Impacts of Sea Level Rise on wave overtopping rates around the coast of England

Dominic P. Hames, BEng, MSc, PhD, CEng, MCIWEM
Principal Engineer, HR Wallingford Ltd, Wallingford, United Kingdom, 0000-0001-9506-280xX
University of the West of England, Bristol
Isabel Vidal, MSc, GMICE
Coastal Engineer, Jacobs, Southampton, United Kingdom . 0000-0002-7433-2580.
*Ben P. Gouldby, BSc. (Hons)
Chief Technical Director, HR Wallingford Ltd, Wallingford, United Kingdom, 0000-0003-0415-5897
* Ben P. Gouldby, BSc. (Hons)
HR Wallingford, Howbery Park, Wallingford OX10 8BA, b.gouldby@hrwallingford.com, 01491 8222

Abstract:
There is unequivocal evidence that global sea levels are rising. It is therefore inevitable there will be socio economic impacts as a result of this. To aid mitigation, and the implementation of adaptation measures, it is vital the magnitude of the potential impact is quantified. Current approaches in the UK make simplifying assumptions regarding the relationship between present day and future economic damages relating to coastal flood risk. The analysis undertaken here supports studies of an improved impact of sea level rise by providing national-scale estimates of changes in wave overtopping rates and flood defence overflow rates, as a result of different amounts of sea level rise. The analysis involves the application of components of an existing risk-based coastal flood risk analysis method. A subset of almost 600 flood defence assets around the country have been analysed for sea level rise rates up to 1m. The resulting analysis shows that, on average, the wave overtopping rate increases by up to 150 times above present day rates for lower return periods and by up to 5 times for higher return periods. This differential arises as a result of non-linearities in overtopping rates with increasing extreme sea levels.

KEYWORDS: Climate change, Coastal engineering, Embankments

1 Introduction

It is well-established that sea levels are rising. Assessment of changes in sea levels over the 20th century are based on tide gauge records and, since 1993, satellite altimeter data. These indicate a linear trend of about 1.7±0.2mm/year over the period 1900-2009, which is approximately 1.9±0.4mm/year since 1961, Church and White (2011). Since 1993, when satellite altimeter data has been available, this rate has increased to approximately 3.3±0.4mm/year, https://sealevel.colorado.edu/. Sea levels are expected to rise in the future due to a combination of thermal expansion of the oceans as the climate gradually warms, and from an increase in freshwater caused by melting glaciers and melting ice on land. As a result, it is important to consider how mean sea levels are projected to change into the future, and how this may change the flood risk from the coast. Within the UK, Palmer *et al* 2018 give projections of sea level rise accounting for Isostatic effects based on information published in the IPCC reports.

Climate change impact analysis is used to motivate emission reduction targets and to support the development of mitigation measures (Committee on Climate Change, 2018). This type of impact analysis therefore has wide-ranging implications. It is therefore appropriate, in the context of coastal flooding, for this analysis to be undertaken using quantified calculations of the physical processes associated with sea level rise and related flooding. It is of note however that current sea level rise impact analysis is based upon a simplified assumption. More specifically, it is assumed that the likelihood of experiencing economic damage in the future, changes according to relationships (defined in terms of standard of protection) that link future economic damages to present day economic damages (Sayers *et al*, 2017). An example of these relationships is shown in Figure 1. These relationships directly govern the magnitude of sea level rise impact that is calculated. It is therefore vital for the integrity of the impact analysis, that they are based on sound evidence. They are currently based on an expert judgment analysis, with little underpinning evidence, undertaken around 15 years ago. Since that time there have been significant advances in terms of the data available and the methods implemented to analyse coastal flood risks (Gouldby *et al* 2014, HR Wallingford, 2015, Gouldby *et al* 2017).

This study seeks to utilise the updated data and methods to develop a robust approach to understanding the influence of sea level rise on wave overtopping rates. These results can provide a more robust basis for the analysis of future sea level rise impacts. The analysis here is based on a recently applied national scale flood risk analysis methodology. The methodology was originally applied to assess present day flood risks. The method, and accompanying data sets, have been applied here to assess the impact of sea level rise on wave overtopping rates. No assumptions have been made regarding the rate of sea level rise. Further work, beyond the scope of that undertaken here, is required to translate the changes in overtopping rates into sea level rise coastal flood risk impact assessment.

2 Methodology

2.1 Flood risk analysis methodology

The risk analysis methodology that underpins the sea level rise investigation detailed here is described in summary below, with full details provided in previous papers (Gouldby *et al*, 2014 and Gouldby *et al*, 2017).

The methodology involves multivariate extreme value modelling of offshore sea conditions. The inputs to this analysis comprise historical sea level information from the National Tide and Sea Level Facility (NTSLF). Wave and wind conditions were obtained from a hindcast of wave conditions using the WaveWatch III Model (WWIII), undertaken by the UK Met Office (Mitchell *et al.*, 2016). The output from the multivariate extreme value model is a monte-carlo data set comprising (many hundreds) of extreme sea conditions defined in terms of peak waves (height period and direction), winds (spread and direction) and sea level (combination of astronomic tide and surge).

The offshore extreme events were transformed to the nearshore (approximately a contour at -5m Ordnance Datum Newlyn (ODN)) using a combination of the SWAN 2D wave transformation model (Booij *et al.,* 1999) and a Gaussian Process Emulator (GPE, Kennedy *et al*, 2006). The GPE was fitted by first selecting a set of so-called design points (approximately 500 extreme sea condition events used to train the emulator) that cover the input data parameter space using a specific algorithm, the Maximum Dissimilarity Algorithm (MDA) (Camus *et al*, 2011 a and b). The SWAN2D model has been run for the set of design points with each "point" comprising an extreme event. The output results from the SWAN model simulations were then used for the emulator fitting.

Once fitted, the emulator was then used to replicate the SWAN model by transforming the entire offshore extreme event set to the nearshore (approximately -5m ODN). These nearshore data were then transformed to coastal structures with overtopping rates determined. The methodology adopted here used the method of Goda, 2000, for the surfzone transformation, and the EuroTop (Pullen *et al*, 2007) empirical formulae for the overtopping calculations, with beach levels assumed to remain unchanged as sea levels rose. EuroTop (Pullen *et al*, 2007) was used as the work described in this paper was undertaken before EuroTop, 2018 was published. This approach to determine overtopping levels contrasted with the earlier study that utilized the SWAN 1D wave model and the BAYONET (Kingston *et al*, 2008) overtopping model. The reasons for this related to the sub-set of structures that were identified (see Section 2.2). In summary, these structures were vertical walls or simply sloping structures, rather than more complex geometries and were hence amenable to the structure specific formulae within EuroTop. The resulting output of the analysis comprises a distribution of extreme overtopping rate, see example provided in Figure 2. The basis of this study was to explore changes in this distribution in relation to sea level rise.

2.2 Sea level rise impact method

The anticipated future rate of sea level rise is subject to significant uncertainties and there are a wide range of potential scenarios that can be adopted (Palmer *et al* 2018). The analysis here makes no assumptions or inference about the rate of sea level rise or likelihood of different scenarios emerging. The change in wave overtopping rates has simply been estimated for a specified set of sea levels at 0.1m increments, with a maximum of 1m. The results are therefore potentially widely applicable in studies that consider different rates of sea level rise under different scenarios.

Whilst it is understood that climate change could lead to changes in storminess and changes in dependencies between extreme waves and sea levels, there is currently little evidence to support quantified estimates of the magnitude or rate of these changes around the coastline of England (Palmer *et al*, 2018), despite some evidence of slight increases in winds in the North Atlantic since 1985, Young and Ribal (2019). For this study, it has therefore been assumed that there are no changes to the present day extreme sea conditions (waves, winds, surges and dependencies). The methodology could readily be refined to incorporate these changes in the future should this be required and should quantified evidence of these changes become available.

It is of note that increases in the depth of water as a result of sea level rise can influence wave transformation characteristics from offshore to the nearshore. In general terms however, the primary influence of sea level rise and related increases in depth, is in shallower water, where greater depth-limited waves can combine with increases in sea level to exacerbate coastal flooding. For this reason (and reasons related to the additional computational effort required), the sea level rise increases were applied to the nearshore data (approximately -5mODN contour). The assumption being that depth related changes in wave conditions in deeper water are minor relative to the changes in shallow water and wave overtopping rate . A sensitivity analysis was undertaken to test this assumption and the results of this are described in Section 2.4.

2.3 Selection of defences

To undertake the analysis a subset of defences around the coast of England was selected. This subset comprised a range of three structure types: vertical walls, shingle beaches and sloping embankments. The structures were chosen to ensure that they were subject to significant present day wave overtopping. This removed noise within the ratios that could have arisen through consideration of estimates of exceptionally low or high present day overtopping rates (i.e. overtopping of tidal flats or cliff protection structures that were not genuine flood defences were not considered). The location of the structures considered is shown in Figure 3. The relative proportion of each structure type comprised: 270 vertical walls; 288 embankments and 34 shingle beaches.

2.4 Testing of offshore to nearshore wave transformation impacts

To provide an indication of the influence of increased water depth on the wave transformation processes from offshore to nearshore, a sensitivity analysis was undertaken. The sensitivity analysis comprised applying a single sea level rise amount (1m) to the offshore sea conditions on the Southwest Coast (Falmouth and Polperro). This is the maximum sea level rise amount considered in the analysis and will have the most significant influence on the wave transformation processes in deeper water. The results of this test were compared with the approach of applying sea level rise directly to the nearshore (i.e. -5m ODN contour). Differences were compared in terms of nearshore wave conditions and subsequent overtopping rates as described below.

For the sensitivity analysis, the emulator was refitted, taking account of an increase in sea level of 1m. The offshore wave conditions were transformed to the two nearshore locations. The wave conditions at the nearshore location (-5m ODN contour) with the sea level rise of 1m added were compared to the present day (i.e. no sea level rise) nearshore wave conditions at the same location. This provided an indication of the influence of sea level rise on the transformation of waves from the offshore to the nearshore, and the resulting conditions at the nearshore. The results of the analysis are shown in Figures 4 and 5. These show a significant spread at Polperro (Figure 5), with both increases and decreases in wave conditions up to around 0.5m in wave height. These changes are a result of changes in levels of refraction and shoaling which can both increase and decrease as a result of changes in depth. Less spread is observed at Falmouth (Figure 4), where sea level rise appears to have little influence on the deeper water wave transformation processes and resulting nearshore wave heights.

The subsequent wave overtopping comparison (i.e. a comparison of wave overtopping rates with 1m sea level rise added at the offshore and nearshore respectively) is shown in Figures 6 and 7 for

Falmouth and Polperro respectively. These show negligible changes in overtopping rates at Polperro and approximately a 6% underestimate at Falmouth.

This analysis gives an indication of the influence of adopting the approach of applying the sea level rise to the nearshore as opposed to the offshore. Whilst it is recognised that in some locations greater influence may be observed, it is considered unlikely that this would significantly influence the overall findings of the study but further analysis is required to provide the evidence of this.

3 Results

The impact of sea level rise on wave overtopping rates has been expressed as a ratio of increase in overtopping rate for specific return periods. These have been averaged over all structures and by structure type. Confidence intervals have been calculated by analysis of the variance of the ratios for each group/sub-group of structures.

Figure 8 shows overtopping increase ratios for all structure types and for a range of return periods. It is striking that there is a considerable difference in the ratios between high and low return periods. Considering overtopping rates of a 1 year return period, the ratio of increase is around a factor of about 30 for 1m of sea level rise. Conversely it is a factor of about 10 for a 200 year return period. Figure 9 shows confidence intervals for the 10 and 1000 year return periods. These are approximately an order of magnitude and a factor 5 for the 10 and 1000 year return periods respectively The reasons for these differences between return periods relates to non-linearities in the overtopping response as a function of increased sea level and are discussed further in Section 4.

Figures 10-12 show the structure specific ratios. It is of note that these differ significantly with relatively low ratios for vertical walls (just over an order of magnitude for 1m of sea level rise at the 1 year return period). It is well-established that overtopping of vertical structures is non-monotonic and increases in sea levels can lead to lower overtopping rates at certain ranges of freeboard (Allsop, 2005). It is likely that this behaviour is influencing the relatively low increase in ratios, particularly at low return periods. For shingle beaches and sloping structures the equivalent ratios are approximately an order of magnitude higher. However, this does not take account of the potential increase of shingle beach crests in line with sea level rise which could reduce these ratios for shingle beaches.

4 Discussion

The analysis has shown a significant increase in wave overtopping and related coastal flooding, that can be expected with future sea level rise (keeping wave conditions constant). Perhaps the most significant finding relates to the expected increases in wave overtopping rates for relatively low return period events, when compared to significantly higher return periods. This result is an artefact of the nonlinearity in the overtopping response as a function of sea level. Figure 13 shows this relationship for a single structure. It is evident there is an exponentially increasing rate of overtopping up to a sea level of 3.8m. As the still water level approaches and exceeds the structure crest level the overtopping process switches to overflow and the rate of increase diminishes significantly.

There are many legacy structures around the coastline of England. These have traditionally been designed without the consideration of future sea level rise but with a significant freeboard, accounting for design wave conditions. Freeboard will diminish in the future with sea level rise. This diminishing freeboard will result in a disproportionate increase in wave overtopping rates for low return periods. Or, in other words, sea level rise is likely to disproportionately increase flooding and related economic and social impacts, associated with frequently occurring events, when compared to more extreme events. This is illustrated in Figure 14, which compares the current expert judgement approach (Sayers *et al*, 2017, shown in Figure 1) with the results of the quantified analysis undertaken here, for embankment structures under approximately 0.3m of sea level rise. This effect increases with greater levels of sea level rise.

The approach of applying the sea level rise to the nearshore, as opposed to offshore conditions, has significantly expedited the analysis undertaken here. Whilst there are benefits, in terms of the representation of the physical processes, to applying it offshore, sensitivity analysis indicates that this is unlikely to influence the generalities of the results shown here as the magnitude of influence is relatively minor when compared to the influence of sea level rise on the shallow water sea conditions and wave overtopping rates. Further sensitivity analysis would however, be required to demonstrate this unequivocally.

5 Conclusion

There is unequivocal evidence that sea levels are rising. There is however, significant uncertainty associated with the rate of sea level and potential future acceleration. There is little evidence to support climate change related increases in extreme sea conditions. This study has therefore focused specifically on assessing the impact of sea level rise on wave overtopping and overflow rates that lead to coastal flooding. No assumptions have been made about the rate of sea rise or future changes in extreme sea conditions. This approach, and the resulting outputs, can be used to inform climate change related impact studies. At present, these types of impact studies make simplistic linear assumptions regarding future impacts of sea level rise. This study has shown that these linear assumptions are inappropriate and can potentially underestimate future impacts.

The analysis here has been based upon a robust national-scale flood risk analysis methodology. The method involves the application of a multivariate extreme value model to offshore sea conditions, resulting in a large monte-carlo sample of extreme sea conditions. These extreme sea conditions have been transformed to the nearshore using a combination of the SWAN wave model and a Gaussian Process emulator. Sea level rise has been added to the nearshore conditions at increments of 0.1m up to a maximum of 1m. Sensitivity analysis indicates that the addition of sea level rise to the nearshore, as opposed to the offshore sea conditions has a limited impact on nearshore sea conditions and related overtopping rates.

The analysis has been undertaken on a subset of structures around the coastline of England. The subset comprises vertical walls, sloping structures and shingle beaches. The analysis shows that there is significant difference in the ratio of overtopping rate increase at low return periods when compared to high return periods. This is a result of the non-linearity of the overtopping response as a function of sea level increase. There is a marked difference in result between vertical wall structures, and sloping structures and shingle beaches. The ratio of increase is significantly less for vertical walls. This is because overtopping rate is a non-monotonic function of sea level for vertical structures. It is recommended that future impact studies consider these differences in structure types and return period overtopping ratios.

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