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COMBINING REGIONAL AND LOCAL SCALE COASTAL FLOOD RISK ASSESSMENT AND HAZARD MODELLING

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Abstract

This paper presents a method to combine regional- and local-scale flood risk assessment with numerical modelling of coastal inundation under sea defence breaching. We review existing coastal defence inspection reports, and by combining structure condition, deterioration, hinterland significance and inundation probability, we generate a risk score for each stretch of coastal defence in North Wales and North-West England. A frontage in North-East Wales deemed to be at high risk was used for a detailed hazard study using a flood model (LISFLOOD-FP), where a 0.5% probability flood was modelled under various sea-level rise and defence breaching scenarios. Flood hazard ratings given partial and total failure of the sea wall under present day, 2050 and 2100, and H++ sea-level scenarios are simulated to identify future flood risk to key infrastructure within the coastal community.

Key words: sea-level rise, sea defence breaching, flood hazard, flood risk assessment, flood modelling

1. Introduction

Increased frequency and magnitude of coastal inundation due to sea-level rise (SLR) threatens to rapidly change the nature of flooding in coastal communities worldwide (Anthoff et al., 2006). Informing effective coastal management requires flexible and practical approaches for realistic understanding of individual events as well as generic regional risk (Wadey et al., 2013). Flood risk assessments require a probabilistic, computationally efficient framework containing evaluation of various combinations of meteorological, tidal and sea defence conditions (Dawson et al., 2005).

EU Floods Directive 2007/60/EC dictates that risk maps of flood extent in human and natural environments along threatened coastlines should be created. The Environment Agency (EA) is responsible for assessing flood risk in England, with Natural Resources Wales (NRW) having similar responsibility for Wales since April 2013. The EA and NRW are responsible for strategic assessments such as Shoreline Management Plans (SMPs), which aim to implement strategies to alleviate flood risk regionally. These are often produced with input from local authorities (Environment Agency, 2009).

Functional failures result in flooding when wave and water level conditions exceed defence design standards. Structural failure occurs where defence components fail to perform as intended under design conditions (Reeve et al., 2009). Coastal defences in England and Wales are routinely inspected and maintained to alleviate risk of breaching, however overtopping often results in localised flooding (Wadey, 2013). There is often a lack of inundation detail in flood modelling specific to wave overtopping (Kortenhaus & Kaiser, 2009) and breaching (Morris et al., 2008). Given that inflow volumes to floodplains can increase by several orders of magnitude during sea defence breaching (Muir Wood & Bateman, 2005), understanding the impacts of different failure mechanisms on flood depth and velocity is critical for mitigating resultant flood hazard.

This study differentiates from other research by comparing inundation extents posed by different sea defence failure scenarios. This study aims to compare inundation extents from different sea defence failure conditions using LISFLOOD-FP (Bates et al., 2005), for a frontage identified from a regional flood risk

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assessment methodology. This study combines the need to better understand the consequences of inundation from breaching and a risk assessment for the frontage.

1.1 Study area

The study area to which the regional risk assessment methodology was applied extends from Glyn y Mor in North Wales to the Solway Firth on the Scottish border (Figure 1). The area encompasses many low-lying, expansive coastal floodplains, which play host to communities and critical infrastructure, such as Rhyl, Fleetwood and Sellafield.

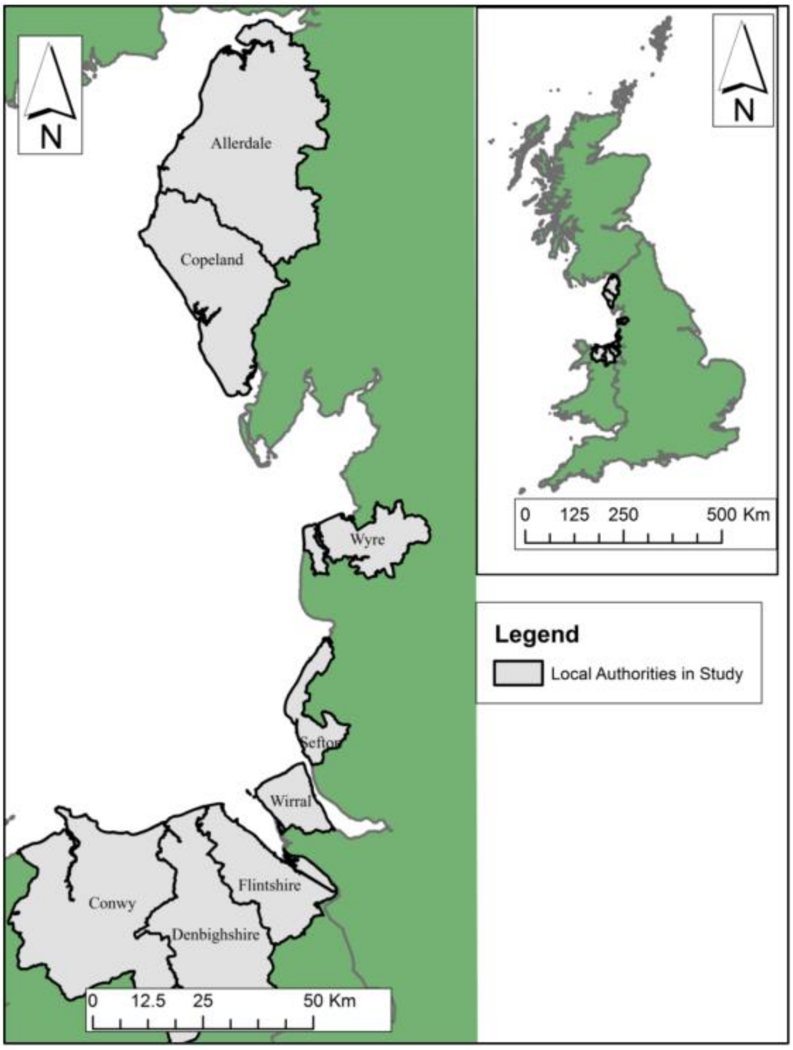

Figure 1: The study area for the regional flood risk assessment, from Glan y Mor in North Wales, to the Solway Firth on the Scottish Border, UK. Areas in grey represent local authorities for which coastal defence inspection reports are available

There is a significant interest in the energy security of this region, with nuclear energy infrastructure located at Heysham, Lancashire, and Sellafield, Cumbria. The Adaptation and Resilience of Coastal Energy Supply (ARCoES) project to which this research contributes, has developed an open source, web-based geospatial decision support tool to allow the energy sector and the coastal community to explore likely and high-end low probability future flood impacts.

For the numerical modelling aspect of this work, we use a frontage deemed to be at high risk when classified using our risk assessment method, which extends from Abergele to the Point of Ayr, in North-West Wales. The area experiences a macrotidal regime, with a mean high water spring tidal range of 6.7 m (NTSLF, 2007), and a wave climate dominated by, locally generated wind waves (of periods less than 10 s) from the North-West.

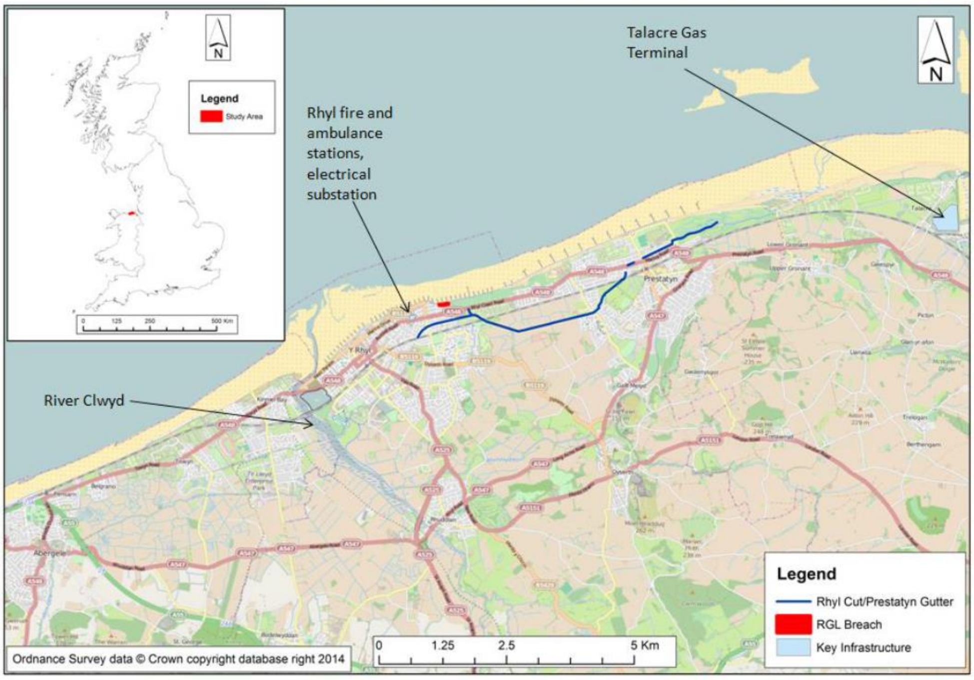

Figure 2: The frontage used in the numerical modelling aspect of this study, from Abergele (West) to the Point of Ayr (East) with the breach at Rhyl Golf Links (RGL)

From 26-28th February 1990, Towyn was inundated when 450 m of sea wall was breached by a 1 in 500 year extreme water level (EWL) (Dawson et al., 2003). Beach erosion intensified the impact of the storm surge to sea defences in Towyn. Resulting inundation reached 2 km inland at a maximum depth of 1.8 m due to the floodplain extent and elevation and caused approximately £50 million damage to property and agricultural land (HR Wallingford, 2003).

2. Methods

Here we describe our method of generating a risk score for each frontage, as well as the use of a flood model to provide detail of the impacts of coastal inundation at Rhyl Golf Links (RGL).

2.1 Regional scale flood risk assessment

Existing defence condition reports for the study area (Figure 1) by Coastal Engineering UK Ltd. (CEUK) and others were reviewed to gain understanding of where the most high risk coastal defences lie, and where breaches in these defences would lead to increased flood hazard. Structure condition and deterioration is determined according to National Sea and River Defence Surveys – Condition Assessment Manual published by the Environment Agency. Hinterland significance is determined in accordance with Defra regulations according to the indicative range of housing units per km of coastline. Each parameter is ranked from 1 (low risk) to 5 (high risk), and used as input in Equation 1 according to methodology developed by CEUK. Defining frontages for the purposes of coastal defence inspection is carried out by the local authorities according to changes in their structure, and do not represent fixed lengths.

$$Risk = Structure\ Condition \times Structure\ Deterioration\ \times Hinterland\ Significance \qquad (1)$$

The product of Equation 1 is then used to classify a frontage as low/medium/high risk following the thresholds and exceptions in Table 1 (Coastal Engineering UK Ltd., 2013).

Table 1: Classifying risk from a coastal defence frontage

Classification	Overall Risk Factor	Exceptions
High	>45	For a defence frontage to be high risk both structure scores should be > 3, and significance score should be ≥3
Medium	>20 - ≤ 45	
Low	<20	If a defence frontage scores ≤2 in both structure condition and structure deterioration it should be considered as low risk

In order to further assess flood risk, and to contextualize the risk in terms of coastal inundation, inundation probability value (Very low: 1 – High: 4) was designated according to the site's exposure, relief and proximity to other water bodies, using the Environment Agency's UK flood map (Table 2).

Table 2: Classifying inundation probability based on Environment Agency flood maps (Environment Agency, 2015)

Inundation Probability Value	Classification	Inundation Return Period
1	Very low	< 1 in 1000
2	Low	1 in 1000 – 1 in 100
3	Medium	1 in 100 – 1 in 30
4	High	> 1 in 30

$$Inundation\ Risk = Output\ from\ Equation\ 1\ \times Inundation\ Probability \qquad (2)$$

The overall inundation risk posed by a frontage is calculated as the product of the inundation probability and the risk score derived from Equation 1, and classified according to Table 3. Whilst this methodology is based on a simple integer scale, it provides a semi-quantitative overview of inundation risk based on available data regarding coastal defence inspection reports. Sources of error in this inundation risk index are likely to include inundation from inland water bodies being confused with coastally sourced flooding, and the associated uncertainty of the flood maps, which do not base their risk assessment on a particular mechanism of failure.

Table 3: Classifying an inundation risk status score from a coastal defence frontage

Classification	Overall Risk Factor	Exceptions
High	>100	If a defence scores 4 for inundation probability it should be considered as high risk.
Medium	>20 - ≤ 40	
Low	<20	If a defence length scores 1 for inundation probability, it should be considered as low risk.

Having applied this methodology to the areas highlighted in Figure 1, Rhyl (North Wales) was deemed to be at a high risk of inundation from a sea defence breach. A frontage encompassing Rhyl, and the other low lying coastal floodplains at Towyn and Talacre was used for further study of coastal inundation under sea level rise and sea defence breaching scenarios (Figure 2). Rhyl Golf Links was selected as the location to apply a breach, due to its poor condition rating, and during the December 2013 storms, a secondary flood gate behind the sea wall was breached, leading to inundation of several properties.

2.2 Inundation modelling using LISFLOOD-FP

LISFLOOD-FP is a two-dimensional inundation model based on a storage cell approach. The model is capable of accurately resolving coastal inundation (Bates et al., 2005) at a reduced computational cost compared to other models (Aronica et al., 2002). The model assumes that the free surface height difference between two cells controls the flood flow, and is capable of taking either time-varying water height (i.e. a tidal cycle) or time-varying discharge to represent river flow. The Towyn flood of 1990, described above, provided a means of validating the modelled flood extent using LISFLOOD-FP against observations, and was shown to yield an accuracy of 78%. Whilst there is likely to be considerable uncertainty in the wave overtopping rates (± 20 - 30%) provided by HR Wallingford (2003), Bates et al. (2005) estimate the error of the tidal curve to be ± 10 cm.

Boundary conditions were based on the data and methodology from McMillan et al. (2011). These EWLs have a confidence level of 0.2 m, and should be considered accurate to one decimal place. Applied boundary conditions are exclusive of waves, and represent still water (tide + surge) only. As the applied failure mechanism is defence breaching as opposed to wave overtopping, we have only considered the propagation of flood water due to the storm tide once it is in the domain. Given the macrotidal regime of the area, the EWL is expected to contribute the majority of the water volume to the area of inundation in a breach event, rather than waves overtopping the resilient sections of the defence. For these reasons, boundary conditions are sufficient for a breaching study. Excluding waves prevents the capture of increased scour at a structure's toe potentially causing it to become vulnerable to failure. Inclusion of a wave and morphological model was beyond the scope of this study, but has been considered in further research (Phillips et al., 2017). Here we consider scenario breaches of vulnerable sections and assess the hazard due to the breach water rather than wave overtopping along the full frontage of the defence.

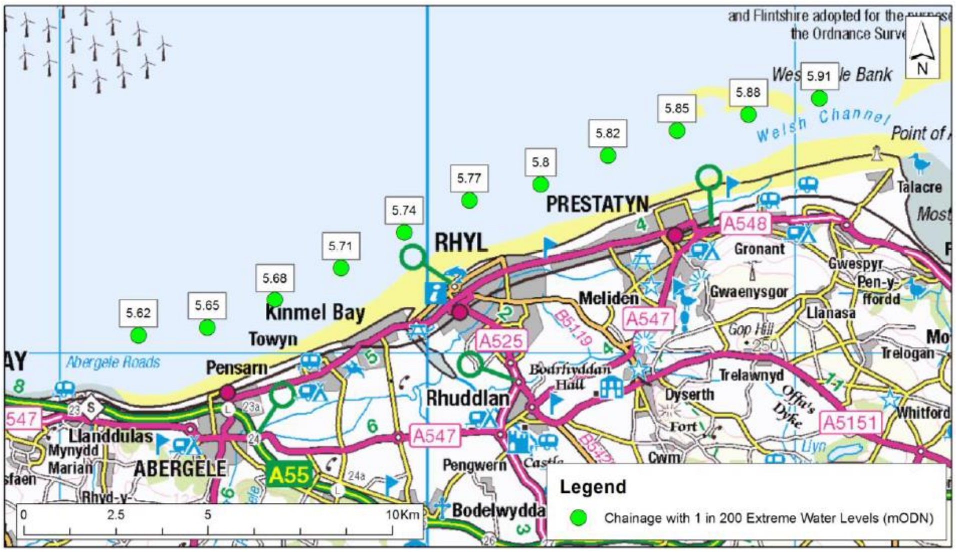

Figure 3: 0.5% probability extreme water levels for the frontage

For joint wave-water level conditions return period analysis provides a range of possible combinations that equate to a 1 in 200 year event. Here we are focusing on the EWL only. The selected return period for this study is a 0.5% or 1 in 200 EWL, as this is the defence standard for most urban areas (EA, 2015). Figure 3 shows the 0.5% probability EWLs as defined by McMillan et al. (2011) for the frontage. The water levels rise from West to East, and thus are highest around Talacre Gas Terminal. McMillan et al. (2011) also provided surge profiles to derive appropriate tidal curves during a base 100-hr storm surge, although they recognise that storm surge dynamics vary greatly depending on the EW event. This study utilised the surge profile and tidal data from the Llandudno tide gauge, as the EA state that this data should be used between Amlwch and the Point of Ayr. Deriving a surge elevation involved multiplying the normalised surge ratio at 15 minute intervals by the difference between the highest predicted astronomical tide (4.74 m ODN) and the 1 in 200 year EWL (see Figure 3). The surge elevation was then added to the tidal prediction to form time varying boundary conditions of total water level. This method was also used by Prime et al. (2015) to set up boundary conditions for LISFLOOD-FP in their study of Fleetwood.

The Digital Elevation Model (DEM) applied is derived from Light Detection and Ranging (LiDAR), and has a spatial resolution of 10 m. Breaches were integrated into the DEM by superimposing the new elevation value at the breach location within the DEM. Therefore the model integrated the following breach scenarios along 175 m of the 1587 m frontage:

- Breach 1 (BR1): A reduction in crest height of 1 m, simulating partial failure of the sea wall;
- Breach 2 (BR2): A reduction in crest height of 2 m, simulating the total collapse of the sea wall during a storm due to failure of the stepped toe.

In BR1, the mechanism of partial failure is likely to be excessive impact during overtopping causing loss of the top 1 m of the sea wall, with terminal scour likely to be responsible for complete collapse of the sea wall (BR2). The breaches were integrated into the simulation to occur just before the EWL at 35 hours and 15 minutes into the 99 hr simulation, with several tidal cycles following.

This study utilised 'medium emissions' SLR projections at the 95th percentile from the UKCP09 user interface, for 2050 (0.22 m) and 2100 (0.60 m), as well as the H++ scenario (1.9 m). The H++ scenario is a low probability, high impact range for maximum sea level rise in contingency planning and in considerations regarding the limits to potential adaptation. SLR greater than 1.8 m by 2100 is < 5% probable (Jevrejeva et al., 2014), but the H++ scenario provides a worst case scenario in terms of flood modelling and introduces significant concerns when planning for longer-term future sea level rise (Lowe, 2009).

To simulate sea defence breaching within LISFLOOD-FP, the model was run until the point at which the breach occurred. This output was then used to warm start the model with a suitable start depth, and ran for the remainder of the 99 hr simulation. Following Prime et al. (2015), inundation extent maps exclude water depths of < 0.05 m, to account for uncertainty in the DEM. Flood hazard rating (FHR) is calculated in Equation 3 as a function of water depth (d), water velocity (v), and debris factor (DF) following the Environment Agency methodology (Surendran et al., 2008). Table 4 classifies the flood hazard rating according to this value.

$$FHR = d \times (v + 0.5) + DF \tag{3}$$

Table 4: Flood hazard rating (FHR) classification

FHR Threshold	Degree of flood hazard	Description
< 0.75	Low	Caution – flood zone with shallow flowing or deep standing water
0.75 – 1.25	Moderate	Flood zone with deep or fast flowing water. Dangerous for some e.g. children
1.25 – 2	Significant	Flood zone with deep or fast flowing water. Dangerous for most people
> 2	Extreme	Flood zone with deep, fast flowing water. Dangerous for all

3. Results

3.1. *Flood hazard rating under present day sea level*

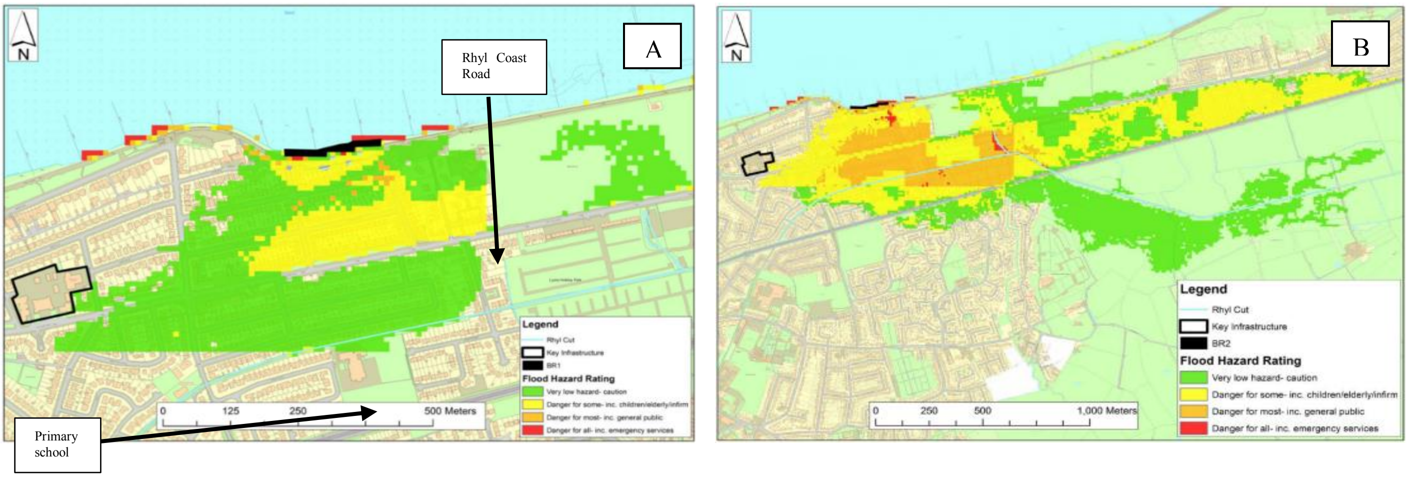

Figure 4: Flood hazard rating under BR1 (A) and BR2 (B) given sea level representative of present day

Figure 4 shows an important difference in flood hazard and flood extent between partial (BR1) and total sea wall failure (BR2). Inundation from BR2 extends to the south of the railway and could impact on additional residential properties, as well as the primary school (largely danger for vulnerable people) and agricultural land (although a very low hazard). More seriously, there is a potential flood hazard to residential property in the neighbouring town of Prestatyn, with most flooded parts posing a danger to vulnerable people. Under BR2, flood hazard to the Rhyl Coast Road significantly increases, with water depth increasing to 0.3 m and greater coverage to the east and south. Figures 4a and 4b show that properties on the south side of the Rhyl Coast Road could face deeper water than some areas closer to the frontage. Figure 4 demonstrates little risk to the key infrastructure given BR1 or BR2, and inspection of the DEM illustrates that these buildings lie < 1 m higher.

3.2 *Flood hazard rating under 2050 sea level*

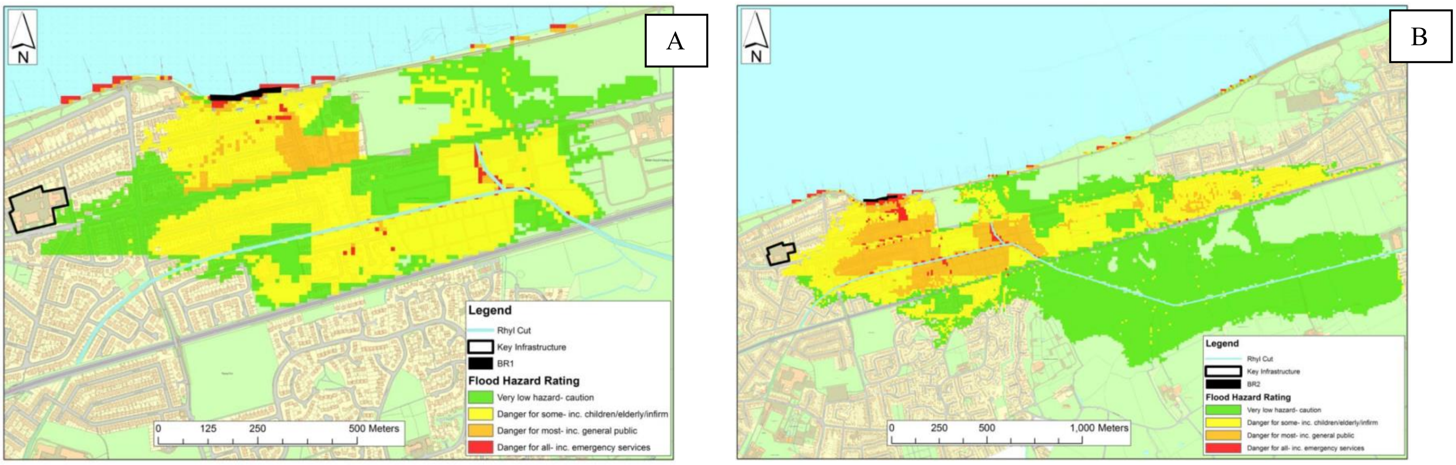

Figure 5: Flood hazard rating under BR1 (A) and BR2 (B) given sea level representative of 2050 (0.22 m)

Sea defence breaching under 0.22 m SLR has increased the inundation extent beyond present-day simulations (shown in Figure 5). The most significant difference is that BR1 in 2050 would cause inundation along a longer stretch of the Rhyl Coast Road, with the extent being comparable to the present-day BR2 scenario, and would likely flood up to the railway. However, the hazard to the Rhyl Coast Road (in BR1 and BR2, see Figure 5) remains very low, although FHR to properties in the south has increased from very low to danger for vulnerable people. Under BR2, water depths along the residential stretch of the A548 are approximately 0.6 m. FHR of properties closer to the breach has increased from present day, with areas experiencing danger for most under BR1 and danger for all under BR2. Danger for some includes children, so pupils at the primary school would be at risk given either breach scenario, although significantly higher under BR2. The increase in water depth from BR1 and BR2 to the fire and ambulance stations, as well as the electrical sub-station, in this SLR scenario, does not warrant a change in hazard rating. However, BR2 in 2050 would likely cause inundation of the railway, although is resistant to BR1.

3.3 Flood hazard rating under 2100 sea level

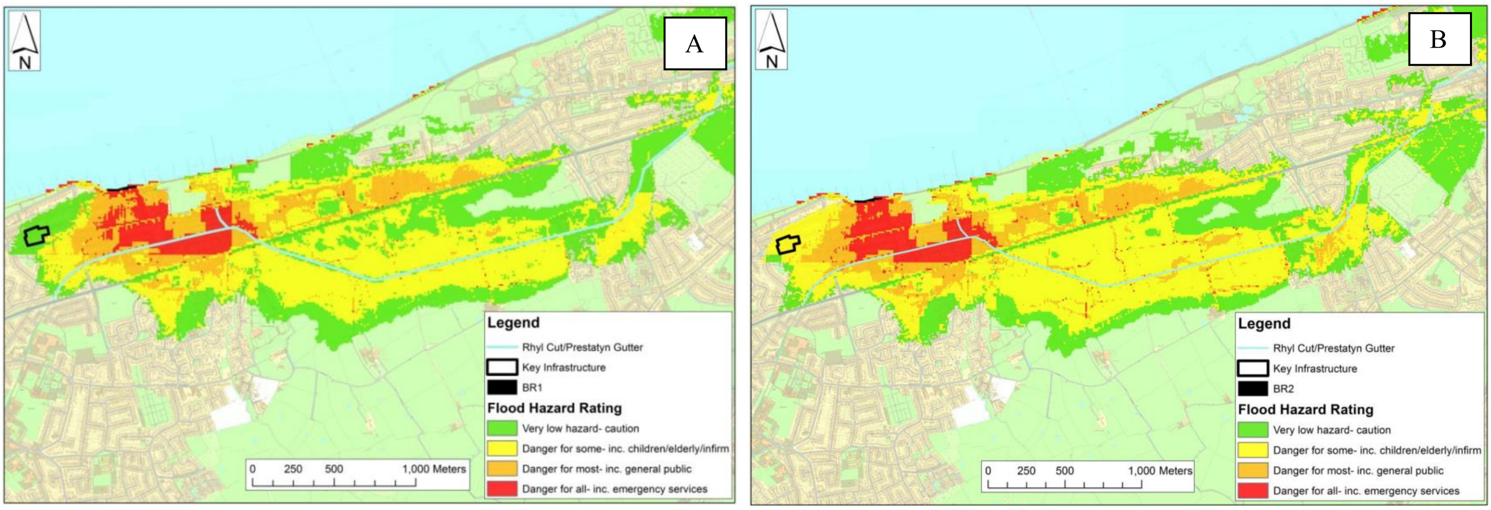

Figure 6: Flood hazard rating under BR1 (A) and BR2 (B) given sea level representative of 2100 (0.60 m)

Figure 6 illustrates that breach scenario impacts the overall flood extent negligibly, particularly to the south. BR2 has not significantly increased BR1's inundation extent, its main impact is to increase FHR, due to increased flood depth. This is particularly visible along the 175m length of the breach, as in BR2 the FHR is danger to all back to the Rhyl coast road. In both scenarios, there is a minimum FHR of danger for most in the residential area between the sea front and the railway. There are significant changes between the flood extents posed by 2050 and 2100 SLR scenarios. The most significant difference is that 2100 SLR has increased the western inundation boundary, resulting in inundation of Rhyl's key infrastructure during BR2, as illustrated in Figure 6b, to depths of 0.25-0.30 m and resulting in flood hazard classified as dangerous to some. Under BR1, the key infrastructure is also inundated but is classified as a very low hazard, with depths around 0.10 m.

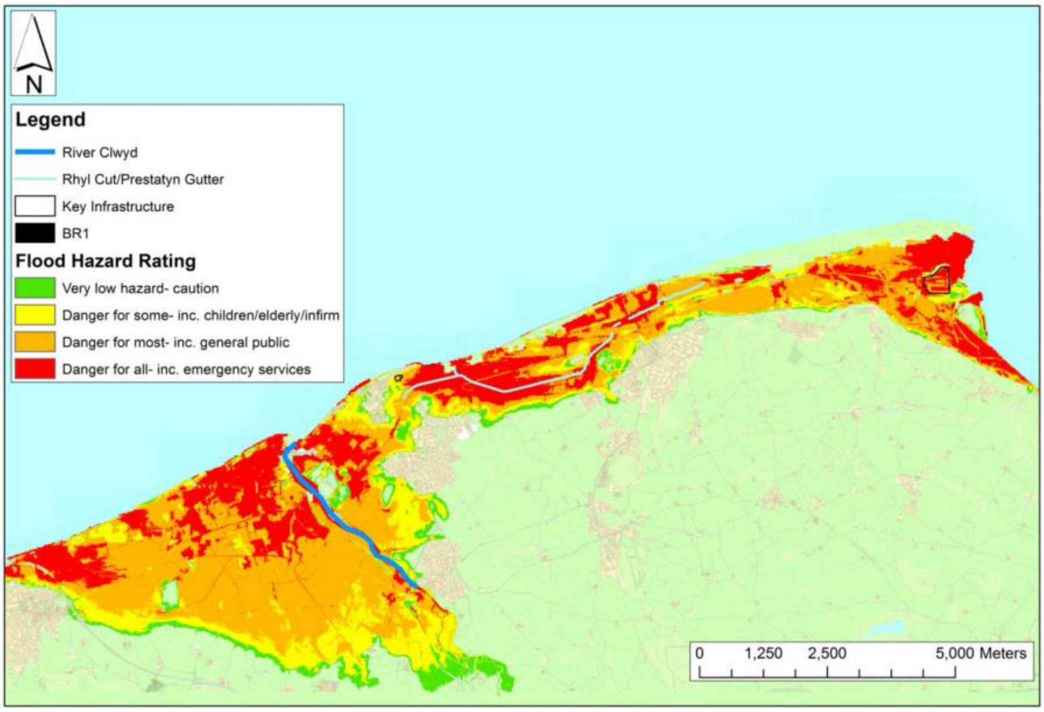

Figure 7: Flood hazard rating under the H++ scenario (BR1)

In Figure 7 (which shows the same model domain but from a regional perspective) , inundation is so extensive under the H++ scenario of 1.9 m SLR that it has completely flooded Towyn, Kinmel Bay and Pensarn, to the extent that most parts are dangerous to all. Any sea defence breaches are irrelevant, as effectively it has no control on inflow volume, and are highly likely to overtop given high spring tides alone. IEs and FHRs from BR1 and BR2 are identical, so only BR1 is illustrated. BR1 may flood slower than BR2, but this is insignificant given the flood magnitude. Additional areas of Rhyl and Prestatyn would flood, including key infrastructure such as a telecommunications mask in Prestatyn, and the hospital in Rhyl, although the surrounding electrical substation and gas works are resistant to the H++ scenario. Figure 7 shows high water depths to the south on the Dee Estuary, and thus inundation of the south-east corner is likely to result from propagation of existing floodplain inundation rather than through overflow of any other defences along the estuary.

4 Discussion

4.1 Flood Vulnerability Overview

This coastal floodplain is one of many regions of England and Wales at risk from increased coastal flooding. Whilst impacts can be largely contained given 0.22 m SLR, 0.6 m SLR represents the maximum threshold for the defences at Talacre and Talacre Gas Terminal (TGT), as well as key infrastructure at Rhyl. Inundation of this infrastructure is likely to have energy supply issues, both in the short term with damage to the electrical substation in Rhyl, and longer term with TGT being flooded. H++ would likely render Towyn, Kinmel Bay, Talacre, and most of Rhyl and Prestatyn uninhabitable, although the probability of SLR of this magnitude is <5%. Abergele is protected from inundation and long-term SLR due to its elevation.

This study assumes that future upgrade of sea defences to an increased crest height has not occurred. Figure 4 demonstrates a significant difference between inflow discharges during the present-day breach scenarios. As Figure 6a shows, the breach is negligible in determining the overall inundation extent given

0.6 m SLR, although results in deeper flood depths. However, Figure 6b demonstrates that FHR under BR2 is slightly higher in properties towards the seafront. Increases in FHR result from increased flood depth and/or velocity. This section demonstrates the lack of relative importance of a sea defence breach given future SLR in determining overall IE, particularly beyond 0.6 m SLR. However, FHR is shown to increase under BR2 regardless of SLR. In the context of existing defence levels, if sea defences are maintained regularly, the greatest flood risk would likely result from wave overtopping as a result of SLR. Given sea defence upgrades, the relative importance of defence failure would increase to present-day levels.

4.2 Comparison with other assessments of flood vulnerability

The most similar flood risk assessment with which a comparison can be made is the Denbighshire strategic flood risk assessment carried out by JBA Consulting (Keeble, 2014), and is visible in Figure 8. This flood risk assessment integrated a sea defence breach at Garford Rd., Rhyl and used a 1 in 200 year EWL, although used TUFLOW rather than LISFLOOD-FP. This makes it comparable to the model outputs in this study.

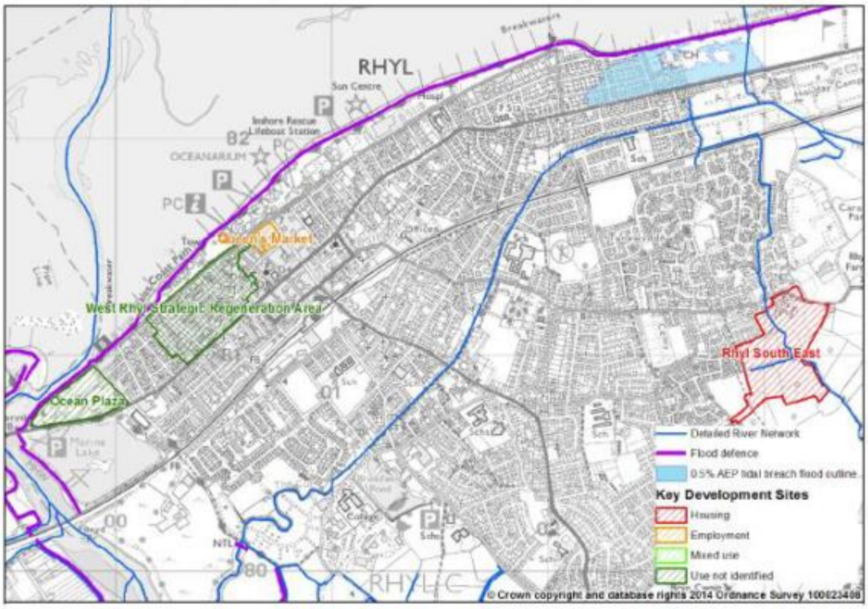

Figure 8: Garford Road Breach under a 1:200 year EWL (Keeble, 2014)

This study has provided the first high resolution tide-surge flood risk assessment for the region, where IEs and FHRs from multiple sea defence breaches have been compared. In many regions, exposure of people or property is usually assessed using coarse resolution models applied to a small number of events. There is a lack of high resolution studies of large areas using LISFLOOD-FP (Wadey, 2013). Similar research has been carried out by Wadey (2013) who carried out an integrative analysis of defences and inundation using the Solent as a case study. However, this work was primarily focussed on providing a framework and methodology for modelling events, and also used a wider range of sea defence failures such as overtopping. It provided no detailed impact assessment from a given flood event, merely assessed the number of properties at risk in settlements in the Solent.

4.3 Limitations

This methodology assumes that the surge profile remains constant in any given event across the modelled frontage, whereas realistically this is unlikely due to their nature. There are also uncertainties regarding the use of statistical models to derive extreme water levels, such as dependence on the quality of input data (McMillan et al., 2011). Another uncertainty is tide-surge interaction, as the peak surge is highly unlikely to coincide with the peak astronomical tide given the macrotidal regime of the frontage. Alternate research in Fleetwood has suggested that offsetting the peak surge by two hours either side of high tide does not significantly alter overall inundation extent (Prime et al., 2015). However, this conclusion cannot be safely extrapolated to this frontage.

The biggest uncertainty in this research can be assumed to be SLR. Results have shown that the importance of sea defence failure in controlling flood volume will diminish over time (assuming defences are not upgraded). Whilst there is a lack of sensitivity analysis of the impact of tide-surge interaction and surface roughness in this study, alternate research provided by Lewis et al. (2011) identified SLR as being the largest source of uncertainty. SLR is an uncertainty in itself, and even small deviations in sea level from the values used in this study, would likely significantly alter IEs.

5 Conclusions

This study has provided flood hazard ratings for North-East Wales in selected SLR and sea defence failure conditions at a finer resolution than what was previously available, although only one extreme water level return period was used. TUFLOW modelling has shown similar flood extents from a breach at Garford Rd. (likely due to the same LiDAR data being used), although differences in the outputs can at least partially be attributed to varying breach lengths. However, until such breaches actually occur and provide actual inundation extents, there is a lack of ability to validate both models, and datasets of wave overtopping volumes as they vary throughout a storm are rare, particularly under breaching scenarios. Sea defence breaches impact less on inundation extents after 2050, but increase flood hazard rating. This study has provided an effective method for combining structure condition, deterioration and hinterland significance from coastal defence inspection reports with Environment Agency flood maps to generate a flood risk score for the area. Such methods can be applied regionally to identify a frontage at risk, to further study using numerical models to determine future flood risk under sea-level rise and sea defence breaching scenarios.

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