Jersey Sea Level and Coastal Conditions Climate Review

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Executive Summary

The National Oceanography Centre has been commissioned by The States of Jersey to undertake a coastal conditions climate review to provide tailored information suitable for contributions toward policy decisions and to identify further areas of study. The review covered up to date regional sea-level projections, an estimation of extreme water levels, probability of combinations of extreme sea levels and wave heights (considering vertical land movement), and absolute sea-level trends.

Extreme event modelling was undertaken which considered four 1D profiles, running East to West across St Aubin's Bay. The study simulated a range of extreme events to assess the amount of overtopped water and changes in parameters such as wave period and direction. The modelling also assessed the impact of the extreme events on the beach, assessing whether sand was lost or gained along the 1D profile, or lost or gained from the profile entirely. Finally, the work investigated the impact of Sea Level Rise (SLR) on extreme water levels, and the impact of SLR on an extreme event of combined wave height and extreme water levels.

The report found that it is likely that Jersey is experiencing a downward vertical land movement, although there is a large range in the potential range of rates from surrounding GPS stations. It would be beneficial to set up a GPS station on Jersey to get a more accurate rate, as, if the land is sinking, then the impact of rising sea levels is exacerbated (e.g. if land is sinking at 1.5 mm a year and sea levels rising at 2 mm a year then a rise of 3.5 mm a year will be observed). Comparing the combined rates from nearby tide gauges that had GPS stations located with 15 km, gives a range of absolute sea level trend rates. It was found that the rate of 2 mm/yr used previously, and this in study, was a good match to the surrounding rates.

Using the latest methods, extreme water level return period analysis was performed and found to be consistent with previous studies, although an approximate 0.33 m difference in extreme water level was noted across all return periods. It is thought that this is due to differences in vertical datum between this and previous studies. Analysis of the joint probability was performed using the latest methods, the results were different due to the unrealistic and pessimistic assumptions made by previous studies. These studies noted that it would be beneficial to redo the joint probability without these assumptions which has been successfully completed for this report.

Waves are not projected to have any change in significant wave height, although 20th century hindcast data does show a small linear increase. Focusing on extreme water levels only, it was found that mean outcomes for 2100 could result in extreme water level events representative of 1 in 150 year conditions occurring every year. With the addition of any waves present during the extreme event, the impact on defences will be even greater. The change in tidal range for a 2 m increase in mean sea-level is estimated to result in a reduction in the tidal range of 0.49 m for spring and 0.24 m for neap tides. This would reduce the impact of flooding by a quarter under high impact low probability SLR scenarios, providing a tangible benefit in the future.

It was found that increasing hypothetical significant wave height resulted in a larger amount of sediment change along the beach profiles. However, when looking at total change along the whole profile, it was found that 2 m, long period waves resulted in the greatest loss of sediment. Comparing the before and after profiles for the scenarios with the biggest changes show that extreme events that have been simulated do not significantly impact on the beach volume, with a maximum loss of 2.5 m^3 of sand per metre across the beach.

With respect to overtopping of defences, it was shown that a peak in total volume was apparent at 2 m. There is a maximum value at wave heights of 5.3 m but it is not known if these high waves are representative of the wave climate in St Aubin's bay. The greatest overtopping amounts are related to the scenarios with the longest wave periods, with wave direction having little impact. All wave heights assessed result in some overtopping of defences, depending on the peak period value being used. For the still water only simulations, an increase in the mean sea-level showed that different profiles had very different responses, however, a 0.6 m rise in mean sea level was required before any overtopping occurred. When adding mean sea level increases to a scenario that includes waves, it was found that the response to SLR was a relatively linear increase in volume overtopped relative to SLR. It was found that, during an extreme event, for every 0.1 m of SLR approximately 300 m^3 of extra water was overtopped for every metre of sea defence.

As a result of the research carried out by this study, identification of further work that would be beneficial to Jersey has been undertaken. Some limited inundation modelling was planned to be carried out within the scope of this study, but due to time constraints it has not been achieved. Inundation modelling is beneficial as it will show the impact of a given total volume of water discharging over the defences. It will also be beneficial to assess and model the impact of extreme rainfall events on the island which can be achieved using a surface flood model.

The XBeach modelling completed for this study consisted of 1D profiles; a 2D storm impact model will provide a more detailed analysis of the ability of sea defences to withstand extreme events across the whole bay, or island, rather than at four points across St Aubin's Bay. Although changes in the beach profile were not found to be significant during the simulated extreme events, the long term cumulative impact of events on the beaches and coastline of Jersey is recommended. The assessment can take the form of models or observations, but ideally a combination of both.

New observational techniques developed at the National Oceanography Centre, use existing radar infrastructure (X-Band) can derive inter-tidal bathymetry, surface currents and wave climate. This technique could be used to monitor beaches and build a spatially and temporally robust dataset of critical coastal areas. Additionally, improvements in satellite monitoring techniques could also potentially be used to supplement in-situ observations.
Therefore, it is recommended that further work should consist of:

- Flood inundation modelling to show the impact of extreme events on coastal communities

- An assessment of the probability of wave peak periods occurring for projected wave heights

- Use of modelling techniques combined with observations to assess the long-term impact of climate on beach morphology

- 2D storm impact modelling to assess in more detail the impact of extreme events

- An assessment of pluvial (rainfall) flooding and the impact of extreme rainfall events combined with SLR and extreme water levels

- Investigation of the potential to establish long term cost-effective monitoring using e.g. satellite data to supplement in-situ observations and models

- Beach survey's to provide better values for sand particles sizes and distribution (required for beach modelling studies)

Contents

1 Glossary

Absolute sea-level rise: changes in the height of the ocean as a result of melting ice or warming seas.

Beach morphology: the study of the interaction and adjustment of seafloor topography and fluid hydrodynamic processes, seafloor morphologies, and sequences of change dynamics, involving the motion of sediment.

Business as Usual: Baseline case where no mitigation or adaptation to address climate change is made.

Chainage: An imaginary line used to measure distance, with values relative to a single arbitrary point.

Computational cost: The cost of running a computational model in terms of length of time and processor requirements. Ocean and coastal models can often have a very high computational cost.

GIA: Glacial isostatic adjustment is the ongoing movement of land once burdened by ice-age glaciers.

Hindcast: a statistical calculation determining probable past conditions (e.g. marine wave characteristics at a given place and time), rr a model simulation of historic events/conditions.

M2 tidal constituent: In most locations, the largest constituent of the tide is the "principal lunar semi-diurnal", also known as the M2 (or M_2) tidal constituent. The period of M2 is about 12 hours and 25.2 minutes, exactly half a tidal lunar day.

Mean High Water Springs: The height of mean high water springs is the average throughout the year (when the average maximum declination of the moon is 23.5°) of two successive high waters, during periods of 24 hours when the range of the tide is at its greatest.

North Atlantic Oscillation (NAO): The North Atlantic Oscillation (NAO) is a weather phenomenon in the North Atlantic Ocean of fluctuations in the difference of atmospheric pressure at sea level between the Icelandic low and the Azores high.

Peak period: The peak wave period (in seconds) is defined as the wave period associated with the most energetic waves in the total wave spectrum at a specific point. Wave regimes that are dominated by wind waves tend to have smaller peak wave periods, regimes that are dominated by swell waves tend to have larger peak wave periods.

Radiative Forcing: Also known as climate forcing, is defined as the difference of insolation (sunlight) absorbed by the Earth, and energy radiated back to space.

RCP: Representative Concentration Pathways (RCPs) are four greenhouse gas concentration (not emissions) trajectories, adopted by the IPCC for its fifth Assessment Report (AR5) in 2014.

Relative sea-level rise: Relative sea level is the sea level related to the level of the continental crust (i.e. land movement). Relative sea level changes can thus be caused by absolute changes of the sea level and/or by absolute movements of the continental crust.

Resilience: The capacity for a socio-ecological system to: (1) absorb stresses and maintain function in the face of external stresses imposed upon it by climate change, and (2) adapt, reorganize, and evolve into more desirable configurations that improve the sustainability of the system, leaving it better prepared for future climate change impacts.

Return period: A return period, also known as a recurrence interval (sometimes repeat interval) is an estimate of the likelihood of an event, such as an earthquake, flood or a river discharge flow to occur. This commonly referred to as a number of years that relate to the probability of occurrence, e.g. a 1 in 10 year return period has a 10% chance of occurring in any given year.

S2 tidal constituent: Principal solar semidiurnal constituent designated S2. Constituents are described by their tidal period (the time from maximum to maximum), T. The period for S2 is 12.00 solar hours.

Semi diurnal: An area has a semidiurnal tidal cycle if it experiences two high and two low tides of approximately equal size every lunar day.

Significant wave height: Significant wave height (H_s) is defined as the mean wave height (trough to crest) of the highest third of the waves ($H_{1/3}$). Therefore H_s = mean($H_{1/3}$)

Still water level: Water elevation due to astronomical tide and atmospheric interactions only, neglecting the impact of waves.

Storm surge: A change in sea level as a result of meteorological influences such as wind and atmospheric pressure. This can both increase or decrease the level predicted by astronomical forcing alone.

Swell waves: Waves that are not generated by the immediate local wind but by distant weather systems. These generally have a longer wavelength when compared with wind waves.

Tidal amphidrome: An amphidromic point is a point of zero amplitude of the tide.

Wind waves: These are a result of the wind blowing over the ocean, the parameters of the wave are determined by the speed and duration of the wind and by the distance it has been blowing over the sea (fetch).

2 Acronyms

Acronym	Definition
ACD	Above Chart Datum
AR5	IPCC 5th Assessment Report
BaU	Business as Usual
CD	Chart Datum
Dir	Wave Direction (clockwise from north)
EWL	Extreme Water Level
GIA	Glacial Isostatic Adjustment
GPD	Generalised Parento Distribution
GPS	Global Positioning System
HAT	Highest Astronomical Tide
Hs	Significant Wave Height
IPCC	Intergovernmental Panel on Climate Change
J14RCP8.5	High Impact Low Probability Climate Scenario
MHWS	Mean High Water Springs
NAO	North Atlantic Oscillation
NCAR	National Centre for Atmospheric Research
NCEP	National Centre's for Environmental Prediction
NOC	National Oceanography Centre
RCP	Representative Concentration Pathway
SLR	Sea-Level Rise
SMB	Surface Mass Balance
SoJ	The States of Jersey
SSJPM	Skew Surge Joint Probability Method
SWL	Still Water Level
Tp	Peak Period
UKCP09	United Kingdom Climate Projection 2009

3 Introduction

The States of Jersey (SoJ) are not subject to UK legislation on climate change, and have not been directly considered under any previous UK climate projections such as UKCP09 [1]. Hence Jersey is not directly covered by the regional sea level rise projections undertaken by the UK in 2009. SoJ are therefore seeking projections on the impact of climate change over the decadal to 100-year timescale. SoJ also require geographically relevant data on the effects of climatic changes to sea-level and the associated impact on the coastal environment. This tailored information will provide the scientific background to inform policy in the context of climate change up to 2100.

The aim of this report is to establish, using the best available science, a baseline of projected regional changes in sea level, surge, offshore waves and tidal range, and to use a case study to explore the impact of these changes on beach morphology and overtopping. The report provides details of the models and methodologies used to derive these projections and explores the impact of extreme events on the coast, in the present day, and under the influence of sea-level rise. The report concludes with implications and recommendations.

The National Oceanography Centre (NOC) have worked closely with representatives from the Department of the Environment, the Jersey Meteorological Department and discussed the report and work with other key departments such as the Department of Infrastructure, and Department of Planning. These departments contributed previous studies and survey data.

4 Study Location

Jersey is located in the English Channel 23 km from the French mainland, it is in an area with a large spring tidal range with a maximum range of around 12.07 m. This high range means that significant coastal flooding is most likely to occur when a storm surge and high water spring tides coincide. The high tidal range also means that even during flood events, water overtopping sea defences will quickly recede, assuming good drainage of the inundated area. Wave impact during extreme events is limited to a window around high water.

Jersey has vulnerable coastlines, particularly in the South of the Island where the capital St Helier is located (Figure 1). This report has focused on the St Aubin’s Bay area as a case study, selected due to the high value infrastructure, large coastal communities and available survey data.

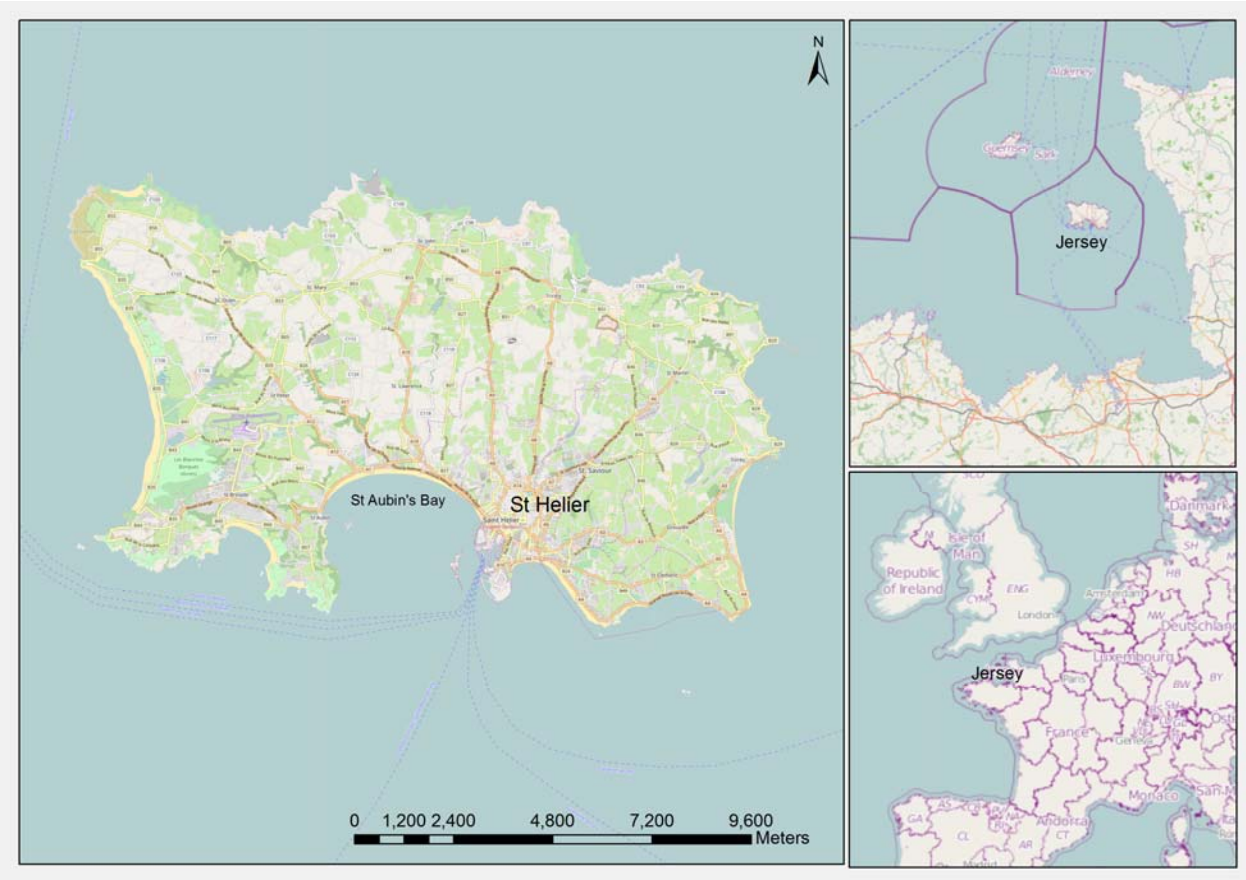

Figure 1: Map of Jersey showing location of St Helier and St Aubin's Bay

5 Study Context - Historical Extreme Events

Jersey has suffered extreme events (surge combined with high tide) in the past, in particular in 2008 and 2014. A brief overview of these events has been included here to provide context to the report. These highlight Jersey's vulnerability to the coincidence of a storm surge passing at high water, generating extreme water levels and waves.

5.1 Details of 2008 surge provided by Jersey Met Office

In 2008 a 1 in 10 year extreme event led to sea wall damage totalling up to £500,000, the event was well predicted by the Jersey Met Office and warning and preparations had been made to improve the ability of the sea defences to resist the storm surge and waves. Early on the 10th March the southerly wind at Jersey Airport strengthened to strong force 7. By 5am, and at about 5:45am, the storm veered southwest and increased temporarily to a mean speed of 37 knots (gale force 8) with gusts up to 52 knots. This coincided with a squall line passing over the Island, accompanied by hail and heavy rain, with a thunderstorm in the vicinity [2].

For the rest of the morning the southwest wind was strong force 6 to 7 at the Airport, but increased markedly to severe gale force 9, gusting to 55 knots around 1pm. A westerly wind of force 8 to 9 persisted for the rest of the day and only eased below gale force early on the 11th.

There were gusts of 60 knots or more from 2pm until late on the 10th, the highest recorded was 67 knots between 4 and 5pm. An anemometer on the tanker berth at St. Helier Harbour recorded slightly stronger winds than the Airport, reaching a maximum of 52 knots (storm force 10) with a gust to 72 knots at around 2pm [2].

Storm surge forecasts estimated residuals of 0.71 to 0.85 m, these calculations suggested that the predicted tide of 11.56 m (CD) was likely to peak at 12.26 m (CD). This is an exceptionally high tide for Jersey with a highest astronomical tide (HAT) of 12.16 m. With the forecast southerly gale force winds, flooding was expected.

During the extreme event the wind veered from south to southwest nearly 2.5 hours before high water. Table 1 shows the predicted tidal heights along with the residuals.

Table 1: Details of the high and low tides during the storm surge in 2008

Date	Tide	Time	Predicted Tide	Forecast Residual	Observed tide	Actual residual
10/03/2008	High	08:09	11.56	+0.71	12.33	+0.77
10/03/2008	Low	14:51	0.73	+1.07	1.94	+1.21
10/03/2008	High	08:27	11.29	+0.80	11.58	+0.29
11/03/2008	Low	15:06	0.96	+0.32	1.26	+0.30
11/03/2008	High	08:45	11.29	+0.43	11.61	+0.41

Looking at the St Helier tide gauge, the highest morning surge was nearly 2.5 hours before high tide. As the wind veered and decreased in speed, this reduced the wind component of the surge and resulted in a sudden drop of 0.2 m in water level. The data also shows that the highest residuals occurred near the time of low tide, exceeding 1.2 metres for about an hour, peaking at 1.26 m.

With the approaching high tide, the warnings issued by the Jersey Met Office proved to be accurate with flooding occurring on the morning tide between St Aubin and Seaside to the East of Beaumont. There were various sites that experienced flooding, such as St Aubin, the La Haule area, Beaumont road way and the Gunsite area. That evening the high tide resulted in more flooding, with First Tower and West Park experiencing flooding and damage to the seawall.

Following the storm, it is estimated that the cost in clean up and repair would total £436,000 with some un-costed items potentially bringing the cost up to £500,000. The time to carry out the repairs was over a year. While this flooding is not unprecedented, it is a rare event with a return period of around 1 in 10 years [2].

5.2 Extreme events in 2014

In 2014, between January and October, a cluster of extreme events resulted in large amounts of damage, requiring emergency repairs in excess of £1.1 million. During this period various defences were breached at high tide such as the sea walls and piers at Gorey, Beaumont, St Aubin, St Aubin's pier and St Catherine's, causing flooding and road closures. Record high tides in March

2014 caused the collapse of the sea wall at Le Bourg, and residential gardens on the seafront at St Clements collapsed into the seawall and on to the beach. Clustering of extreme events creates additional stress on defences or can cause loss of beach volume, exacerbating damage and resulting in greater overall costs in clean up and repair.

6 Global and Regional Sea-Level Rise Projections

6.1 Introduction

The impact of future storm events will be influenced by sea-level rise (SLR). While there are robust global projections, sea-level rise at the regional scale is not uniform and may differ substantially from the global average sea level rise [3]. These variations are due to dynamical ocean processes, changes in gravitational fields associated with ice mass loss and air-sea heat and freshwater fluxes. Regional sea level projections produced for the United Kingdom in 2009 [1] (due to be updated in 2018) do not cover Jersey, and do not benefit from more recent research. These are now considered to be conservative projections [3].

The RISES-AM project aimed to address coastal impacts of climate change for high-end emissions scenarios [4]. The project has updated the 2009 regional sea-level rise projections using global sea-level projections for different emission scenarios (low, medium or high) as input and producing sea-level patterns or maps that show the contribution of each individual sea level component such as thermal expansion, contribution from glaciers, ice sheet in Greenland and Antarctica and contribution from land water. The regional sea-level rise projections calculated by RISES-AM have been used for this study to provide the most up to date projections that are currently available. The projections calculated by RISES-AM will be used in the 2018 regional sea-level rise projections update.

6.2 Representative Concentration Pathways

The latest research Intergovernmental Panel on Climate Change (IPCC) AR5 has defined four new climate scenarios referred to as representative concentration pathway (RCP) scenarios [5]. These four RCP's are a consistent set of projections of the components of the radiative forcing named according to their 2100 radiative forcing level estimated from greenhouse gases and other forcing agents. These scenarios are produced by integrated assessment models up to 2100. It should be recognized that while the RCP's span a wide range of total forcing values, they do not span the full range of plausible emissions in the literature [6].
Of the four RCP's the two selected to be used within the latest research are RCP4.5 (medium emissions) and RCP8.5 (high emission) these RCP's both infer a global average warming greater than 2^0C with respect to pre-industrial temperatures. Using the latest IPCC report [7] in which projections of changes in the climate are made. The changes relate to scenarios that combine natural (solar radiation) and anthropogenic (radiation change due to atmospheric greenhouse gases and aerosols) forcing. The different scenarios are performed with prescribed CO_2 concentrations, which are unique for each scenario. Table 2 shows the different expected

outcomes in temperature change relative to a baseline average temperature between 1986 and 2005 for each RCP.

Table 2: Projected response of climate to different representative concentration pathways showing mean temperature increase and range 5th to 95th percentiles.

Climate Scenario	Mean (^{0} C) (+/- 1 standard deviation)	Range (5th to 95th Percentiles)	Outcomes of RCP
RCP2.6	1.6 (0.4)	(0.9 – 2.3)	Carbon Emissions peak by 2040 and then reduce
RCP4.5	2.4 (0.5)	(1.7 – 3.2)	Potential outcome if Paris climate change agreement is adhered too.
RCP6.0	2.8 (0.5)	(2.0 – 3.7)	Potential outcome if Paris climate change agreement is not fully adhered too.
RCP8.5	4.3 (0.7)	(3.2 – 5.4)	Business as Usual

The RCP 2.6 scenario is defined by a mid-century radiative forcing around 3.1 W m^{-2} which drops to 2.6 W m^{-2} by 2100. To achieve this scenario, greenhouse gas concentrations must substantially reduce over time. RCP 4.5 and 6.0 are both stabilisation scenarios where the radiative forcing is stabilized before and after 2100 respectively by employing policy and deploying technological solutions to reduce greenhouse gas emissions. RCP 8.5 is defined as having radiative forcing that increases more rapidly than the other RCP's and continues to increase until 2200. This is in spite of a stabilizing of emissions in the scenario post 2100 and atmospheric concentrations post 2200. This highlights the fact that the climate has a long feedback response time to short term anthropogenic effects. This makes RCP8.5 akin to "Business as Usual" and RCP4.5 equivalent to the mitigation that has been proposed under the Paris agreement in 2015.

6.3 Projected global sea-level rise

The previous section shows that RCP4.5 and RCP8.5 represent scenarios with global average warming greater than 2^0C with respect/ to pre-industrial levels. These were the two RCP's selected for global and regional sea level projections (Figure 2). The conventional approach to projected sea level rise is based on the simulation of individual sea level components: such as contributions from ocean thermal expansion, melting/dynamics of glaciers and the ice sheets. These contributions are then summed up to give an overall SLR value. The RISES-AM project followed this approach and considered projections of the main sea level components:

- Thermal expansion
- Glacier surface mass balance (SMB)
- Greenland SMB and dynamical changes
- Antarctica SMB and dynamical changes
- Changes in land water storage

The latest IPCC report gives a likely range (66%) for global sea-level rise by 2100, implying that there is a 34% chance that sea-level rise may lie outside this range, in part due to the difficulties in assessing ice mass loss from both Greenland and Antarctica [8].

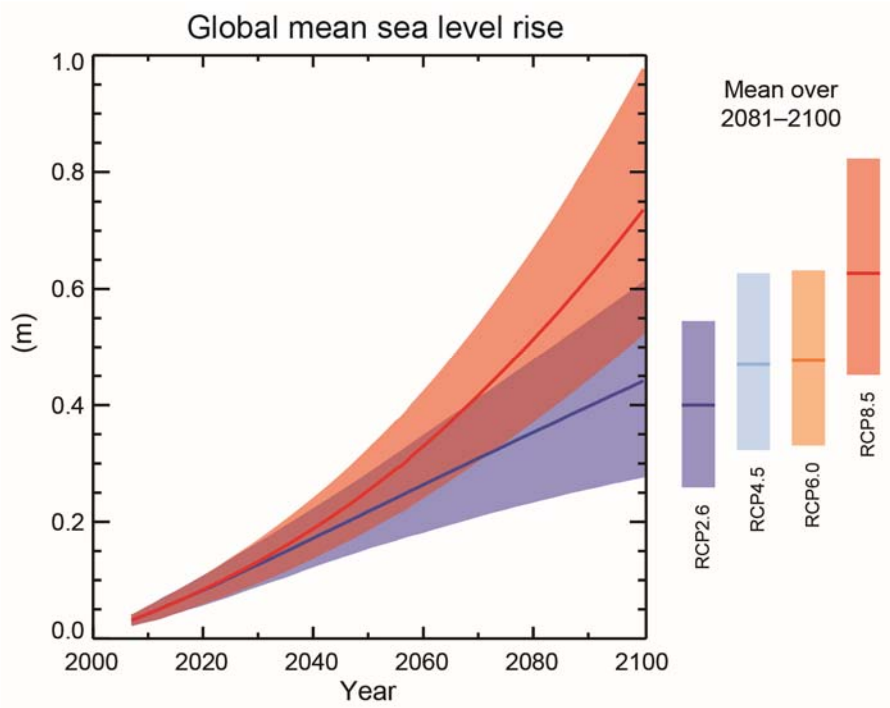

Figure 2: Projections of global mean sea level change over the 21st century relative to 1986-2005. The likely range is shown as a shaded band with the corresponding median value given as a solid line [6].

Table 3: Median values and likely ranges for projections of global mean sea level rise in metres at 2100 relative to 1986-2005 for the four RCP scenarios.

Climate Scenario	Median (m)	Likely Range (m)
RCP2.6	0.43	0.28 to 0.60
RCP4.5	0.52	0.35 to 0.70
RCP6.0	0.54	0.37 to 0.72
RCP8.5	0.73	0.53 to 0.98

With mean sea levels continuing to rise in the 21st century the impact assessment, risk management, adaptation strategy and long-term decision making for coastal areas depends on future projections of sea level and crucially, the low probability, high impact, projections. While these high impact projections are unlikely to be realised, they are still plausible and should not be ruled out when considering adaptation and mitigation policies.

It is projected that by 2100 when compared with 1986-2005, global sea-level will be 0.53-0.98 m higher (likely range 66% only), with a median of a 0.73 m increase for the higher impacting climate scenario RCP8.5. For RCP4.5, the global mean sea-level will be 0.35 – 0.70 m higher (likely range, 66% only), with a median increase of 0.52 m (Table 3). There is also an upper limit scenario

(J14_RCP8.5) based on RCP8.5 which determines that a global average sea-level rise greater than 1.8 m has less than 5% probability of occurring by 2100 [9]. Figure 3 shows the probability distribution for J14_RCP8.5, which is a high impacting low probability representative concentration pathway, produced as part of the RISES-AM project.

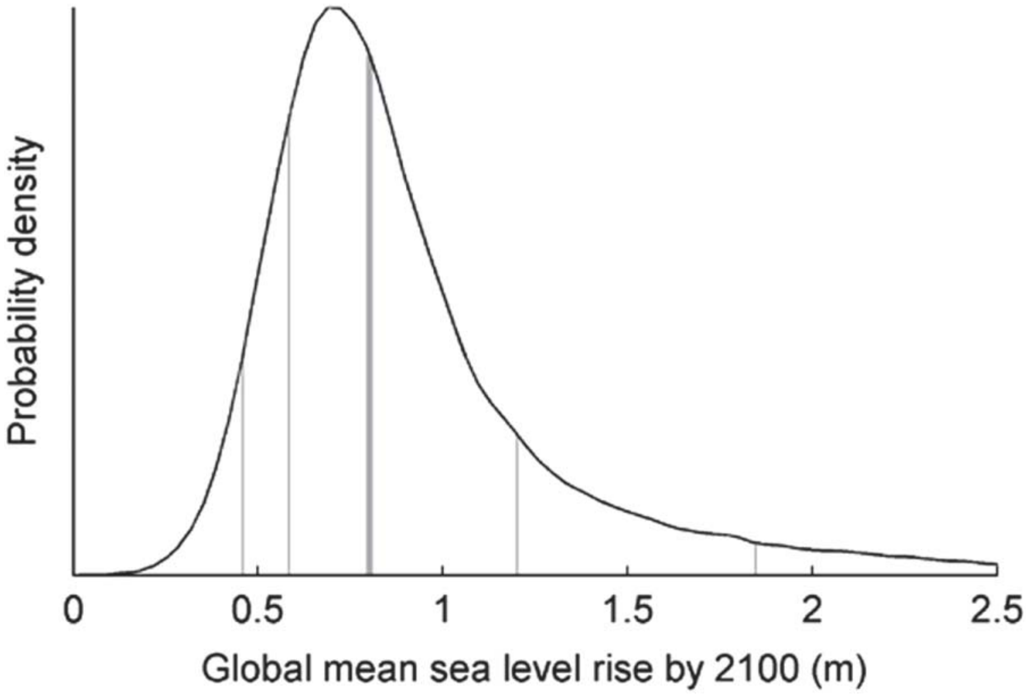

Figure 3:Projected global mean sea level rise by 2100 relative to 2000 for high end emissions scenario J14_RCP8.5. Vertical grey bars indicate the 5th, 17th, 50th, 83rd and 95th percentiles in the probability distribution [9].

6.4 Future projections of regional sea-level rise

One of the outputs of the RISES-AM project is the production of regional sea level rise projections, in 10 year intervals, for RCP4.5 and RCP8.5, up to 2100. For the Island of Jersey, the closest regional dataset point was identified, the location of which is shown in Figure 4. The regional SLR projections for the two RCP pathways, and the upper limit scenario, are shown in Table 4. The data consists of the three RCP scenarios, four time periods for each, and 6 percentile values. This highlights the range of possible regional SLR values that could be realised in 2100, and will be different to the global values that have been projected in section 5.3.

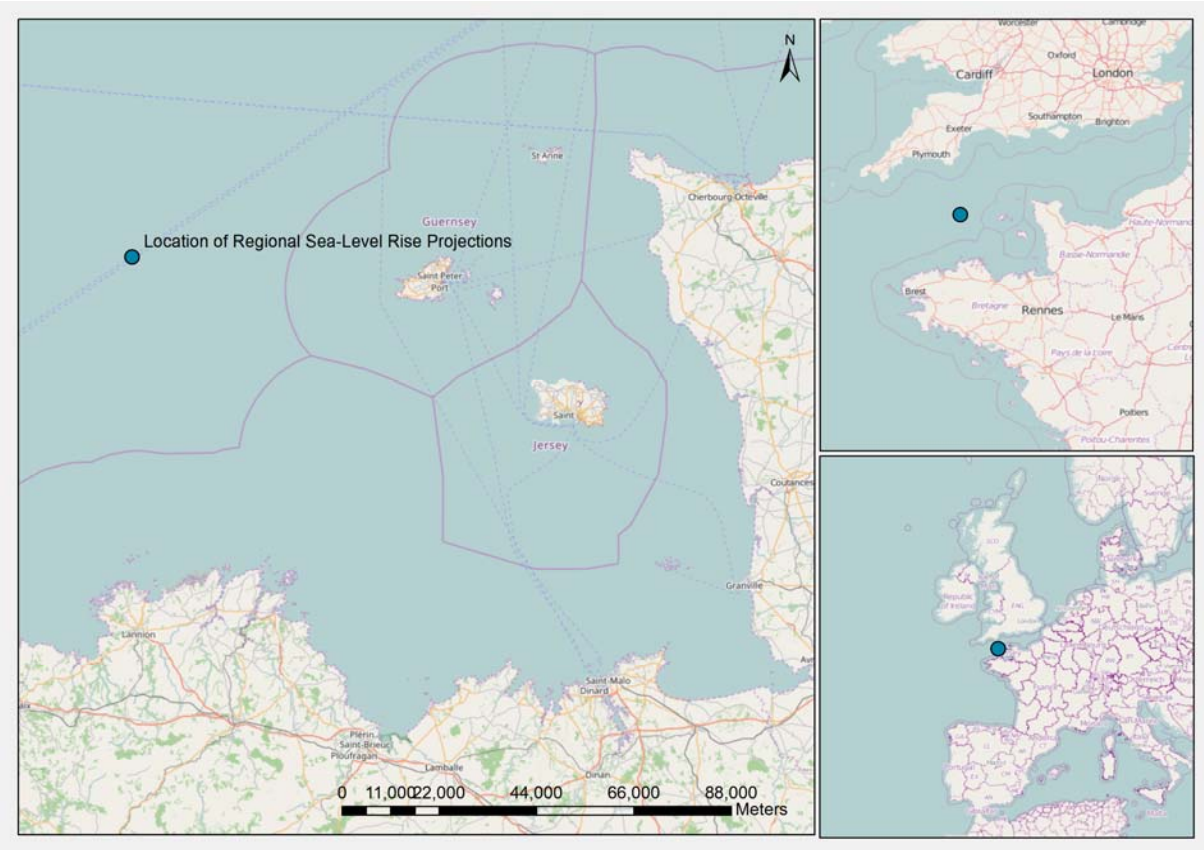

Figure 4: Closest data point from regional SLR model to Jersey for latest regional SLR projections

The 54 different regional SLR projections in Table 4 highlight the uncertainty in present SLR projections, both across different climate scenarios, and across the same time epoch. Rather than considering each of these projections, a manageable selection of eight SLR scenarios have been used, that cover the range of potential SLR outcomes. Table 5 lists the selected SLR values from Table 4 rounded to one decimal place.

Table 4: Projected regional sea-level rise (m) for each climate scenario across the 5th, 17th, 50th, 83rd, 95th and 99th percentiles for the three time epochs, 2030, 2050, 2080 and 2100 corresponding to the data point shown in Figure 5.

Climate Scenario		Percentiles					
	Year	5th	17th	50th	83rd	95th	99th
AR5_RCP4.5	**2030**	0.08	0.10	0.12	0.15	0.16	0.18
AR5_RCP8.5	**2030**	0.09	0.11	0.13	0.15	0.17	0.19
AR5_RCP4.5	**2050**	0.15	0.18	0.22	0.26	0.29	0.32
AR5_RCP8.5	**2050**	0.17	0.21	0.25	0.30	0.33	0.36
AR5_RCP4.5	**2080**	0.25	0.31	0.39	0.46	0.52	0.58

AR5_RCP8.5	**2080**	0.33	0.40	0.48	0.56	0.62	0.69
AR5_RCP4.5	**2100**	0.31	0.38	0.48	0.58	0.65	0.73
AR5_RCP8.5	**2100**	0.43	0.53	0.65	0.77	0.86	0.97
J14_RCP8.5	**2100**	0.40	0.54	0.77	1.21	1.82	2.69

Table 5: List of SLR scenarios used in the study that cover the range of regional SLR projections.

SLR Parameter Number	SLR (m)
1	0.1
2	0.2
3	0.3
4	0.5
5	0.6
6	1.0
7	1.2
8	1.8

The majority of projections are at the lower values, hence being covered by 0.1, 0.2, 0.3 and 0.5 m with the smaller amount of middle projections being covered by 0.6 m. The low probability high impact (yet still plausible) SLR values, are covered by 1.0, 1.2 and 1.8 m. However, it should be noted that the rate of sea-level rise is projected to decrease over the long term due to reduced emissions.

6.5 Limitations and uncertainty of projections

A lot of uncertainty is associated with European climate projections, due to variability in climate model predictions, and the strong influence of physical processes such as storm tracks and jet streams, which are currently not well represented within models [10]. Europe's climate is one of the world's most variable due to the location of the end of the Atlantic jet stream and the associated storm track configuration. Translating global climate studies to the impact of the global climate on the coast is still not fully explored [11], with current regional climate studies focusing on rainfall and temperature [12], with storm winds, surges and waves under represented. It is therefore important to note that while this research is the most up to date in terms of regional SLR projections, there are inherent limitations and uncertainties.

7 Vertical Land Movement Trends

It is important to understand the direction and rate of vertical land movement at the coast, particularly for regions outside the previous ice marsh, such as Jersey. It can have a significant positive or negative impact on the apparent rate of sea-level rise. If the vertical rate is positive, then the land is rising and will help to reduce the impact of sea-level rise. Conversely, if it is negative, the land is sinking and will exacerbate sea-level rise.

Post glacial rebound (also known as Glacial Isostatic Adjustment (GIA)) is the rise of land masses that were depressed by the weight of ice sheets during the last glacial period. In the UK, Scotland and the North of England were covered by these ice sheets and are currently rising as a result of this rebound which is also causing a corresponding downward movement of the southern half of the country. This effect will increase the apparent rate of SLR in Southern areas of the UK making coastal flooding more likely.

Using available data from French and UK GPS land movement stations, the vertical movement rate for the region surrounding Jersey has been calculated. The locations of the land movement GPS stations are shown in Figure 5.

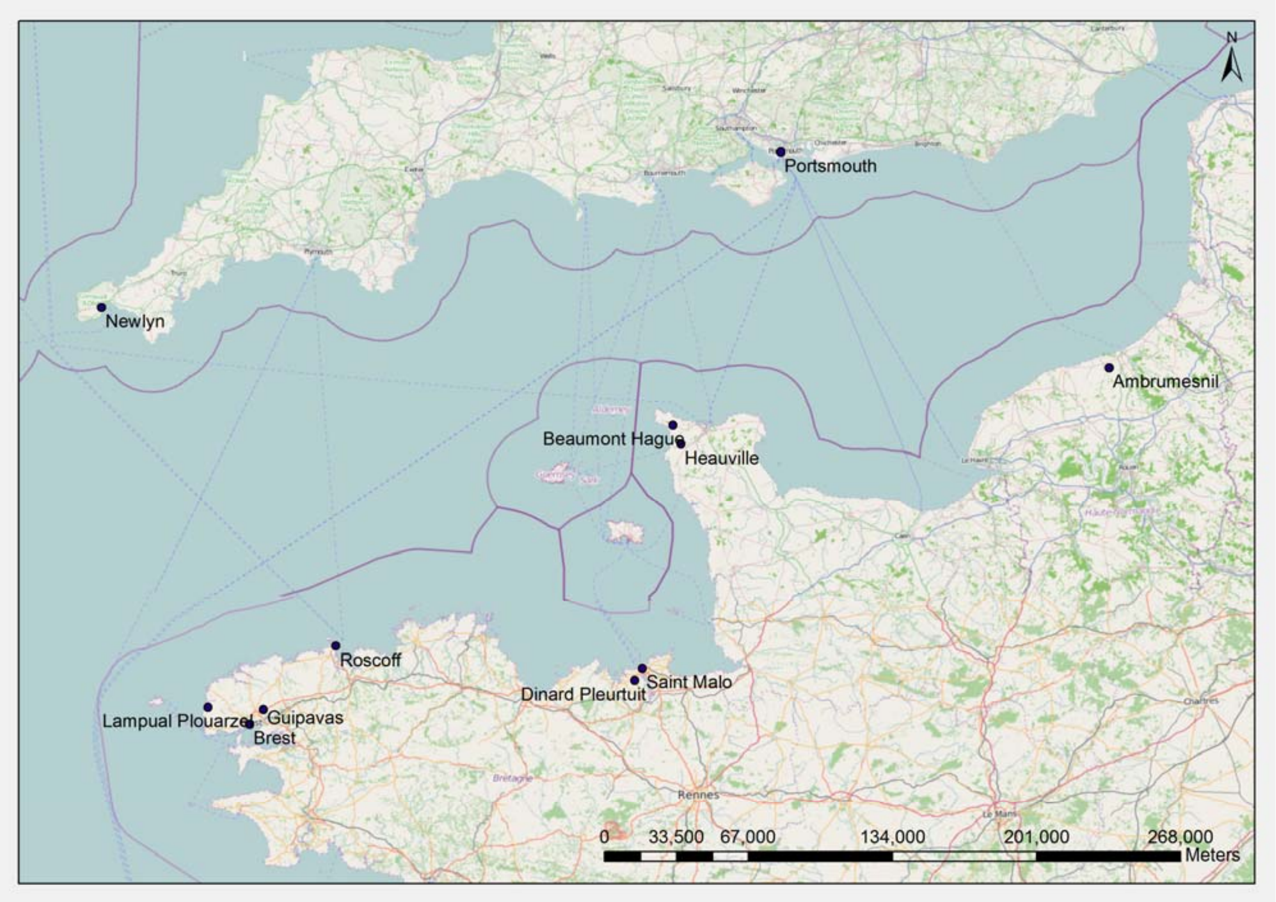

Figure 5: Locations of GPS vertical movement stations for area surrounding Jersey

Table 6: Vertical land movement rates for all stations surrounding Jersey including time span and completeness of data.

Station Name	Vertical land movement rate (mm/yr)	Time span of dataset (years)	Data completeness (%)
Newlyn	-0.17 +/- 0.14	15.25	89.43
Portsmouth	0.07 +/- 0.23	12.13	86.61

Station Name	Vertical land movement rate (mm/yr)	Time span of dataset (years)	Data completeness (%)
Roscoff	-1.28 +/- 0.33	4.35	97.42
Lampual Plouarzel	-0.53 +/- 0.2	6.32	86.02
Guipavas	-0.49 +/- 0.15	11.2	91.01
Brest	0.01 +/- 0.11	15.16	73.90
Dinard Pleurtuit	-0.84 +/- 0.38	5.42	94.14
Saint Malo	-0.63 +/- 0.47	3.87	97.95
Heauville	-0.3 +/- 0.19	11.26	81.32
Beaumont Hague	-0.21 +/- 0.35	6.78	94.02

It can be seen that there is large variability in the rate of vertical land movement across all stations. However, aside from Brest, the data show negative or downwards land movement. This would be expected for areas just outside the ice sheet, present during the last glacial period. It is likely Jersey will also be subject to vertical land movement in the same direction i.e. sinking. However, there is large uncertainty on exactly what the rate is likely to be. Looking at Table 6 the rates vary from -0.84 mm/yr at Dinard Pleurtuit to 0.01 mm/yr at Brest. This could mean that there is either little impact on the rate of SLR, or an almost 50% increase, assuming a rate of SLR of around 2 mm per year.

Contrasting this with the contribution that vertical land movement makes to the RISES-AM regional global SLR projections from section 5, for 2030, 2050, 2080 and 2100 (Table 7); the contribution remains the same for each representation concentration pathway. This is because GIA is dependent on the ice sheets that were present during the last glacial period and have since melted, and not the amount of CO_2 projected to be emitted into the atmosphere.

Table 7: Vertical land movement or GIA contribution to regional sea level projections

Time Period	AR5_RCP4.5	AR5_RCP8.5	J14_RCP8.5
2030	0.0069	0.0069	0.0069
2050	0.0109	0.0109	0.0109
2080	0.0168	0.0168	0.0168
2100	0.0207	0.0207	0.0207

Table 7 shows that regional projections estimate a contribution of around 0.021 m by 2100, whereas the higher rates of vertical land movement would suggest this contribution could be closer to 0.075 m. Thus, the regional sea level projections could be underestimating this contribution by 0.054 m. This contribution in context to the overall sea-level rise projected by 2100, shows that vertical land movement has a relatively minor impact on the SLR projections for Jersey.

During a post-study dissemination event in Jersey it was identified that there is a GPS base station on Jersey operated by the planning department that could allow a measurement of the vertical land movement to be made. Efforts are being undertaken to acquire this data and any rates calculated will be appended to this report in due course. Any rates calculated will reduce the uncertainty surrounding the vertical land movement rate that Jersey is experiencing and provide more confidence in sea level trends and regional sea level rise projections.

8 Regional Sea-Level Trends

In addition to vertical land movement and regional sea level projections, there is also variation in the sea-level trend at specific locations along the coast. These variations can be over relatively short distances due to different factors such as vertical land movement and changes to the tidal range and timing. Having a vertical land measurement located near to a tide gauge allows a relative sea level trend to be measured. These sea-level trends can be calculated over varying time periods depending on the relevant tide gauge. Three time horizons have been considered; 1900 to 2013, 1960 to 2013, and 1970 to 2013, these take into account the varying lengths of tide gauge records. Table 8 shows the absolute sea-level trend for each tide gauge, for each time horizon where data exists. Some locations such as Brest have more than one GPS station nearby so have multiple entries. Figure 6 shows the location of these tide gauges.

Table 8: Absolute sea level trend for tide gauges with robust GPS records.

ABS_SLT = absolute sea-level trend and ABS_SLT_U = absolute sea-level trend uncertainty.

Tide Gauge	GPS	Distance apart (m)	ABS_SLT 1900 (mm/yr)	ABS_SLT_U 1900 (mm/yr)	ABS_SLT 1960 (mm/yr)	ABS_SLT_U 1960 (mm/yr)	ABS_SLT 1970 (mm/yr)	ABS_SLT_U 1970 (mm/yr)
BREST	BRST	292	1.539	0.11	1.623	0.11	2.58	0.11
BREST	GUIP	9213	1.039	0.15	1.123	0.15	2.08	0.15
NEWLYN	NEWL	2	1.599	0.14	1.613	0.14	2.272	0.14
CHERBOURG	BMHG	14006	*No Data*	*No Data*	1.079	0.35	1.079	0.35
CHERBOURG	HEAU	12930	*No Data*	*No Data*	0.989	0.19	0.989	0.19
LE CONQUET	LPPZ	9790	*No Data*	*No Data*	*No Data*	*No Data*	2.178	0.2
ROSCOFF	ROTG	11	*No Data*	*No Data*	*No Data*	*No Data*	0.392	0.33

While there are more tide gauges that could be used on the UK and French coastlines, only ones with a nearby robust GPS velocity were used. All stations and gauges required at least 70% valid data. Two assumptions have been made to generate the sea-level trends, the first assumption is that the linear vertical land movement estimated by the GPS station is consistent over the multi-decadal to century timescale of the tide gauge record. The second assumption is the land motion by the GPS antenna is consistent with that affecting the tide gauge, at the level of a few tenths of a millimetre per year.

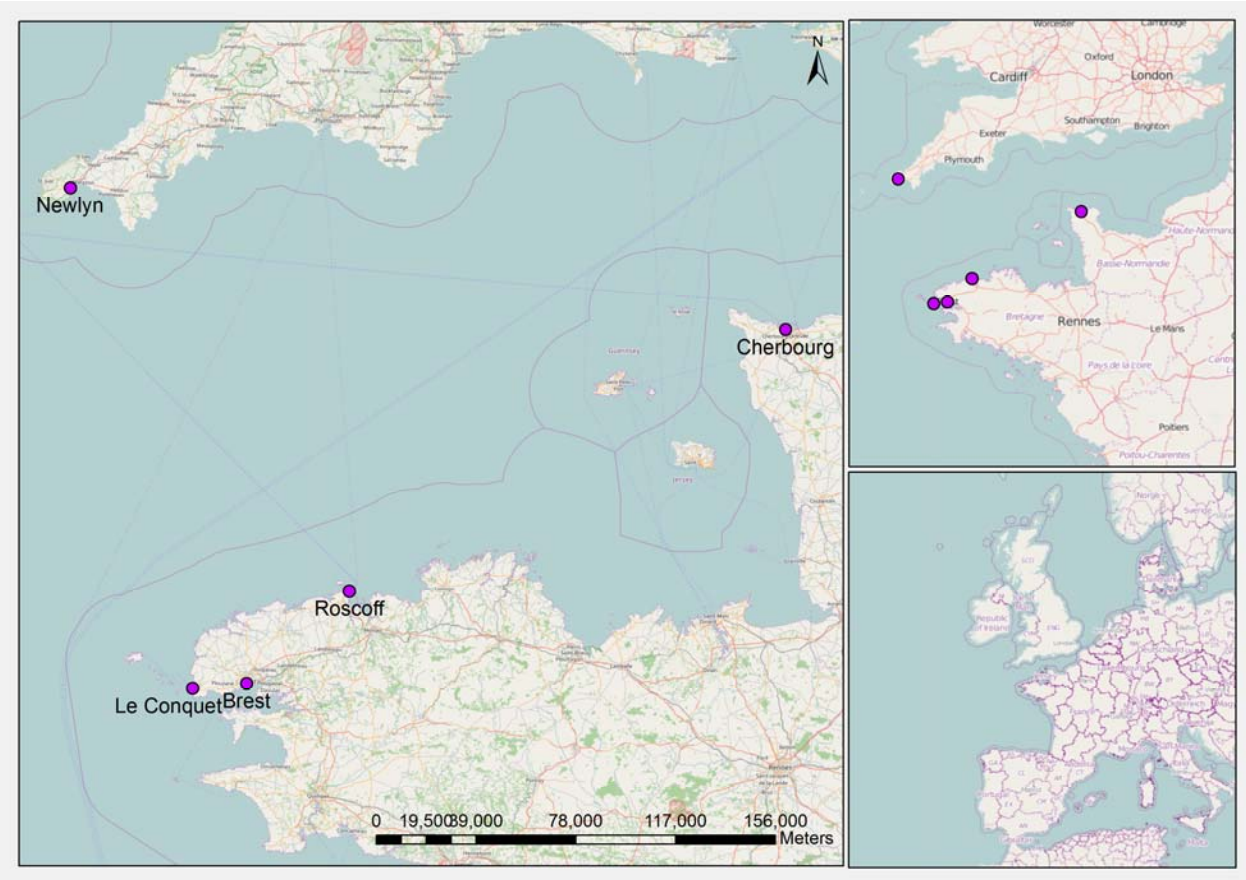

Figure 6: Locations of the different tide gauges for absolute sea level trends, (some locations have more than one GPS station linked so have multiple trends.)

The data shows that there is quite a variation in the absolute sea-level trend, ranging from 1mm/yr at Brest from 1900 to 2013 to 2.6 mm/yr at Brest, but for a different GPS station 9 km away, for the period 1970 to 2013. This highlights the impact that a longer dataset and distance between the GPS and Tide gauge has, i.e. the GPS station at Brest that is within 300 m of the gauge has a 0.5 mm/yr increase over the GPS station located just over 9 km away. When considering a time period of 1970 to 2013, the rates increase by around 1 mm/yr to 2.6 mm/yr and 2.1 mm/yr respectively. This increase in rate is also present in the Newlyn gauge. Both Newlyn and Brest have noticeable changes in the rate between 1960 and 2013, and between 1970 and 2013. There is little change between 1900 to 2013, and 1960 to 2013, suggesting that between 1960 and 1970 the rate of the absolute sea level rise has accelerated. However, this acceleration is not present at Cherbourg. The assumption is that the rate of sea level rise is 2 mm/yr which is consistent with previous reports and is also a good match to the observed trend in mean sea-level.

9 Extreme Still Water Level Return Period Assessment

9.1 Introduction

In 2008 the Environment Agency took on the role of producing a strategic overview of the coastline in England, giving it an overarching role in the management of the English coastline. In response to outdated and inconsistent approaches to flood and erosion risk management, a research and development project was set up to deliver better information using improved methods and longer data records. The project provided a consistent set of extreme sea levels around the coast of England, Wales and Scotland. The improvements afforded by this research are used to support successful risk based flood and coastal erosion risk management.

This study replicates this methodology known as skew surge joint probability (SSJPM), for the coast of Jersey. The outputs from the methodology consist of extreme peak sea levels of annual exceedance, ranging from 1 in 1 year to 1 in 10,000 years [13].

9.2 Skew surge joint probability – methodology overview

Skew surge joint probability is used to derive extreme water levels around the coastline. Storm surges arises when gradients or changes in atmospheric pressure affect the level of the water surface. Low pressure (e.g. during storm conditions) acts to raise the sea surface level, where high pressure will lower it. Winds can also drive currents that will act on the surface changing the sea level e.g. offshore winds that are orientated parallel to the coastline, with the coastline to the right relative to the direction of wind. These winds will result in currents orientated towards the coast causing a rise in the local sea level. The combination of all these components is known as storm surge, and can increase or decrease sea levels. As these processes are meteorological in origin, they are independent from the astronomical tide and so can occur at any point of the tidal cycle.

Skew surge is defined as the height difference between the predicted astronomical tide and nearest experienced high water (Figure 7). Using this definition results in the removal of all phase differences (timing differences), between predicted and observed data, which eliminates the impact of illusory residuals. Relying on surge residuals rather than the skew surge can result in illusory surge residuals which can over predict the extreme water level, if for example, the observed tide occurs slightly earlier than predicted. This is particularly applicable to surge residuals in the mid tide range (Figure 7) [13].

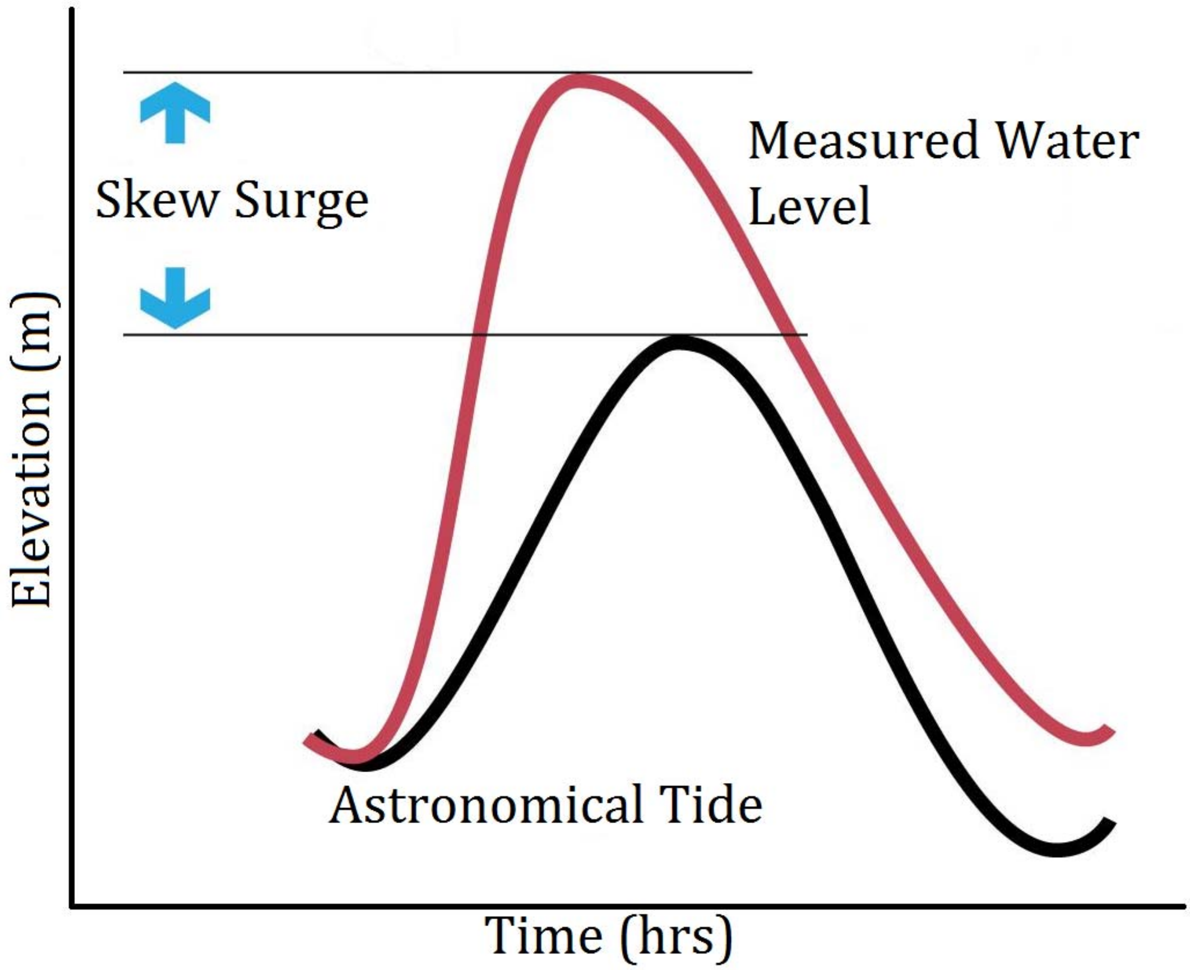

Figure 7: Illustration of skew surge

To apply SSJPM, the tide gauge data was de-trended by a rate of 2 mm/yr. This rate is the net combination of land movement and changes in water level due to SLR. Analysis from section 7 has shown that this historic rise is appropriate to use for the study. Therefore, the de-trended data will be consistent for all years and independent of sea level rise. The peak observed water level for each high tide was extracted, and the predicted high tide was also calculated. As mentioned the difference between these is known as the Skew Surge. This process was repeated across the whole tidal gauge data set [13].

A Generalised Pareto Distribution (GPD) was fitted to the skew surge distribution, the parameters of the GPD were set to provide the best fit possible to the extreme skew surges above a specified threshold in the upper tail of the distribution (Figure 8).

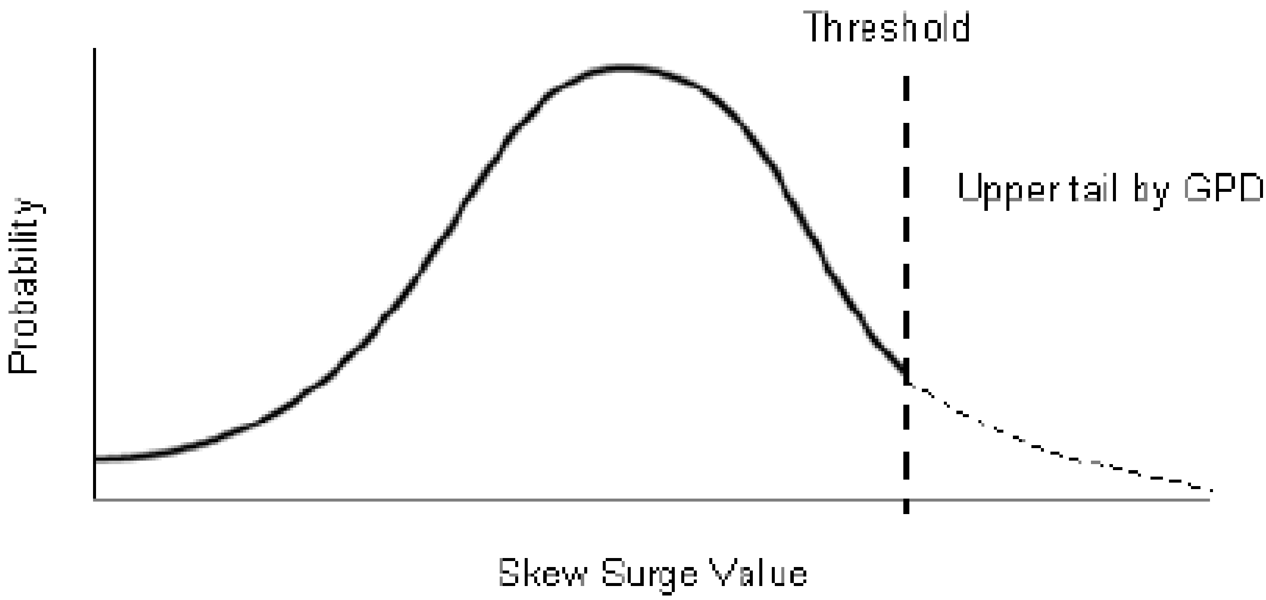

Figure 8: Schematic of the Generalised Pareto Statistical Distribution

Joint Probability analysis was used to form a probability distribution of all possible total sea levels from the skew surge distribution and peak tide levels from the full nodal cycle. The analysis has assumed independence between skew surge and peak tidal levels. The final stage of the SSJPM was to express the probability distribution of total sea levels in terms of return periods [13].

9.3 Skew surge joint probability – analysis results

The results of the SSJPM analysis for St Helier are shown below in the form of a linear plot of return period against extreme water level (Figure 9) and a tabular data showing the return period values and the 95% confidence interval (Table 9).

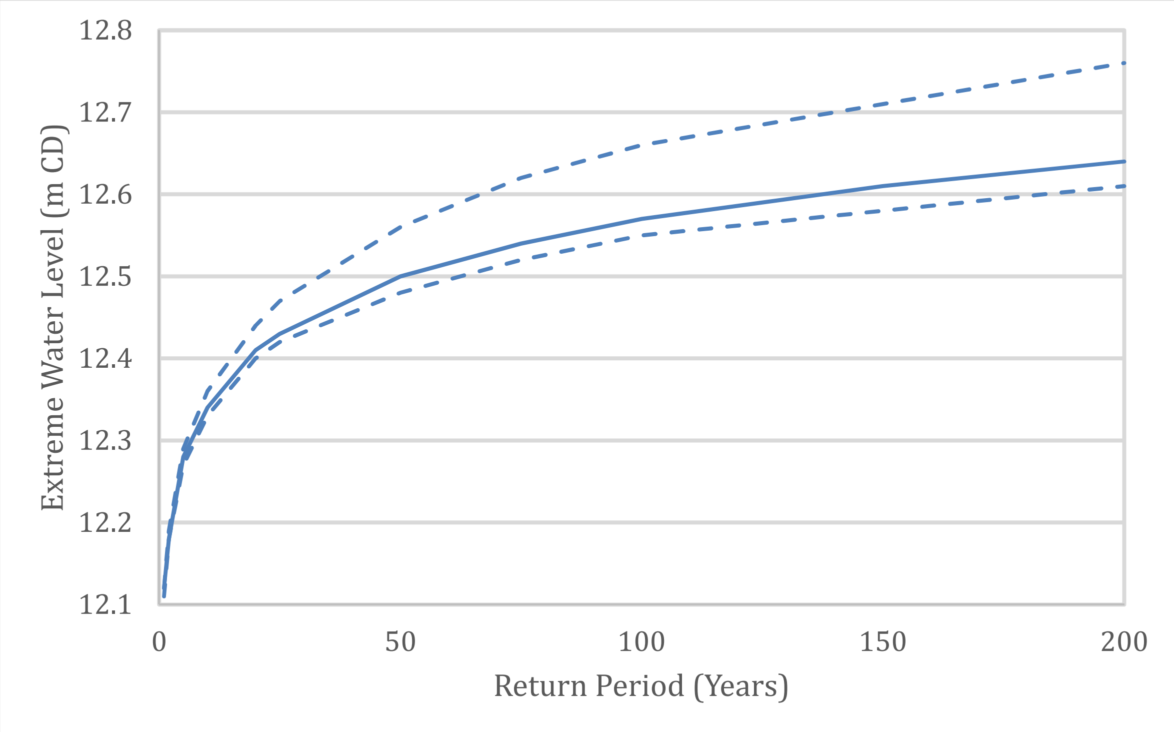

Figure 9: Linear plot of return period against extreme water level up to a 1 in 200-year event, the solid line represents the return period values and the dashed lines indicate the 95% confidence intervals.

Table 9: SSJPM Results for St Helier, showing still water level for a range of return periods.

Return Period (years)	Extreme Still Water Level (m CD)	95th Confidence Interval (m CD)	
1:1	12.12	**12.11**	**12.12**
1:2	12.18	**12.18**	**12.19**
1:5	12.28	**12.27**	**12.29**
1:10	12.34	**12.33**	**12.36**
1:20	12.41	**12.4**	**12.44**
1:25	12.43	**12.42**	**12.47**
1:50	12.5	**12.48**	**12.56**
1:75	12.54	**12.52**	**12.62**
1:100	12.57	**12.55**	**12.66**
1:150	12.61	**12.58**	**12.71**
1:200	12.64	**12.61**	**12.76**
1:250	12.66	**12.63**	**12.8**
1:300	12.68	**12.64**	**12.83**
1:500	12.74	**12.69**	**12.93**
1:1000	12.81	**12.76**	**13.08**

Return Period (years)	Extreme Still Water Level (m CD)	95th Confidence Interval (m CD)	
1:10,000	13.06	**12.93**	**13.78**

These extreme water level results have been computed with the best quality data available, using the most up to date methodology, and are suitable for use in assessing the probability of occurrence of present day storm surges.

9.4 Comparison of extreme still water levels with HR Wallingford 2009 report

A previous study by HR Wallingford in 2009 calculated extreme water level return periods. The extreme water levels were based on tidal levels from a previous HR Wallingford study in 1991. The tidal levels had been updated to account for changes in mean sea level over the last two decades, based on an assumed rate of SLR of 2 mm/yr. The tidal levels were then analysed to provide estimates of exceptionally high tidal levels, with estimated return periods between 1 and 100 years. Table 10 shows these estimated still water levels, which include a tide and a surge component for the different return periods.

Table 10: Extreme still water levels extracted from Table 2.1 HR Wallingford 2009

Return Period (years)	Extreme Still Water Levels (m ACD)
	First Tower, St Aubin's Bay
1:1	12.437
1:10	12.668
1:20	12.737
1:50	12.829
1:100	12.899

Comparing the results from Table 9 with the HR Wallingford's values in Table 10 shows that the HR Wallingford's values are more pessimistic with extreme water levels for the same return period being around 0.33 m higher. It was unexpected that the difference between every return period level would nearly be the same and it is suspected that this difference may be due to different vertical datum's being used as a reference point. The return periods calculated in HR Wallingford's report were calculated using data from a previous tide gauge, before the current one was installed in 1992. The new gauge is a high-quality bubbler gauge installed as part of the UK National Tide Gauge Network. This study used data from the current tide gauge to determine extreme sea levels. It is unknown what the vertical datum of the previous gauge was. The offset of 0.33 m is potentially a difference between Ordnance Datum's, e.g. Newlyn (used in the UK) versus Jersey's own vertical datum. If the old tide gauge was set to Newlyn Ordnance Datum, then this would explain the difference, however, it has not been possible to clarify if this was the case. Aside from this, the two datasets show similar extreme water level return periods levels lending confidence to the results from both reports.

10 Projections of Storm Surges and Significant Wave Height

10.1 Waves

Previously global climate models did not include the ability to simulate ocean waves. This means that wave climate projections are not directly available from the UKCP09 work. The available research from other sources are summarised below.

The COWCLIP (Coordinated Wave CLImate Projection) project has derived multi-model ensembles of wave climate projections [14]. The results of this work show a good agreement among the models of a consistent wide spread decrease in wave climates, particularly in the subtropics and North Atlantic. An increase was only found to occur over about 7% of the global ocean, predominantly in the Southern Ocean, associated with a strengthening of westerly winds [14].

More recent research using RCP8.5 and RCP4.5 data as inputs, shows that for both scenarios wind speed and wave height will increase in the Arctic and Southern Ocean, and decrease in the Pacific. For the North Atlantic, the trend reduces in the medium to long term [15].

Statistical projections of changes in ocean wave heights, using sea-level pressure information from multiple global climate models, has shown that significant wave height increases in the tropics, and in high latitudes in the Southern Hemisphere. Under RCP8.5, it is projected that the climate condition for 2070-2099 is that the probability of occurrence, of present 1 in 10 year extreme wave heights, are likely to double or triple in several coastal regions around the world. These wave height increases are primarily driven by increased sea level pressure gradients, and therefore increased surface wind energy [16]. Given that Jersey is not located in the tropics or high latitudes in the Southern Hemisphere, it is not currently projected to experience any increase in significant wave heights up to 2100.

10.2 Projected changes to annual mean significant wave height

Projected changes of annual mean significant wave height (Hs), show that the largest change is projected to be in the Southern Ocean, where the mean Hs at the end of the 21st century are approximately 5 to 10% higher than present day means [17]. This is thought to be due to the projected strengthening of westerlies over the Southern Ocean, particularly during austral winter. Another region of Hs increase is the tropical South Pacific, associated with a projected strengthening of austral winter easterly trade winds in the multi-model data set. For all other regions negligible change or a decrease is projected, with decreases associated with the trade wind region of the North Pacific, the mid latitude westerlies in all basins, and in the trade and monsoon wind regions of the Indian Ocean [17]. As Jersey is not located in these regions it is unlikely to be affected by increases to annual mean Hs.

10.3 Projected changes to storm surges

Surges are not usually modelled at the global scale as they are only appreciable in shallow water and are predominantly generated on continental shelves. This ignores tsunamis generated by displacement of the seabed in the deep ocean. However, higher mean sea levels as a result of SLR can significantly decrease the return period for exceeding given threshold levels [18]. Figure 10 shows the impact of an increase of 0.65 m, which is consistent with the most likely outcome for RCP8.5 in 2100. It shows a large decrease for all return periods, e.g. a present day 1 in 500-year event would now be a 1 in 1-year event. Therefore, even quite small increases in mean sea-levels will have a large impact on the return period experienced during extreme events.

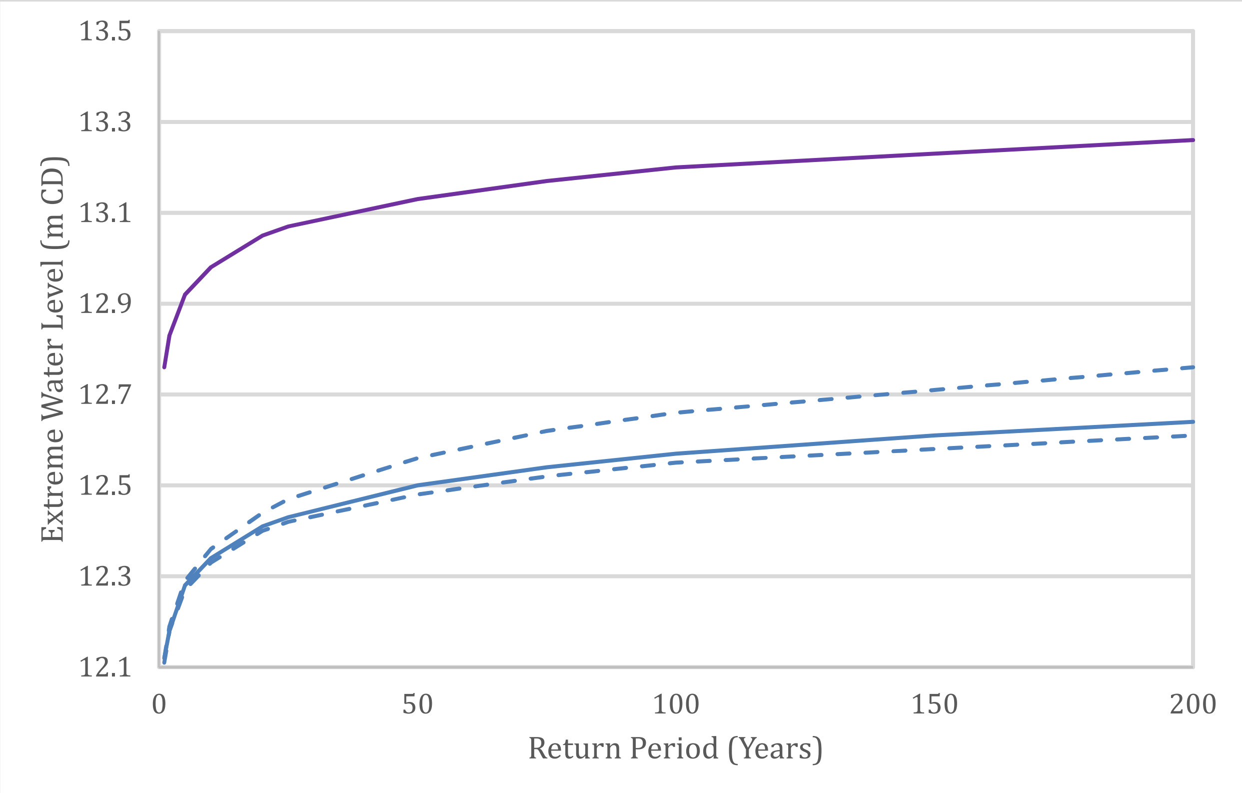

Figure 10: Impact of 0.65 m of SLR on return period values for Jersey. Purple shows the extreme water level for a given return period for an increase in mean sea level of 0.65 m. The blue line shows the present-day relationship with associated confidence interval

11 Historical Changes in Winds, Waves and Storminess

It has been argued that wind-sea and swell waves may show different inter-annual variability [19]. Therefore an increase in the frequency of storm events will result in a reduction in the time of swell decay between storms, and provides a higher residual swell level [20]. This, as an initial condition for the growth of newly generated young waves, means that swell wave variability is primarily associated with the occurrence of storms, and the wind sea changes with the magnitude of the wind speed and local fetch. Previous research has investigated this possible relationship, and found that the intensity, frequency, track and speed of storms has less effect on the monthly mean and maximum wave height, than the strength of westerly winds. This suggests that the recent observed increase in wave height is more likely caused by an intensification of the background westerly atmospheric circulation, than by changing storminess [21–23].

Global satellite altimeter data (TOPEX/Poseidon) spanning a period of more than 20 years has been analysed for any indications of measurable trends in extreme value return period estimate of wind speed and wave height [24]. There appears to be a positive trend in the 100 year return period values of wind speed, but no consistent trends for the 100 year return period wave height. However due to the limited duration of the altimetry dataset available, associated confidence levels in the magnitude of these estimates are low [24].

There is a history of strong variability in the northwest European wave climate. Inter-annual variability in the modern wave climate is strongest in the winter, and can be related to atmospheric modes of variability such as the North Atlantic Oscillation (NAO) [25]. Rather dramatic increases in wave heights have been observed between 1960 and 1990, but this is seen as one part in a longer history of variability. Since 1990 there has been no clear pattern, natural variability is strong and anthropogenic contributions is uncertain. Two possible explanations for the observed increase in wave height with NAO are increases in zonal wind, increasing the build-up of waves over several days, or an increase in the frequency and intensity of storms [26].

Various climate reanalysis projects have been carried out recently. A climate reanalysis consists of a climate model run for a historical period, using data assimilation of the available observation data, to obtain the best analysis fields that represent the state of the atmosphere throughout decadal simulations. Two wave numerical hindcasts were realised for the North Atlantic Ocean based on the model WaveWatchIII. The first hindcast uses wind fields originating from the 20CR reanalysis which produced wind data for the period 1900 to 2008 [27]. This hindcast only provides significant wave height [28]. The second wave hindcast used winds from the NCEP/NCAR reanalysis which covers the period 1948-2012 and uses a higher spatial resolution [29]. This hindcast provides significant wave height, peak period and wave direction [30]. The closest point in this hindcast to Jersey that produces valid data was used to assess the changes in waves throughout the 20th century (Figure 12). It was found that both hindcasts had a linear increasing trend in significant wave height, both were small increases with gradients of 5.3×10^{-6} for the 1900 to 2008 and 8.3×10^{-6} for 1948 to 2012. Ultimately this results in a very small increase in significant wave height with no obvious increase in the extreme wave height experienced over the 20th century.

12 Joint Water Level and Wave Height Probability Assessment

12.1 Introduction

With respect to coastal engineering, joint probability refers to two or more partially related environmental variables that occur simultaneously. Examples of these are high waves and high water levels, high wind-sea and high swell, and large river flows and high sea levels. As coastal flooding is associated with times of high waves and high water levels, it is therefore beneficial to consider the joint probability of these variables when considering a response to climate change. This study will focus on the joint probability of high water levels and high wave heights. Determination of the joint sea state depends on an assessment of the probability of a given water level, and a given wave condition. The correlation between these two variables depends upon the meteorological conditions which produce them, and the exposure of the coastline under study. Every probability of occurrence or return period will have a range of a combination of water levels, and significant wave heights, that satisfy the same probability of occurrence.

For any coastline there is some correlation between the occurrence of large waves and high sea levels, as extreme storm events tend to cause both storm surges and high waves. However, as the storm does not contribute to the underlying tidal level which is dependent on relative position of the Moon, Sun, Earth, and other very slowly changing factors such as coastline topography rather than meteorological conditions, then the degree of correlation will vary. As Jersey has a very large tidal range of 12 m, then this will have a much larger impact than coastlines with micro (<2 m) or meso (2 m – 6 m) tides.

For Jersey, the largest storm surges are caused by depressions moving eastwards up the English Channel, because the tracks are often to the north of Jersey, these depressions cause strong south-westerly winds, veering westerly. With Jersey's position relative to the mainland of France, these conditions give rise to wind waves from southwest and west, with swell waves from the west. This means that the western coast is the most exposed, and will be subjected to more extreme events than other coastlines. The degree of this greater exposure is expressed as a correlation factor. This factor takes into account the variation in the association between water level and wave conditions as the severity of either increases.

12.2 Previous joint wave height and water level probability assessments

HR Wallingford performed joint probability assessments for Jersey in 1991 and 2009. The study in 1991 assessed the Fauvic seawall and assigned a correlation factor of 1 between extreme water level, and extreme wave heights. This was then used as the basis for assessment of the defences. Joint probability research has moved since 1991 and better methods are now available to allow more accurate assessments of the dependence and joint extremes of a coastline. Table 11 shows the joint probability results from the HR Wallingford 2009 study for St Aubin's Bay.

Table 11: HR Wallingford joint probability conditions for St Aubin's bay taken from Table 2.3 in HR Wallingford 2009.

Site	Likelihood of event occurring in any one year (Return Period)									
	1:1 year		1:10 year		1:20 year		1:50 year		1:100 year	
	EWL	Hs	EWL	Hs	EWL	Hs	EWL	Hs	EWL	Hs
St Aubin's Bay (HR7)	11.746	3.10	12.331	3.80	12.459	4.00	12.506	4.20	12.700	4.43
	12.004	2.97	12.506	3.49	12.506	3.83	12.714	4.00	12.614	4.33
	12.414	2.57	12.576	3.29	12.69	3.29	12.714	3.80	12.863	3.50
	-	-	12.714	3.03	12.714	3.16	12.814	3.29	12.899	3.46

Key: EWL extreme water level (m ACD), Hs significant wave height

The joint probability research undertaken by this study will address the concerns raised by the HR Wallingford 2009 report, as it was felt the method it followed in both the 1991 and 2009 studies was likely to result in a more pessimistic assessment of the frequency and intensity of flooding.

12.3 JOIN-SEA joint probability assessment

The approach used by this report is based on proposals by Coles and Tawn 1990 [31]. The methodology followed has been extensively used and is well validated, and is known as JOIN-SEA [32–34]. JOIN-SEA uses a bivariate or mixture of two bivariate probability distributions that is then fitted to the largest values or upper tails of the wave height and water level dataset. The output of the analysis is in the form of joint probability curves (Figure 13). The curve represents a given annual probability of occurrence, for example a 1 in 200 year, and the different combinations of water level and wave height along the curve all have the same probability of occurrence. The curves show that increasing the extreme water level requires a reduction in the wave height to retain the same annual probability of occurrence.

For this study the tide gauge located in St Helier's harbour was used to provide water level data, the observed high water elevation values were extracted, and the closest wave height in time from the wave dataset was assigned as the high water wave value. The wave dataset predominantly comprises an offshore wave model that provided significant wave height and direction at hourly intervals. All joint probability analysis is very dependent on the length and quality of the input water level and wave height data, and efforts were made to ensure the best data available was used. The closest model point that had suitable data was out in the main channel approx. 100 km from Jersey. Figure 11 shows the location used to provide wave data which is located towards the middle of The English Channel, it also shows the location of the wave buoy operated by the Jersey Met Office. As the offshore model wave data originates so far from Jersey it needs to be transformed so it is more representative of the waves nearshore at Jersey.

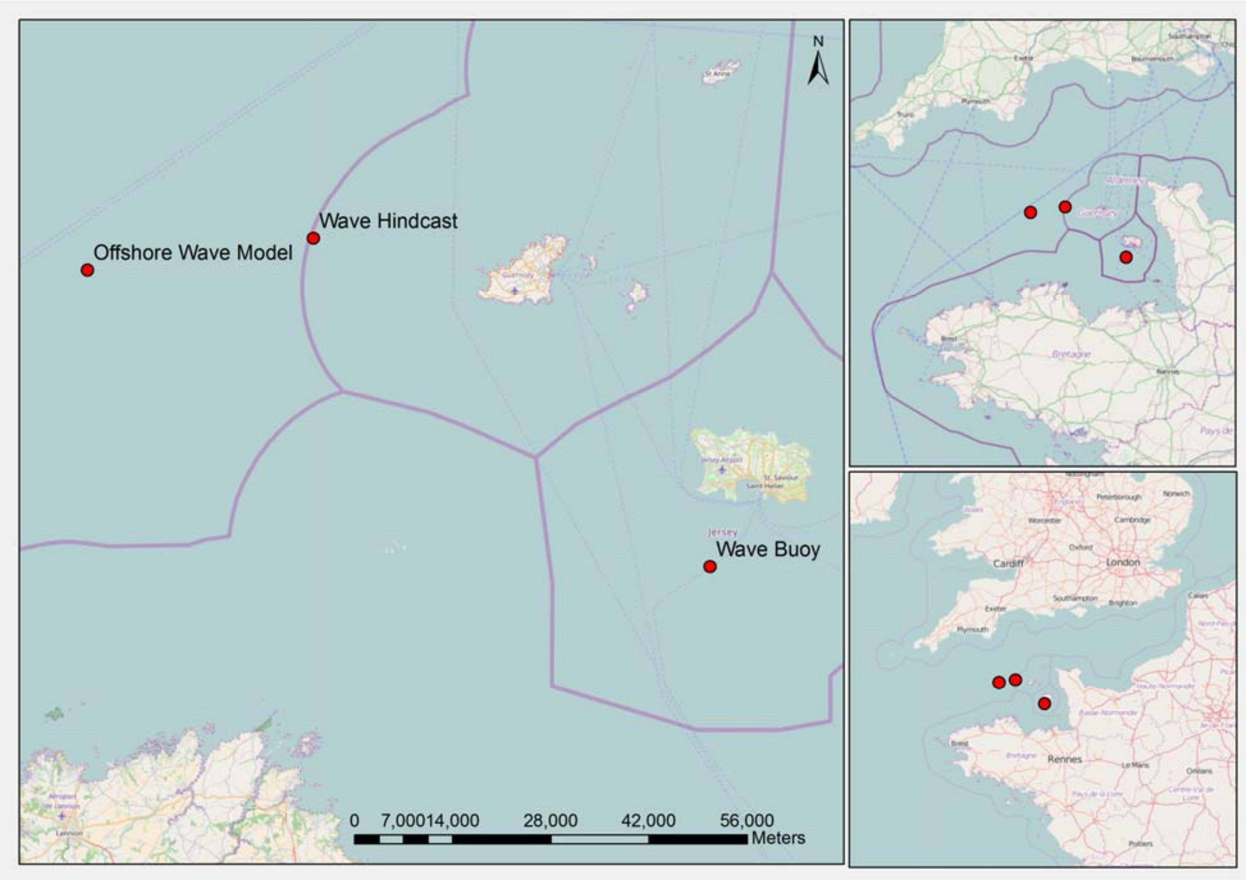

Figure 11: Locations of data points for Jersey wave buoy, wave hindcast model and offshore wave model.

12.4 Transforming waves from offshore model to wave buoy

The waves that are generated as output from the offshore model will not be representative of the waves that will be present during extreme events close to the coastline of Jersey. Ideally a model would be used to transform these waves into ones that would be present at the coast. However due to time limitations this was not possible so the next best option was to use available wave buoy data and determine if a clear relationship is present between the waves offshore and waves at the buoy, that could then be used to transform the waves. By plotting both sets of waves, a linear regression can be performed, resulting in a transform equation. Figure 12 shows a plot of both the significant waves offshore, and at the buoy. The linear regression trend line and associated equation can also be seen.

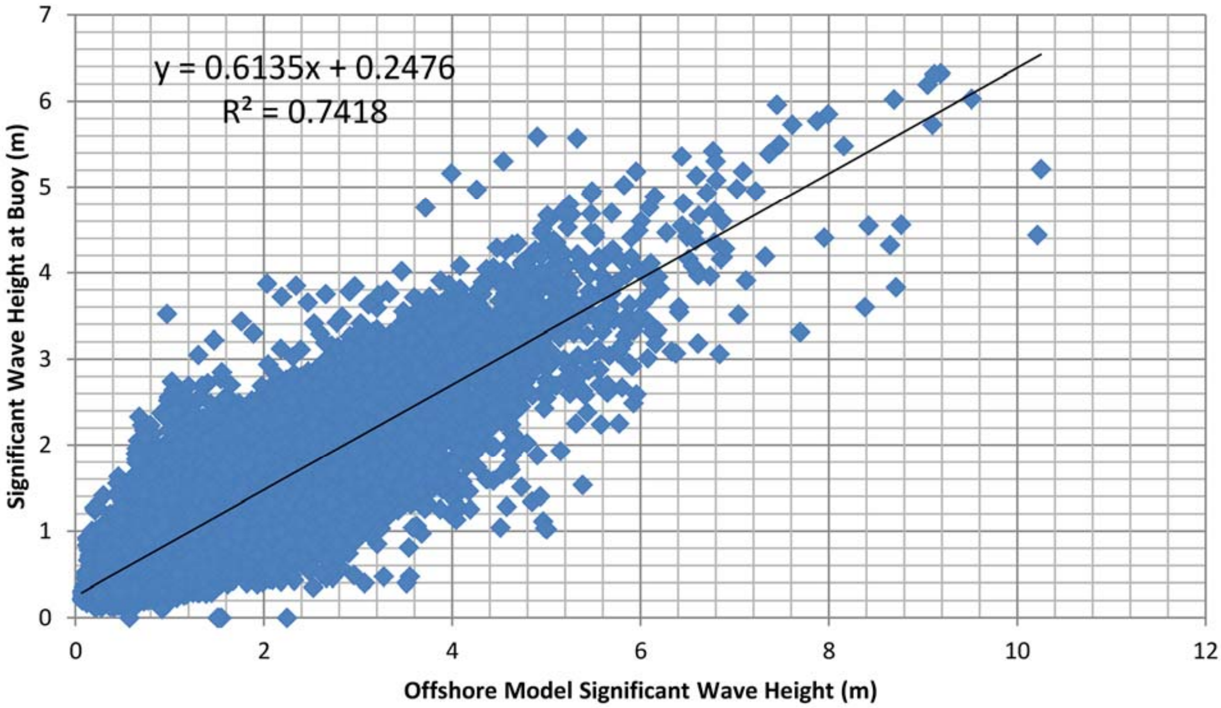

Figure 12: Significant wave height from offshore model against significant wave height at wave buoy.

This derived equation was applied to the offshore model wave data to "transform" them into waves that would be representative at the wave buoy location. However, while the wave buoy is much closer to Jersey it is still around 12 km distance from St Aubin's Bay. To check that these waves are representative of the waves at the entrance to St Aubin's Bay, the wave breaker depth was checked to ensure that these waves would not have broken before entering the bay. The breaker index defines that the maximum wave height possible is 78% of the water depth. Given the large tide range at Jersey, waves at the wave buoy are representative of waves within St Aubin's Bay during an extreme event. This approach was considered to be suitable given the constraints of the study. Ideally a wave model would be used to transform the waves generated offshore to the specific points where the storm impact model takes over.

12.5 Results of joint probability assessment

The results of the joint probability assessment are shown in Figure 13. The data show that each return period ends up being a contour or curve, and that every combination of water level and significant wave height on the curve has the same probability of occurrence. Figure 13 only shows four different return periods although more are presented in Table 12 (which shows tabulated results). Due to the high tidal range at Jersey the curves are elongated with small changes in the water level resulting in large reductions in significant wave height at heights above Mean High Water Springs (MHWS) of 10.69 mCD.

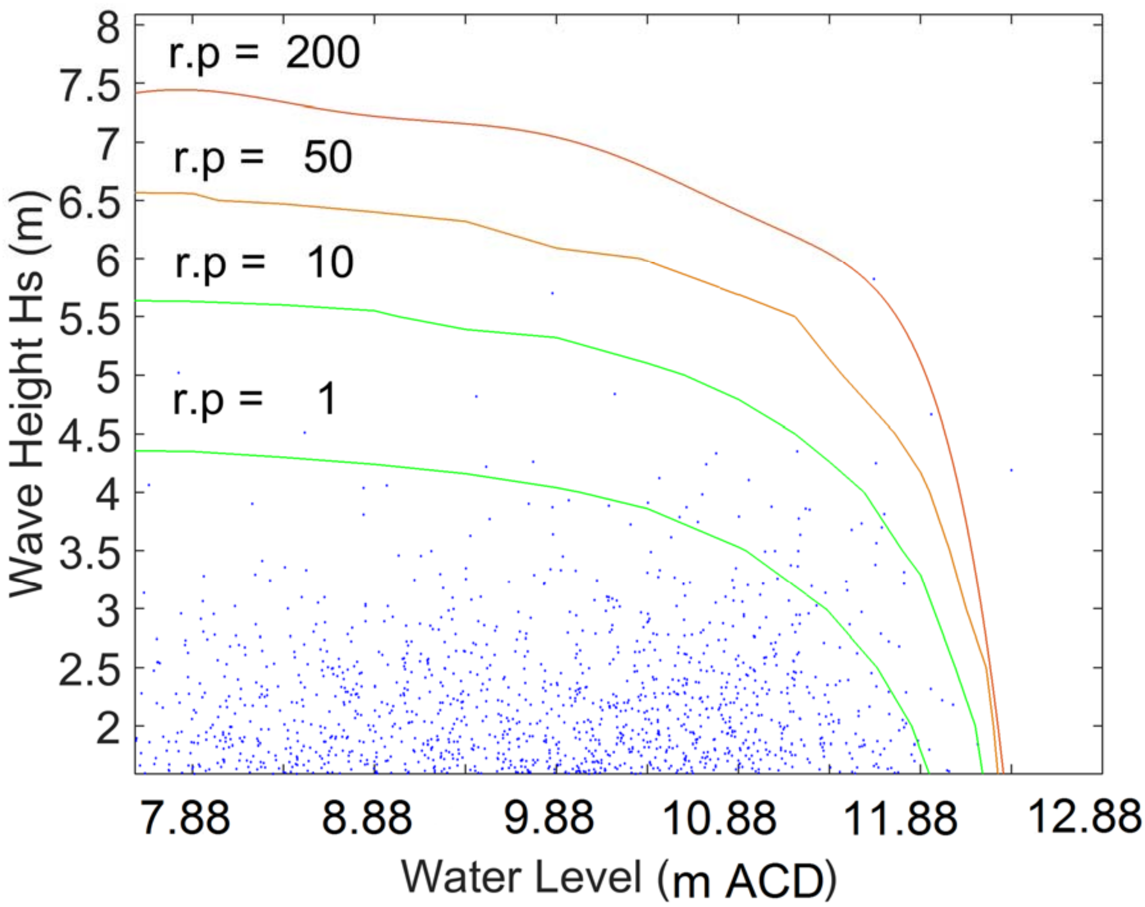

Figure 13: Joint probability assessment results for St Helier, four different return periods are displayed.

Table 12: Tabulated results of joint probability analysis extreme water levels are relative to chart datum (mCD)

	Likelihood of event occurring in any one year (Return Period)											
	1:1 year		1:10 year		1:20 year		1:50 year		1:100 year		1:200 year	
WL/Hs Combination (m)	**EWL**	**Hs**	**EWL**	**Hs**	**EWL**	**Hs**	**EWL**	**Hs**	**EWL**	**Hs**	**EWL**	**Hs**
1	-	-	-	-	-	-	-	-	-	-	6.88	7.40
2	-	-	-	-	-	-	-	-	-	-	7.38	7.40
3	-	-	-	-	-	-	6.88	6.57	-	-	7.88	7.40
4	-	-	6.88	5.64	6.88	5.99	7.38	6.57	6.88	7.05	8.38	7.30
5	-	-	7.38	5.64	7.38	5.99	7.88	6.56	7.38	7.05	8.88	7.30
6	-	-	7.88	5.63	7.88	5.97	8.02	6.50	7.88	7.05	9.38	7.27
7	-	-	8.38	5.60	8.38	5.93	8.38	6.47	8.38	6.90	9.67	7.00
8	6.88	4.36	8.88	5.55	8.88	5.90	8.88	6.40	8.88	6.90	9.88	6.90
9	7.38	4.36	9.01	5.50	9.38	5.78	9.38	6.32	9.38	6.57	10.38	6.90

	Likelihood of event occurring in any one year (Return Period)											
	1:1 year		1:10 year		1:20 year		1:50 year		1:100 year		1:200 year	
WL/Hs Combination (m)	**EWL**	**Hs**	**EWL**	**Hs**	**EWL**	**Hs**	**EWL**	**Hs**	**EWL**	**Hs**	**EWL**	**Hs**
10	7.88	4.35	9.38	5.39	9.88	5.71	9.88	6.09	9.86	6.50	10.78	6.50
11	8.38	4.30	9.88	5.32	10.38	5.60	10.34	6.00	10.38	6.47	10.88	6.37
12	8.88	4.24	10.38	5.10	10.5	5.50	10.88	5.69	10.88	6.00	11.38	6.07
13	9.38	4.16	10.58	5.00	10.88	5.20	11.19	5.50	11.38	5.61	11.5	6.00
14	9.88	4.04	10.88	4.79	11.16	5.00	11.38	5.13	11.45	5.50	11.69	5.50
15	10.01	4.00	11.19	4.50	11.38	4.60	11.45	5.00	11.69	5.00	11.88	5.30
16	10.38	3.86	11.38	4.26	11.41	4.50	11.74	4.50	11.88	4.63	11.91	5.00
17	10.88	3.53	11.57	4.00	11.74	4.00	11.88	4.17	11.91	4.50	11.98	4.50
18	10.92	3.50	11.78	3.50	11.88	3.62	11.93	4.00	11.98	4.00	12.07	4.00
19	11.36	3.00	11.88	3.29	11.92	3.50	12.04	3.50	12.07	3.50	12.13	3.50
20	11.64	2.50	11.95	3.00	12.06	3.00	12.13	3.00	12.21	3.00	12.26	3.00
21	11.83	2.00	12.07	2.50	12.15	2.50	12.24	2.50	12.27	2.50	12.28	2.50
22	11.88	1.79	12.18	2.00	12.24	2.00	12.28	2.00	12.31	2.00	12.33	2.00
23	11.95	1.50	12.23	1.50	12.27	1.50	12.31	1.50	12.33	1.50	12.36	1.50
24	12.05	1.00	12.26	1.00	12.29	1.00	12.32	1.00	12.35	1.00	12.36	1.00
25	12.1	0.50	12.28	0.50	12.31	0.50	12.34	0.50	12.35	0.50	12.37	0.50

Key: WL = extreme water level, Hs = significant wave height

12.6 Comparison of joint probability

Comparing the two joint probability results, it is clear there are noticeable differences, with the HR Wallingford 2009 study reporting much higher significant wave heights and slightly higher extreme water levels across the range of combinations of water level and significant wave height. The slightly higher water levels are potentially due to inconsistencies in water level return period levels between this report and the 2009 report. The 2009 version was based on a 1991 report using data from a previous tide gauge rather than the gauge used in this study, which has been in place since 1992. It is not known if the two gauges used different vertical datum's which may account for the 0.33 m offset present in the extreme water level only analysis.

The 2009 HR Wallingford report used the same assumption of a previous 1991 study; that, for Jersey, the largest waves and the highest tidal levels would occur simultaneously. This assumption was made to allow a consistent approach to the comparison of the performance of the coastal defences around the island, rather than to precisely quantify the performance of the defences. Due to this it was considered that the accuracy of this assumption is not a significant concern and represents a "worst case" scenario.

However, research has shown that this assumption is only likely to be valid along coasts affected by hurricanes. The HR Wallingford 2009 report is therefore pessimistic in its assessment of the frequency and intensity of flooding that it predicts.

13 Changes to Tidal Range from Projected Sea-Level Rise

13.1 Introduction

There are many impacts from increasing mean sea-levels, one such impact is on the tide range and duration. For an area such as the European shelf the tide is dominated by semidiurnal constituents. This means that focusing on the response of the M_2 tidal constituent is an appropriate metric to inform the impact of SLR on the tide for the region.

The M_2 tidal amplitude responds to SLR in a spatially non-uniform manner, with substantial amplitude increases and decreases for 2 and 10 m SLR scenarios. As well as being spatially non uniform, the M_2 tidal response itself is also non-linear between 2 and 10 m of SLR, something that is particularly prevalent in the North Sea. Under 2 m of SLR, the M_2 constituent is particularly responsive in resonant areas of the Bristol Channel and Gulf of St Malo with increases and decreases observed respectively. For a 2 m SLR the spring tide range increases by up to 0.35 m at Cuxhaven and decreases by up to 0.49 m at St Malo [35].

There are also changes in shallow water tides such that with increased SLR, the tidal wave speed and wave length are increased in near resonant areas. For large shallow areas SLR causes reduce energy dissipation by bottom friction. The combination of these impacts results in the migration of the amphidromes and a complex pattern of change that is non-linear with respect to SLR.

As the amount of SLR projected is uncertain, if a high end SLR scenario is realised than substantial alterations to tidal characteristics can be expected. These alterations could have wide reaching implications on the requirements for flood defence resilience due to increased tidal range and changes to the tidal phase.

13.2 SLR scenario tidal modelling

To explore this impact further, analysis has been carried out using the Dutch Continental Shelf Model, based on non-linear shallow water equations. The model encompasses most of the European Shelf, and has been developed jointly by Delft Hydraulics, Rijkswaterstaat and the Royal Netherlands Meteorological Institute (KNMI). The model has been in development since the 1980's and is used operationally for storm surge forecasting. The model has been continuously redeveloped, calibrated and validated, hence there is high confidence in its output [35].

Five different simulations were run, three with the M_2 constituent in the tide only for the present day, 2 m of SLR and 10 m of SLR. The final two simulations simulate the present day and 2 m SLR for 34 tidal constituents. The 34 tidal constituents represent 98% of the observed tidal range. The model was spun up for a 5 day period in all simulations then for the M_2 runs the simulation was run for a further 5 days which was the period analysed, resulting in a 10 day simulation overall. For the 34 tidal constituent model, the spin up was 5 days but total run time was 30 days, giving 25 days of analysis to use.

The percentage change in depth across the model domain for both values highlighted Jersey as an area where significant alterations to the tide might be expected. This is because it is a shallow area with a large percentage change in absolute depth.

13.3 Results of tidal simulations

The Gulf of St Malo is a region identified as having a particular decrease in the M_2 tidal amplitude. Table 13 provides more detail on the magnitude of the changes in the M_2 tide with both 2 and 10 m of SLR. The table also shows the changes in the phase of the M_2 tide it was found that the arrival of the peak of the M_2 tide was altered in the 2 m SLR simulation in a spatially variable manner. For St Malo this was a negative change in the order of 2 ^{0}/hr. This increases to a decrease of 13 ^{0}/hr for the 10 m SLR simulation. In terms of differences from the present-day simulation this results in a reduction to 91% for 2 m SLR and 54% for 10 m SLR.

Table 13: Results of the 2 m and 10 m SLR simulations for St Malo M_2 Tidal Constituent. (↓↑ - reduction or increase)

Location	M_2 Amplitude (m)			% control amplitude		M_2 Phase (degree/hr)		
	Control	+2m	+10m	+2m	+10m	Control	+2m	+10m
Saint-Malo	381	-0.33 ↓	-1.75 ↓	91 ↓	54 ↓	170	-2	-13

Saint Malo was one of the ports with the largest change, Figure 14 presents the change in tidal curves from the present day and under 2 m SLR and 10 m SLR.

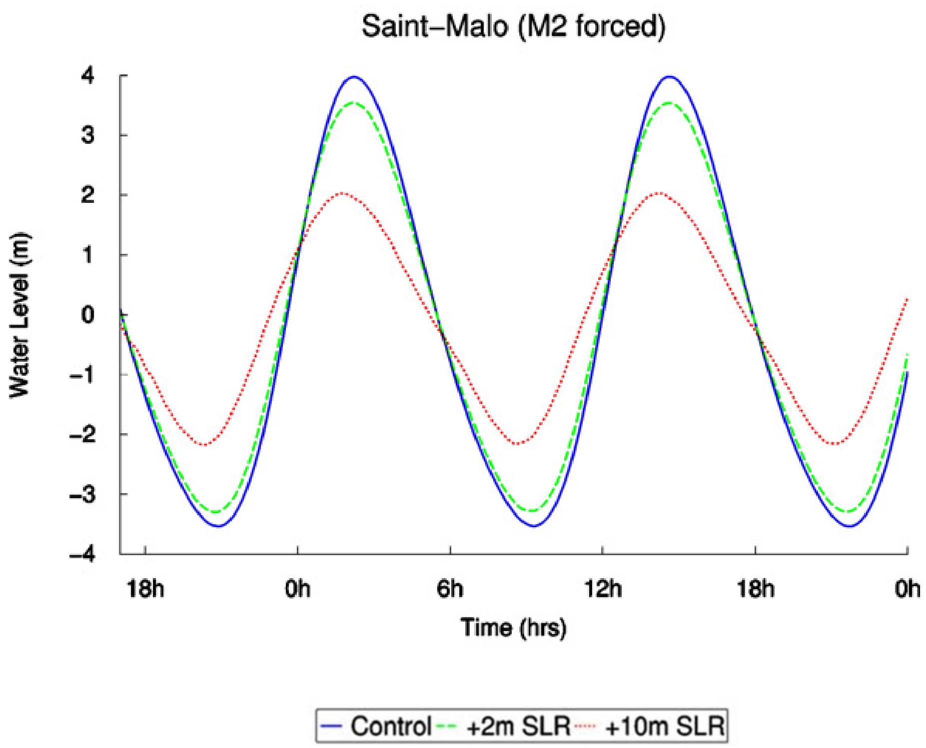

Figure 14: Changes to the tidal curve for 2 m SLR and 10 m SLR for Saint-Malo port with blue showing the present day control curve, the green representing 2 m SLR and red identifying 10 m of SLR [35].

The simulation runs with 34 tidal constituents, to enable a comparison with the spring (M_2 and S_2 in phase) and neap (M_2 and S_2 out of phase) tides. The changes in amplitude and phase for both M_2 and S_2 will show what impact SLR will have on spring and neap tides. Only 2 m of SLR was simulated, Table 14 shows the results for St Malo.

Table 14: Results for St Malo for tidal simulation with 34 constituents for 2 m SLR. (↓↑ - reduction or increase)

Location	M_2			S_2			M_2-S_2 (Neap)			M_2+S_2 (Spring)		
	Control Amplitude	**Change + 2m**		**Control Amplitude**	**Change + 2m**		**Control Amplitude**	**Change + 2m**		**Control Amplitude**	**Change + 2m**	
	(m)	**(m)**	**(%)**	**(m)**	**(m)**	**(%)**	**(m)**	**(m)**	**(%)**	**(m)**	**(m)**	**(%)**
Saint Malo	**0.392**	**-0.37**	**91↓**	**1.60**	**-0.13**	**92↓**	**0.232**	**-0.24**	**90↓**	**0.552**	**-0.49**	**91↓**

At St Malo, the change in neap tidal range is smaller than the M_2 tidal amplitude change. The results show that the changes in amplitude to the M_2 and S_2 constituents are positively correlated, with greater changes occurring for spring tides, and for the M_2 constituent, than for neap tides. The change in tidal range for the 2 m SLR simulation for spring tides for St Malo show that it experiences a larger change in range on the spring, rather than the neap tide. Both the M_2 and S_2 experience changes of the same sign, which results in the large alteration to the tidal range shown by the 2 m SLR simulation.

On the spring tide the change in tidal range is a reduction of 0.49 m which is 25% of the 2 m of mean projected sea-level increase. This is one of the biggest reductions for the whole European Shelf. The difference in range between the M_2 only simulations and the 34 tidal constituents show that St Malo has large contributions from other semidiurnal, diurnal and other harmonic constituents. However, to fully understand these changes a much longer model simulation of 1 year would be required. In summary, this analysis has shown that based on modelling a 2 m SLR, Jersey would experience one of the greatest decreases on the European Shelf in tidal range for a given increase in mean sea level.

14 Extreme Event Modelling: Storm Impact Model

The results of the joint probability analysis from section 12 have been used to assess the impact of extreme events on the beach in St Aubin's Bay.

Of the different return periods that were calculated as part of the joint probability analysis, two were selected, 1 in 10 year, and 1 in 200 year combinations. The 1 in 10 was selected to represent a “common” extreme event that is consistent with past events, such as the storm surge in 2008. The 1 in 200 year represents the extreme event that sea defences are commonly designed to be resilient against. Given the large range of water levels and wave heights that correspond to both return periods, selections were made to reduce each of these down to four while also capturing the variability present. Figure 15 shows the four different combinations that were selected for both of the return periods. These combinations were then used as the basis for the extreme event simulated within a storm impact model known as XBeach [36]. The combinations selected have the widest range in both water level and wave height across the two return periods for water levels above Mean High Water Springs (MHWS). Any combinations with a water level below MHWS (10.69 mCD) were removed. Combinations below MHWS while having the same probability of occurrence will have a minor impact on the coast due to the low water levels and high wave heights, resulting in waves breaking on the lower beach rather than the defences.

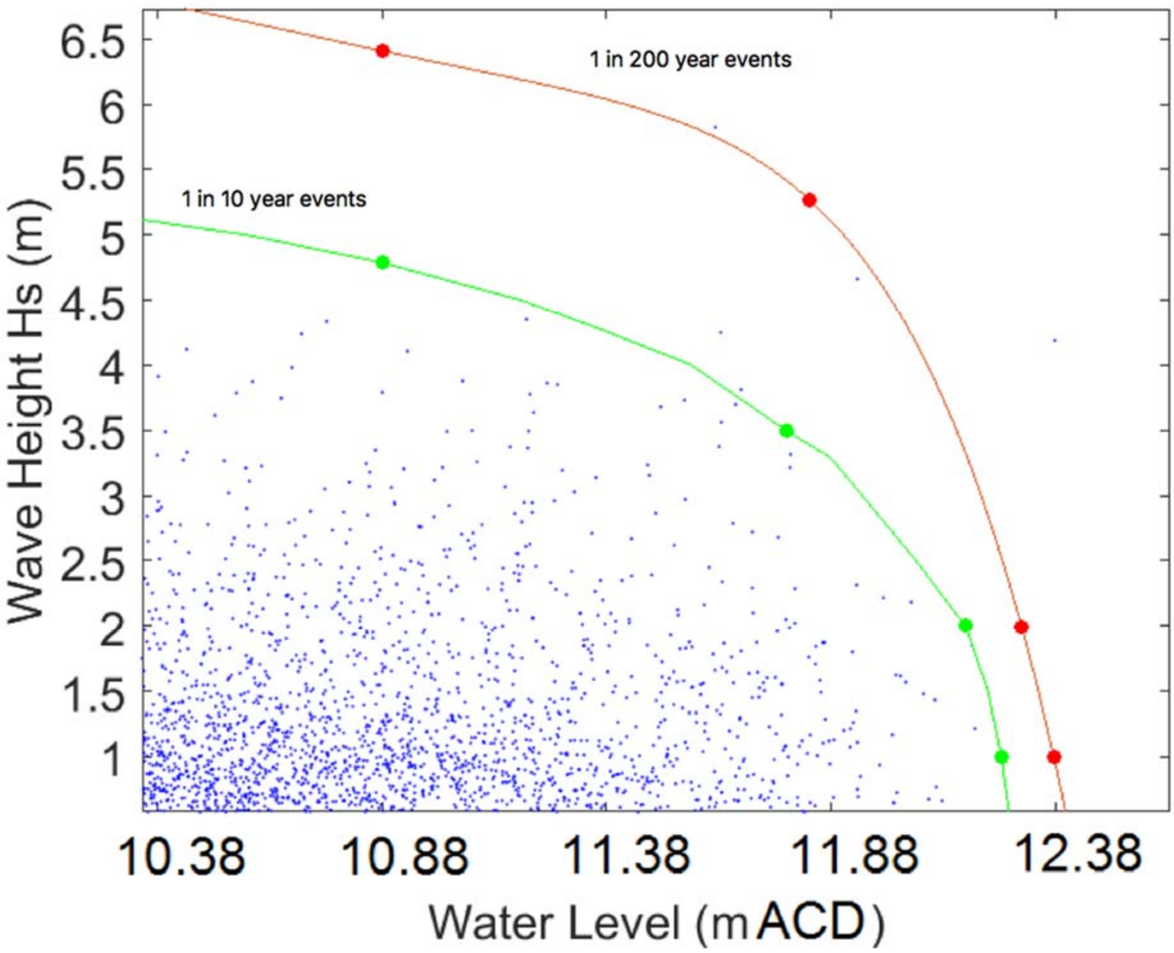

Figure 15: Close up of joint probability curves showing the 8 combinations selected for simulation. The green line shows 1 in 10 year values and the red represents 1 in 200 year events.

The model used to simulate the impact of extreme events is XBeach. XBeach is a two-dimensional model for wave propagation, long waves and mean flow, sediment transport and morphological changes of the nearshore area, beaches, dunes and back-barrier during storms. XBeach concurrently solves the time-dependant short wave action balance, the roller energy equations, the nonlinear shallow water equations of mass and momentum, sediment transformations and bed update on the scale of wave groups. It can also calculate the overtopping of sea defences during extreme events. Figure 16 shows an example 2DH simulation that shows the impact of Hurricane Sandy on the North American coastline. As well running in 2DH there is a 1DH version where a single beach profile perpendicular to the shoreline is used to reduce the computation cost and allow multiple simulations in a short timeframe (Figure 17).

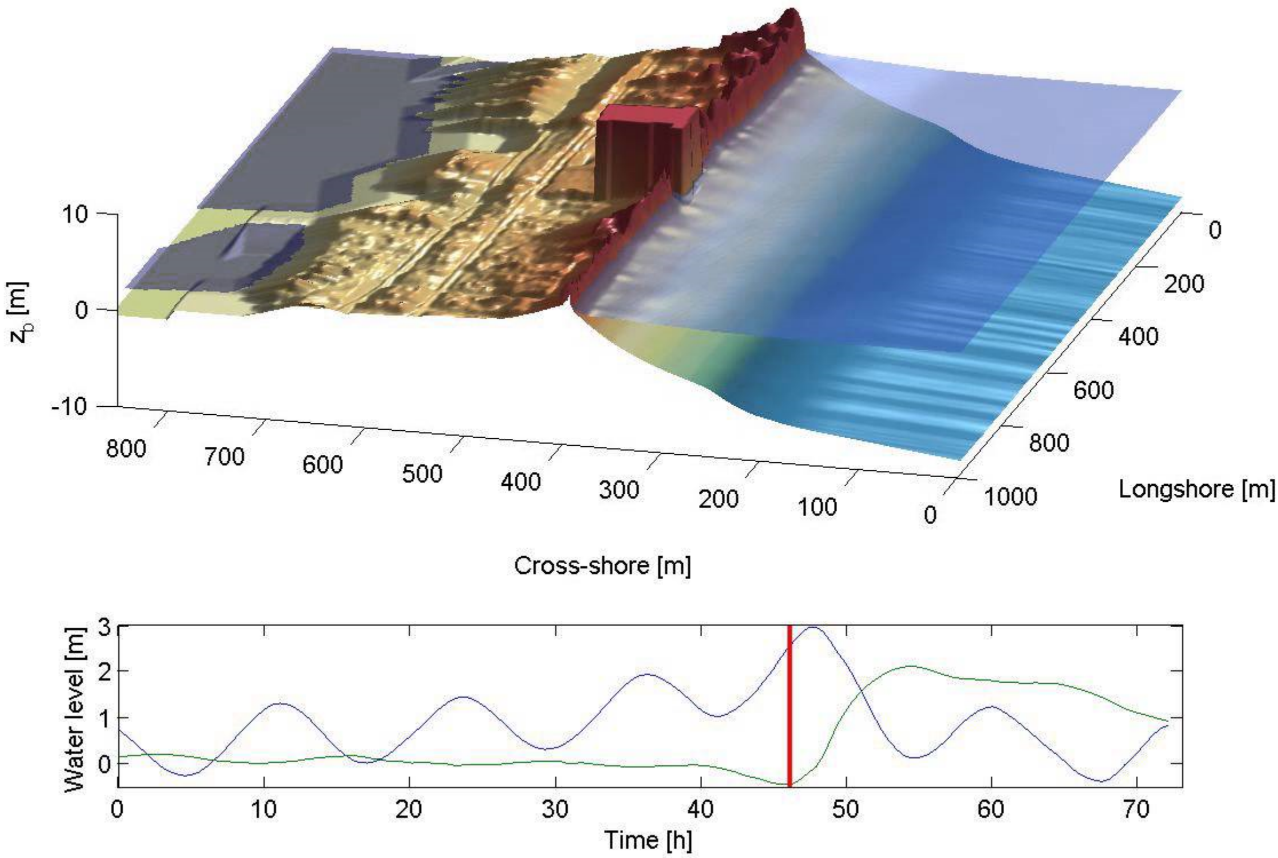

Figure 16: Example of a 2DH XBeach simulation.

Source: Kees Nederhoff: https://www.youtube.com/watch?v=qw7kvt-aBdU

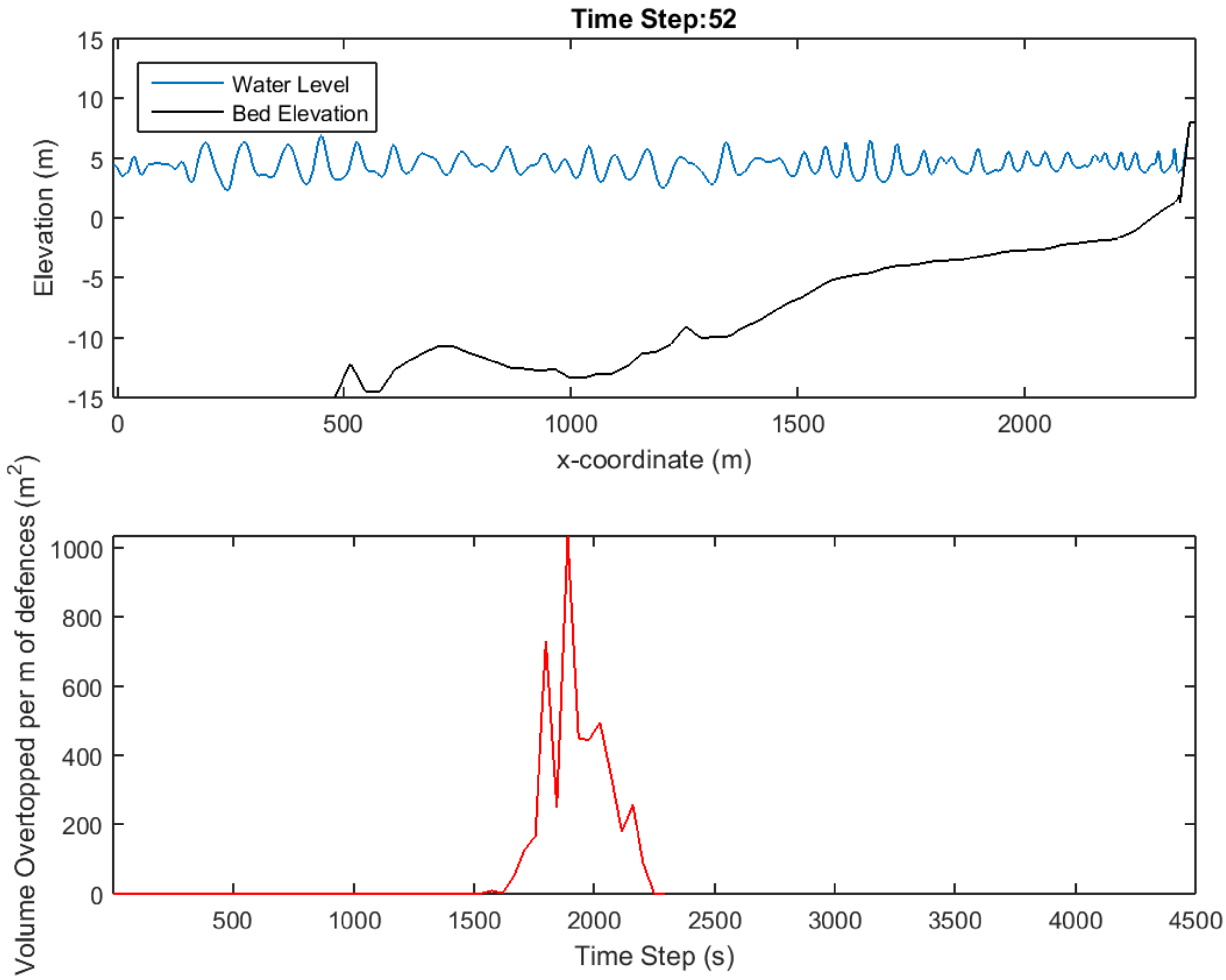

Figure 17: Example output of 1DH XBeach simulation for a profile in St Aubin's Bay, top graph shows beach profile with simulated extreme event consisting of surge and waves. The bottom graph shows the volume of water that overtopped the defences throughout the simulation. As the model consists of a 1D profile, cross-shore model with dimensions in the vertical and cross-shore. While discharge is typically m3/s when there is no alongshore dimension (m2/s) is often used, a discharge per linear meter and the alongshore variability is assumed to be uniform.

For this study the model was used in 1DH mode due to the time limitations of the project and the associated computational cost. Four 1DH profiles were selected from east to west across St Aubin's Bay. Each one terminating on the shore at a point of historical flooding or vulnerability. Profile 1 at La Haule slipway, Profile 2 at Gunsite, number 3 at First Tower and number 4 at West Park. Figure 18 shows the location and extent of these profiles.

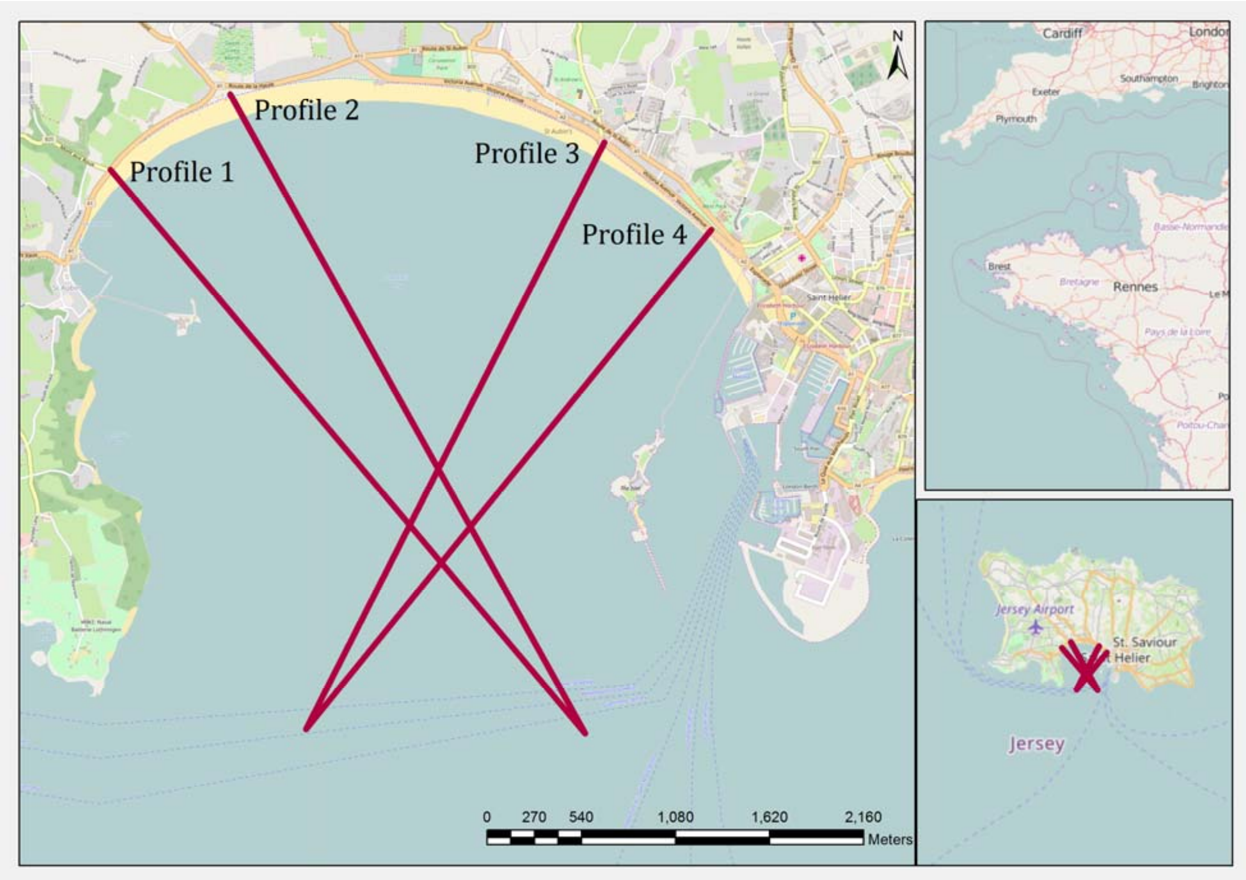

Figure 18: Beach profiles used in 1D XBeach simulations

Bathymetry data collected during a survey under taken by GeoSurv in 2012 was provided by the Department of Infrastructure. This was used to generate the land elevations of the majority of the beach profile (lower and middle beach) with the upper beach gaps being filled by data collected during a site visit by NOC. Figures 19 and 20 show the location of the Department of Infrastructure's data and our own data respectively. This data was combined together to produce 1D beach profiles and the resulting profiles are shown in Figure 21. Each of these profiles are then used as the model domain for each of the storm impact scenarios.

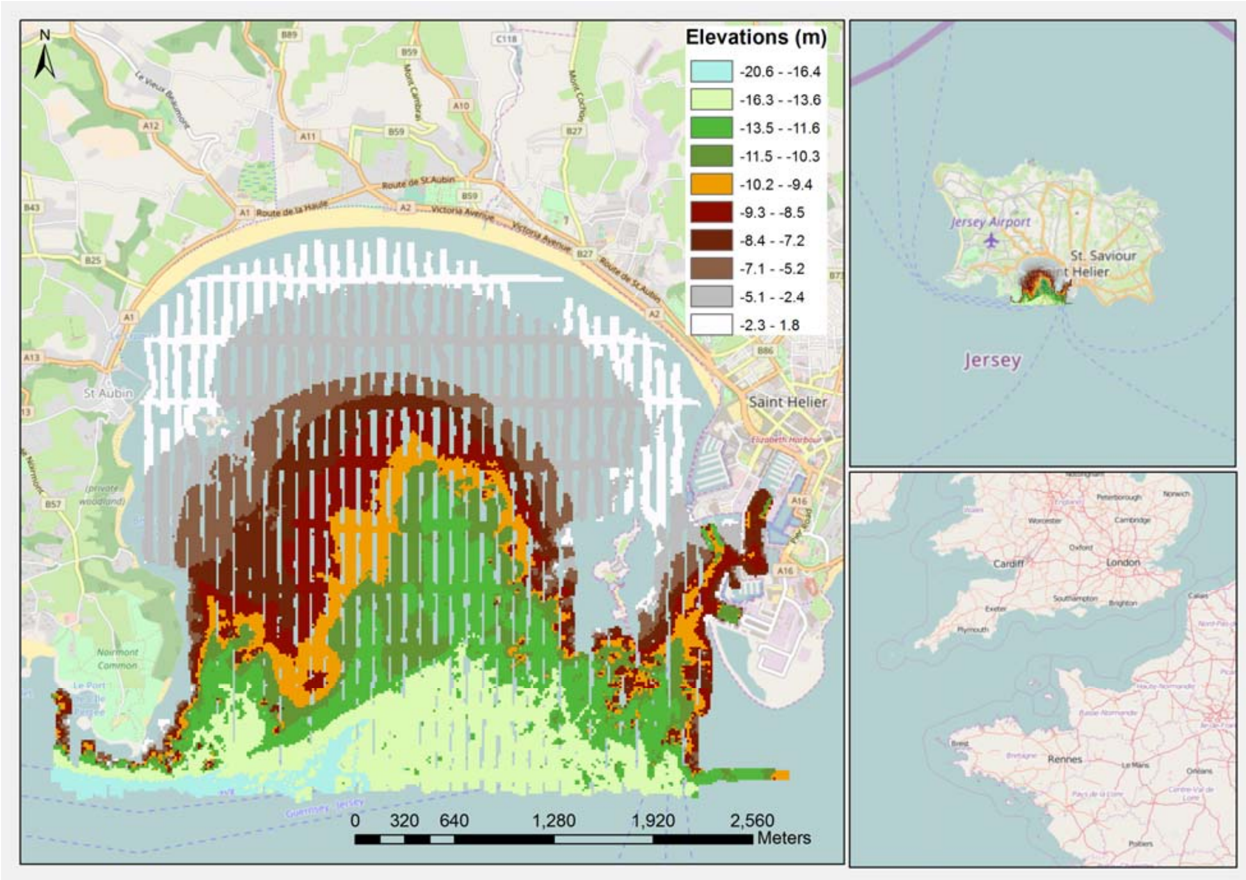

Figure 19: Bathymetry data collected on behalf of Department of Infrastructure by GeoSurv in 2012.

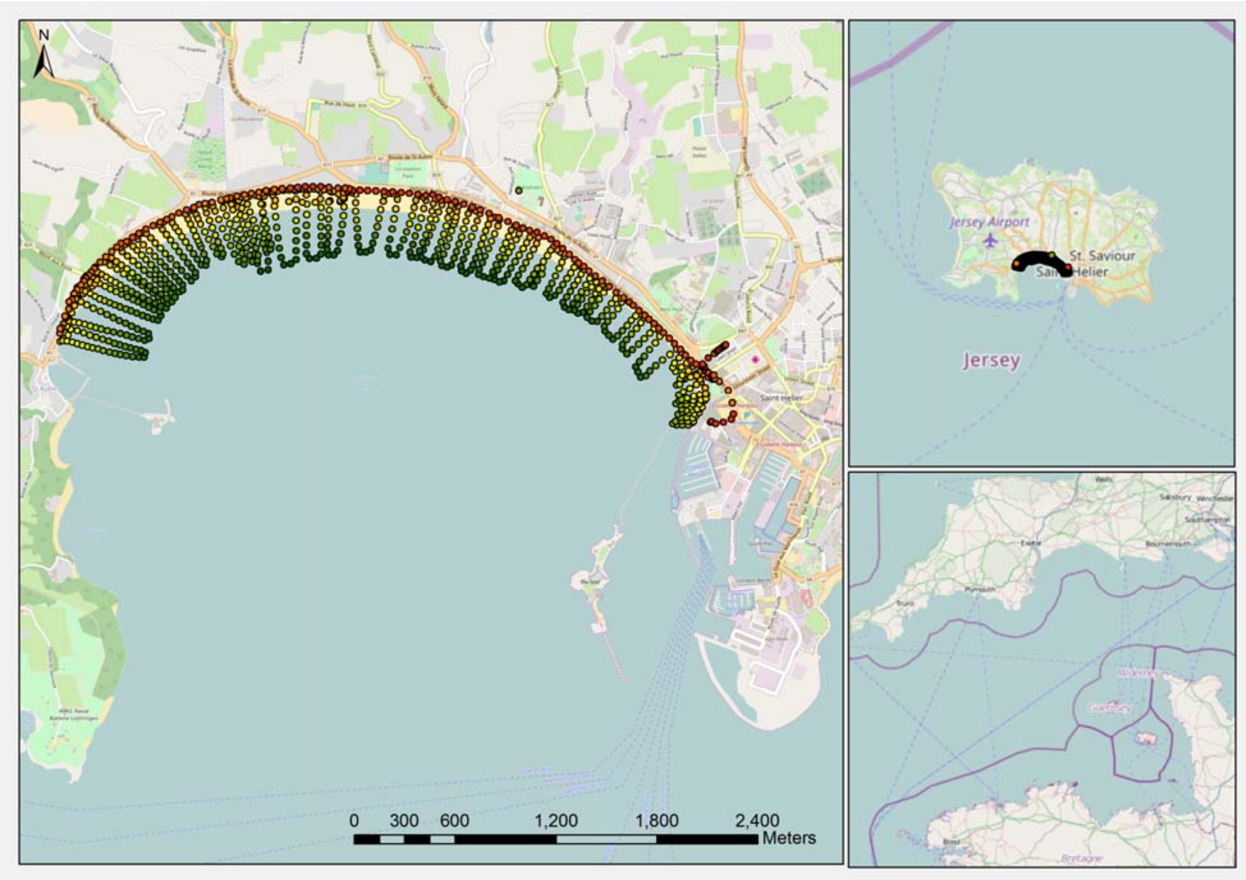

Figure 20: GPS survey track followed by survey vehicle during NOC and Jersey Met Office survey

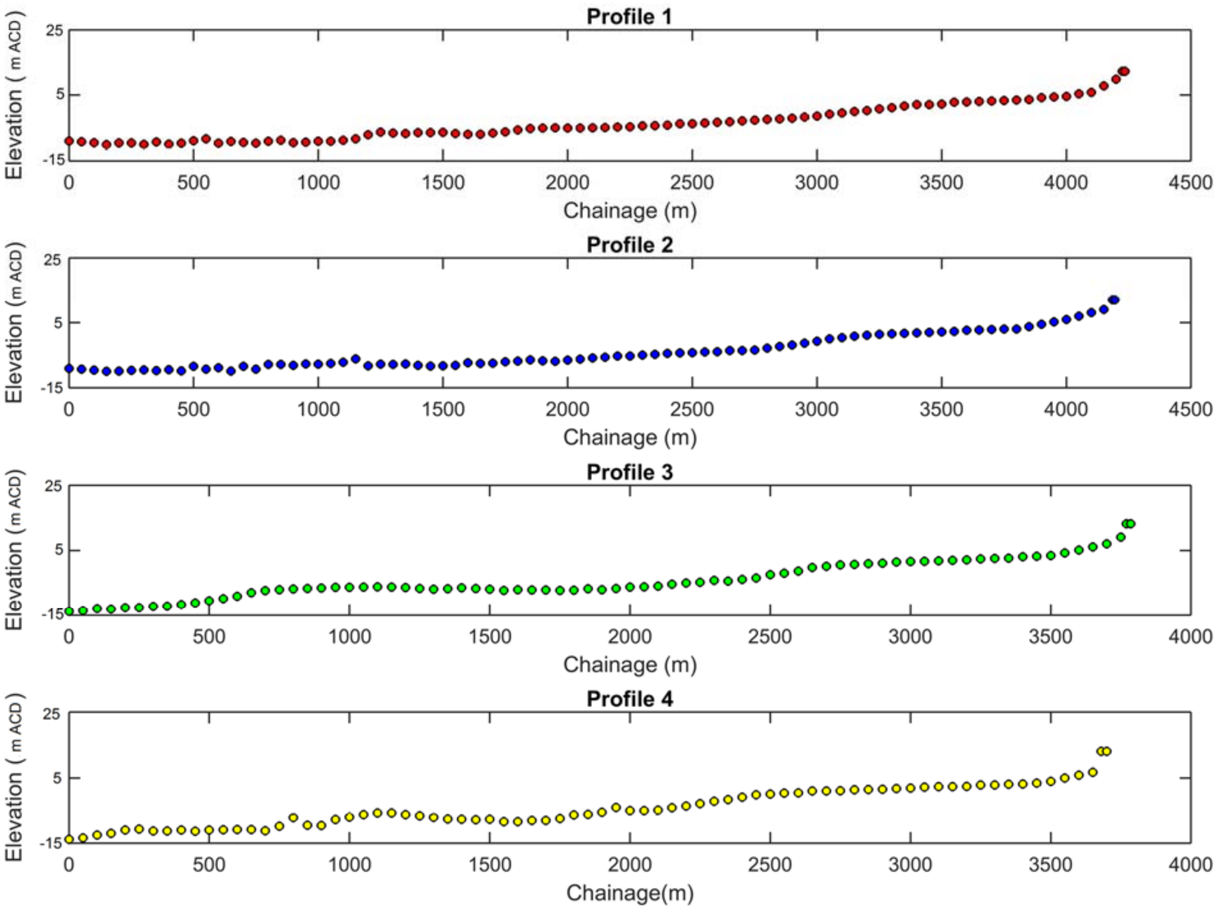

Figure 21: Beach profiles used as an input for extreme event simulations, profiles include height of any parapets present

Once the beach profiles had been selected, parameters that match the extreme event being considered are assigned to the model simulation. This requires details of the waves and water level during the extreme event. While the joint probability analysis provides a significant wave height and water level, other parameters such as peak period and wave direction are also required. Using wave buoy data, significant wave height, peak period and wave direction can all be plotted against each other. This allows the selection of suitable wave directions and peak periods that could occur together for a given significant wave height. Histograms have also been used to identify the most common and extreme peak periods for different ranges of significant wave height. For each significant wave height, the most common and extreme values are simulated to represent the potential range of peak periods (Figure 22). Due to the short data sets that contained peak period data, values 0.1 m either side of the selected Hs values (Figure 15) were used in generating a histogram of peak period. As shown in Figure 22, for all significant wave heights between 0.9 m and 1.1 m. It can be seen that the most common period was 10.3 s and the most extreme was 19.7 s These were the ones used for significant wave heights of 1 m. This was repeated for all the different wave heights simulated.

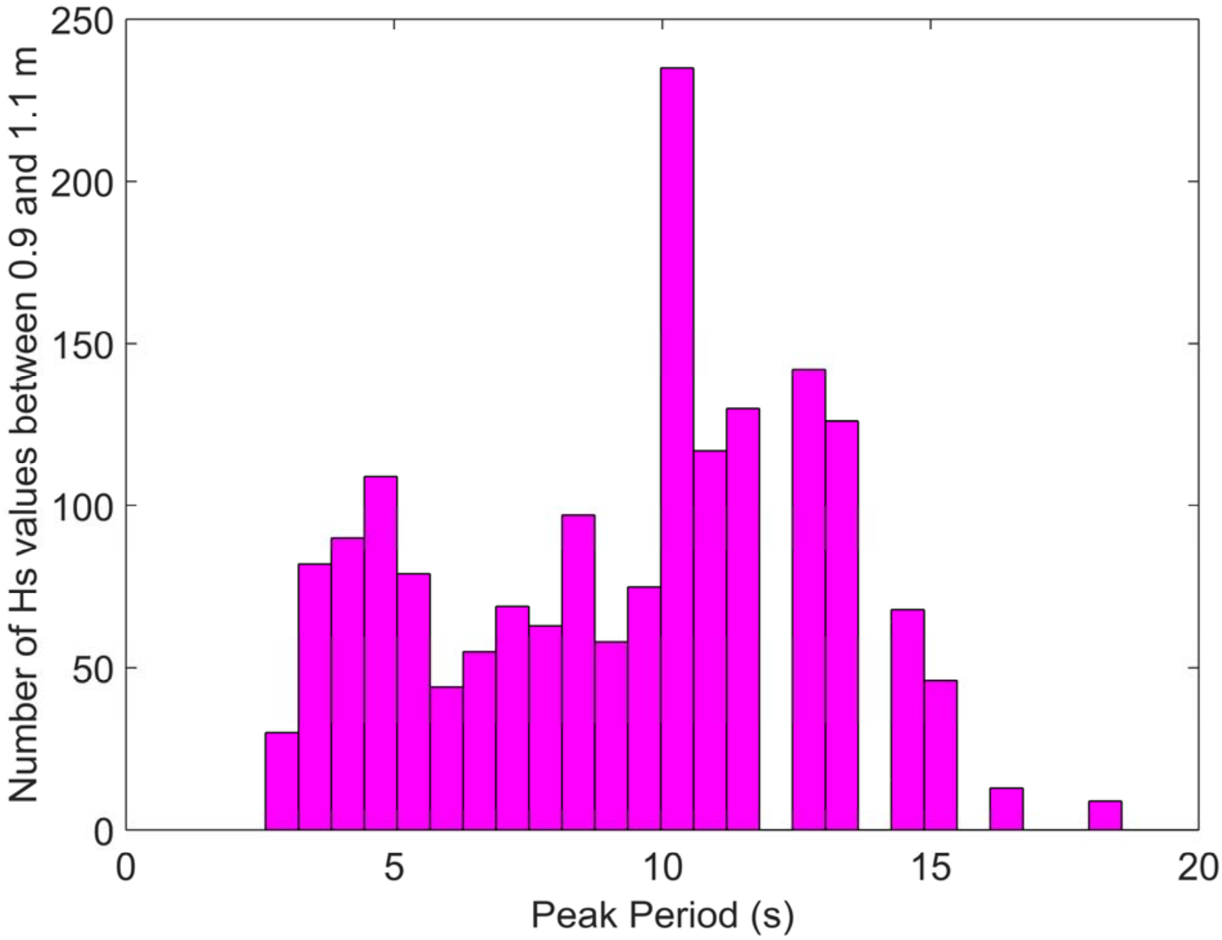

Figure 22: Histogram for all Hs values between 0.9 m and 1.1 m for the wave buoy between 2011 and 2012.

For wave direction, if the range in directions logged by the buoy for the significant wave height being considered was small, e.g. between 250^0 and 270^0, then the middle wave direction in the range was used i.e. 260^0. Waves with heights of 3 m or more were found to have these small ranges in wave direction. Waves below 3 m had a much larger range in wave direction, so minimum, middle and maximum values were used to assess the impact of wave direction. These values covered a range in wave direction that could impact on the coastline in St Aubin's Bay. This resulted in three different directions being simulated for 1 and 2 m waves. Figure 23 shows the relationship of significant wave height and wave direction that demonstrates the increase in the range of suitable directions for decreasing significant wave heights. It should be noted that the confidence in the wave direction data from the buoy is low. As the wave monitoring equipment is mounted to a navigation buoy rather than a purpose-built buoy. The full list of parameters used in each scenario simulated is available as a spreadsheet provided alongside this report.

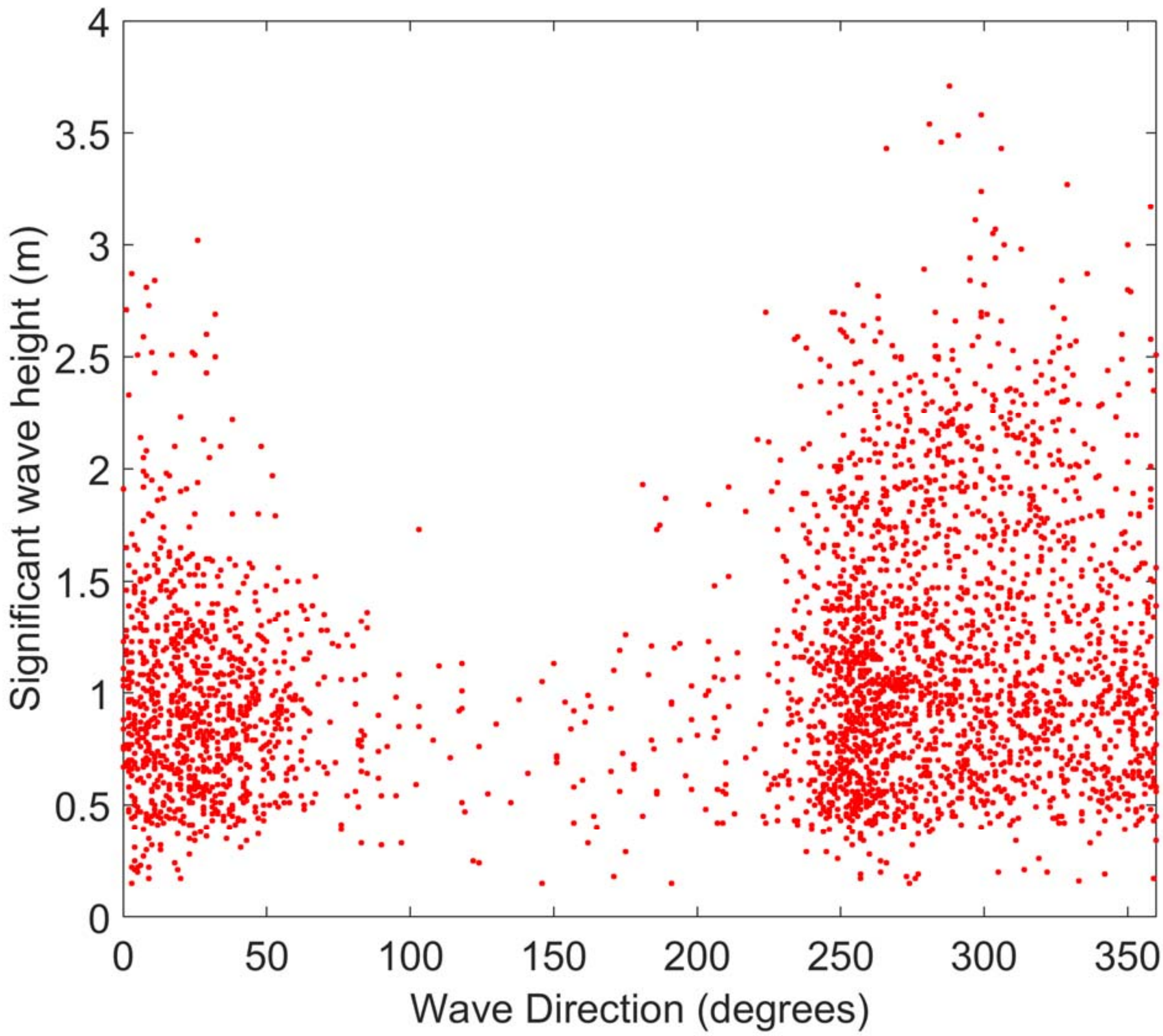

Figure 23: Wave direction against significant wave height at wave buoy

Once the wave parameters have been selected, an underlying storm surge needs to be created. This is a time varying water level that peaks at the desired extreme water level from the joint probability analysis. It also needs to be a good representation of a storm surge for the location. To produce this representation, a historical storm surge was used as the basis of the curve. The storm surge that occurred on the 10th March 2008 was converted into a representative normalised curve with values of zero corresponding to no surge and 1 for the peak of the surge. This representative curve can then be combined with an extreme water level value, and added to an underlying MHWS predicted tidal curve. This results in a storm tide curve that peaks at the desired water level and is representative of the region (Figure 24).

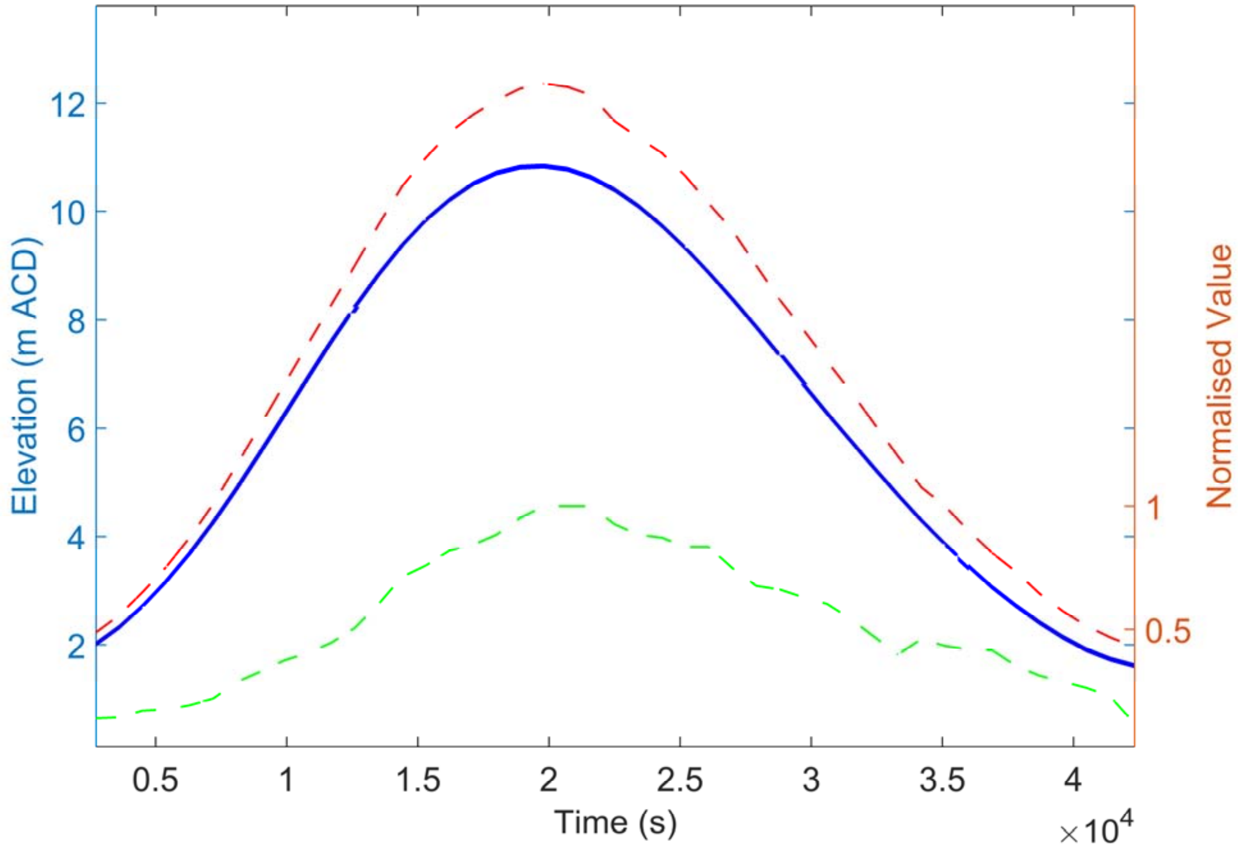

Figure 24: Diagram showing example of producing storm tide, solid blue line is a predicted MHWS curve for Jersey, green dotted line is the representative surge curve, and red dashed line is the output storm tide for inclusion in XBeach simulations.

This time varying extreme water level curve can then be used along with the wave parameters as inputs to simulate an extreme event across each of the four beach profiles. The storm impact model is able to provide many different parameters as output but the ones considered for this report are the total volume overtopped during the event and the positive, negative and total change in the volume of sediment on the beach. The positive and negative values indicate how much sediment has eroded or accreted across the beach profile while the total will show if sediment is lost or gained across the whole profile.

14.1 Beach morphology: response to present day extreme events

Figure 25 shows an example of both the starting beach profile and the simulated beach profile after a 1 in 200 year extreme event. It can be seen in this scenario that there has been accretion of sand directly at the base of the toe of the defences and erosion of the beach slightly further offshore in front of the defences.

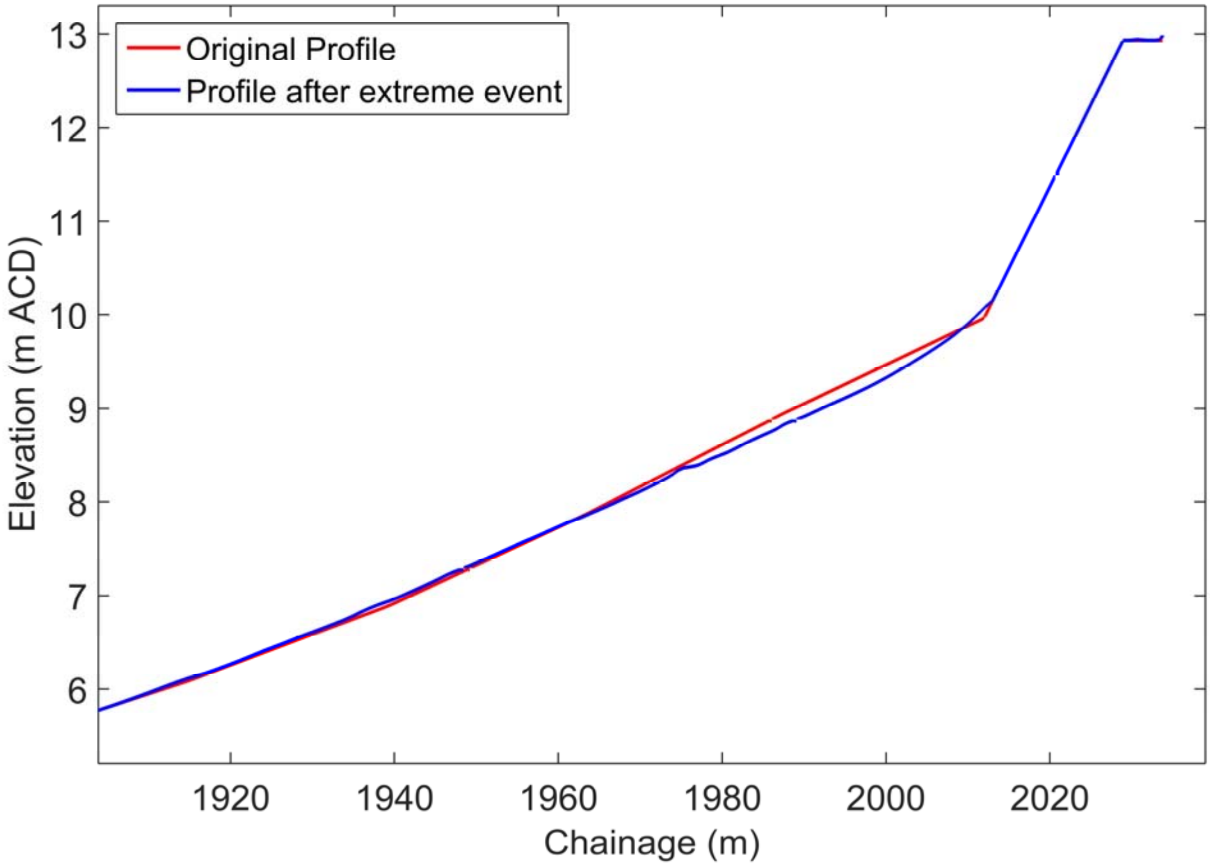

Figure 25: Example of changes to beach morphology due to an extreme event of a 1 in 200 RP with an WL of 6.45 m, Hs of 2 m and a Dir of 270 with a Tp of 19.7 s.

The results of each of the different scenarios simulated are shown in Figure 26 where the amount of sediment that has accreted along each beach profile is plotted against significant wave height. This is repeated with sediment that has eroded along the profile. Finally Figure 27 shows the total change along each profile showing if any sediment has been lost or gained overall.

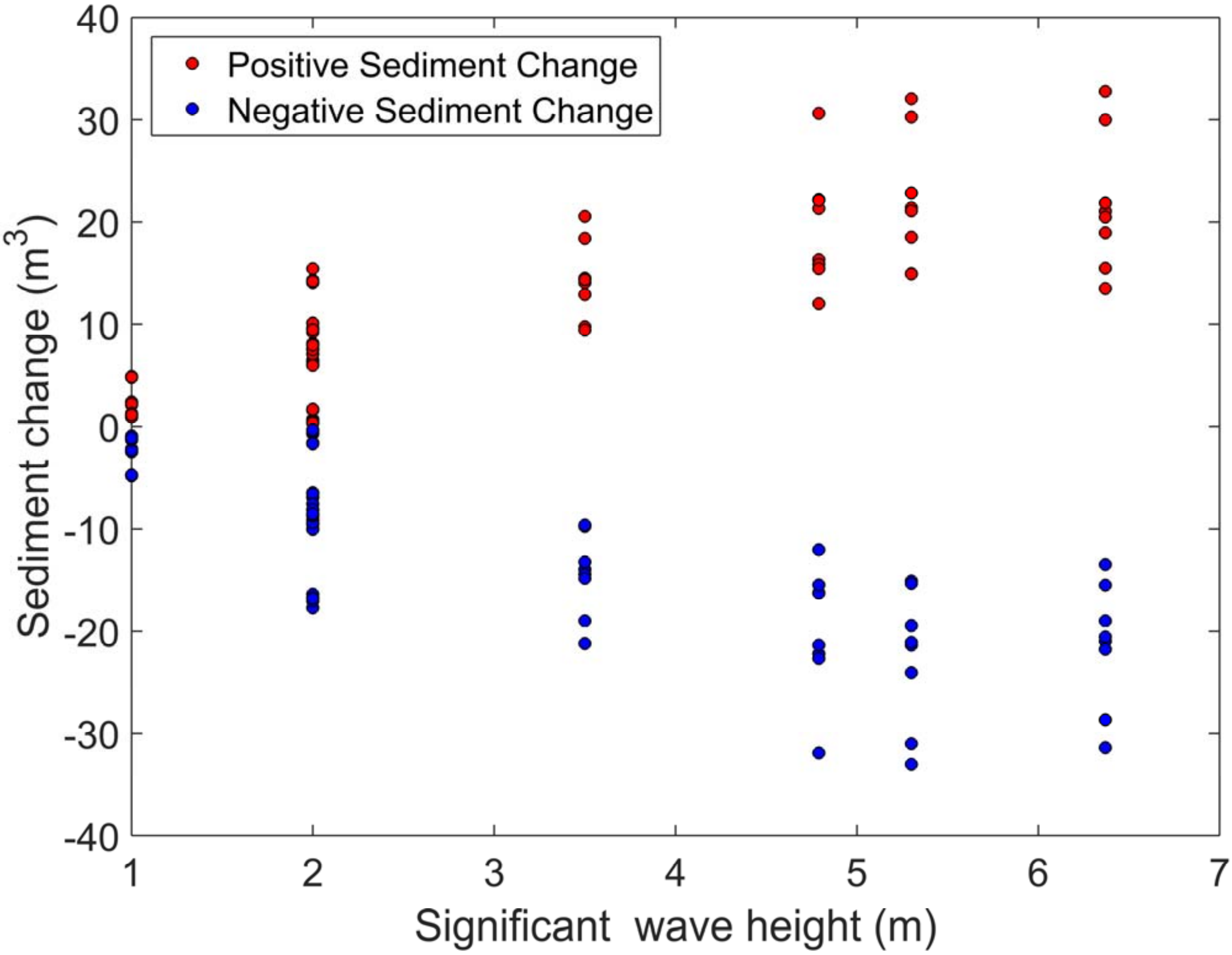

Figure 26: Positive (red dots) and negative (blue dots) sediment change across the whole profiles against significant wave height used in the extreme events.

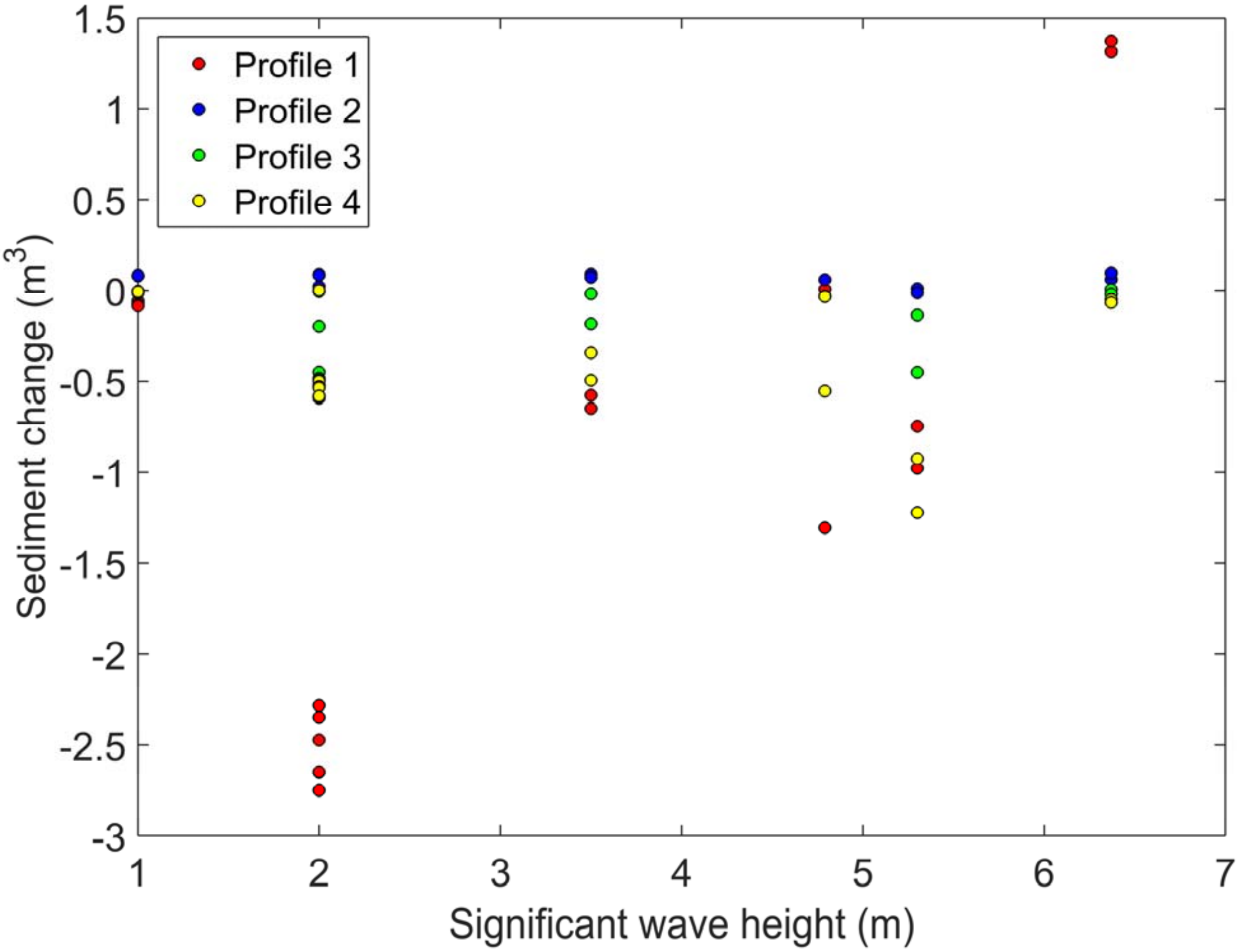

Figure 27: Total sediment change for every scenario showing sediment lost or gained from beach profile.

Figure 26 shows that as the significant wave height increases, both the positive and negative change in sediment increases. This is due to the greater wave energy from larger significant wave heights being able to move more sediment. This is then able to mobilise and move sediment along the profile. A levelling of the amount of change is evident from around 5 m significant wave height suggesting that heights above this threshold do not significantly increase the amount of sediment being mobilised. Figure 27 shows that the absolute change over the whole profile does not increase with increasing significant wave height. It tends to be around zero for most wave heights and profiles. However, it reaches a maximum loss at 2 m of significant wave height with total loss of 2.5 m^3 of sediment per metre across the beach. A maximum gain is also evident at 6.4 m wave height where around 1.5 m^3 of sediment is gained for every metre across the beach. The figure also shows that profile 1 is more sensitive to sediment loss and gain. The other profiles have little overall change with profile 4 exhibiting some small losses of 1 m^3.

Generally, it can be seen that higher wave heights result in the greatest sediment movement along the profile, but it is the 2 m waves with longer wave periods that result in the greatest removal of sediment from profile 1 although the magnitude of the loss is small and for only one profile. Therefore, it can be seen that while large significant wave heights result in larger erosion and accretion along the beach profile, it does not translate into sediment being lost or gained from the beach itself. There is also some uncertainty regarding the presence of these large significant wave heights due to the assumption that waves at the wave buoy will be the same at the mouth of St Aubin's Bay. Without a wave transform model, it cannot be assessed whether these are representative.

For the largest sediment change scenario, the starting profile, end profile after the extreme event and points of max and min sediment change are all shown in Figure 28 and Figure 29. Figure 28 shows the whole profile with the points of max and min sediment change marked and Figure 29 shows a close up of the two points with the addition of the end profile showing the change between the two. Overall it was found that the impact of SLR and climatic changes (i.e. sensitivity to wave direction) on St Aubin's Bay beach profile are negligible.

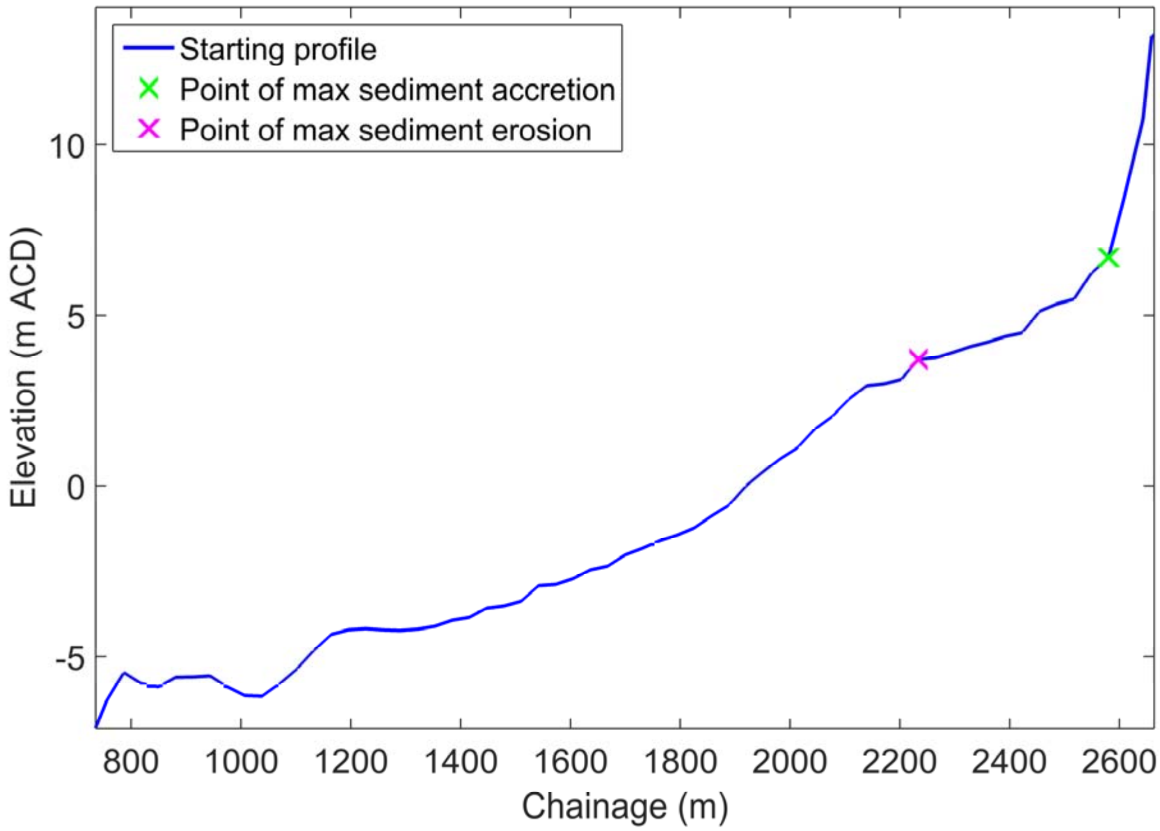

Figure 28: Profile two showing locations of max and min sediment change for greatest sediment change (Scenario 10).

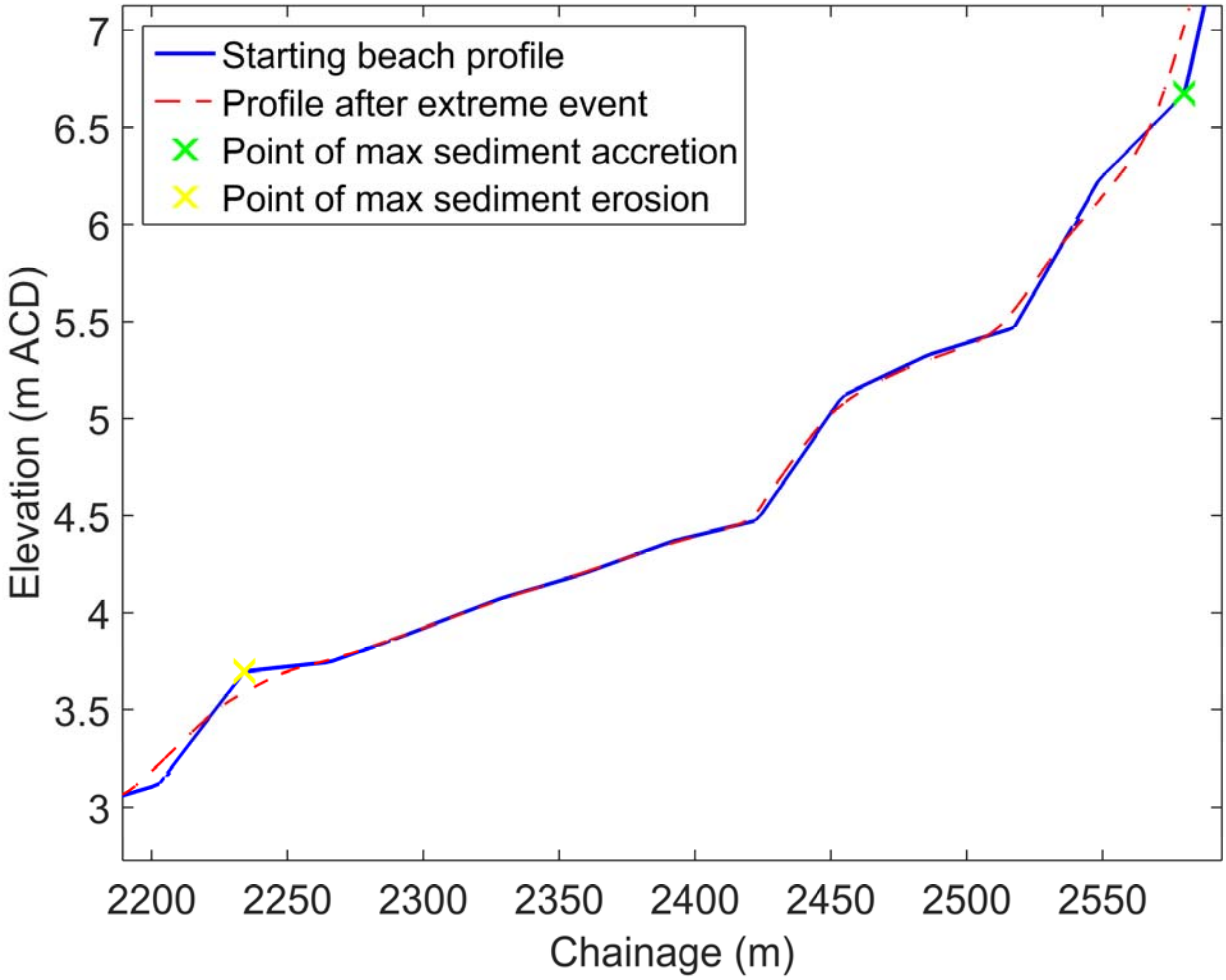

Figure 29: Close up of profile 2 showing locations of max and min sediment change, both the starting profile (blue) and the end profile (dashed red) are shown.

As Figure 28 shows the greatest overall change scenario across all profiles, the impact of extreme events on beach morphology over the course of the extreme events being simulated is minor. However, it should be noted that the sediment parameters used in the simulation have not been validated so would benefit from beach surveys to calculate the sand distribution on the beach.

14.2 Overtopping of defences: vulnerability of defences to overtopping during present day extreme events and future storm surges

The total volume of water that overtops the defences during each extreme event has been calculated for each scenario. Each scenario was simulated 5 times with the total volume for each being averaged to provide a mean total volume value. This was required to take into account the variations in wave spectrums that are generated from the input wave parameters. Figure 30 shows the results for a selection of scenarios for each profile. Table 15 shows the list of scenarios that have been selected. (For full list and results please see associated spreadsheet) For the scenarios that had a range of wave directions being simulated, the direction that resulted in the greatest volume was used. It was noted that the variation in wave direction did not result in much variation in mean total volumes. For the simulations it was also assumed that the wave height would be the same across the bay.

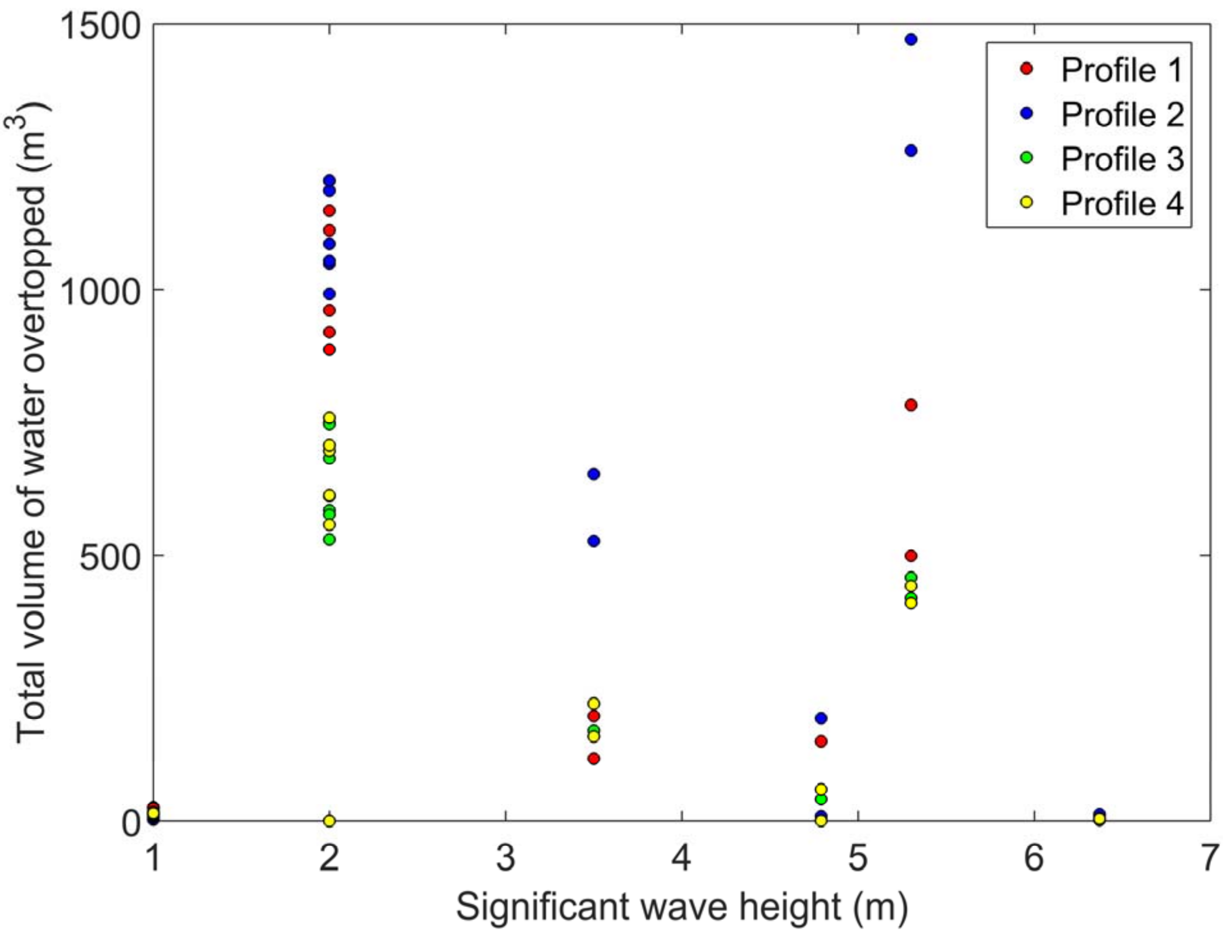

Figure 30: Mean total overtopping volume for each profile for a selection of scenarios simulated.

Table 15: List of parameters used for each of the selected scenarios displayed in Figure 31.

Profile	Return Period (yr)	WL (m)	Hs (m)	Dir (^{0})	Tp (s)	Average Total Volume (m^3)	Standard deviation	% ST to Mean
1	10	5.00	4.79	260	13.30	150.3	21.3	14.2
1	10	5.90	3.50	260	11.80	198.0	37.1	18.8
1	10	6.30	2.00	235	19.70	960.5	129.5	13.5
1	10	6.38	1.00	270	33.00	529.6	57.5	10.9
1	200	5.00	6.37	260	9.20	10.7	4.5	41.9
1	200	6.00	5.30	260	11.80	782.5	129.0	16.5
1	200	6.45	2.00	235	19.70	1203.1	58.4	4.9
1	200	6.48	1.00	270	33.00	645.2	40.6	6.3
2	10	5.00	4.79	260	13.30	193.6	46.9	24.3
2	10	5.90	3.50	260	11.80	652.5	51.7	7.9
2	10	6.30	2.00	200	19.70	1086.0	189.4	17.4
2	10	6.38	1.00	195	33.00	343.3	73.8	21.5
2	200	5.00	6.37	260	9.20	13.5	4.3	32.3
2	200	6.00	5.30	260	11.80	1470.7	130.7	8.9
2	200	6.45	2.00	270	19.70	1204.4	82.1	6.8
2	200	6.48	1.00	120	33.00	379.6	52.4	13.8
3	10	5.00	4.79	260	13.30	42.1	21.9	51.9
3	10	5.90	3.50	260	11.80	221.7	32.9	14.9
3	10	6.30	2.00	200	19.70	584.8	75.7	12.9
3	10	6.38	1.00	195	33.00	231.8	42.9	18.5
3	200	5.00	6.37	260	9.20	5.0	9.6	189.7
3	200	6.00	5.30	260	11.80	458.5	97.9	21.4
3	200	6.45	2.00	200	19.70	749.2	115.7	15.4
3	200	6.48	1.00	120	33.00	268.2	37.8	14.1
4	10	5.00	4.79	260	13.30	60.5	29.7	49.2
4	10	5.90	3.50	260	11.80	221.2	21.1	9.5
4	10	6.30	2.00	270	19.70	613.6	93.0	15.2
4	10	6.38	1.00	120	33.00	227.7	13.9	6.1
4	200	5.00	6.37	260	9.20	4.6	6.4	139.5
4	200	6.00	5.30	260	11.80	442.4	82.0	18.5
4	200	6.45	2.00	200	19.70	758.6	165.3	21.8
4	200	6.48	1.00	270	33.00	259.7	78.1	30.1

The peak period used in each scenario has been plotted against mean total volume for that scenario to show the impact of wave period on the amount of water overtopping the defences (Figure 31). It can be seen that there is a maximum in the volume of water overtopped at peak periods of around 12 seconds. This corresponds to the scenario that has a 6 m WL and 5.3 m significant wave height. Peak periods of around 20 seconds also contribute a large amount of volume. These scenarios are the result of a 6.45 m extreme water level and 2 m significant waves. While there is some doubt over the 5.3 m waves being representative at the entrance to St Aubin's Bay, a question a wave transformation model could answer. The 2 m waves in contrast have no such doubts about them. It can also be seen that there is a threshold in overtopping volume at around 12 seconds where peak periods below this result in little overtopping and above this large volumes can be expected. This shows that the coastline is more vulnerable to waves with long periods that are also known as swell waves.

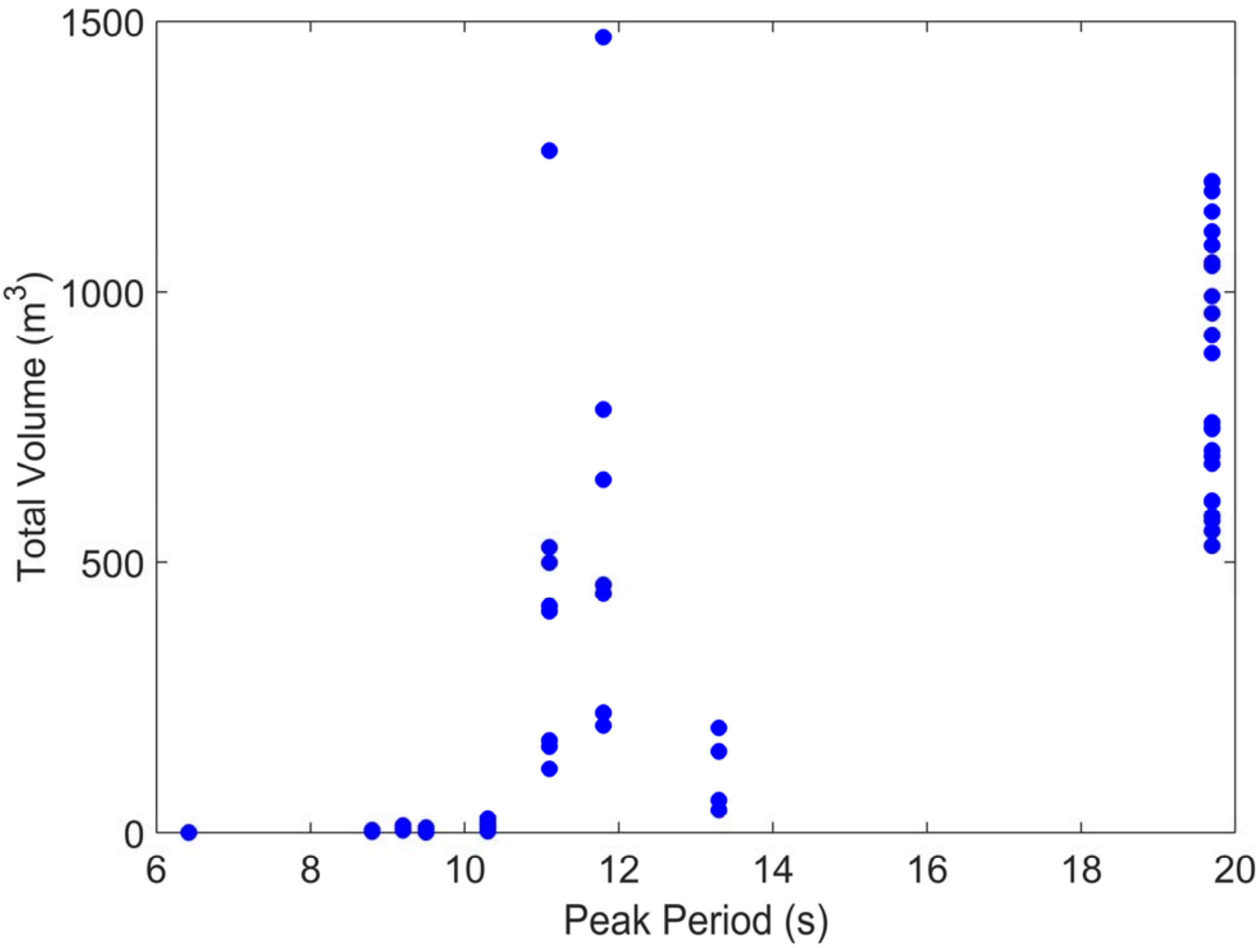

Figure 31: Peak period when compared with total volume of overtopped water

As previously mentioned, each scenario that was simulated was run 5 times and averaged to give a mean result. This was to take in account differences in the wave spectrums generated by the input wave parameters. In addition to the mean, the standard deviation across the 5 runs was calculated and its percentage size when compared with the mean total volume value was plotted against mean total volume. This shows how representative the mean overtopped volume is of the extreme event. Figure 32 shows this relationship and highlights that small overtopped volumes are very variable across the 5 runs and thus have standard deviations exceeding the mean volume i.e. the percentage size is greater than 100%, whereas for greater overtopped volumes this quickly decreases to below 20% meaning low variation in the volume of water overtopping the defences across the 5 runs making the mean value representative of the extreme event.

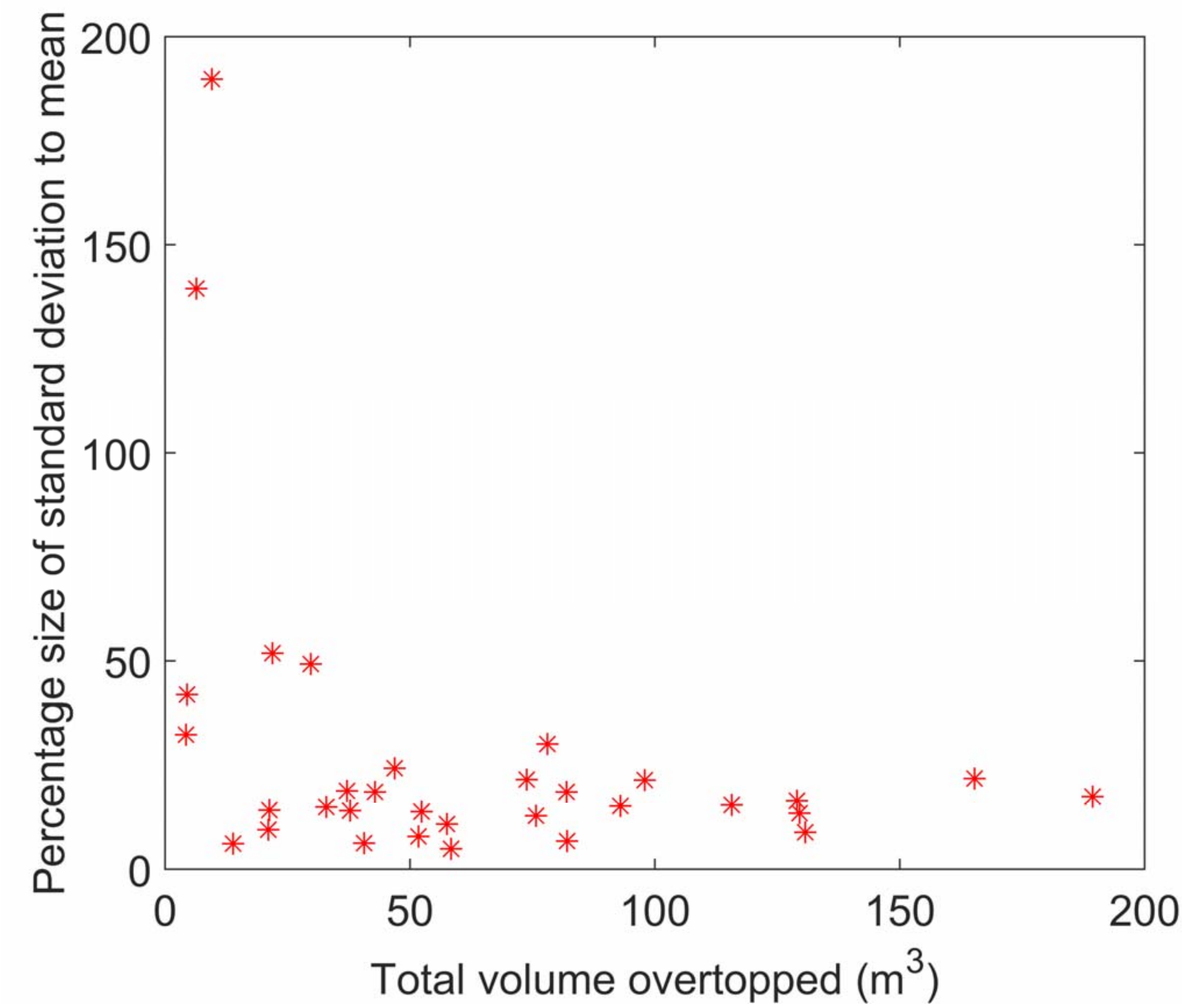

Figure 32: Mean total volume for a selected scenario against the percentage size of the standard deviation against the mean total volume.

14.3 Increase in impact of extreme water levels with projected sea-level rise

A 1 in 200-year extreme still water level event (value taken from results in section 8) has been simulated with increasing amounts of SLR. From the present day at 0 m in intervals of 0.1 m to the highest projected plausible value of 1.8 m. This will give an indication of the vulnerability of the current defences to increasing mean sea levels. The storm impact model was again used but with no wave parameters defined, just the same storm surge curve with all water level values increased by the SLR parameter of a given simulation. Table 16 shows the different overtopping volumes that were a result of increasing mean sea-levels for each profile. This is also displayed in Figure 33.

Table 16: List of every scenario simulated for extreme water level event and increasing mean sea-levels

Profile	Return Period	EWL (m)	Sea-level rise (m)	Total volume of water overtopped (m^3)
1	200	6.48	0.0	0.0
1	200	6.48	0.1	0.0
1	200	6.48	0.2	0.0
1	200	6.48	0.3	0.0
1	200	6.48	0.4	0.0
1	200	6.48	0.5	0.0
1	200	6.48	0.6	21.1
1	200	6.48	0.7	146.8
1	200	6.48	0.8	387.9
1	200	6.48	0.9	774.0
1	200	6.48	1.0	1304.0
1	200	6.48	1.1	1964.6
1	200	6.48	1.2	2744.1
1	200	6.48	1.3	3643.6
1	200	6.48	1.4	4685.1
1	200	6.48	1.5	5862.7
1	200	6.48	1.6	7205.3
1	200	6.48	1.7	8729.8
1	200	6.48	1.8	10400.7
2	200	6.48	0.0	0.0
2	200	6.48	0.1	0.0
2	200	6.48	0.2	0.0
2	200	6.48	0.3	0.0
2	200	6.48	0.4	0.0
2	200	6.48	0.5	0.0
2	200	6.48	0.6	0.0
2	200	6.48	0.7	0.0
2	200	6.48	0.8	0.0
2	200	6.48	0.9	0.0
2	200	6.48	1.0	0.0
2	200	6.48	1.1	0.0
2	200	6.48	1.2	0.0
2	200	6.48	1.3	3.3
2	200	6.48	1.4	83.4
2	200	6.48	1.5	294.0

Profile	Return Period	EWL (m)	Sea-level rise (m)	Total volume of water overtopped (m^3)
2	200	6.48	1.6	653.5
2	200	6.48	1.7	1168.8
2	200	6.48	1.8	1837.9
3	200	6.48	0.0	0.0
3	200	6.48	0.1	0.0
3	200	6.48	0.2	0.0
3	200	6.48	0.3	0.0
3	200	6.48	0.4	0.0
3	200	6.48	0.5	0.0
3	200	6.48	0.6	0.0
3	200	6.48	0.7	0.0
3	200	6.48	0.8	0.0
3	200	6.48	0.9	0.0
3	200	6.48	1.0	0.0
3	200	6.48	1.1	0.0
3	200	6.48	1.2	0.0
3	200	6.48	1.3	0.0
3	200	6.48	1.4	0.0
3	200	6.48	1.5	0.0
3	200	6.48	1.6	0.0
3	200	6.48	1.7	0.0
3	200	6.48	1.8	0.0
4	200	6.48	0.0	0.0
4	200	6.48	0.1	0.0
4	200	6.48	0.2	0.0
4	200	6.48	0.3	0.0
4	200	6.48	0.4	0.0
4	200	6.48	0.5	0.0
4	200	6.48	0.6	0.0
4	200	6.48	0.7	0.0
4	200	6.48	0.8	0.0
4	200	6.48	0.9	0.0
4	200	6.48	1.0	0.0
4	200	6.48	1.1	0.0
4	200	6.48	1.2	0.0
4	200	6.48	1.3	0.0
4	200	6.48	1.4	0.0
4	200	6.48	1.5	0.0
4	200	6.48	1.6	0.0

Profile	Return Period	EWL (m)	Sea-level rise (m)	Total volume of water overtopped (m³)
4	200	6.48	1.7	0.0
4	200	6.48	1.8	0.0

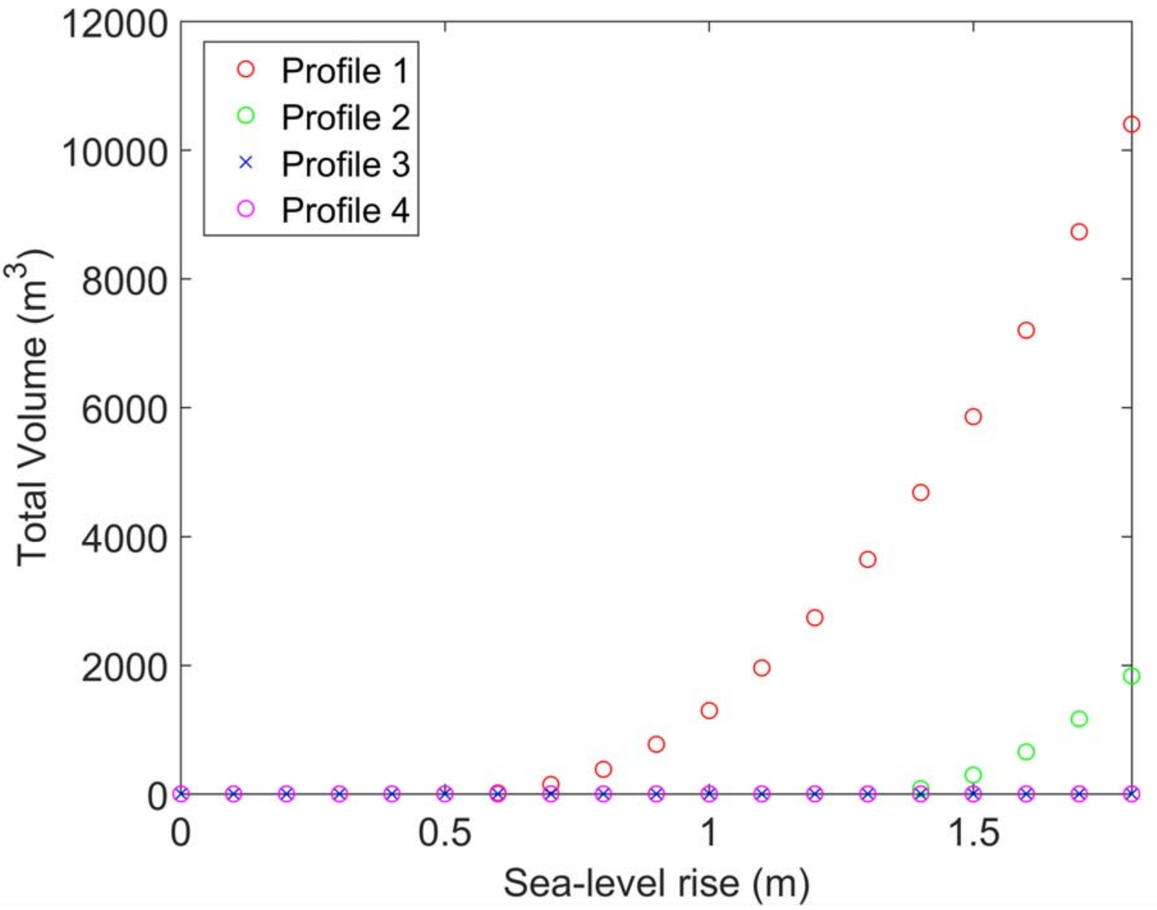

Figure 33: Impact of increasing mean sea-levels on total volume overtopped for a 1 in 200-year extreme water level event.

Figure 33 shows that profile 1 is by far the most vulnerable to sea-level rise, but even this profile is able to withstand sea-level rises of over 0.5 m before any overwashing occurs. Profile 2 is a little more resilient requiring SLR over 1.2 m before overwashing and finally both profile 3 and 4 both have no overwashing even at the maximum SLR value of 1.8 m. However, it should be made clear that these simulations have been undertaken with no waves and consist of just surge and tide so any waves that would be present during these extreme events would have a far greater impact and would reduce the threshold for water overtopping defences and increase the vulnerability of the coastline.

14.4 Increase in overtopping of defences during extreme events due to projected SLR

Due to the computational cost, only one extreme event for one profile was selected to simulate the impact of increasing mean sea-levels. The 1 in 10-year joint probability event with the lowest variation (i.e. lowest % standard deviation to mean) was selected from the Profile 2 joint probability results and run with increasing sea levels in intervals of 0.1 m from 0 m to 1.8 m, Table 17 shows details of the scenarios selected. Figure 34 shows the results of these 19 simulations, as expected the volume that overtops the defences increases significantly with increasing mean sea level rise. It also shows that waves greatly increase the vulnerability when compared with storm surges alone.

Table 17: Details of the scenario simulated with 19 different SLR parameters from 0 m to 1.8 m including total volume of water overtopping defences

Profile	Return Period	WL (m)	Hs (m)	Dir (^{0})	Tp (s)	SLR (m)	Total Vol (m^3)
2	10	5.9	3.5	260	11.8	0	756
2	10	5.9	3.5	260	11.8	0.1	964
2	10	5.9	3.5	260	11.8	0.2	1050
2	10	5.9	3.5	260	11.8	0.3	1265
2	10	5.9	3.5	260	11.8	0.4	1419
2	10	5.9	3.5	260	11.8	0.5	1575
2	10	5.9	3.5	260	11.8	0.6	1583
2	10	5.9	3.5	260	11.8	0.7	1971
2	10	5.9	3.5	260	11.8	0.8	2550
2	10	5.9	3.5	260	11.8	0.9	2841
2	10	5.9	3.5	260	11.8	1.0	2944
2	10	5.9	3.5	260	11.8	1.1	3226
2	10	5.9	3.5	260	11.8	1.2	3063
2	10	5.9	3.5	260	11.8	1.3	4166
2	10	5.9	3.5	260	11.8	1.4	4840
2	10	5.9	3.5	260	11.8	1.5	4670
2	10	5.9	3.5	260	11.8	1.6	5451
2	10	5.9	3.5	260	11.8	1.7	5979
2	10	5.9	3.5	260	11.8	1.8	5967

Due to the different extreme events being simulated with SLR, i.e. a 1 in 200-year water level event and a 1 in 10-year joint probability event. The water level with 1.8 m of SLR in the joint probability event is roughly equal to an SLR of 1.2 m for 1 in 200-year extreme water level event. This is due to a difference in the water level of 0.58 m (6.48 m – 5.90 m). For the extreme water level event, at 1.2 m of SLR this is just under the threshold of flooding whereas with the joint probability event results in a volume of 6000 m^3 water overtopping the defences. This means that the combination of surge, water level and waves lead to the most significant impact on coastal defences, leading to overtopping and inundation. The increase in overtopped volume and SLR is largely linear, with total volume increasing by around 3000 m^3 for every 1 m (300 m^3 per 0.1 m SLR) increase in SLR.

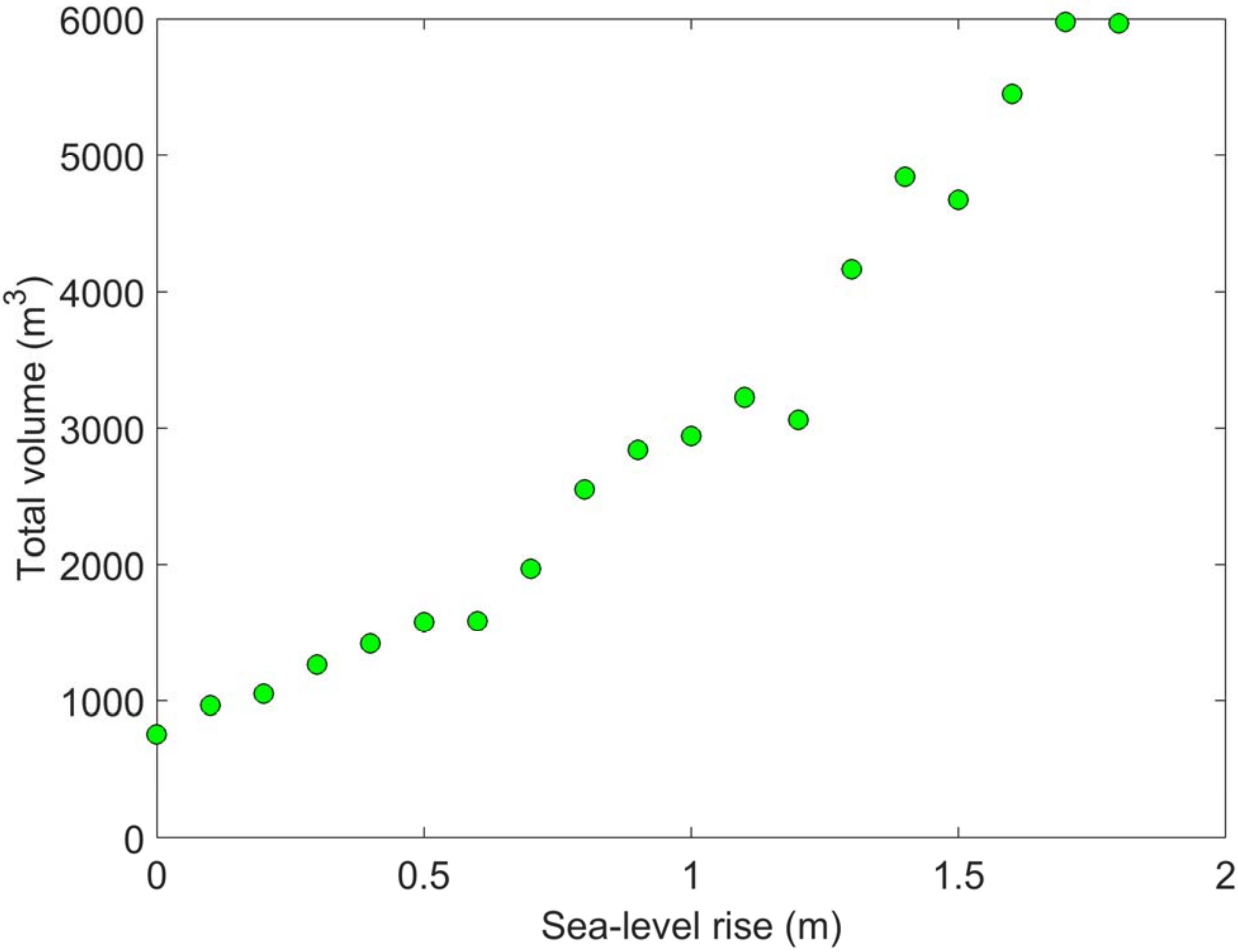

Figure 34: Relationship between sea-level rise and total volume overtopping defences for scenario outlined in Table 17

15 Key Findings

This study has established sea level rise (SLR) as an increasing environmental hazard for The States of Jersey. The study has involved a comprehensive review of available information, and has used up to date methods and outputs from the scientific research community to establish baseline SLR projections, and probabilities of occurrence of extreme events (defined as water level resulting from high tide and surge, combined with waves). The study focused on St Aubin's Bay as a specific case study location, which involved gathering field data to enable modelling of extreme event scenarios and an assessment of sea defence overtopping.
A number of stakeholders have had input into the study which has endeavoured to source all relevant local data as input. Data from the local GPS station (used to refine land movement estimates) was not available in time to combine into this study, however the study has established that land movement is a very small (negligible) factor in the overall projected SLR changes for Jersey.

The key findings from the study are that:

1. The impact of future storm events will be influenced by sea-level rise (SLR). SLR projections vary depending on the emissions scenario being considered, and on the rate of change of the physical processes that influence sea levels. Global and regional projections are non-uniform due to variations in to ocean dynamic processes, changes in gravitational fields from ice mass loss, and air-sea heat and fresh water fluxes. There are differences between the global projections and the regional projections investigated for this study, therefore it is important to continue to investigate and monitor these changes on a local/regional basis

2. The seas around Jersey are rising and the trend indicates an accelerating rate of increase. From 1900 to 1960 the rate of increase was c. 1 mm/year, from 1960 onwards this increased to approximately 2 mm/yr. The projections suggest that a suitable baseline figure for future rates of increase is 3 mm/year.

3. Vertical land movement is taken into account when assessing SLR. Regional assessment shows that the magnitude of land movement for Jersey, relative to sea level rise is negligible (currently estimated as maximum of 7.5 cm up to 2100). The data sourced from around the region shows that time span for data is important with longer spans showing lower rates. The bigger changes are generally related to the smallest time spans. This suggests that ideally 15 years of data is required to establish a robust rate of vertical land movement.

4. Using the mean emissions scenario for climate change (based on achieving the targets identified in the 2016 Paris Agreement) and using the most likely outcome from that scenario, Jersey is projected to experience an SLR of 0.48 m by 2100. On the same basis, the low probability, high impact scenario (based on 'business as usual' i.e. no curbing of emissions) is projected to result in 0.77 m of SLR by 2100. With a 1 in 20

chance (95th percentile) of a 1.8 m SLR being realised. The lowest possible SLR range based on aggressive curbing of emissions is between 0.28 m and 0.6 m by 2100. These values are all relative to sea levels in 2010. For nearer term estimates the study has established baseline figures of between 10 cm (best case) and 20 cm (worst case) of SLR by 2030, and between 20 cm (best case) and 40 cm (worst case) for 2050.

5. Joint probability analysis has been completed for combined extreme water levels and waves. The results are a useful guide for future studies and policy and are a much greater improvement over previous work by HR Wallingford as the assumption made that large waves occur at the largest extreme water levels is both pessimistic and unrealistic.

6. For this part of the world, waves are not projected to have any significant change in significant wave height, although hindcast data does show a small linear increase. However, the greater impact will be from increasing mean sea levels. The combination of existing wave conditions with increasing sea levels will result in a higher frequency of extreme events. Under a median sea level rise projection (0.48 m by 2100) a 1 in 150 year event will occur on an annual basis

7. The combination of increased sea levels and waves (modelled using the current wave climate) will result in significantly greater overtopping of defences. All wave heights result in some overtopping of defences, with the largest overtopping amounts related to the scenarios with the longest periods. Wave direction has little impact. Peak overtopping volume occurs at a significant wave height of 2 m with a peak period of 19.7 s.

8. For profile 2, which is vulnerable to combined extreme water and significant wave height events, every 0.1 m of SLR will lead to approximately 300 m^3 of extra water per metre overtopped during an extreme event. This work has shown that it is the combination of waves, surge and SLR that will impact the coast the most as for profile 2 the highest SLR parameter during the joint 1 in 10-year event was equal to 1.2 m of SLR for the extreme water only event. This was just below the threshold of flooding, the addition of waves to the model meant that the defences went from being resilient and able to resist the extreme event, to being overtopped by 6000 m^3 of water per metre of defences. Being able to assess the likelihood of a given wave height having a specific period would be useful in assessing the vulnerability of the coast.

9. The case study work has shown that for St Aubin's Bay the area to the West is most at risk from initial future rise in sea-level. Comparing the before and after profiles, shows that for the simulated extreme events there is no significant impact on beach morphology. It would be beneficial to use a model to simulate the impact of long term wave climate and assess the impact on the beach morphology rather than the impact of extreme events only.

10. SLR will impact tidal range. The study has investigated the impact arising from high values of SLR and has shown that the change in tidal range for a 2 m increase in mean sea-level is estimated to result in a reduction of the tidal range of 0.49 m for spring and 0.24 m for neap tides. This will reduce the impact of flooding by a third under high impact low probability SLR scenarios, providing a tangible benefit in the future.

16 Recommendations

This study has established the data available for sea level studies, and completed modelling for the selected case study area, producing baseline output data that clearly shows sea level rise as an increasing hazard for jersey. The recommendations are focused on three topic areas:

- Progressing and refining the SLR modelling to give greater spatial coverage and extend the outputs to include economic impact and risks
- Working in collaboration with other departments and stakeholders to build a cohesive understanding and response to the baseline information produced.
- To put in place now a strategy for in-situ and remote monitoring of specific environmental parameters that will reduce uncertainties in modelling work and form the basis of a long-time series which will provide highly valuable insights and enable more effective risk management over time.

Progressing SLR modelling

There is clear value in progressing this work further to assess the impact on coastal infrastructure and communities through inundation modelling. Inundation modelling will show what the impact of a given total volume of water discharging over the defences would be. Our recommendation is that the 1D XBeach modelling is expanded into a 2D storm impact model, this would provide a more detailed analysis of the ability of sea defences to withstand extreme events across the whole bay or island rather than at four points across St Aubin's Bay. This 2D model would then be used to 'drive' the inundation model. The inundation modelling should be focused initially on specific vulnerable locations and should be carried out with input from the infrastructure and planning departments.

The impact of inundation is clearly heavily influenced by hydrological factors therefore opportunities to carry out combined modelling or co-analysis of results is strongly recommended. A model showing the impact of extreme rainfall events on the island, can be achieved using a surface flood model.
As changes in the beach profile were found to be minimal during the simulated extreme events it would be worthwhile to assess the long term cumulative impact of events on the beaches and coastline of Jersey. The assessment can take the form of models or observations.

In summary:

- Develop model from 1D to 2D

- Carry out inundation modelling, combine with hydrological model
- Use output to quantify impact / identify risks, including cumulative impacts on coastline

Working in collaboration

Coastal change has potential impact on, and therefore interest from a wide range of stakeholders. As this study, has shown there are several departments and organisations within The States of Jersey who hold data, models or other information relevant to this work. To maximise the value of this and any further work we strongly recommend that a cross department / multidisciplinary 'steering group' is established who can comment on and shape future efforts, ensure cross compatibility of any modelling (as far as practicable) and act on results and recommendations, as well as reduce the risk of duplication of effort.

In-situ and remote monitoring of specific environmental parameters

All work on sea level science is built on observational data, the most powerful of which are the high quality long time series records, such as those held at http://www.psmsl.org/ hosted by the NOC. These data combined with satellite observations, land movement measurements and a host of other sources enable the science that helps to manage risks from SLR.

Jersey have a high quality tidal record, a GPS station and an offshore wave buoy already in place, however there is an opportunity to augment these measurements using other sources, and also potentially to link into other existing marine observation systems to enhance management of the coastal environment. Further work is needed to establish options and costs, however as an example, new coastal observational techniques developed at the National Oceanography Centre use XBand radar to monitor critical or dynamic coastal zones, the key benefit being that this infrastructure is ubiquitous in the marine environment. The algorithms use radar clutter to derive inter- tidal bathymetry, surface currents and wave climate. This technique could be used to monitor beaches and build a spatially and temporally robust dataset of critical coastal areas. In many cases in-situ data can be used to validate models and longer time series will over time reduce uncertainties considerably.

We recommend therefore carrying out an assessment of options and costs for increasing marine observational monitoring around Jersey. This should be considered in collaboration with the Jersey Met Office, coastguard and harbour authorities, and take into account wider regional efforts such as those being carried out by IFREMER in Brittany.

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18 Appendix: Position Datum's

18.1 Jersey Transverse Mercator and local ordnance datum

GeoSurv Limited undertook a geophysical survey within the bays of St Aubin and Greve D'Azete, Jersey in 2012. Various datasets were collected including bathymetry within St Aubin bay. This was used to produce beach profiles that were used as part of the extreme event modelling undertaken by this report. National Oceanography Centre with the help of the Jersey Met Office also undertook some survey work in November 2016 that covered the top of the beach linking nicely with the survey data from GeoSurv. This section details the vertical and positional datum's used.

GeoSurv was asked to provide the survey data in Jersey Transverse Mercator (JTM) and NOC has copied this process. The parameters used to project the data from WGS84 datum to JTM was provided to both GeoSurv and NOC in the document; Position Transformation Date Survey Report on the Jersey Network and the Jersey Transverse Mercator Grid.

The position datum used by both GeoSurv and NOC was WGS84. Details of WGS84 are provided below:

Table 18: Parameters of WGS84

Parameter	Definition
Ellipsoid	WGS84
Datum	WGS84
Semi major axis	6378137.00 metres
Semi minor axis	6356752.314 metres
Flattening	298.257223563
Eccentricity Squared (e2)	0.00669437999

JTM parameters used to compute and collate the survey operations, position, data acquisition, data processing and all subsequent calculations are presented in Table 19:

Table 19: Parameters of JTM Projection

Parameter	Definition
Projection	Jersey Transverse Mercator
Latitude of origin	49.225^0
Longitude of central meridian (CM)	-2.135^0
False easting of origin (metres)	40000.000
False northing of origin (metres	70000.000

Parameter	Definition
Scale factor at central meridian	0.9999999

The vertical datum used by both the survey vessels used by GeoSurf and the vehicle used by NOC were obtained relative to the WGS84 reference ellipsoid and were subsequently reduced to Chart Datum (GeoSurv) and local Ordnance Datum (NOC). The relationships between Ellipsoid Datum, Ordnance Datum (local) and Chart Datum provided by GeoSurv are given in Figure A1.

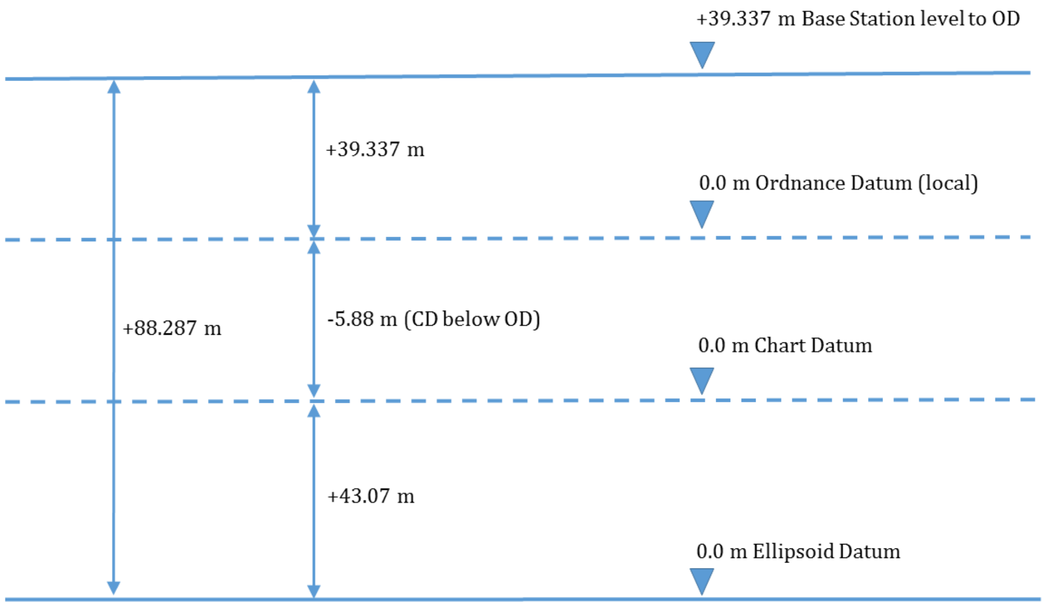

Figure A1: Ellipsoid Datum, Ordnance Datum (local) and Chart Datum relationship for Jersey, offsets provided by GeoSurv survey in 2012.

The relevant offsets were applied to the survey data collected by NOC and were found be in good agreement with the survey data collected by GeoSurv in 2012.

19 Appendix 2: Data Sources

Type of Data	Source
Wave Parameters	Jersey Wave Buoy (1996 – 2012) NOC (National Oceanography Centre) European Shelf Model
Sea Level	St Helier Tide Gauge: https://www.ntslf.org/ (1992 – 2015)
(Wave) Hindcast	SONEL: http://www.sonel.org/ (1900 – 2012)
Vertical Land Movement	SONEL: http://www.sonel.org/ (2001 or later - 2016)
Sea Level Trends	PSMSL: http://www.psmsl.org/ SONEL: http://www.sonel.org/ (1900 – 2016)
Sea Level Projections	NOC(National Oceanography Centre): (2010 – 2100)
GPS Beach Survey Data	November 2016 field visit
Bathymetry	GeoSurv: Surveyed 2012