num non-resi damaged	1685
Max damage(M)	23
Av depth (damaged)	0.29
Max depth	1.1
NPV, 80-yr AAR (M)	2465

Metric	Total
No of cells	1091
Total damage(M)	1173
Num cells damaged	186
Num resi damaged	35668
Num non-resi damaged	1564
Max damage(M)	22
Av depth (damaged)	0.27
Max depth	1.05
NPV, 80-yr AAR (M)	1686

Figure 9: A screenshot of the visualisation prototype comparing two scenarios, in this case sea level model RCP4.5 at the 90th percentile on the left with the 50th percentile on the right (highlighted as a red ring). A description is provided below using the orange block letters as reference points.

Two scenario comparison mode functionality:

a. [As with the single scenario] Set the scenario. Use the drop-down lists and sliders to select the scenario to be presented.
b. [As with the single scenario] Map of the region. A visual representation of the data for the selected scenario. The user can choose to show:
    - Flood depth
    - Financial damage
    - Elevation
    - Population density

   In addition, the cursor hover-over functionality provides further information, including:
    - Number of buildings affected (residential and non-residential)
    - Socio-economic descriptor for the region
c. [As with the single scenario] A summary table of key metrics for the whole region and (if selected) sub-region.
d. [As with the single scenario] A time series plot of the average annual risk for the whole region, for the given scenario and each of the sea level rise confidence intervals.
e. A bar chart which compares the key metrics between the two scenarios.
f. A more detailed analysis of the differences between the scenarios at the hexagonal region level. There is a histogram of damages to highlight trends in economic damages, and a scatter plot of the damages for each scenario plotted against each other for each hexagonal region to show whether the different scenarios are creating more regions of damage and/or making the existing damaged regions better or worse.

3.5. Stakeholder Engagement

The task delivery team (Arup, NOC and UCAM) organised an early stakeholder meeting with the Environment Agency (who have the responsibility for flood risk management in England) in 2020 as the development process was beginning. This confirmed that the proposed visualisation prototype was of interest to the Environment Agency, and could potentially be part of discussions to inform how they undertake flood risk management in the future accounting for climate change. The Environment Agency agreed to provide data as needed for the case study location and to help with physical modelling advice as required.

In March 2021, shortly after the first draft version of the visualisation prototype was able to process the physical modelling results, a second stakeholder session was held with the Environment Agency. During this session, a live demonstration of the visualisation prototype was done on an MS Teams meeting. The following is a list of feedback from the Environment Agency about the visualisation prototype:

- There's a lot of value in this as it explains uncertainty in a better way and helps the user to understand their own appetite for risk.
- This could be very useful for managed retreat as those decisions are often cost-based and time critical; this also helps to understand how long you have to adapt to future changes with sea level rise

- It is a good means of visualising sea level change as people often struggle to understand this in a meaningful way.
- It is useful to see how a change in one small parameter can affect a whole city.
- Different stakeholders will want the information at different scales. The public will focus on information contained in each cell, whereas the City of Hull would focus on the whole city and the EA would look at larger scales. The functionality could be tailored to different stakeholders.
- The The National Flood Risk Assessment 2 (NAFRA2) is a national flood risk assessment in development by the UK Government and the Environment Agency; if the visualisation prototype could work with the NAFRA2 outputs it could provide some interesting additional insight
- Long-Term Investment Scenarios (LTIS) is a high-level national scenario-based assessment of flood risk and it would be interesting using the visualisation protype at national level, subject to establishing the links between the two
- A function where future defence raising could be tested at a high level, by raising defences by a crude amount (e.g. 0.5m), would be very interesting for decision makers
- Building in 3D visualisation may be of interest in certain circumstances

It would be interesting to see how the modelling framework and visualisation prototype scale up to larger areas such as the Thames, the Severn Estuary or certain cities on the South CoastThe Environment Agency hase expressed interest in sharing the visualisation prototype with more people in their organisation to understand its potential. The method of doing this with a prototype is under consideration by the task team and further discussions will be undertaken with the Environment Agency about this.

4. Recommendations

4.1. A roadmap for improved data visualisation and coastal decision-making in respect of future sea level rise

Physical modelling improvements

The physical hazard modelling framework allows rapid modelling of flood inundation for a large number of input condition combinations in short periods of time. The data presented here are based on 21,350 model runs, comprising 122 sea level rise increments, 7 extreme water level return periods, and 25 wave conditions. The resulting matrix of model runs can be completed in a few hours on a standard laptop PC.

The framework developed is adaptable so that different methodologies can be introduced at each of the 3 model steps for application in new case study locations, including different methods to calculate overtopping and overflow, or using an alternative flood spreading model. The balance between model accuracy and efficiency can therefore be tuned for each application at a given location based on the needs of the end user (e.g. aiming for near real time feedback to facilitate interactive workshops or for production of high fidelity static datasets that can inform robust decisions over critical infrastructure investments).

Production of a fully validated flood spreading model for Hull was not within the scope of this study. Using simplified and coarse resolution modelling techniques means that the validation is important to understand the fidelity of the results and match this to the needs of the end users. Past historical flood data, other model studies and expert knowledge of the area will be used in this validation process, to identify if simplified modelling is producing results of sufficient accuracy for planning purposes.

Future work on the physical hazard modelling will most likely include adaptations to coastal defences, e.g. raising the crest level, to allow rapid, broad-brush impact assessment of improved coastal defences.

Economic modelling improvements

Some possible improvements to be investigated are listed below:

- Enhance the depth damage curve considerations so the user can explore consequences with and without a warning, which has a big impact on damages. This would need with and without damage curves and would potentially allow comparison of an early-warning system vs flood defences.
- Consider the Social Value metric across the whole area bringing the social category of areas at risk into the visualisations.
- Consideration of infrastructure impacts from flooding. For example, if roads are blocked by water then the time to get to the hospital will change for many areas. Illustrate this time difference and the potential impact. This could also apply to other indirect impacts such as emergency services, evacuation routes, lost schooling, lost local business etc.
- Move the “static” risk modelling (based on average return periods and average annual risk) to an alternative approach which is entirely stochastic where simulations are run over time and it is probabilistically determined what events would happen in each specific year. This would require thousands of runs and time to build up a “cloud” of scenarios to see what potential realistic future scenarios might be. This could allow for post-flooding recovery periods to be factored in which, in turn, provides another lever to governments to avoid future total damage.
- The method could be trialled in a region where the receptor data is not as detailed as the UK Environmental Agency dataset to explore the uncertainty of receptor datasets

Visualisation improvements

Some possible improvements to be investigated are listed below:

- Include more 3D concepts for more realistic mapping to help communicate better to the public and decision makers
- There will be a need for different metrics plotted in different ways depending on feedback from different stakeholders e.g. insurance, public, risk management organisations, economists, investors etc

Digital Processing improvements

Some possible improvements to be investigated are listed below:

- Productionise the capability to take it beyond a proof of concept
- Robustness improvements throughout
- Link the various aspects of the interface together e.g. zooming in one map does the same on the other
- Testing, verification, validation in preparation for wider use

4.2. Exploitation plan

This task has proven that the prototype sea level planning and scenario visualization tool is a viable prospective means of communicating to users the high degree of uncertainty that is inherent in current projections of sea level extremes. Ultimately, such a tool has strong potential for future commercialisation, provided that follow-on funding can be secured to implement the recommended development work outlined in section 4.1 Thus, the task consortium plans to continue engagement with existing stakeholders (outlined in section 3.5) to explore use cases and funding opportunities to refine the prototype in respect of the Humber case study area. At the same time, the task consortium is keen to identify other potential beneficiaries and funding bodies (port operators, coastal communities, insurers, planning authorities etc), who might support the enhancement of the prototype to a commercial standard and to facilitate its application to other geographical areas. With this in mind, the task consortium plans to engage with WP8 co-ordinators to identify potential funding bodies and beneficiaries, whilst also pinpointing the key messages (in terms of results and concepts) to be communicated to them. In the first instance, the WP5 leader and task lead from Arup will attend training sessions to help with recognition of IP for project partners and identify key exploitable results.

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