National
Oceanography Centre
NATURAL ENVIRONMENT RESEARCH COUNCIL

National Oceanography Centre

Internal Document No. 16

The impact of tidal lagoons on future flood Risk on the North Wirral and Conwy coastline, UK

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2015

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DOCUMENT DATA SHEET

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PUBLICATION DATE 2015

TITLE
The impact of tidal lagoons on future flood risk on the North Wirral and Conwy coastline, UK.

REFERENCE
Southampton, UK: National Oceanography Centre, Southampton, 88pp.
(National Oceanography Centre Internal Document, No. 16)
(Unpublished manuscript)

ABSTRACT

This report considers the viability of tidal lagoons in the North Wirral and Conwy coastlines, to mitigate future flood risk and reduce the cost of damage in these areas. The report is aims to provide information on the feasibility and benefits of tidal lagoons as mitigation and adaptation strategies to future sea-level rise, as part of the RISES-AM project.

Sea-level has been rising since instrumental records began in the 1700s, and has been rising at a rate of 3.0 ± 0.7 mm / yr-1 since 1990 (Hay et al., 2015). Low probability, plausible high-end sea-level rise scenarios, where global average warming exceeds 2^{o}C in respect to the pre-industrial level, estimate up to 0.98 m sea-level rise (SLR) by 2100 (Church et al., 2013). There is a move away from hard defences in favour of strategies which can mitigate flood risk benefit and allow coastal communities to adapt to and benefit from high-end SLR scenarios (Linham and Nicholls, 2010). Tidal lagoons could be one such innovative option.

The report aims to assess the impact of the construction of tidal lagoons on flood risk on the North Wirral and Conwy coastline, under future high-end sea-level rise scenarios. Computer simulations of extreme flood events, using a 2D hydrodynamic model called LISFLOOD, will estimate changes in the extent and depth of flooding following the construction of a lagoon under both present day and future extreme climate conditions. The results of LISFLOOD suggest that:

- Colwyn Bay and the North Wirral coastline are not areas at increased flood risk under baseline future high-end SLR, due to steep topography and existing defences.
- Infrastructure at Stanlow oil refinery and Connah's Quay in the North Wirral domain and residential areas in the Colwyn Bay domain at Llandudno, Rhyl and Prestatyn experience increased flood risk under RCP 4.5 (0.72 m SLR) and RCP 8.5 (0.98 m SLR) with no tidal lagoon. This is due to low-lying topography.
- The presence of a tidal lagoon on the North Wirral provides flood risk benefit to infrastructure at Stanlow and Connah's Quay as the magnitude of tidal currents is limited through the Dee and Mersey Estuary. However the size of the lagoon and the bathymetry of Liverpool Bay may mean the lagoon in this study may not be financially feasible.
- The construction of a tidal lagoon at Colwyn Bay increases extent and depth of inundation at Llandudno, Rhyl and Prestatyn under all sea-level rise scenarios. Increased flood risk in these areas following the construction of a tidal lagoon is reason enough not to build a lagoon in this location.

Tidal lagoons have the potential to offer flood risk benefit and become part of integrated strategies to minimise flood risk in coastal areas. The benefits of tidal lagoons are dependent on their shape, size and location, and feasibility studies should consider impacts in the near- and far-field.

KEYWORDS

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Introduction

This report aims to explore the viability of tidal power lagoons in North-west England and North Wales. The report will highlight the threat of high-end sea-level rise scenarios to coastal communities, and consider adaptation and mitigation strategies to minimise the extent and depth of inundation and cost of damage from flood events. A high-end scenario is when global average warming exceeds 2^{o}C in respect to the pre-industrial level (Church et al., 2013). This report will investigate tidal lagoons as innovative, 'green' options to renewable energy generation. This report intends to provide information for use by the above named organisations, and others, as to the benefits of tidal power lagoons to mitigate flood risk and reduce the cost of damage to coastal communities in the North Wirral and Colwyn Bay. The report will investigate the effectiveness of tidal lagoons to minimise the risk of inundation and reduce the impact and damage from flood events under present-day and future high-end sea-level conditions. The project will allow for the quantification of impacts to address present issues and anticipate future challenges (RISES-AM, 2015). The recommendations contained within this report cannot guarantee prevention of coastal flooding in all situations, and instead should be used as the basis for formulating bespoke adaptation strategies for each location.

Aim

The aim of this project is to quantify and assess the impacts of land-attached tidal lagoon adaptation options on likely extent of coastal inundation and protection on the North Wirral and Colwyn Bay coastline. High resolution modelling of potential flooding is undertaken to inform RISES-AM on the feasibility of mitigation and adaptation options to extreme sea-level rise scenarios.

Objectives

- To use LISFLOOD to conduct high resolution modelling to identify likely change in water depth, extent of inundation and protection on the North Wirral and Colwyn Bay coastline. Scenarios will model coastal inundation with and without a tidal lagoon, under present-day sea-level conditions and a series of future extreme coastal sea-level scenarios.
- To create depth damage curves on the North Wirral and Colwyn Bay coastline to quantify cost of each extreme scenario, to quantify the cost of damage of each scenario.
- Inform RISES-AM about the extent of likely near- and far-field impacts from tidal lagoon adaptation options on the North Wirral and Colwyn Bay coastline.

Sea-level rise

Sea-level has been rising over the period of instrumental record, since approximately 1700, and is projected to accelerate into the next century and beyond (IPCC, 2007; Church et al., 2013). As a result of analysis of tide gauges and satellite altimetry data, it is estimated that sea-level rise (SLR) accelerated from 1.2 ± 0.2mm from 1901 to 2009, to 3.0 ± 0.7mm from 1993 to 2010 (Hay et al., 2015). However uncertainty in the sea-level budget remains, and the discrepancy in the distribution of tide gauges and their period of record means that rates of past SLR may never be fully accounted for (Gehrels, 2010; Grinsted et al., 2015). Regardless, observational records can inform scientists on how sea-level could respond to human-induced climate change in the future.

Rate of future sea-level rise

Future global mean sea-level rise (GMSLR) is one of the more certain and damaging aspects of human-induced climate change (Anthoff et al., 2009). GMSLR is projected to accelerate into the twenty first century, caused primarily by thermal expansion and melting of land ice (Church et al., 2013). The Intergovernmental Panel on Climate Change (IPCC) AR5 report, released in 2013, provides sea-level projections up to 2100 covering a likely range (66%) with medium confidence (Jevrejeva et al., 2014a). Four Representative Concentration Pathways (RCPs), associated with temperature changes up to 6^{o}C in respect to the pre-industrial level, are calculated by simulating contributions from sea-level components (Table 1) (Church et al., 2013).

Table 1: Median values and likely ranges for projections of global mean SLR (m) in 2100, relative to 1986 – 2005 for four RCP scenarios (Church et al., 2013).

Climate scenario	Median (m)	Likely range (m)
RCP 2.6	0.44	0.28 – 0.61
RCP 4.5	0.53	0.36 – 0.71
RCP 6.0	0.55	0.38 – 0.73
RCP 8.5	0.74	0.52 – 0.98

There is great uncertainty surrounding the rate of future SLR. Thermal expansion and ice cap melting will contribute to GMSLR, while the growth of Antarctica and increased terrestrial storage may limit the rise (Church and White, 2006; Lichter et al., 2011). Uncertainty surrounding future GHG emissions and the response of global ice sheets to increasing temperatures means SLR may lie outside the stated likely ranges (Jevrejeva et al., 2014a). Ongoing localised vertical land movement, glacial isostatic adjustment, will also add uncertainty to future SLR (Nicholls et al., 2014). Although there is a great deal of regionally variability in the measured values, mean sea-levels around the UK exhibit rises that are mostly consistent with the global figure (Woodworth et al., 2009).

It can be inferred from AR5 that there is a 34% chance that future SLR projections may be higher than the values shown in Table 1 (Jevrejeva et al., 2014b; Grinsted et al., 2015). Studies that are based on the relationship between sea-level and air temperature suggest that SLR may exceed 1 m (Rahmstorf, 2007; Grinsted et al., 2009). Jevrejeva et al. (2014b) use a probability density function to estimate there is < 5% probability that sea-level will rise above 180 cm (Figure 1). The UK Climate Projection (UKCP09) report estimates 0.93 m to 1.9 m SLR by 2100a in a low-probability sea-level range (H++ scenario) for contingency planning purposes (Lowe et al., 2009). These projections suggest a rise in sea-level above the likely range, and focus on high-end scenarios, where global average warming exceeds 2°C in respect to the pre-industrial level (RISES-AM, 2015). Estimation of low probability but plausible future SLR projections is crucial for long-term decision making in coastal areas (Jevrejeva et al., 2014a).

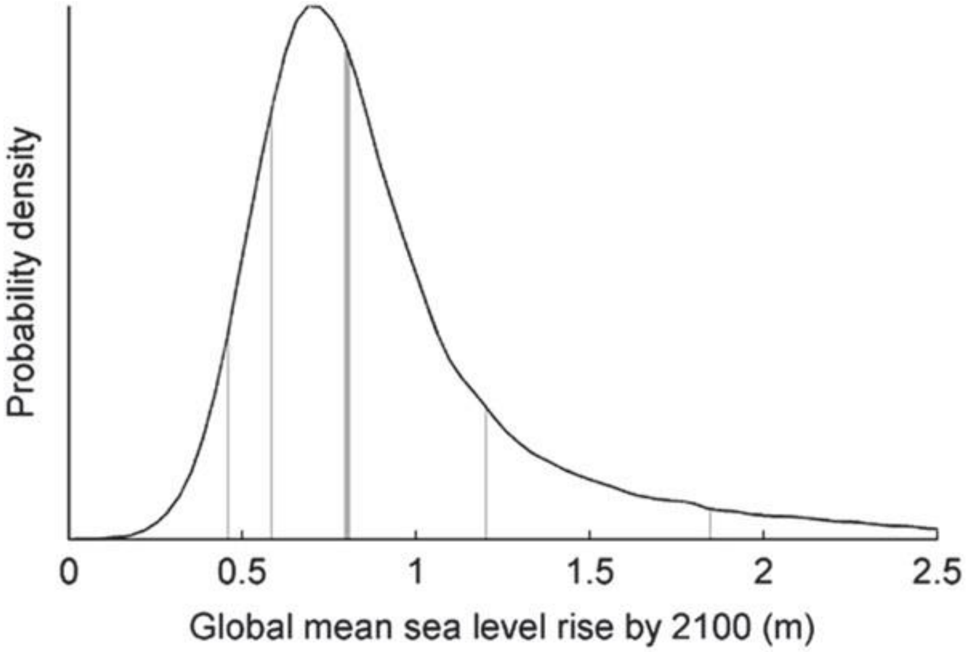

Figure 1: Projected global mean SLR by 2100, relative to 2000, for RCP 8.5 scenario and uncertainty. Grey bars indicate 5, 17, 50, 83 and 95th percentile uncertainty (Jevrejeva et al., 2014b).

Impacts of future sea-level rise

GMSLR will drive physical and socio-economic impacts in densely populated coastal areas (Small and Nicholls, 2003; Nicholls et al., 2014). 150 million people live within 1 m of mean sea-level and 35% of global GDP is located within 10 m of mean sea-level (McGranahan et al., 2011; Hinkel et al., 2014). Coastal populations are threatened by SLR because of reduced return periods and increased frequency and magnitude of coastal flooding. Coastal flooding is defined by the Flood and Water Management Act 2010 as “any case where land not normally covered by water becomes covered in water”. The flood frequency curve, shown in Figure 2, illustrates that increasing sea-level by 0.5 m causes extreme water levels (the combined effect of tide, surge and mean water levels known as storm tides) to occur every 65 years, reduced from 100 years (McInnes et al., 2003; Wong et al., 2010). Increased frequency and magnitude of extreme events will cause degradation and damage to coastal environments and natural defences, such as salt marshes and sand dunes, potential saltwater intrusion and long term erosion and habitat loss (Nicholls et al., 1999; Lichter et al., 2011).

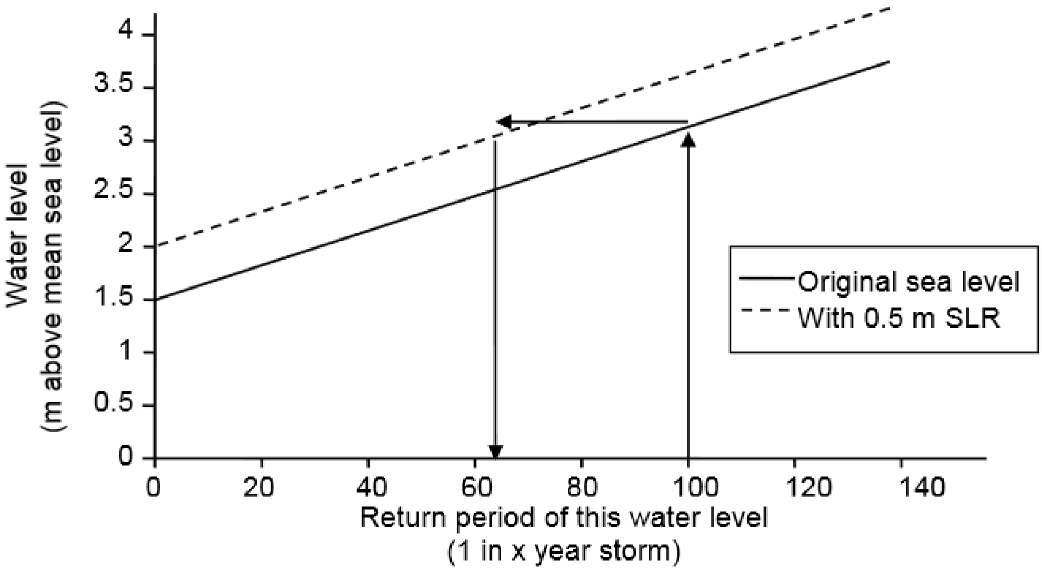

Figure 2: Increase in the probability of extreme water levels occurring as a result of SLR, without adaptation (Linham and Nicholls, 2010).

There is a need to reduce the risk of coastal flooding over time (mitigation) and to reduce the impacts from flood damage and to minimise land loss (adaptation) (DEFRA, 2012; Nicholls et al., 2014). Without protection in coastal areas, up to 187 million people may be displaced due to land loss, assuming GMSL rises between 0.5 m to 2.0 m by 2100 (Nicholls et al., 2007). Through appropriate risk management and intervention, it is possible to increase the resilience of coastal areas to flood events (Environment Agency, 2009a). This can be achieved by upgrading existing, natural defences to continue to provide flood defence to coastal communities (Linham and Nicholls, 2010). In addition to this, artificial, hard defences have the potential to provide protection from extreme water levels up until the point the defence fails and overtopping occurs (Nicholls and Cazenave, 2010). However responses to the effects of SLR in coastal areas will not be universal and strategies should be tailored to individual locations (Anthoff et al., 2010). The impacts of extreme SLR will require intervention in coastal regions to reduce flood risk over time and damage to properties, infrastructure and industry (Wong et al., 2014).

Mitigation of and adaptation to sea-level rise in coastal areas

The Flood and Water Management Act (2010) calls for UK strategies for coastal flood management and protection to move away from dealing solely with hard defences and drainage, and towards sustainable, innovative approaches to work with and adapt to natural processes. Mitigation aims to increase the resilience and resistance of coastal populations, to reduce flood risk over time (Nicholls et al., 1999; Fitzgerald et al., 2008). Adaptation to extreme future SLR aims to reduce the costs and damage of SLR, and take advantage of economic opportunities (Tol et al., 2008). Adaptation and mitigation strategies should consider extreme SLR projections that lie above the likely range estimated by the IPCC estimated by the IPCC (Hinkel et al., 2013; Grinstead et al., 2015). Adaptation offers a tool box of multi-disciplinary interventions and technologies which cover knowledge, equipment and experience to mitigate the consequences of SLR, and exploit potential benefits (Table 2) (Arnbjerg-Nielsen et al., 2015). Adaptation consists of more than implementing one specific strategy or technology, and can include capital goods (seawalls and dikes), knowledge, capacity building and strategic development (Linham and Nicholls, 2010). Adaptation strategies can be tailored to local conditions, as evident with the broader, holistic Delta Project, Netherlands (Van Koningsveld et al., 2008; Brown et al., 2014). Mitigation of and adaptation to SLR is an ongoing process, requiring continuous review to minimise coastal vulnerability, but complete protection from coastal flooding and erosion is not feasible (Wilby and Dessai, 2010).

Table 2: Options for adaptation (Dronkers et al., 1990).

Options for adaptation	
Protect	Defend vulnerable coastal areas, with a particular focus on population centres, economic activities and natural resources through the use of hard defences.
Accommodate	Coastal communities continue to occupy areas vulnerable to coastal flooding and erosion, but measures are taken to accept greater degree of flooding by changing land uses, construction techniques and improving community preparedness.
(Planned) retreat	Abandon vulnerable coastal areas and inhabitants resettle in areas of new development back from the shoreline.

Responses to Climate Change: Innovative Strategies for High-End Scenarios, Adaptation and Mitigation

Responses to Climate Change: Innovative Strategies for High-End Scenarios, Adaptation and Mitigation (RISES-AM), an EU-wide project led by UPC Barcelona, aims to assess the vulnerability of coastal ecological and economic systems at local, regional and global scales across the full range of emissions (RCP) and socio-economic (SSP) pathways (RISES-AM, 2015). The project focuses on high-end scenarios, where global average warming exceeds 2^{o}C in respect to the pre-industrial level, in vulnerable areas and will allow for the quantification of impacts to address present issues and anticipate future challenges (RISES-AM, 2015).

The project aims to highlight the advantages of adaptation measures as flexible options for coastal management, with novel, 'green' options as part of adaptative pathways (University of Southampton, 2015). Assessment of impacts and deficits of adaptation and mitigation strategies will be based on computer modelling tools to allow for comparisons. However, trade-offs may have to be made between mitigation and adaption to balance multiple land uses and interests and avoid socio-economic and ecological tipping points (Helmholtz-Zentrum Geesthacht, 2015). The results of the project will inform decision- and policy makers on the affordability and achievability of adaptation and mitigation measures to facilitate integrated management and legislation in the face of future change.

The National Oceanography Centre, Liverpool, is operating a RISES-AM case study from Great Orme's Head to Southport, known as subcell 11a of the Shoreline Management Plan (Halcrow, 2011). This project will assess the impacts of the implementation of adaptation measures in this subcell. Adaptation and mitigations strategies should aim to reduce flood risk and provide benefits to coastal communities, a tidal lagoon will be considered as a novel intervention or 'green' option.

Tidal lagoons as adaptation options

Tidal lagoons are engineered impoundment structures that generate clean, renewable energy and can provide protection from coastal flooding (Frid et al., 2012). A tidal lagoon may be offshore or land attached to form part of the shoreline, and is expected to have a 120-year infrastructure lifespan (Ahmadian and Falconer, 2012). Notable tidal projects around the world include barrages at Sihwa Lake (254 MWh) in South Korea and La Rance in France (240 MWh). However, barrages are known to have detrimental effects on local environments, and a higher cost of deployment (Hogan et al., 2014). Tidal lagoons offer a permanent flooding solution as well as clean energy generation (Wolf et al., 2009).

Tidal lagoon power concept

The World Energy Council (2010) states that if less than 0.1% of the renewable energy within the ocean could be converted into electricity this would satisfy the present world demand for energy more than five times over. The tidal power lagoon approach to energy generation utilises the predictable nature of the tides (Figure 3). This allows for reliable energy generation 14 hours a day, through the gradual release of impounded seawater through sluices and turbines (Figure 3) (O Rourke et al., 2010; Kadiri et al., 2014). Tidal power lagoons will most likely provide protection to areas at risk of inundation in much the same way as hard defences, e.g. seawalls. Seawalls act to dissipate and deflect incoming waves and can also minimise erosion risk (Linham and Nicholls, 2010).

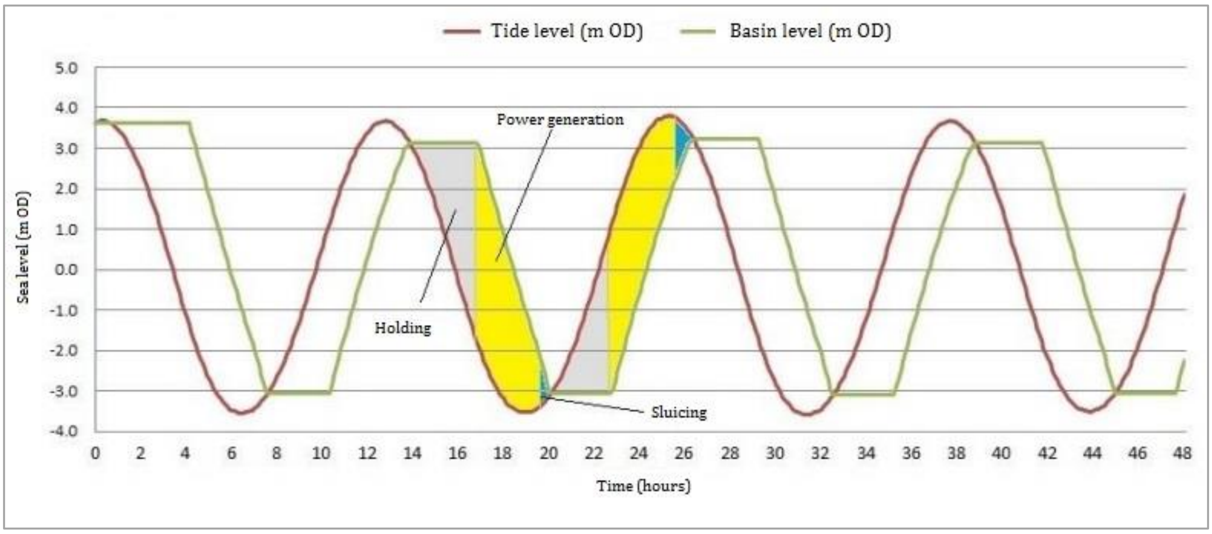

Figure 3: 48 hour tidal lagoon power generation sequence, including holding and sluicing (TLSB, 2014a).

Tidal lagoon structures have low-head hydroelectric turbines built into a power house with the capacity to produce clean, renewable energy (Cornett et al., 2013). Tidal lagoons can generate power in three different modes; ebb generation, flood generation and two-way generation (Cousineau et al., 2012). Water levels within the lagoon are controlled to create the necessary 'head' difference to allow for maximum power generation (Hogan et al., 2014). Therefore two-way power generation on the flood and ebb tide creates the largest power output (Burrows et al., 2009). The potential power generated by tidal range structures can be expressed as:

$$P \propto AH^2$$

where P = potential generated power, A = wetted impoundment surface areas and H = head difference across the impoundment wall (Denny, 2009). Consequently the optimal location for tidal range structures is locations with large tidal ranges (Kadiri et al., 2012). The electricity produced from tidal lagoons is thought to be cheaper than offshore wind and similar in cost to nuclear energy, and resolves the environmental concerns associated with tidal barrages (Johnstone et al., 2013).

Impacts of tidal lagoons

The impact of tidal lagoons on the environment is dependent on lagoon size, shape, operating mode and number of lagoons (Polagye et al., 2010). Much of the current literature on the impacts of tidal power projects focuses on the impacts of proposed tidal barrage schemes e.g. Severn Barrage, which fell through due to the potential ecological impacts (Kirby and Shaw, 2005; Frid et al., 2012). The impacts of tidal power lagoons can be assumed from this literature, and information obtained through modelling of coastal environments (Neill et al., 2009; Xia et al., 2010a).

Tidal power generation through the installation of tidal stream turbines in the water column, placed directly on the sea floor, will likely alter coastal habitats, sediment dynamics and water column processes at a local and regional scale (Kirby, 2010; Frid et al., 2012). Changes to sediment dynamics and water column processes will subsequently alter benthic substrate and water quality (Cornett et al., 2013; Shields et al., 2011). Tidal amplitude, current velocities and wave height are likely to be altered, causing local scouring and potential resuspension of contaminated sediments, resulting in overall net reduction in water quality (Wolf et al., 2009; Kadiri et al., 2012;). Energy extracted from interactions between quarter (M4) and semi-diurnal (M2) currents will increase tidal amplitude, which can exacerbate coastal flooding (Wolf et al., 2009; Neill et al., 2012). Dual mode energy generation will alter the exposure of intertidal areas, as upper intertidal areas are submerged for a longer period therefore shifting the balance of exposure for local species (Crumpton, 2004; Polagye et al., 2010). All effects are to a large degree dependent upon the mode of operation of the lagoon and are site specific.

All impacts of implementation of tidal power projects feedback into one another, as a result of the dynamic nature of coastlines and change in processes a tidal power project can bring. Falconer et al. (2009) modelled hydrodynamic changes in the Severn Estuary following construction of a barrage and a lagoon, and found that maximum currents upstream of the barrage decrease over a large area, but the lagoon only causes a small decrease. Modelling has been used to show that tidal energy extracted from tidal asymmetry exacerbates impacts on sediment dynamics, than energy extracted from tidal symmetry (Neill et al., 2009). 2D model simulations have shown that the implementation of a barrage will reduce the predicted suspended sediment levels from 1200 mgl^{-1} to 200 mgl^{-1}, potentially due to changes in tidal current velocities. Full analysis of potential impacts on local environments is required before the implementation of any tidal power projects.

Tidal lagoons in the UK

The UK is becoming increasingly dependent on imported fuel from politically unstable parts of the world and UK gas production has fallen 64% since 2000 (Denny, 2009). Tidal lagoon power will give the UK the ability to achieve the Government's low carbon targets to reduced GHG emissions by at least 80% by 2050 compared to 1990 levels, and obtain 15% total energy from renewable resources by 2020 (Cobb, 2011; Hogan et al., 2014). The UK has a distinct advantage in having some of the largest tidal range resources in the world and suitable locations for tidal power generation (Figure 4). The 120-year lifespan of a tidal lagoon will generate clean power, provide value added from wider industrial benefits and reduce fossil fuel imports by as much as half a billion pounds per year by 2027 (Yates et al., 2013).

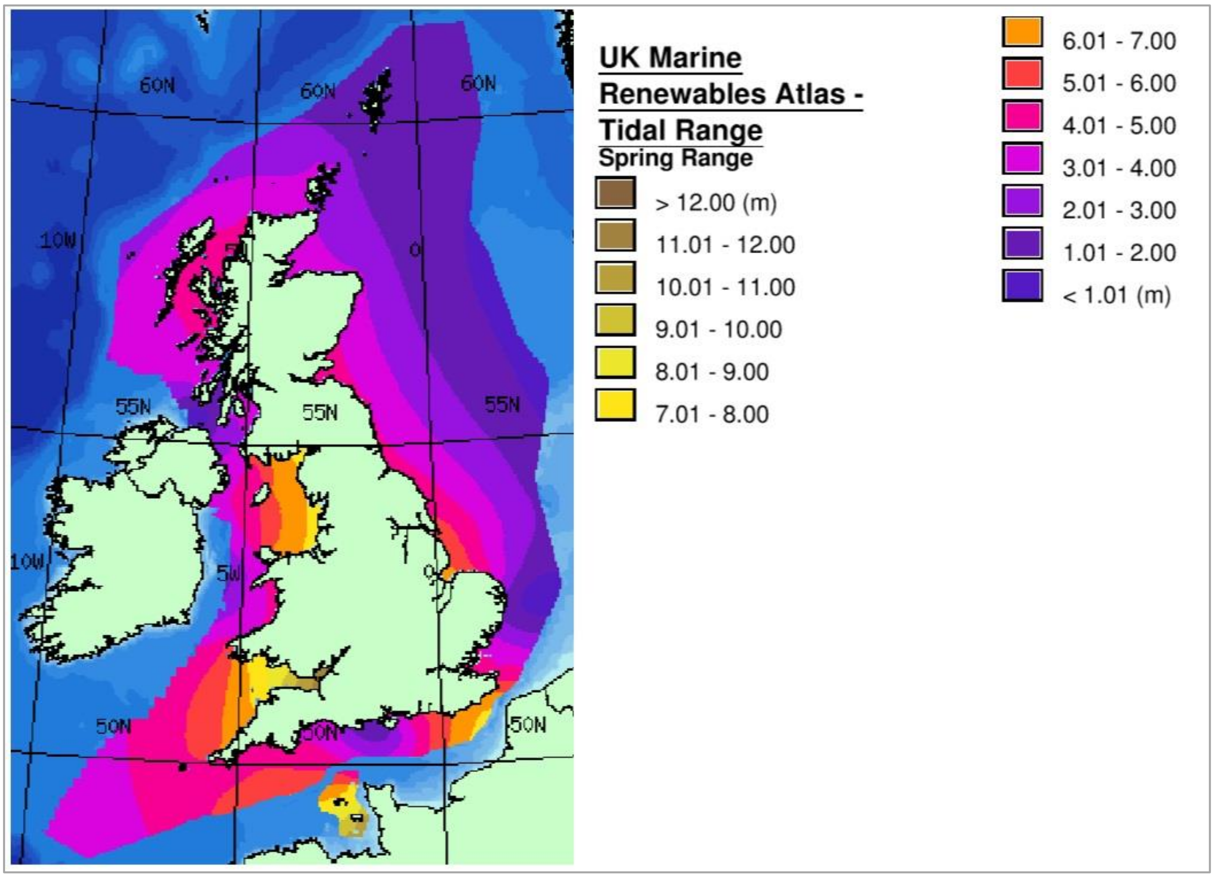

Figure 4: Mean spring tidal range in the UK (ABPmer, 2015). Yellow to brown areas indicate largest tidal range, and most suitable locations for tidal lagoons.

The UK Government announced plans for 6 tidal lagoons to be built around the British and Welsh coast (Harrabin, 2015). Once operational in 2030, six lagoons could generate 30 TWh of electricity per annum, equivalent to 18 million barrels of oil, enough to power 7.9 million homes (Hogan et al., 2014). The tidal power lagoon sector could sustain up to 71,000 jobs, add £27 billion to UK GDP by 2027 and reduce CO_2 emissions by 5.3 million tonnes by 2030 (Burrows, 2009; Macalister, 2014). Several of the proposed locations, e.g. Colwyn Bay, suffer from frequent coastal flood inundation so the construction of a tidal power lagoon could provide defences that the Government would otherwise have to invest in to withstand storm surges and SLR.

Case study: Swansea Bay Tidal Lagoon, Wales.

Swansea Bay, located between the River Tawe and Neath, has a tidal range of 10.5 m and is the first proposed tidal lagoon project in the UK (Figure 5) (TLSB, 2014a). Tidal Lagoon Swansea Bay (TLSB) aims to install 6 – 10 dual operation sluice gates and a 240 MW capacity power station to generate approximately 420 GWh net annual output, to power 121,000 homes (10% of Wales' use) (TLSB, 2014b). The lagoon seawall is not a formal flood defence, but will provide coastal protection up to a 1 in 1000 year event (0.1% Annual Exceedance Probability (AEP)) inclusive of climate change (URS, 2014). The project represents an investment of £650 million, in the order of £1.3 million per MW of installed capacity (Atkins, 2004; TSLB, 2013).

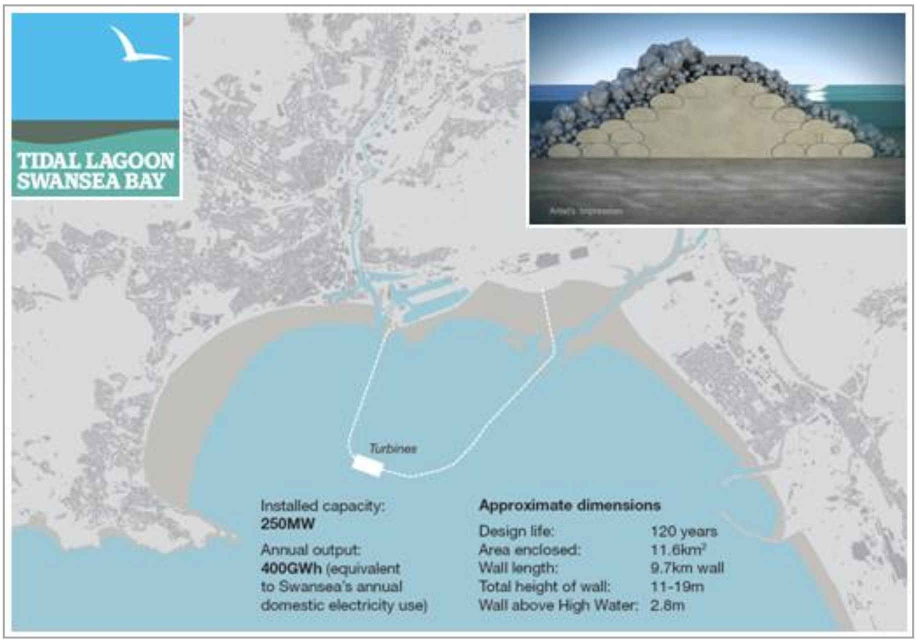

Figure 5: Location and specification of Swansea Bay Tidal Lagoon, and cross section of the lagoon seawall (TLSB, 2014a).

The lagoon comprises of a seawall, turbine housing and cable route, which exports the lagoon's power to the National Grid (TLSB, 2014b). The seawall was designed by TLSB in partnership with City and County of Swansea Council, Environment Agency / Countryside Council for Wales (subsequently known as Natural Resources Wales), Neath Port Authority, Swansea University Bay Council and Port Talbot Borough Council. Over 25 designs, including those in Figure 6, were considered to optimise access, power generation, minimise costs and reduce environmental impact to local SSSIs (TLSB, 2014c). A land attached lagoon reduces the cost of the seawall as 30% of the impoundment is made up of the coastline (TLSB, 2014c). A land-attached lagoon provides a viable ratio of seawall to enclosed area for power generation, reduces overall impact on coastal processes, simple grid connection and ease of access (URS, 2014).

Option J3 has a good wall to area ratio leading to high potential energy output, avoids encroachment of nearby Crymlyn Burrows SSSI and is located in shallow area so capital costs are reduced (Figure 6) (TLSB, 2014c; 2014d). This design was suggested for assessment as part of a Preliminary Environmental Information Report (TLSB, 2014d). The 9.5km long tidal lagoon sea wall will extend 1.5 km offshore and cover an area of 11.7km2 of seabed, foreshore and intertidal area (TLSB, 2014b; URS, 2014). The sea wall will be made of sediment filled geotextile tubes covered in rubble and rock armour from the local area and stepped with an uneven surface to reflect incoming wave energy seawards (Figure 5) (TLSB, 2014c; URS, 2014).

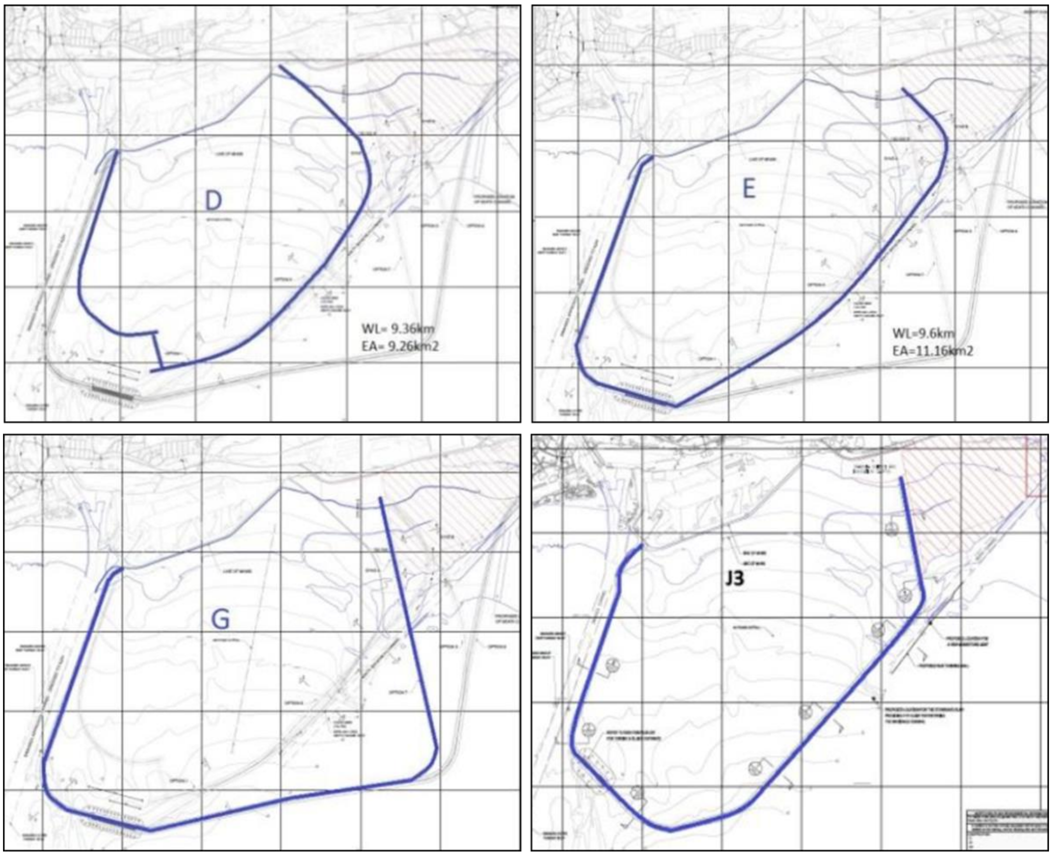

Figure 6: Four lagoon sea wall designs for Swansea Bay. Option J was taken forward to Preliminary Environmental Information Report, with 3 further designs to option J considered (TLSB, 2014c; 2014d).

Computer simulations of 1 in 1000 year extreme water level events and the impact of climate change in the Bay and surrounding area was conducted using 2D hydrodynamic model DHI Mike 21 (ABPmer, 2012; 2013). Results of the modelling showed that the lagoon seawall provides flood risk benefit to infrastructure and elements onshore of the project with a maximum reduction in MHWST of approximately 0.01 to 0.02 m (ABPmer, 2012). The lagoon seawall is unlikely to increase extreme sea-level outside the lagoon, with most significant changes in water level seen within the lagoon, and it is unlikely to be overtopped as a result of extreme sea-levels (URS, 2014). However concern has been raised about the lack of modelling using observational data assessing the impacts of TLSB on sediment supply and wind-blown sand to recreational beaches, mud accumulation in foreshore and shallow intertidal areas and impacts on Blackpill SSSI (Pye and Blott, 2014). A similar modelling exercise will be completed after 50 years to assess the lagoon efficiency and if further adaptation to SLR is required (URS, 2014). The project represents an ambitious, new direction to secure the UK's energy requirements, while offering an innovative strategy to adapt to and mitigation against future extreme SLR.

Flood inundation modelling in coastal environments

Accurate prediction of flood water depths, water velocity and inundation extent is a key component of flood forecasting, coastal protection studies and risk assessments (Néelz and Pender, 2009). Numerical inundation models can be used to predict impacts of climate change, SLR, extreme water levels and adaptation options in coastal environments (Nicholls et al., 2014). Inundation models use high resolution topographic data to simulate physical processes by calculating rates of change across time and space that will result from different combinations of variables, e.g. meteorological conditions, tidal conditions and coastal defence systems (Pender and Néelz, 2007; Robins et al., 2011). However all forecasts are estimates of what could happen in the future, and do not consider future defence structures that may be built (Dawson et al., 2005; Hallegatte et al., 2013). A range of models, as shown in Table 3, are available and can be used to determine the potential depth and extent of flooding and identify & assess adaptation options.

Table 3: Models for coastal flood inundation (Syme et al., 2004; Pender, 2006; Syme, 2006; Evans et al., 2007; Pender and Néelz, 2007; Néelz and Pender, 2009).

Method	Distinguishing features	Available software	Application
0D	Uses geometric methods to project water levels horizontally and does not involve modelling of physical processes.	ArcGIS	Broad scale assessment of flood extent and flood depths often referred to as the 'bath tub' technique.
1D	Uses St Venant equations to simulate unidirectional floodplain flow, and can model flow through hydraulic structures.	Infoworks RS (ISIS), Mike 11	The agreement between computed and observed water levels for one flood does not, however, guarantee a similar level of performance for subsequent flood events.
2D-	Simplified solution of the two-dimensional shallow water equations (minus the law of conservation of momentum for the floodplain flow).	LISFLOOD	Allows local variations in water level, velocity and flow direction to be modelled. Broad-scale modelling of inundation where inertial effects are not required. Provides successful handling of large volumes of water.
2D	Solution of the two-dimensional free surface shallow water equations.	TUFLOW, TELEMAC 2D	Design scale and broad-scale inundation modelling if used over a coarse resolution grid. Combines ocean, terrestrial and atmospheric processes
2D+	2D plus a solution for vertical velocities using continuity only.	TELEMAC 3D	Coastal modelling where 3D velocity profiles are required.

The correct modelling approach should be selected based on the aims of the project. 0D and 1D models simulate unidirectional flow, and are not suitable for simulating non-uniform and spatially variable flow patterns which are common in tidal and fluvial floods (Néelz and Pender, 2009). Simulation of inundation over tidal floodplains, with defence structures in place such as embankments, often use a 2D modelling approach (Bates et al., 2005a). 2D models use a variety of numerical methods (such as finite difference or finite volume) and grids (boundary fitted, structured or unstructured), and are flexible enough to be linked with 1D models (Néelz and Pender, 2009).

2D models are powerful tools for investigating and quantifying the impacts of coastal inundation, (Horritt and Bates, 2001; Néelz and Pender, 2009). LISFLOOD, a computationally efficient, 2D hydrodynamic inundation model is widely used to simulate floodplain inundation by solving shallow water equations (Bates et al., 2000; Lewis et al., 2011). LISFLOOD operates over a raster grid to predict the dynamic propagation of flood waves from a user-defined boundary over floodplains under the influence of gravity (Figure 7) (Dawson et al., 2005b). The model assumes that the flow between two cells within the domain is a function of the surface height difference of the two cells and gravity (Bates et al., 2005b).

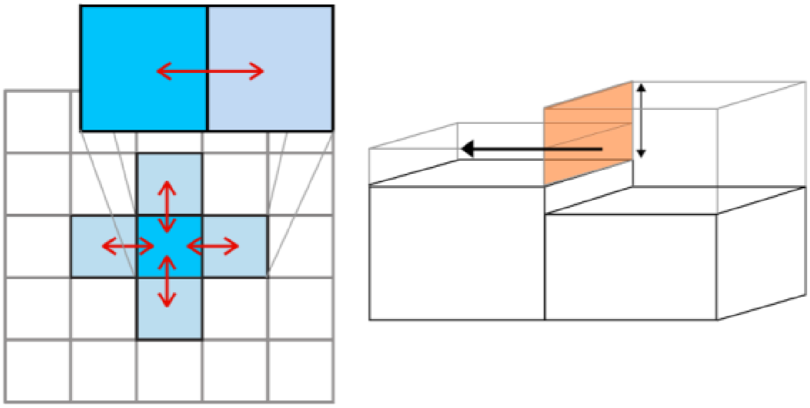

Figure 7: Representation of flow between cells in LISFLOOD (Bristol University, 2015).

LISFLOOD has been successfully used in coastal environments to model the risk of future inundation and SLR. Peak flood water depths have been modelled in the Severn Estuary, UK and the Solent, UK, as a result of low probability, extreme SLR scenarios (Bates et al., 2005a; Wadey et al., 2012; Quinn et al., 2013). LISFLOOD model has been proven to deal with large volumes of water in large domains (Bates et al., 2005a; 2005b). Results from LISFLOOD can also be combined with saltwater depth damage curves to give economic costs of flooding events (Penning-Roswell et al., 2003; Prime et al., 2015). Abrupt climate change and extreme SLR of 5-6 m in the Thames Estuary results in 1000 km^2 of land being frequently inundated, which subsequently results in £97.8 billion of direct damage, at 2003 prices (Figure 8) (Dawson et al,. 2005).

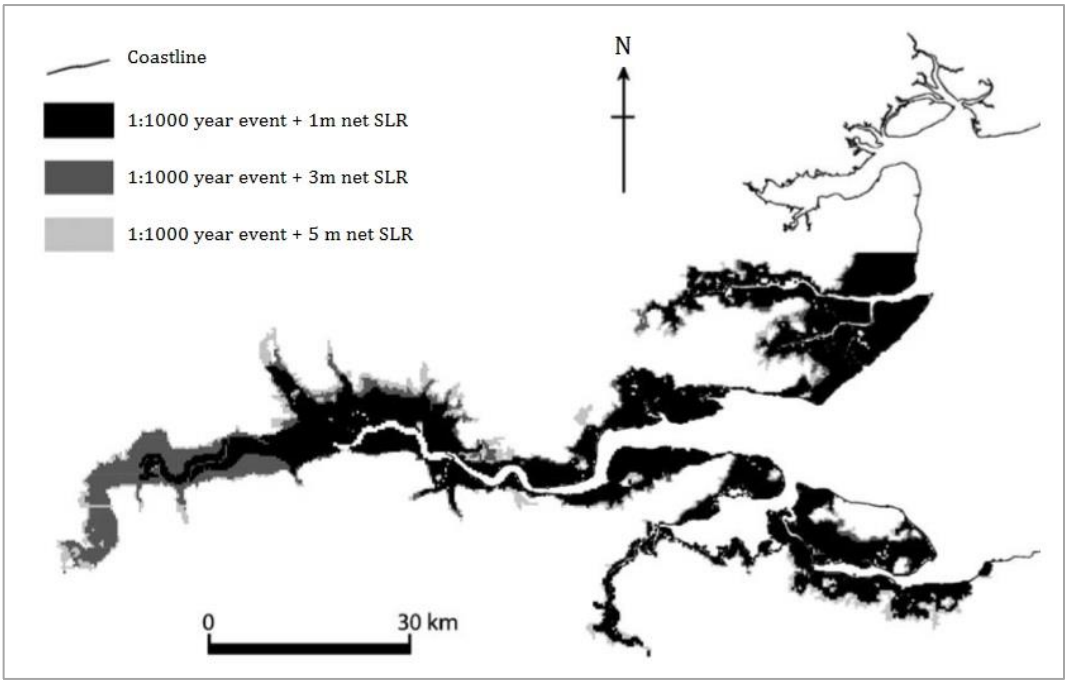

Figure 8: 1:1000 year (0.1% AEP) flood inundation extent after 1, 3 and 5m SLR in the Thames Estuary (Bates et al., 2005a).

2D models are powerful tools for investigating and quantifying the impacts of coastal inundation, however limitations and assumptions have been assessed to ensure the correct model is selected for the task at hand (Néelz and Pender, 2009). LISFLOOD has been shown to outperform 0D and 1D model flood extent prediction, and is suitable for inundation modelling in coastal environments. However the results are dependent on the floodplain friction coefficient selected and sensitivity of the domain to this value (Acrement and Schneider, 1984; Bates et al., 2005b). Model resolution and quality of topographic data used is likely to have the most significant effect on the ability of the model to simulate flood inundation (Dawson et al., 2005; Villaret et al., 2011; Tarrant et al., 2015). In addition to this, uncertainty surrounding the rate and extent of SLR and storm surge climate will have significant impact on predictions (Lewis et al., 2011). TUFLOW, another 2D model, has particular strengths in dealing with rapid wetting and drying, treatment of levees and embankments and modelling hydraulic structures, therefore is well suited to complex overland and piped urban flows (Syme and Apelt, 1990; Syme, 2001; Liang et al., 2008). TELEMAC, a 2D or 3D model, operates on an unstructured flexible mesh of triangles which can be graded to allow for higher resolution to capture nearshore processes, and coarser offshore resolution (Xia et al., 2010b; Robins et al., 2011). These features are not essential to modelling in this instance. Therefore LISFLOOD is a suitable option. It is clear that simple hydraulic models based on key hydraulic principles, such as LISFLOOD, are preferable over simple GIS methods for predicting flood extent (Bates et al., 2005a).

Project site

Great Orme's Head to Southport

Land attached tidal lagoons, as adaptation options resilient to future SLR, will be assessed in North-west England and North Wales. The region is important for tourism, industry and is of environmental significance (Halcrow, 2011). Large residential areas, tourism assets and infrastructure are currently protected from erosion and flood risk by seawalls, revetments, groynes and flood embankments. However coastal management and intervention using hard fences has led to beach lowering and erosion of dunes, which would otherwise provide natural flood defences (EA Wales 2010a; 2010b). This area of the North-West incorporates two large estuaries, the Dee and the Mersey as well as the smaller Clywd. The tidal regime within Liverpool Bay and Colwyn Bay is controlled by the tide propagating in the Atlantic Ocean, forcing large volumes of water into the Irish Sea via St. Georges Channel and Northern Channel (Williams et al., 2012). The predicted astronomical tidal levels within Liverpool and Colwyn Bay relevant to this study can be seen in Table 4, however these levels do not account for changes in water level due to atmospheric pressure (surges).

Table 4: Tidal levels (mCD) for Liverpool and Llandudno from 2008 to 2026 (NTSLF, 2015).

Tidal Contour	Liverpool (m CD)	Llandudno (m CD)
Highest Astronomical Tide (HAT)	10.37	8.59
Mean High Water Spring Tide (MHWST)	9.39	7.68
Mean High Water Neap Tide (MHWNT)	7.45	5.97
Mean Low Water Neap Tide (MLWNT)	3.16	2.20
Mean Low Water Spring Tide (MLWST)	1.12	0.48
Lowest Astronomical Tide (LAT)	0.02	-0.42
Chart Datum to Ordnance Datum Factor	-4.93	-3.85

North Wirral

The North Wirral coastline (53.2°N, 3.11°W) faces North-West into the Irish Sea, located between the River Mersey to the east and the Dee Estuary to the west (Halcrow, 2011). The region is located within the boundary of the Metropolitan Borough of Wirral which has a population of 1.38 million, with over 3,000 residential properties and 1,000ha of agricultural land (Armour et al., 2012; Wolf, 2014). There are a number of stakeholders, see Table 5, involved in coastal management of the area (Halcrow, 2013). The Welsh bank of the Dee Estuary is characterised by industrial and commercial activities whilst urban and agricultural areas are situated on the north bank, including West Kirby (Halcrow, 2011). The Mersey estuary has a deep narrow mouth, with rocky shores which are largely industrialised with extensive port facilities, power stations & oil refineries and onshore wind farms (EA Wales, 2013).

Table 5: List of stakeholders associated with coastal management on the North Wirral (Environment Agency Wales, 2010b; 2013).

North Wirral stakeholders and partners	
Cheshire West and Chester	Mersey Docks and Harbour Company
Environment Agency	Natural England
Flintshire County Council	Network Rail
Highways Authorities	Peel Holdings
Local landowners	Sefton Metropolitan Borough Council
Liverpool City Council	Wirral Metropolitan Borough Council
Manchester Ship Canal Company	United Utilities

The North Wirral is macrotidal and has the second largest tidal range in the UK at 10.35 m (NTSLF, 2015). Peel Energy, in partnership with the Northwest Regional Development Agency, has been investigating the potential for tidal power schemes in the region for several years (MTP, 2011). Exploitable tidal stream resources have been identified in the Mersey, with 40-100 GWh of potential power generation (Burrows et al., 2009). One potential location for a tidal lagoon in the North Wirral has been explored by the Department of Engineering, University of Liverpool. The lagoon stretches from Hoylake to Wallasey and the eastern seawall follows the Queen’s Channel. The area that will be modelled in the North Wirral can be seen in Figure 9. The domain covers 1038 km^2, including 60.22 km of digitised coastal and river defences.

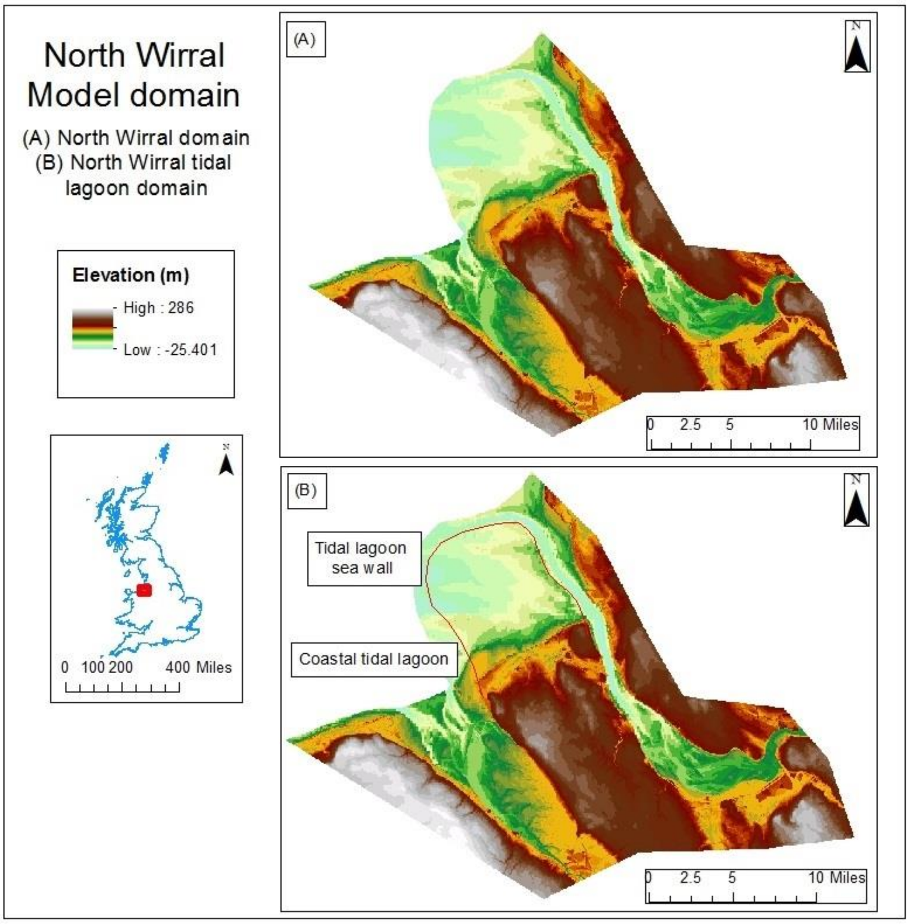

Figure 9: North Wirral domain and extent at 10m resolution (A) baseline domain with no lagoon sea wall; (B) tidal lagoon domain with seawall.

Energy output from a tidal power lagoon is primarily driven by the volume of impounded water. The North Wirral lagoon covers a large area therefore it is assumed it will generate more energy. Details of the tidal lagoon to be considered in this report are given in Table 6. The bathymetry of Liverpool Bay, which is up to 15.16 m deep in some areas, will increase cost of the project as deep water requires a higher seawall. The rounded shape of the seawall is thought to be more efficient than an elongated shape (TLSB, 2014c). The lagoon seawall will be uniform in height and stand at 12.19 m which is 2 m above MHWST. This is the design standard used by TLSB (TLSB, 2014c). A lower lagoon seawall, at 10.19 m (MHWST), will also be considered which will save building costs and it is assumed it could offer greater protection to surrounding areas from flooding. Water on the flood tide will likely overtop the seawall and fill the lagoon, hopefully reducing the magnitude of the flood in other areas of the domain. However there is a trade-off, as this will reduce energy production.

Table 6: North Wirral tidal lagoon specification.

	North Wirral Tidal Lagoon
Area (km^2)	139.1
Seawall length (km)	34.92
Seawall height (m)	10.19 / 12.19
Energy potential (net annual output GWh)	1439.65
Cost (£ GBP) *	60.21 million

** Estimated unit cost of building 1km of vertical seawall £1.72 million (EA, 2007; Linham et al., 2010). This cost includes direct construction costs, direct overheads, costs of associated construction works, minor associated work, temporary works, compensation events and delay costs. This does not include Value Added Tax (VAT) or external costs such as consultants, land and compensation payments.*

Geomorphology and flood risk

Liverpool Bay is a shallow basin with depths rarely exceeding 30 m, and acts as a net sink for coarse sediment (Williams et al., 2012). The Wirral is a flood dominated system and the predominant risk of flooding in the area is from extreme tidal conditions and tidal / fluvial flood events (MTP, 2011). The Environment Agency identifies the majority of the Wirral lies within flood zone 3 (> 0.5% AEP in any year), however this does not consider defences (Environment Agency, 2015). The North Wirral has been subject to severe coastal flooding in recent years. The storm surge in winter 2013 led to the crests of the sea walls at West Kirby, Meols and Hoylake being exceeded (MTP, 2011; Wirral Council, 2014). Industrial areas of Ellesmere Port, Stanlow and Frodsham, located to the south east of the Wirral, are at high risk to tidal inundation (MTP, 2011). Flood risk in the Mersey Estuary is managed by channel and raised defences, and pumping for land drainage purposes (EA, 2009). Sand dunes provide natural defence at West Kirby and Hightown (Halcrow, 2013).

Biodiversity

Extensive areas of Liverpool Bay and the Dee Estuary are nationally and internationally designated areas of importance for habitats and wildlife, including Special Protection Areas (SPA), RAMSAR sites, Sites of Special Scientific Interest (SSSI) or Special Areas of Conservation

(SAC), and are important sites for overwintering birds (MTP, 2010). Mudflats, Atlantic salt meadows and salt marshes in the Dee Estuary are Annex I habitats which support Annex I species including *Salicornia* spp. (pioneer glasswort), *Puccinellia maritima* (common saltmarsh grass), *Suaeda maritime* (sea blite) and *Cochlearia x hollandica* (hybrid scurvy grass) (JNCC, 2015). The site is also important for overwintering birds, hosting 5.4% of the UKs population of *Gavia stellata* (Red throated diver) and 3.4% of the population of *Melanitta nigra* (Common scoter) (JNCC, 2010). Any energy infrastructure or flood mitigation design must accommodate these designated areas, and strive to minimise impact on them.

Colwyn Bay

Colwyn Bay (53.2°N, 3.42°W), located on the North Wales coastline in Conwy County Borough faces into the Irish Sea and is the second largest town in North Wales (CBC, 2015a). Colwyn Bay has a population over 30,000, with some communities living below the high tideline (Halcrow, 2011). The coastline is economically important for the region, as it provides approximately 40% of tourism in Wales (Welsh Government, Coastal Tourism Strategy, 2008). Stakeholders in the region are listed in Table 7.

Table 7: List of stakeholders associated with coastal management in Colwyn Bay (Environment Agency Wales, 2010a).

Colwyn Bay stakeholders and partners	
CEMEX U.K.	Natural England
Conwy County Borough Council	Natural Resources Wales
Denbighshire County Council	Network Rail
Dŵr Cymru Welsh Water	United Utilities
Local landowners	

Colwyn Bay is a macrotidal environment and has a tidal range of 9.01 m (NTSLF, 2015). Feasibility and consultation work is currently being undertaken by Tidal Lagoon Power for a lagoon in Colwyn Bay, one of six planned for the UK (Harrabin, 2015; Macalister, 2015). A potential lagoon location and seawall was designed specifically for this project. The lagoon was designed to extend from Rhos-on-Sea to Kinmel Bay to follow the natural curve of the coastline, and not to restrict the River Clwyd. The lagoon should provide flood risk benefit to Colwyn Bay. The domain for Colwyn Bay can be seen in Figure 10, covering 395 km^2, with 40.03 km of coastal and river defences. The lagoon seawall will be uniform in height and stand at 10.48 m, which is 2 m above MHWST. Further details of the lagoon can be seen in Table 8.

Table 8: Colwyn Bay tidal lagoon specification.

	Colwyn Bay Tidal Lagoon
Area (km^2)	39.3
Seawall length (km)	15.8
Seawall height (m)	10.48
Energy potential (net annual output GWh)	411.9
Cost (£ GBP) *	27.29

** Estimated unit cost of building 1km of vertical seawall £1.72 million (EA, 2007; Linham et al., 2010). This cost includes direct construction costs, direct overheads, costs of associated construction works, minor associated work, temporary works, compensation events and delay* *costs. This does not include Value Added Tax (VAT) or external costs such as consultants, land and compensation payments.*

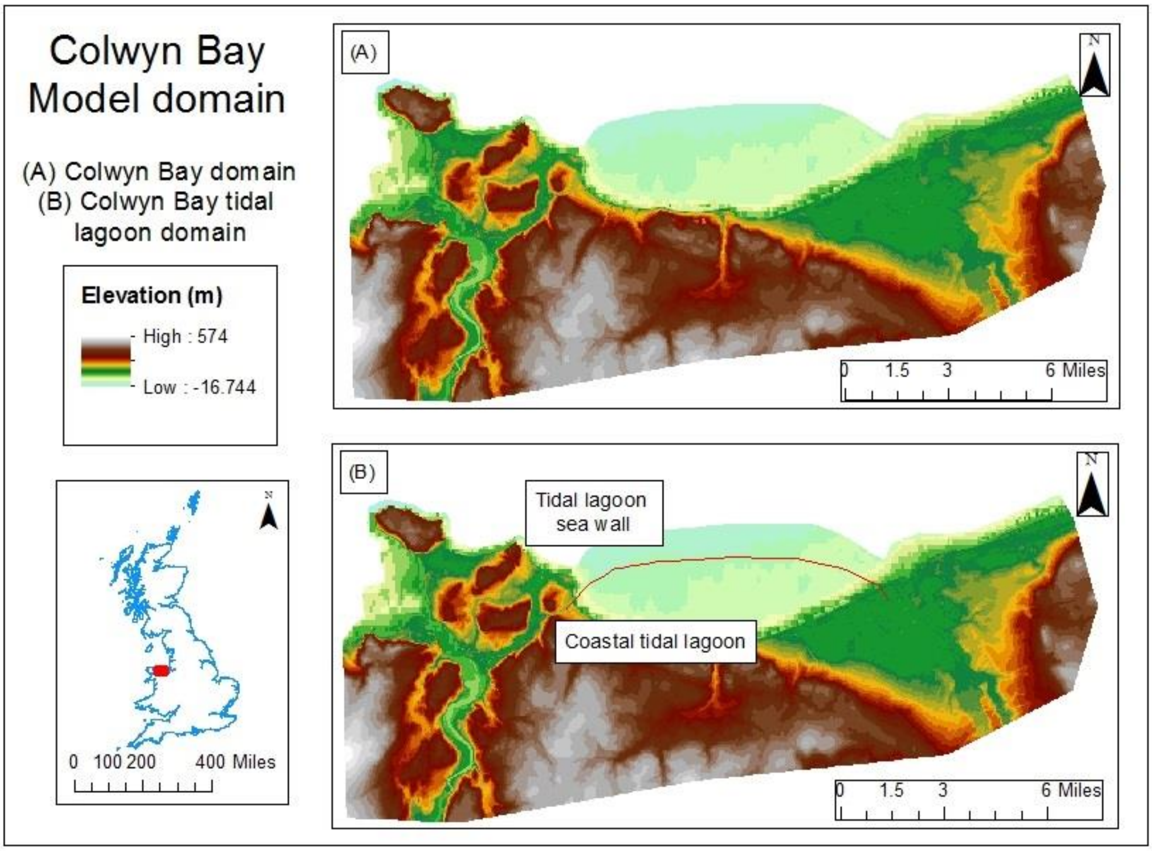

Figure 10: Colwyn Bay domain and extent at 10m resolution ((A) baseline domain with no lagoon sea wall; (B) tidal lagoon domain with seawall.

Geomorphology and flood risk

Much of the Conwy coastline, up to 10 km offshore, consists of shallow sand banks that act to restrict tidal flood generation, however SLR is likely to limit this (Anderson, 2012). Llandudno, built on a tombolo made of fluvial and glacial material, is at particularly high risk of flooding due to low relief (Goudie and Gardner, 1996). The shoreline at Colwyn Bay has been effectively fixed through human intervention since the 19th century as a result of masonry sea walls which have been built from Rhos-on-Sea eastwards 4 km to Old Colwyn (Williams et al., 2012). In contrast, the coastline from Old Colwyn to the Point of Ayr is one large embayment with gently curved cuspate bays (Williams et al., 2012). Fine sediment moves from west to east, eventually settling in Liverpool Bay (Halcrow, 2013). This movement has resulted in historic loss of beach level across the foreshore of approximately 10-20mm per year, resulting in increased exposure and undermining of sea defences (CBC, 2010).

In 2014, 208,000 properties, or one in six buildings, in Wales were shown to be at risk from coastal flooding. with an average annual cost of flooding at approximately £200 million (Natural Resources Wales, 2011; 2014). Conwy's history of flooding highlights its susceptibility to inundation events, as a result of low relief and overtopping of 37 km of coastal defences (Figure 11) (CBC, 2015b). Notable flooding events include the coastal storm of 1990 where Towyn's defences breached to flood 4 miles^2 (Conwy County Borough Council, 2011). 5,000 local residents had to be evacuated and over 2,800 properties were affected (Anderson, 2012). There is a risk of tidally induced flooding along the Conwy coastline, notable in urban areas at Llandudno, Colwyn Bay and Kinmel Bay (Conwy County Borough Council, 2011). Despite Conwy County being one of the most defended coasts in the U.K, there is still a need for further protection other thousands of properties will remain at risk (CBC, 2015c). Flood awareness, early warning systems and flood proofing are also key strategies at present (EA Wales, 2010a).

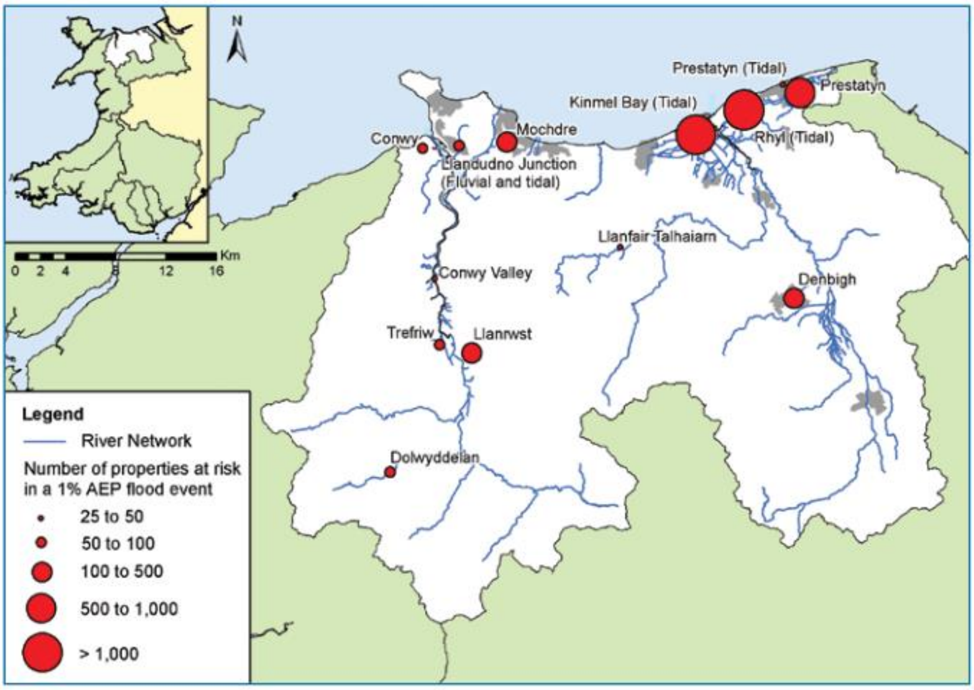

Figure 11: Number of properties in Colwyn Bay currently at risk of a 1% AEP flood event. (EA Wales, 2010a, pp. 8).

Biodiversity

Conwy Bay is recognised as an area of national and international importance, and areas have been designated as SSSIs, Special Protection Areas and Special Area of Conservation (CCW, 2009). Sandbanks and mudflats are highly productive, species-rich Annex I habitats supporting *Cerastoderma edule* (common cockle), *Lanice conchilega* (sand mason worm) and the nationally scarce *Zostera noltei* (dwarf eelgrass) (JNCC, 2015). Rocky reefs, located at Great and Little Ormes, support rock boring sponges including *Halichondria panacea* (breadcrumb sponge) and *Cliona celata* (red boring sponge) (CBC, 2010). However, much of the original sand dune habitats along Colwyn Bay and Kinmel Bay have been destroyed by development for housing, golf courses and caravan parks (CBC, no date).

Methodology

Figure 12 shows the steps taken from creating the input data for LISFLOOD to obtaining maximum flood inundation depth and extent, and the economic coast of each scenario.

Figure 12: Flow chart to the show the methodology (from Prime et al., 2015).

LISFLOOD model setup

The model input data required for LISFLOOD is shown in Figure 13, and explained further in this section.

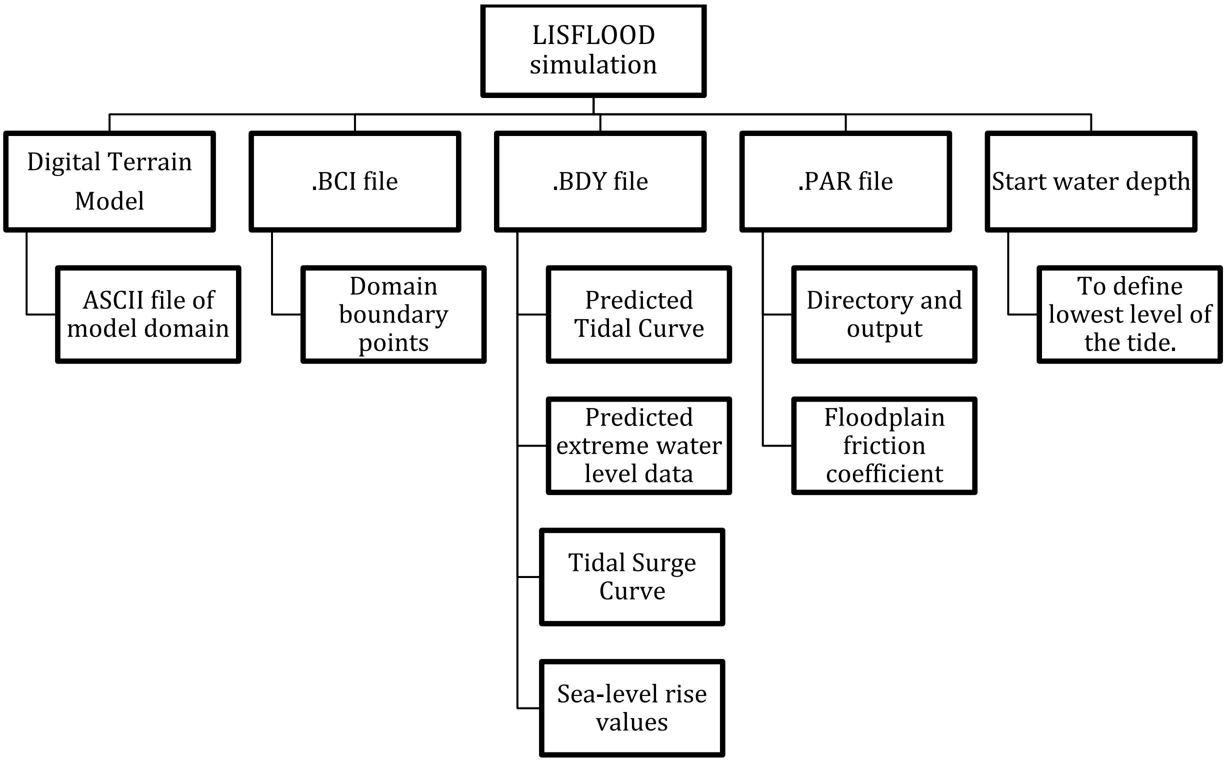

Figure 13: Diagram to show files and input data required for model simulations.

Digital Terrain Model and bathymetry

LISFLOOD utilises high resolution topographic data, to provide good predictions of dynamic flood inundation in fluvial and coastal environments for scenario modelling of future change (Bates et al., 2005a; Dawson et al., 2009). The Digital Terrain Model (DTM) was created in ArcMap (v10.2.2) using 1 m resolution LiDAR data (Environment Agency Geomatics, 2014). The LiDAR data was resampled to 10 m to reduce computational cost while maintaining detail of urban areas, roads and rivers. Spatial averaging of the LiDAR data meant features including river and sea defences were 'smeared out.' Sea and river defence crests were digitised into the raster to give an accurate representation of the floodplain (Bates et al., 2005b). The offshore boundary of each model domain was set beyond the mean low water mark in areas, to include intertidal areas and allow space for boundary conditions to force the model. The boundary was set just outside the extent of the tidal lagoon to allow the model to force against the tidal lagoon wall. To account for the influence of the tidal lagoon seawall on inundation along the coast, the extent of the landward boundary was set a minimum of 3 km inland. Bathymetry data, digitised from marine charts, was added to the DTM where the boundary of the domain extends out beyond the extent LiDAR data (Edina Digimap, 2014). Co-ordinate data at 10 m intervals along each domain boundary was exported from ArcMap which provides the base for the time varying boundary conditions in the model (.BCI file). Appendix 1 provides further detail on the process for creating the .BCI file and DTM.

The position and extent of the offshore boundary in each domain was tested in LISFLOOD with no tidal lagoon present under RCP 4.5 (0.72 m SLR). Figure 14 shows there is a difference in the extent and depth of inundation in the North Wirral and Colwyn Bay domain with a boundary set further offshore (Appendix 2 for finer resolution). This is particularly evident in the North Wirral domain, where an offshore boundary means maximum water depth is 1.148 m greater, and extent of inundation moves further inland in the upper Dee and Mersey Estuary. The offshore boundary in the Colwyn Bay domain increases depth of inundation by 1.08 m, but there is not a significant change in extent of inundation. The size of the model domain is therefore influencing the depth and extent of inundation. The volume of water entering the model is not a fixed value: it increases as the size of the domain increases (Bates et al., 2000). Therefore the study domain will be identical in both the baseline and tidal lagoon scenarios. This method will increase computational cost but should provide more reliable, comparable results.

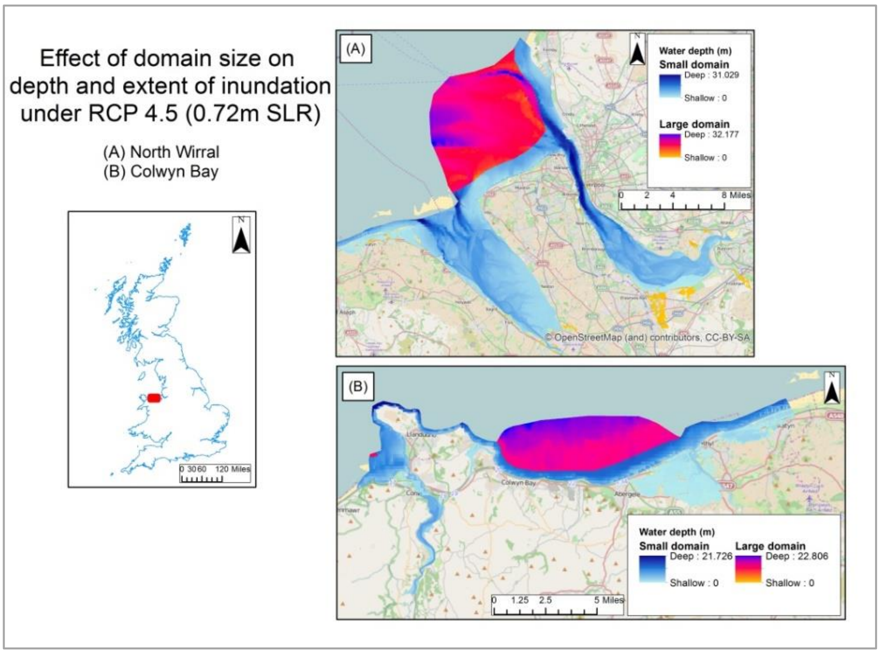

Figure 14: The effect of domain size on depth and extent of inundation under RCP 4.5 (0.72 m SLR) in (A) North Wirral; (B) Colwyn Bay.

Extreme Water Level Data and Predicted Tide and Surge Curve

The Environment Agency has generated extreme tide levels around the UK at 16 different return periods, at 2 km intervals along the UK coastline (Environment Agency, 2011). These extreme water levels are calculated using the skew surge joint probaility method (SSJPM) on tide gauge data (McMillan et al., 2011). Each 10 m data point in the domain boundary is assigned an extreme water level elevation based on the closest EA data point. In this instance, a 1/200 year return period (0.5%) was used to force the storm tide in LISFLOOD; this is the standard that coastal flood defences in the UK are built to (McMillan et al., 2011; Williams et al., 2012). Extreme water level elevations are combined with representative surge curves for tide gauges around the UK (Environment Agency, 2011).

A predicted tidal curve over a 100 hour cycle was generated for Liverpool Gladstone Dock and Llandudno based on the highest astronomical tide (HAT) of 2015 from 26 September to 3 October, obtained using POLTIPS-3 (National Tide Sea-level Facility, 2015). 15-minute interval data for two days either side of HAT overlaid on to the surge curve, lining up the tide and surge peaks. This methodology is in line with that proposed by the Environment Agency, and assumes that the peak of the tide and surge occur at the same time (MacMillan et al., 2011). However it is known that the surge often occurs before or after the peak of the tide (Horsburgh and Wilson, 2007). Future model simulations could look to incorporate a skew surge.

Sea-level rise parameter

A baseline SLR parameter, 0 m, was selected to represent present-day sea-level conditions. To simulate high-end SLR, RCP 4.5 (medium emission) and RCP 8.5 (high emission) projections were selected from IPCC AR5 (Church et al., 2013). LISFLOOD can only operate sea-level rise parameters in even numbers, therefore RCP 4.5 was rounded up to 0.72 m SLR. Projections in the 95th percentile will be used, which represent low probability, high impact SLR. The SLR values (Table 9) are added to all water level values to produce the time-varied water elevation for HAT in 2100.

Table 9: LISFLOOD sea-level rise parameters.

Scenario	SLR parameter (m)
Baseline conditions	0
RCP 4.5	0.72
RCP 8.5	0.98

Friction coefficient

The friction coefficient for all model runs is specified in the .PAR file. The sensitivity of the model to friction co-efficient was tested by running the same scenario, with a tidal lagoon present under RCP 4.5 (0.72m SLR), at a low friction value (0.018) and a high friction value (0.03). A difference in extent and depth of inundation was seen in both domains under the three different values (Figure 15 and Figure 16). There is a greater difference in the extent of inundation in the Colwyn Bay domain between each friction value. This is most likely due to the topography of the land – low-lying land in Colwyn Bay allows for water to move more easily across the domain with a lower friction value. There is less of a difference in extent of inundation in the North Wirral domain, as the topography is restricting the movement of water. There is a difference of 0.08 cm in water depth between high and low friction values in the North Wirral domain and 0.002 cm in the Colwyn Bay domain. A difference in extent of inundation shows that both model domains are sensitive to the selected friction values. This is interpreted as a limitation of the model and considered when interpreting the results. The same friction value (0.03) has been applied to every cell in the model and is a median value representative of intertidal to arable areas (Bates et al., 2005; Prime et al., 2015). Future modelling could vary the friction coefficient across the domain to reflect changes in land use, and compare model predictions to observed flood levels to obtain an optimum level of fit (Horritt and Bates, 2001).

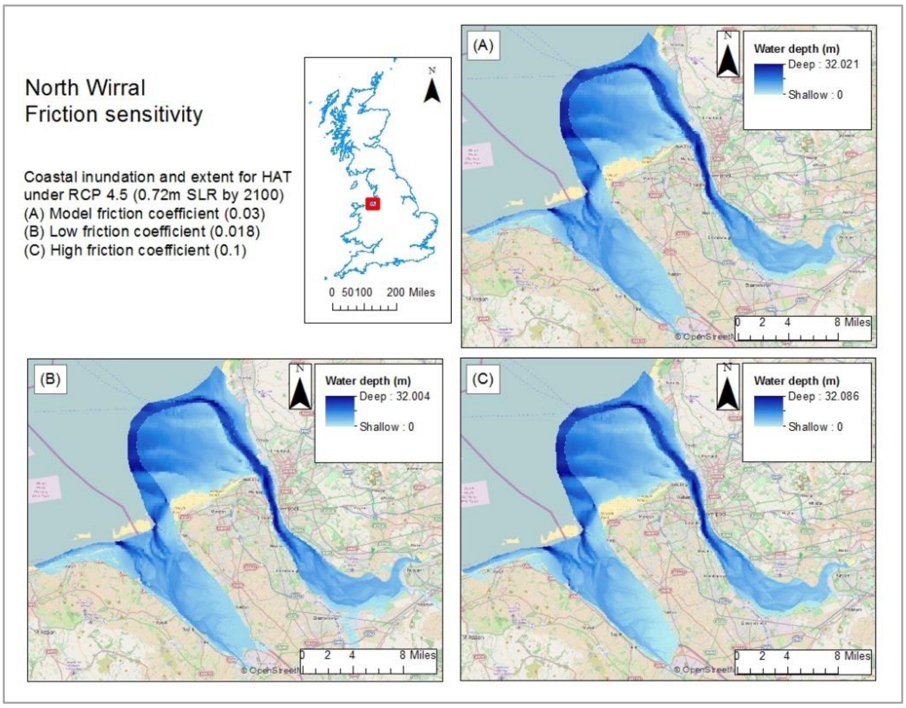

Figure 15: Extent and depth of inundation in the North Wirral under 3 friction values (A) 0.03; (B) 0.018; (C) 0.1.

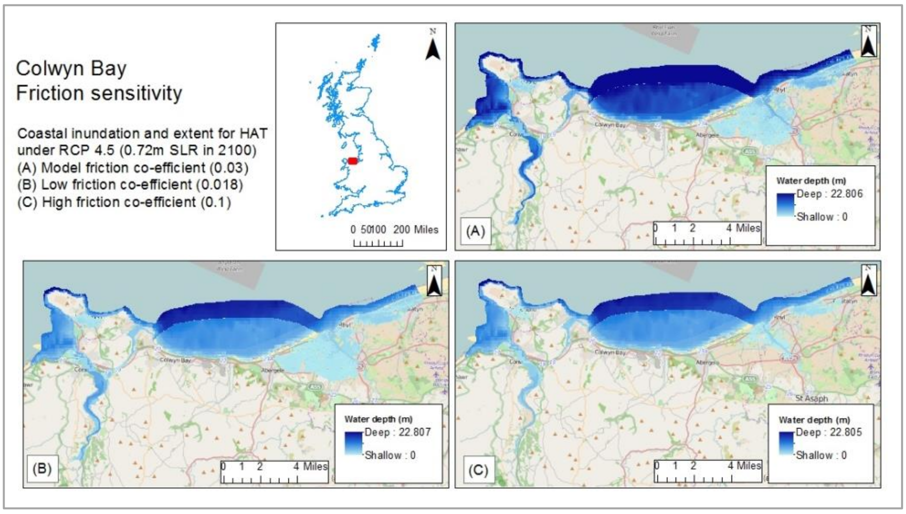

Figure 16: Extent and depth of inundation in Colwyn Bay under 3 friction values (A) 0.03; (B) 0.018; (C) 0.1.

LISFLOOD model scenarios

28 scenarios were run in total with different combinations of variables, including domain size, sea-level rise and presence of a tidal lagoon in the domain (Appendix 3). Status quo scenarios were run to provide a baseline comparison, including present-day sea-level and domains with no lagoon present. SLR was modelled in the domain with and without a tidal lagoon to determine the impact rising sea-level will have on the depth and extent of inundation, with no intervention or tidal lagoon. The presence of a tidal lagoon was modelled at all SLR scenarios, at two heights; one at the level of MHWST at one 2 m above this. SLR and lagoon scenarios can be compared against baseline scenarios, to determine the change in depth and extent of inundation. These scenarios were run on the assumption that the socio-economic status quo is maintained up to 2100, and there is no future development within the floodplain (Dawson et al., 2005).

Analysis

LISFLOOD creates a .MAX file for each model scenario which can be converted to a raster file in ArcMap. Each model scenario output can be visualised and presented in ArcMap with symbology to represent depth and extent of flood inundation as a result of the combination of variables set in LISFLOO. The .MAX files are also analysed in Matlab to determine area of inundation above 0.05m (km^2) and volume of inundation (m^3) to allow for quantitative comparison of scenarios. Water depths less than 0.05 m are not considered to be damaging as they are below the vertical accuracy of the LiDAR data used for the model domain (Prime et al., 2015).

The .MAX file for each model scenario result is combined with 25 m land cover data and salt water damage curves for urban, suburban and agricultural areas to calculate the economic cost of each scenario. (Edina Digimap, 2007; Penning-Roswell et al., 2013). Saltwater depth damage curves relate the depth of inundation to the cost of damage, and provide direct, tangible losses for flooded different land uses (FEMA, 2015a). Saltwater does greater damage to properties and land than freshwater, therefore the damage costs are higher (Williams, 2010). Increased depth of inundation will result in greater the damage to the building fabric, clean-up and drying costs and damage to household inventory items (FEMA, 2015b). The values reflect economic losses, rather than financial losses to individual property owners and do not consider indirect losses (Penning-Roswell et al., 2013). Indirect losses are classed as damage to health, loss of income, increased travel costs or loss of utility services (Penning-Roswell et al., 2013). The results of depth damage analysis assign a cost of each flood event to assist with analysis of inundation.

Results

Higher resolution maps for the North Wirral results are presented in Appendix 4 – 12, and Colwyn Bay in Appendix 14 – 21.

North Wirral

Baseline scenarios

The results of North Wirral baseline scenarios, shown in Figure 17, provide estimations of the extent of inundation under different sea-level conditions in the North Wirral. No tidal lagoon is present in the domain.

Figure 17 (A) shows present-day sea level (0 m SLR). The North Wirral coastline, from Hoylake to Wallasey, is not inundated and is protected by current defences in place. The North Wales coast experiences some inundation; leisure facilities are most significantly affected with Prestatyn Golf Club flooded to 1.23 m, Pontin's Holiday Park up to 0.35 m and Rhyl Golf Club being most flooded up to 0.67 m. The disused Ministry of Defence rifle range at Sealand is flooded to 0.30m and floodplain of the Dee Estuary at Connah's Quay are flooded up to 1.93 m. Upper areas of saltmarshes are inundated to a depth of 1.16 m at Ince Bank, 2.13 m at Parkgate Marsh and 1.78 m at Bagillt Marsh. Inundation occurs through the centre and to the west of Stanlow oil refinery and petrochemical site. Inundation occurs here up to a maximum depth of 0.35 m, close to the banks of the River Gowy which runs through the site. Water has moved inland to Stoak, and has flooded the A5117 and nearby sewage works at Thornton-le-Moors. The Mersey has broken its banks on the North at Hale Point and flooded agricultural farmland at Hale, up to 0.75 m.

Figure 17 (B) shows 0.72m SLR, under RCP 4.5 emission scenarios. Water depth in the domain does not increase by more than 0.711m, because this is the limit of the sea-level rise parameter that has been set (0.72 m). Extent of inundation increases in the model from present-day sea-level by 24.15 km^2, to 475.33 km^2 total, including the sea. Flooding now occurs on the North Wirral coastline, to east of Meols and west of Moreton at Wirral Beach Caravan Park up to 0.35 m. Properties 50 m inland, behind the marine lake at West Kirby, are inundated up to 0.25 m on Riversdale Road. Flooding occurs at Talacre and the Point of Ayr; caravan parks and holiday parks are flooded up to 1.73 m. This includes Presthaven Sands Holiday Park, Triangle Wood Caravan Park, Talacre Holiday Home Park and Point of Ayr Holiday Park. The Point of Ayr gas terminal, owned by Liverpool Bay Operating Company Ltd is flooded to 2.07 m. Residential areas and road networks are widely affected in Prestatyn, which has a population of over 16, 780, and flooding occurs 2.7 km inland, up to 1.72 m maximum depth (DCC, 2013). Flooding occurs from the upper extent of the saltmarshes to the A 548 between Oaklands and Mostyn, from 1.57 m to 3.96 m depth. Shotton Paper Mill and Deeside Industrial Park, at the mouth of the River Dee, experience inundation on the western perimeter of the factory to a depth of 0.15 m. In the same location on the Dee Estuary, Tata Steel Works experiences flooding up to a maximum depth of 0.23 m to the south of the factory. Inundation also occurs at Connah's Quay Power Station, a combined cycle gas turbine power station owned by E.ON, up to 0.25 m depth. 4.24 km^2 area of the 8 km^2 Stanlow refinery site is flooded to with a maximum depth of 1.33 m. Transport networks, including Stanlow Port, the Stanlow railway station and the railway and the A5117 are also flooded. Ince Marshes and Helsby Marsh, to the south of the Manchester Ship Canal are inundated to a maximum depth of 0.75 m. The floodplains of the River Weaver are also inundated, to a maximum depth of 0.77 m, but no residential areas at Frodsham are affected under this scenario. Ditton Brook, at Widnes, has overtopped and caused flooding of surrounding land and properties to the west to flood to a maximum depth of 1.19 m. Inundation at Hale moves further inland, but does not reach residential area or impact transport networks.

Figure 17 (C) shows 0.98m SLR, under emission scenario RCP 8.5. Water depth increases by 0.27 m relative to figure 16 (B), and inundation extent increases by 9.21 km^2 from RCP 4.5, to 484.54 km^2. On the North Wirral coastline, inundation covers a greater area at Wirral Beach Caravan Park up to a maximum water depth of 0.69 m. Properties 200m inland, behind the marine lake at West Kirby, are inundated up to 0.48 m on Salisbury Avenue and Hoscote Park, and up to 1.04 m on Shrewsbury Road. Inundation occurs at Connah's Quay Power Station up to

0.25 m depth. Extent of inundation of residential areas at Prestatyn does not increase significantly, but maximum water depth increases to 2.27 m. Extent of inundation at Stanlow refinery site has increased by 0.3km^2 and is now flooded up to 1.62 m. Water has moved 6.11 km inland from Ince Banks, beyond the M56 and has flooded the floodplains of the River Gowy. Flooding occurs at Ince Marshes and surrounds the GrowHow UK factory (producing ammonia and nitric acid) to a maximum depth of 0.47 m. Frodsham Marsh and floodplains of the River Weaver flood to a greater extent, but residential areas remain protected. Overtopping at Ditton Brook, Widnes, has now resulted in inundation of the A562 and residential properties to the north, to a maximum depth of 0.43 m.

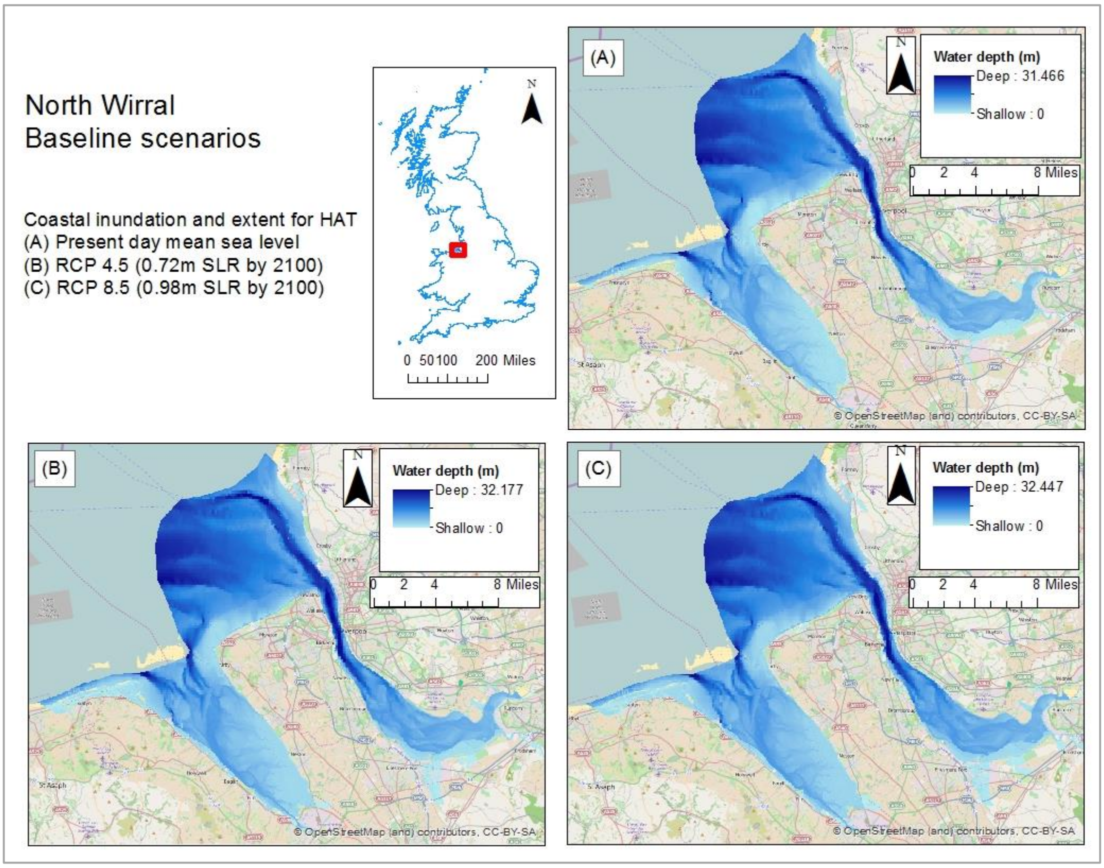

Figure 17: Baseline coastal inundation and extent for the North Wirral under (A) present-day sea-level conditions, (B) RCP 4.5 and (C) RCP 8.5.

The depth and extent of inundation increases most significantly at Stanlow refinery as sea-level rises in the North Wirral domain. Flood risk at Stanlow refinery increases under emission scenario RCP 4.5 (0.72 m SLR) and 8.5 (0.98 m SLR), relative to present-day sea-level. Figure 18 shows how inundation depth and extent increases with sea-level rise here. Stanlow refinery is important infrastructure for the area, creating jobs and income for over 1,000 employees; therefore it is an area where adaptation and mitigation could benefit flood risk (United, 2015).

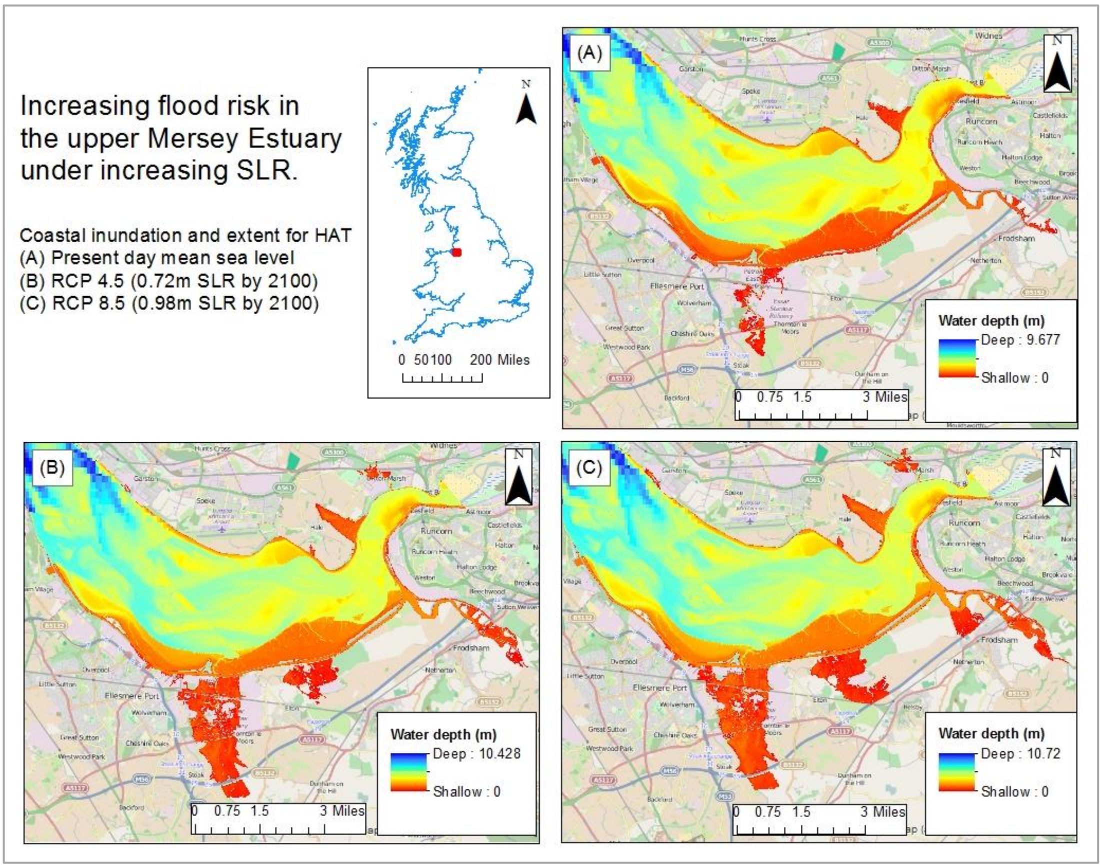

Figure 18: Baseline coastal inundation and extent at Stanlow oil refinery and petrochemical site under (A) present-day sea-level conditions, (B) RCP 4.5 and (C) RCP 8.5.

Tidal lagoon scenarios

The same domain used for the baseline scenarios is used to model inundation in the North Wirral following the implementation of a tidal lagoon, with a uniform seawall height of 12.19 m.

Figure 19 (A) shows inundation which may occur following the implementation of a tidal lagoon on the North Wirral under present-day sea-level. There is a total of 422.13 km^2 inundation in this scenario, which is 29.05 km^2 less than baseline scenario. The North Wirral coastline, behind the tidal lagoon from Hoylake to Wallasey is protected and water does not reach the coastline. North Wales experiences similar extent inundation seen in the baseline scenarios, with Prestatyn Golf Club, Pontin's Holiday Park and Rhyl Golf Club flooded, but maximum water depth is reduced up to 0.15 m. There is no inundation at Stanlow or Connah's Quay. Parkgate Marsh is inundated up to 1.72 m, approximately 0.40 m shallower than the baseline scenarios. Ince Banks and Frodsham Marsh are not inundated at all, they remain exposed.

Figure 19 (B) shows inundation which may occur following the implementation of a tidal lagoon on the North Wirral under RCP 4.5 (0.72 m SLR). Extent of inundation increases by 19.97 km^2 from present-day sea-level, to 442.10 km^2. There is a 33.23 km^2 reduction in inundation compared to the baseline scenario. Extent of inundation at Talacre and Prestatyn is also similar to the baseline scenario, and water depth is also shallower. Inundation at the Point of Ayr holiday park is 1.91 m in the 'no lagoon' scenario, and 1.59 m with a tidal lagoon. Flooding to the south of Prestatyn is as shallow as 0.02 m, compared to 1.06 m under baseline scenarios. As with the baseline scenario, flooding occurs on the west coast of the Dee Estuary from the upper extent of the saltmarshes to the A 548 between Oaklands and Mostyn. However water is up to 0.53 m shallower, with maximum depth up to 3.61 m. The lower marsh at Ince Bank is inundated to a maximum depth of 0.66 m, and the upper marsh remains exposed due to a reduced tidal range and hydroperiod. Stanlow, Frodsham, Hale and Widnes remain protected.

Figure 19 (C) shows inundation which may occur following the implementation of a tidal lagoon on the North Wirral under RCP 4.5 (0.98 m SLR). The extent of inundation increases by 6.93 km^2 from RCP 4.5, to a total inundation extent of 449.04 km^2. This is 35.51 km^2 less than the baseline scenario. The length of the North Wirral coast remains protected. The extent of inundation on the North Wales coast is similar to RCP 4.5, but water depth is shallower than the baseline scenario under RCP 8.5 up to 0.47 m. The gas turbine power station at Connah's Quay is not flooded, but inundation occurs in the surrounding area to a maximum depth of 0.14 m. Inundation occurs at West Kirby to a similar extent as seen in the baseline scenarios, but it is 0.2 to 0.3 m shallower. Ince Bank is now inundated to the upper limit of the marsh, up to a maximum water depth of 0.37 m, which is 1.83 m shallower than the baseline scenarios. No flooding occurs at Stanlow or Frodsham. Flooding occurs on the northern bank of the Rivery Mersey at Hale up to 50 m inland, to a maximum depth of 0.13 m.

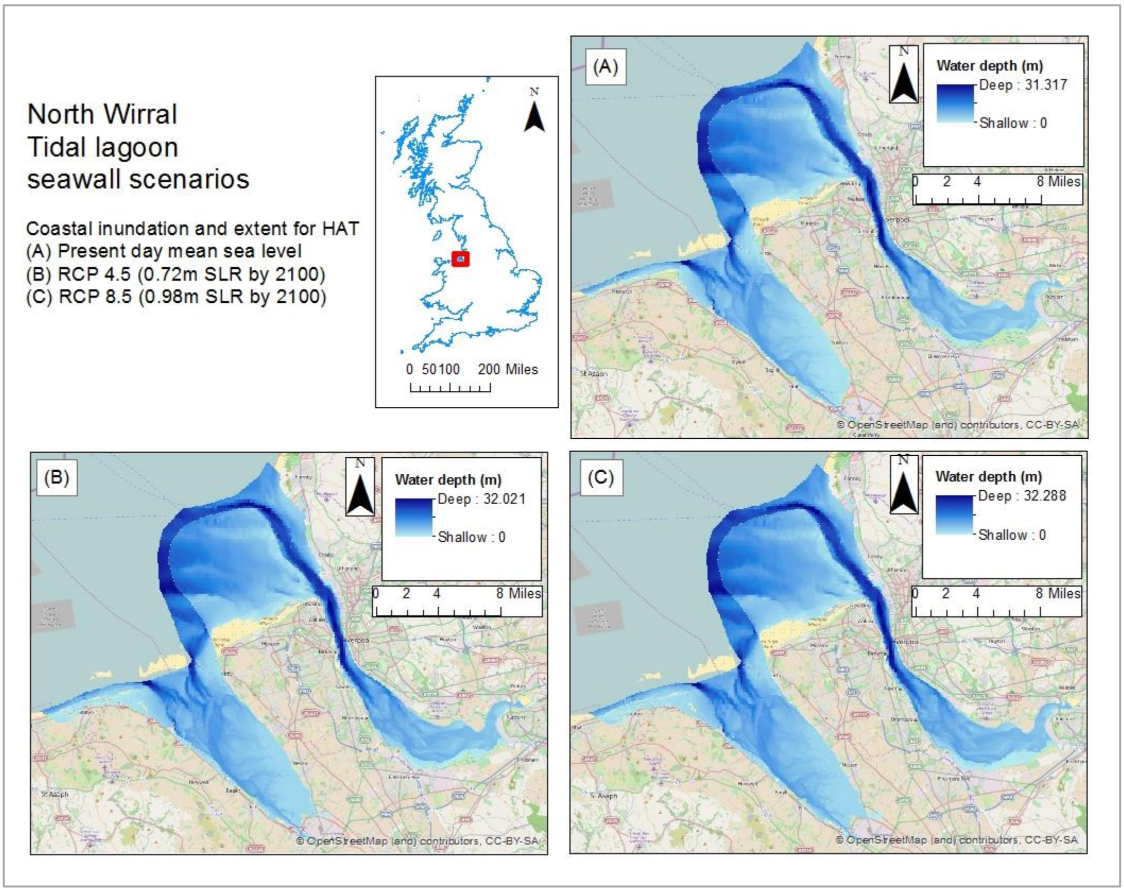

Figure 19: Coastal inundation following the implementation of a tidal lagoon in the North Wirral under (A) present-day sea-level conditions, (B) RCP 4.5 and (C) RCP 8.5.

The presence of a tidal lagoon in the North Wirral appears to provide flood risk mitigation to industrial areas in the region under all sea-level scenarios. The model results suggest that the depth and extent of inundation is reduced following the implementation of a tidal lagoon (

Figure 20). It should be noted that outputs show maximum extent for the whole model run, and the maximum extents for different scenarios may not occur at the same time in the tide.

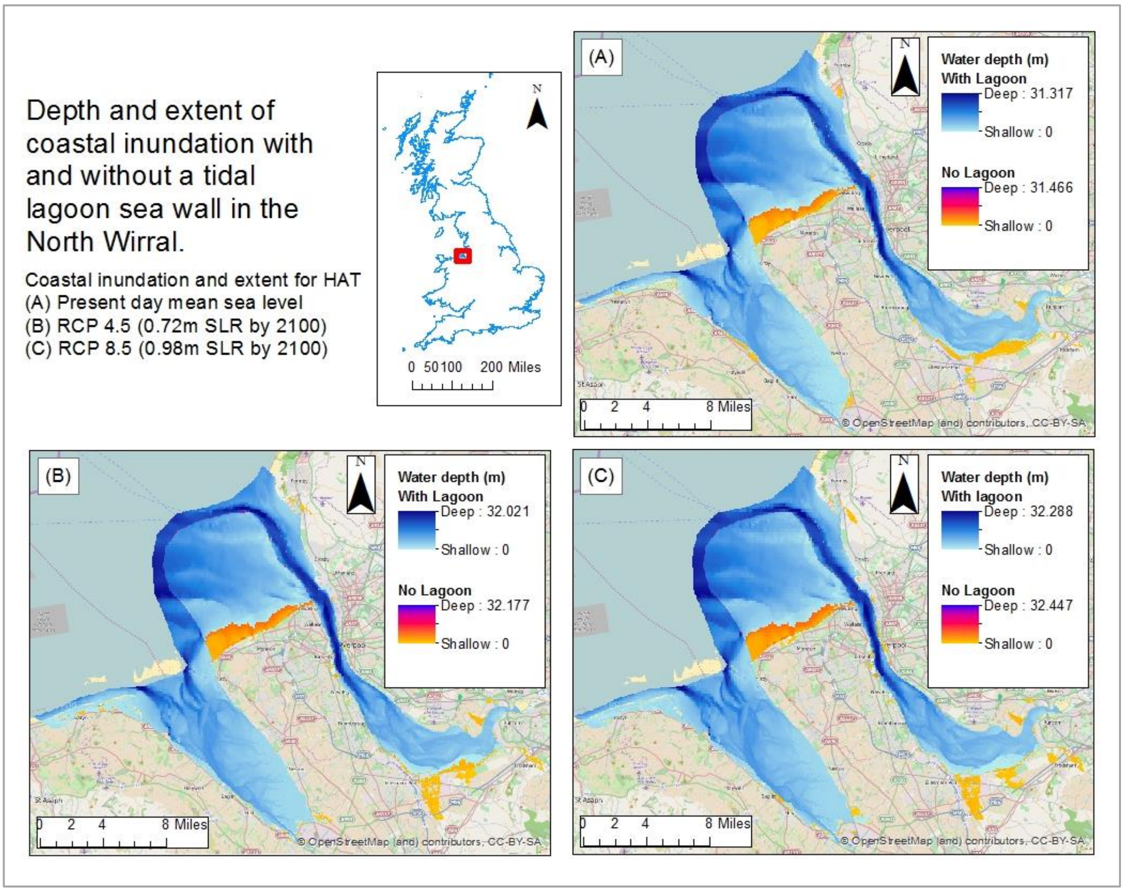

Figure 20: Comparison of depth and extent of inundation in the North Wirral with and without a tidal lagoon under (A) present-day sea-level conditions, (B) RCP 4.5 and (C) RCP 8.5.

Change in tidal lagoon sea wall height

Depth and extent of inundation was modelled in the North Wirral with a tidal lagoon seawall at the height of MHWST, 10.19m (Figure 21). There is no reduction in the extent of inundation, but water depth is reduced in all scenarios.

Figure 21 (A) shows inundation under present-day sea-level, and inundation at Stanlow occurs up to a maximum of 0.14 m. The same location is inundated up to 0.51 m in the baseline scenarios, with no tidal lagoon present. Figure 21 (B) shows inundation under RCP 4.5 (0.72 m SLR), and inundation at Prestatyn Golf course occurs to a maximum depth of 3.07 m. At this same location, inundation occurs to a depth of 2.90 m under the baseline scenarios and 2.65 m under the higher tidal lagoon seawall scenarios. Flood risk is increased in North Wales following the implementation of a lower tidal lagoon seawall. 14.22km^2 less inundation is evident in Figure 21 (C), under RCP 8.5 (0.98 m SLR), than the baseline scenario with no tidal lagoon. However this is 18.59km^2 greater extent in inundation than with a tidal lagoon seawall at 12.19m.

The lower tidal lagoon seawall does not appear to provide as great a flood risk benefit as initially thought. A greater reduction in the extent of inundation was expected, not just the change in water depth. Flood risk is actually increased in North Wales, and the model suggests that a lower tidal lagoon seawall causes greater depth of inundation, compared to the baseline scenarios.

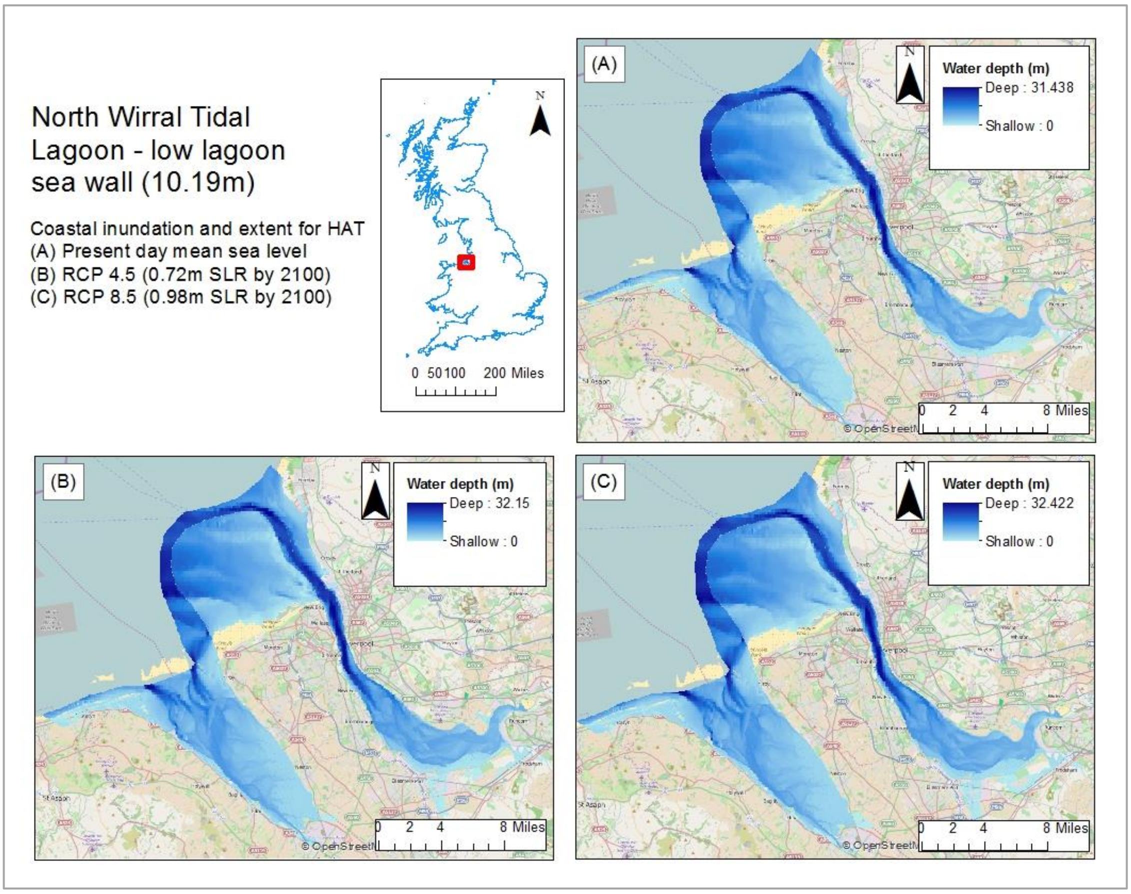

Figure 21: Coastal inundation following the implementation of a lower tidal lagoon seawall in the North Wirral under (A) present-day sea-level conditions, (B) RCP 4.5 and (C) RCP 8.5.

Economic Analysis

Figure 22 shows economic analysis using depth damage curves for saltwater intrusion under baseline scenarios and tidal lagoon scenarios in the North Wirral for urban, suburban and agricultural land use based on salt water depth damage curves (data for all scenarios in Appendix 13) (Penning-Roswell et al., 2005; 2013). The greatest cost of damage from inundation under all sea-level scenarios is seen in suburban areas, as this is the most common land use. The cost of damage in urban and then arable areas is not as high. Damage costs increase most significantly from present-day to RCP 4.5 (0.72 m SLR), as this is the biggest increase in SLR. It can be seen that the presence of a tidal lagoon seawall reduces the costs of inundation under all sea-level conditions for arable, urban and suburban land uses. The cost of damage is reduced in suburban areas under RCP 8.5 (0.98 m SLR) with a tidal lagoon in place by £1.2 billion. The cost of damage in arable areas is reduced by £1.5 million, and £156 million in urban areas following the implementation of a tidal lagoon. However, the costs remain high regardless as a result of extreme future SLR.

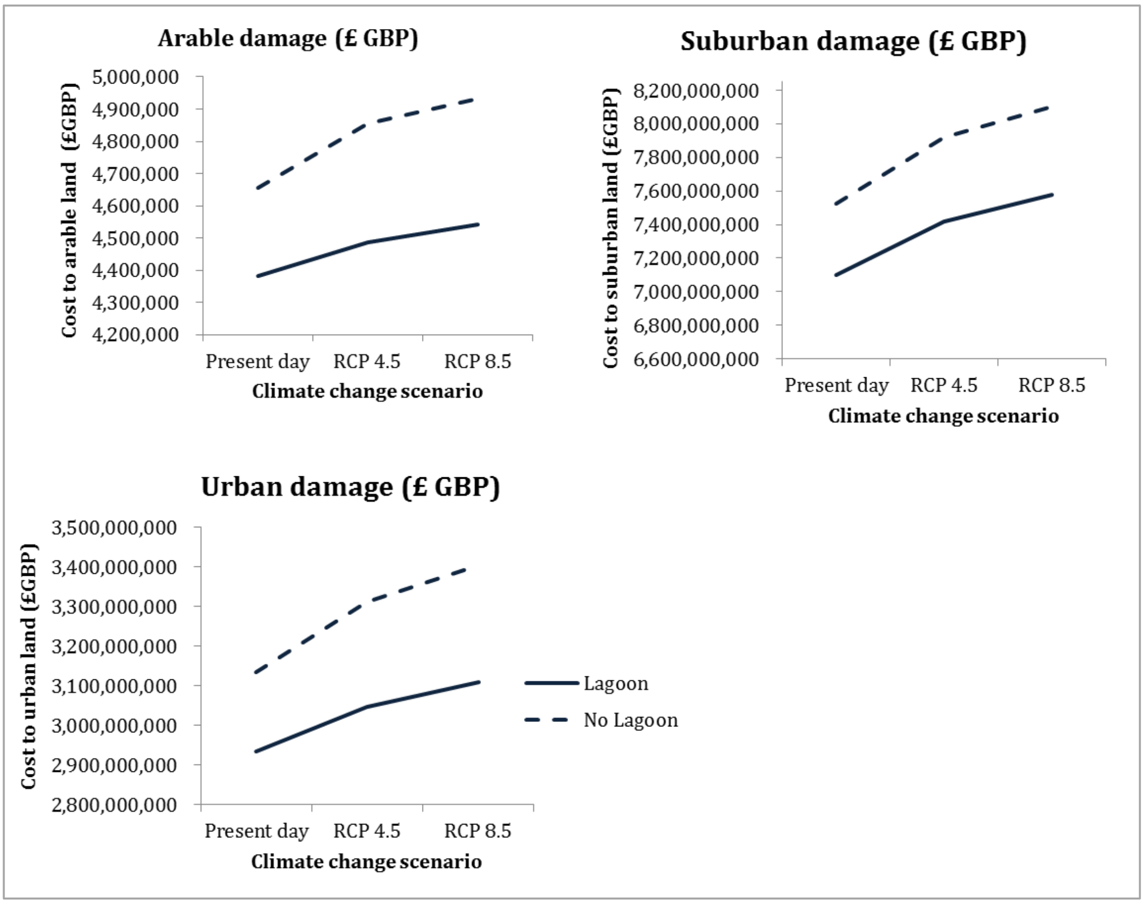

Figure 22: Depth Damage Analysis for the North Wirral for arable, urban and suburban land use (£ GBP).

Colwyn Bay

Baseline scenarios

Baseline scenarios (Figure 23) provide estimation of the depth and extent of inundation under different sea-level, with no tidal lagoon present in Colwyn Bay.

Figure 23 (A) shows inundation which may occur on the North Wales coast under present-day sea-level conditions. Inundation covers 93.65 km^2 in this scenario. Current defences and steep topography of the coast restricts inundation in Old Colwyn and Colwn Bay. Inundation mainly occurs on the floodplains of the River Clwyd; Clwyd View Caravan Park is flooded to a maximum depth of 0.42 m. Kinmel Bay, at the mouth of the River Clwyd, experiences inundation to a depth of 0.72 m. This also affects transport routes, such as the A 548. Inundation does not occur at Rhyl Golf Course or at Pontin's Holiday Park, Prestatyn. As shown in Figure 17 (A) this area was inundated in the baseline scenarios at present-day sea-level in the North Wirral domain. This could be due to the size of the domain and volume of water entering the model.

Figure 23 (B) shows inundation which may occur on the North Wales coast under RCP 4.5 (0.72 m SLR). Inundation increases in area by 25.70km^2 from present sea-level conditions to 119.35km^2. Old Colwyn and Colwn Bay remain protected and are not flooded. Conwy experiences inundation to a depth of 1.31 m, affecting Conwy Golf Course, Aberconwy School and Conwy Borough County Council Building. Low-lying land on the floodplains of the River Ganol is inundated at Rhos-on-Sea and Penrhyn Bay to a depth of 1.5 m, flooding the golf course and areas of Glanwydden. Inundation mostly affect residential properties in Rhyl, which has a population of 25, 149 (DCC, 2014). Deepest inundation is seen on arable land and fields 1.1 km inland at Prestatyn, to a depth of 2.45 m. 16.35 km^2 inundation occurs to the west of the River Clwyd, on the floodplains of the River Gele, at Towyn, Kinmel Bay and Abergele which have a combined population of over 32,000 (CBC, 2011a; 2011b). Flooding also impacts the A 547, as inundation reaches a maximum in Towyn on 0.95 m. Inundation occurs at Prestatyn and Rhyl, up to 1.3 km inland. This floods the North Wales Coast Railway, and stations at Prestatyn and Rhyl.

Figure 23 (C) shows inundation which may occur on the North Wales coast under RCP 8.5 (0.98m SLR). Inundation increases by 6.3km^2 from RCP 4.5 to 8.5, and covers 125.65km^2. Colwyn Bay and Old Colwyn are also not flooded under the most extreme SLR scenario. Llandudno experiences inundation, which appears to result from overtopping of defences at West Parade. Llandudno station, cricket club and primary school are affected, with maximum inundation up to 1.31 m. There is no significant increase in inundation extent at Rhos-on-Sea, but water depth increases to 2.24 m. Inundation covers a total area of 18.12 km^2 in Kinmel Bay and Abergele, with maximum water depth to the west of Abergele at 0.60 m. There is a greater extent of inundation at Rhyl; flooding mainly affects floodplains to the East of the River Clwyd and residential areas to the west on the banks of the River Clwyd. Retail parks, schools, churches and residential properties are most affected. Similar extent of inundation at Prestatyn is seen, as in Figure 23 (B), but maximum water depth has increased to 2.75 m.

Baseline scenarios confirm that areas of the North Wales coast are at risk of flooding with increasing sea-level under high-end scenarios. Sea-level increases flood risk in Prestatyn, Rhyl, Kinmel Bay, Towyn, Rhos-on-Sea and Llandundo. Colwyn Bay and Old Colwyn are not flooded in these baseline scenarios and are not at a high risk under increasing sea-level.

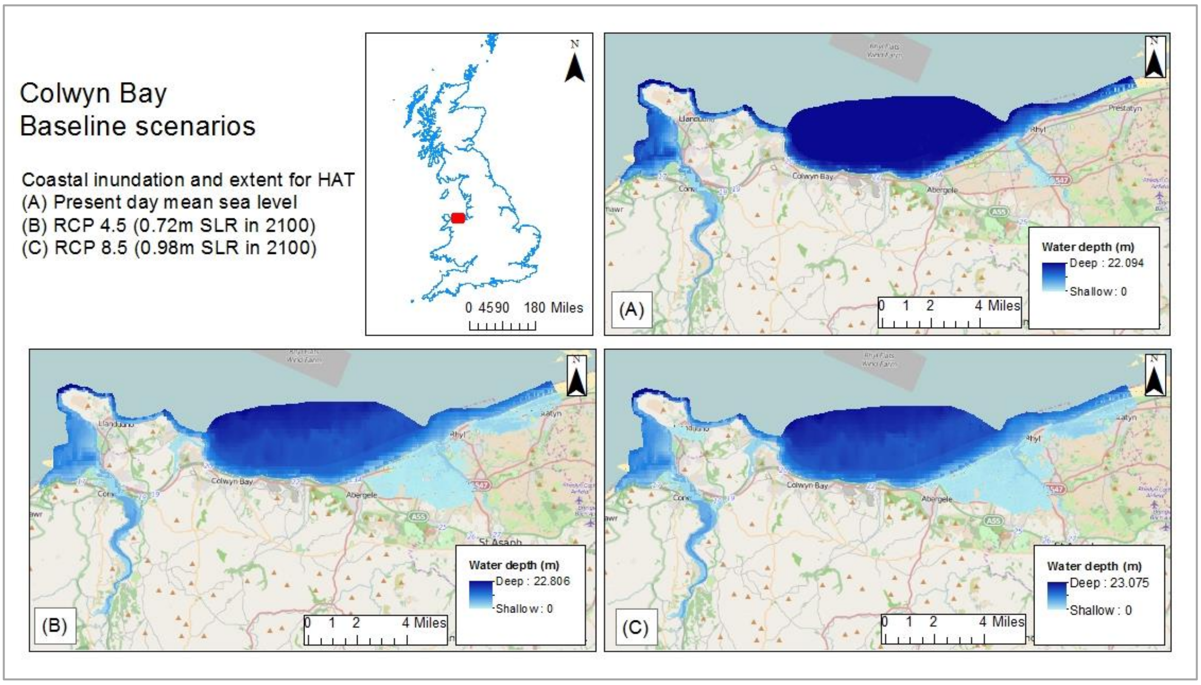

Figure 23: Baseline coastal inundation and extent for Colwyn Bay under (A) present-day sea-level conditions, (B) RCP 4.5 and (C) RCP 8.5.

Tidal lagoon scenarios

Figure 24 shows inundation and extent of flooding in Colwyn Bay with the addition of a tidal lagoon seawall.

Figure 24 (A) shows inundation depth and extent in Colwyn Bay under present-day sea-level, following the implementation of a tidal lagoon seawall at 10.48 m. Inundation covers a total area of 95.95 km^2, which is 2.3 km^2 greater than without a tidal lagoon. Colwyn Bay does not experience inundation, and intertidal areas remain exposed. Inundation occurs up to 380 m inland at Llandudno from the east at North Parade and Mostyn Crescent, to a maximum depth of 0.33 m. The floodplains of the River Ganol flood but do not cause inundation of properties at Rhos-on-Sea or Penrhyn Bay. Inundation of arable low-lying land occurs between Rhyl and Prestatyn, with inundation primarily occurring on the floodplains of the River Clwyd, with maximum water depth to the east of Kinmel Bay up to 0.89 m.

Figure 24 (B) shows inundation depth and extent in Colwyn Bay under RCP 4.5 (0.72m), following the implementation of a tidal lagoon seawall. Inundation covers an area of 118.87km^2, which is a 22.93km^2 increase from the present-day. Flooding in figure 23 (B) covers an area of 0.47km^2 less than baseline, most likely due to protection of Colwyn Bay, and beaches and intertidal areas are not flooded. There is significant inundation at Llandundo, as 1.94 km^2 is flooded to a depth of 1.70 m. Residential areas, Llandudno Golf Course and railway station are flooded, and Great Orme is cut off from the mainland. Flooding occurs at Rhos-on-Sea which follows the North Wales Coast Railway; the peninsula is not cut off but water reaches a depth of 3.18 m. Water floods over low-lying land from the River Clwyd up to 0.70 m. This causes flooding of the A 548, North Wales Coast Railway and Prestatyn Railway Station. The A 525 and A 547 at Rhyl are also flooded. Prestatyn experiences inundation up to 1.3km inland, with water depths of 2.25m on arable land and 0.58m in residential areas.

Figure 24 (C) shows inundation depth and extent in Colwyn Bay under RCP 8.5 (0.98 m), following the implementation of a tidal lagoon seawall. Inundation covers an area of 123.93 km^2 inundation, which is 1.72 km^2 less than the baseline scenario at RCP 8.5. Colwyn Bay remains protected from inundation by the tidal lagoon seawall. Great Orme Head becomes isolated from the mainland. The area of inundation at Llandudno covers 2.33km^2, to a maximum depth of 1.87 m. All residential properties in the area are flooded, with local schools, railway, church and golf course inundated. Inundation of low-lying floodplains of the River Ganol occurs between Conwy and Rhos-on-Sea, which cuts off the peninsula from the mainland. 22 km^2 of inundation occurs at Kinmel Bay, Abergele and west Rhyl. A small area of north Rhyl is cut off as flood water joins up to the south. Water reaches a maximum depth of 2.44 m at Kinmel Bay and 0.86 m at Abergele. Extent of inundation does not increase significantly at Prestatyn but is deeper, with water depth up to 2.66 m in residential areas.

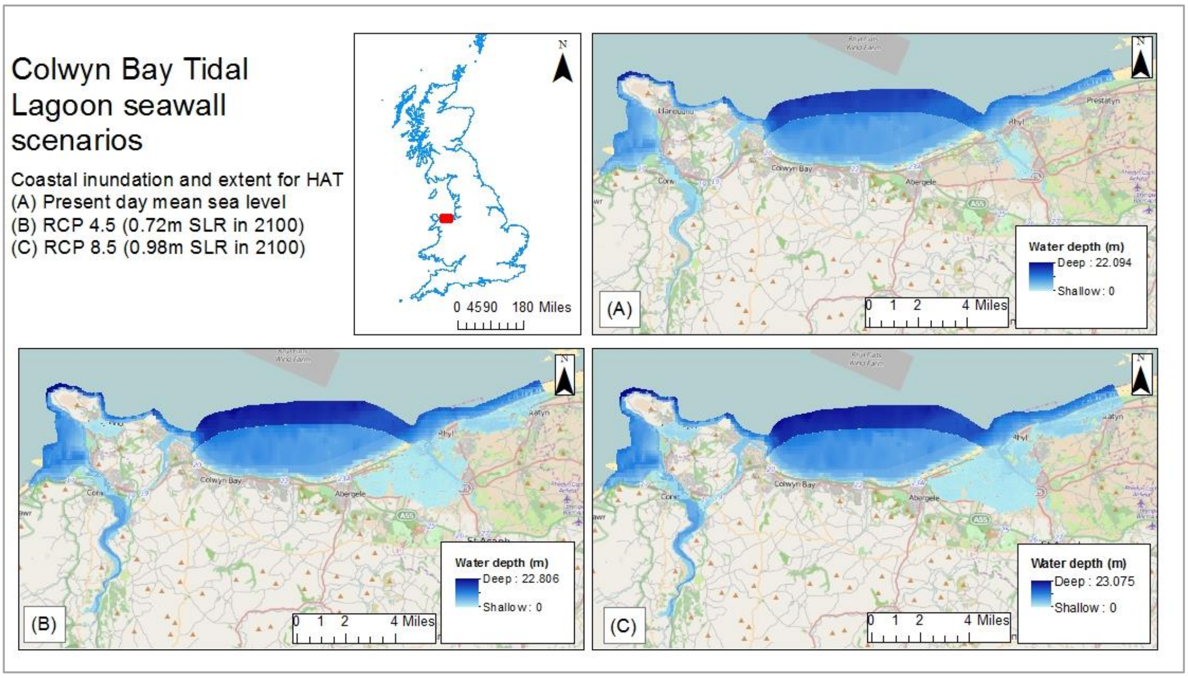

Figure 24: Coastal inundation following the implementation of a tidal lagoon in Colwyn Bay under (A) present-day sea-level conditions, (B) RCP 4.5 and (C) RCP 8.5.

Flood risk increases significantly in Llandudno with the presence of a tidal lagoon in Colwyn Bay, as sea-level rises (Figure 25). This impacts local amenities, transport networks and residential areas. The presence of a tidal lagoon in Colwyn Bay does not provide flood risk benefit in Llandudno.

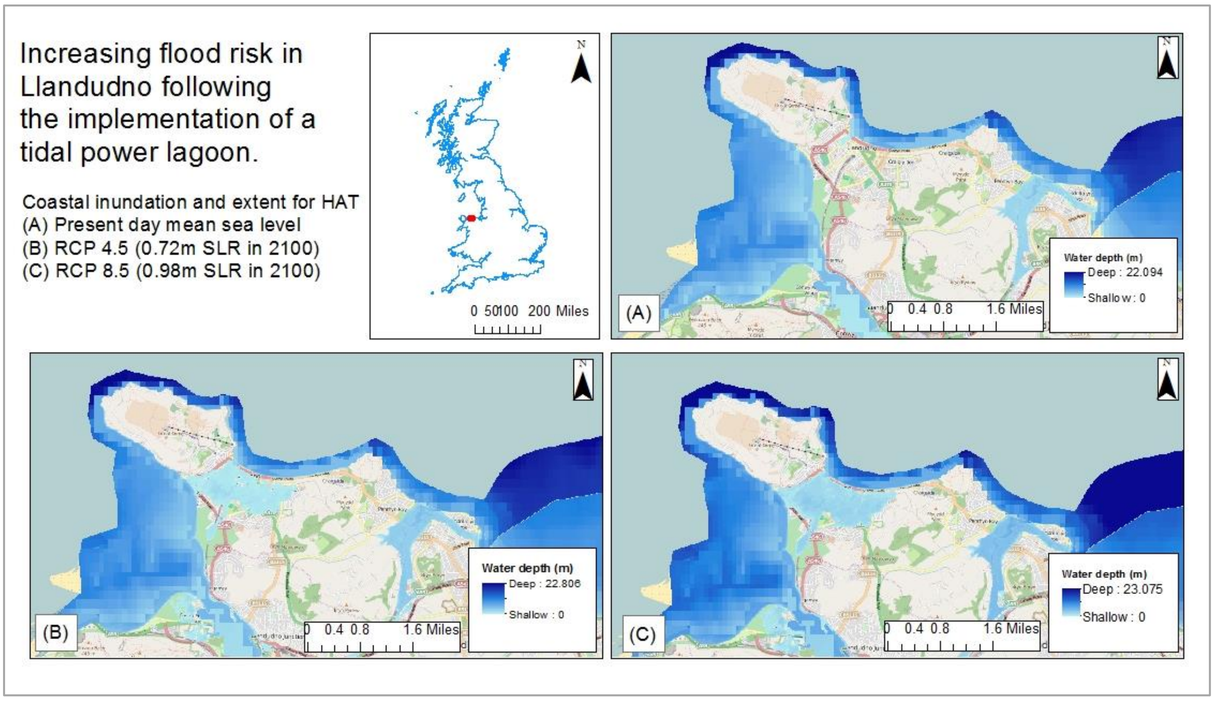

Figure 25: Increasing flood risk in Llandudno following the implementation of a tidal lagoon under (A) present-day sea-level conditions, (B) RCP 4.5 and (C) RCP 8.5.

Flood risk increases in Rhos-on-Sea, Rhyll and Prestatyn too, following the implementation of a tidal lagoon, as shown in Figure 26. No protection is offered in low-lying areas from the implementation of a tidal lagoon at Colwyn Bay. Figure 26 also highlights that Colwyn Bay and Old Colwyn do not experience inundation in either baseline or tidal lagoon scenarios.

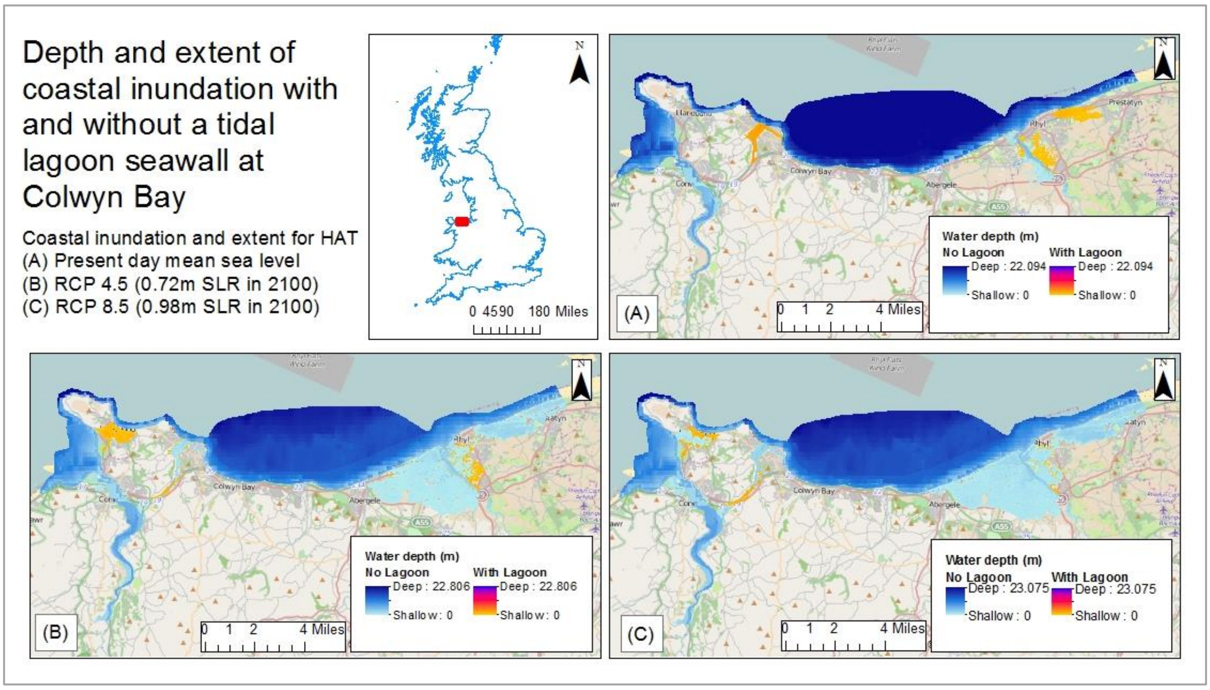

Figure 26: Comparison of depth and extent of inundation in Colwyn Bay with and without a tidal lagoon under (A) present-day sea-level conditions, (B) RCP 4.5 and (C) RCP 8.5.

Economic analysis

Depth damage curves apply a financial cost to each flood event; Figure 27 shows the analysis from the baseline scenarios and scenarios with a tidal lagoon sea wall in Colwyn Bay for urban, suburban and agricultural land use based on salt water depth damage curves (data for all scenarios in Appendix 22) (Penning-Roswell et al., 2005; 2013).

The cost of damage as a result of inundation increases with SLR. Suburban areas experience greatest cost of damage under future sea-level rise; £1,111,000,000 under present-day sea-level, increasing to £1,404,200,000 under RCP 85 (0.98 m SLR). Lowest cost of damage is to arable land; £1,072,500 under present-day sea-level, increasing to £1,764,500 under RCP 85 (0.98 m SLR). The cost of damage following the implementation of a tidal lagoon is greatest is suburban areas. The greatest cost of damage in suburban areas is £1,396,100,000 under RCP 8.5 (0.98 m SLR). This is £8.1 million less than the baseline scenario for suburban areas. The cost of damage is £16,000 less in arable areas following the implementation of a tidal lagoon. These are savings in respect to the cost of damage as a result of inundation, however the costs do remain similar. The cost of inundation is £5.1 million more in urban areas under RCP 8.5 (0.98 m SLR) with a tidal lagoon. With or without a tidal lagoon seawall, damage in the future will be extensive.

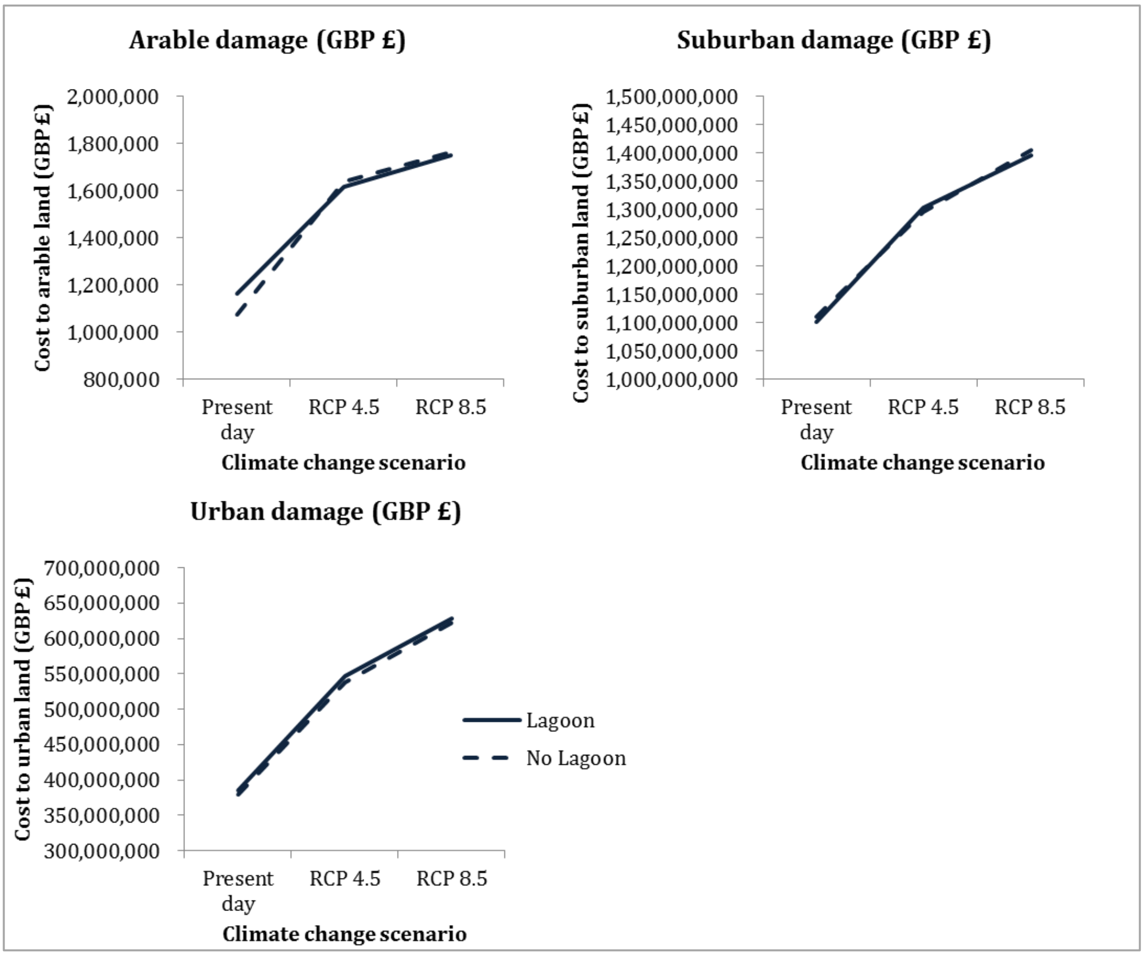

Figure 27: Depth Damage Analysis for Colwyn Bay for arable, urban and suburban land use (£ GBP).

Discussion

Impact of sea-level rise

LISFLOOD was used to estimate coastal inundation as a result of a storm tide under extreme SLR in the Dee & Mersey Estuary and Colwyn Bay. Baseline scenarios in each domain show that extreme SLR will result in greater extent and depth of inundation by 2100. Flood risk increases with time as relative sea-level rises, however it should be noted that defence heights are maintained at the present level in the model simulation. Infrastructure in the North Wirral domain, notably Stanlow oil refinery and Shotton steel works and paper mill are at increasing flood risk as sea-level rises (Figure 18). Residential areas and holiday parks at Talacre, Prestatyn, Rhyl, Kinmel Bay and Llandundo on the North Wales coast are likely to experience increasing inundation as sea-level rises. The Environment Agency flood risk maps also identify these areas as being in flood zone 3; areas with greater than 0.5% probability of flooding in any year (EA, 2009b; 2010a). Flood risk increases significantly within the first 0.72 m of SLR due to the low-lying topography of the Conwy coast and much of the Dee and Mersey Estuary. However these scenarios do not account for waves or meteorological impact, or potential changes to defences over the coming century. Baseline inundation scenarios confirm that extreme SLR will increase inundation in certain areas of the NW.

The economic cost of damage as a result of extreme SLR is potentially high. The cost of damage increases as sea-level rises, and is highest in urban and suburban areas due to the high clean-up cost and repair (Penning-Roswell et al., 2013). Intangible, indirect losses will also be felt in areas with increasing flood risk. Inundation of factories will result in loss of jobs, income and welfare; Stanlow oil refinery employs over 900 people, GrowHow UK over 400 people and Shotton Paper Mill over 300 (Pycroft et al., 2015). Damage to Connah's Quay power station and Point of Ayr gas station could impact power supply throughout the NW region (EnergyUK, 2015). Transport routes will be closed and damage to the North Wales Coast Railway could impact tourism, commuting and business. Similar impacts were seen at Dawlish, Devon in 2014 as 80 m of South West railway was flooded, and collapsed during a storm surge (BBC, 2014). The railway was closed for 3 months while cliff stabilisation and seawall repairs were completed and barriers and signalling equipment replaced (Network Rail, 2014). It is estimated the railway closure cost the economy £1.2 billion (BBC, 2015). Baseline scenarios suggest that strategies to minimise the risk of inundation in these areas is required to avoid the forced displacement of coastal population and detrimental effects on local economy under SLR (Nicholls et al., 2011).

Baseline scenarios also identify areas that are not at risk of inundation under future SLR. The baseline scenarios suggest that that Colwyn Bay and Old Colwyn is not at high risk of inundation under future SLR scenarios. The model suggests the North Wirral coastline is also at low flood risk under future SLR scenarios, apart from a small area of low-lying land at Meols. The extent of flooding in these areas is contained due to the steep topography and defences already in place. The location and shape of the tidal power lagoon in each domain was selected before the baseline scenarios had been completed. It is recommended that future inundation modelling focusing on the feasibility of tidal power lagoons use baseline scenarios as an aid to deciding where the lagoons should be placed to minimise flood risk.

Impact of implementation of a tidal lagoon seawall

Tidal power lagoons may provide flood risk benefit in areas identified by baseline model scenarios that are likely to experience greater depth and extent of inundation under future SLR.

Reduced flood risk and inundation

A 0.5 km^2 area of inundation occurred to the east of Meols under RCP 8.5 (0.98 m SLR), on the North Wirral coastline in the baseline scenarios. No flooding occurs in this location under the tidal lagoon scenarios under RCP 8.5 (0.98 m SLR). A tidal lagoon on the North Wirral acts as a hard defence and prevents water moving into this area of the domain. Therefore flood risk in this area appears to be eliminated. However 0.5 km^2 area of inundation between Hoylake and Wallasey would most likely constitute a small increase in flood risk under future SLR in the North Wirral (Environment Agency, 2009a). The low flood risk on the North Wirral coast is unlikely to warrant a large tidal lagoon to provide protection. Therefore mitigation of flood risk in this area, from a tidal lagoon or otherwise, may not be a priority for Environment Agency and Wirral Borough Council.

Flood protection may not be a priority between Hoylake and Wallasey, but a tidal lagoon on the North Wirral coastline appears to provide flood risk benefit to other areas in the North Wirral domain. Baseline scenarios suggest that industrial areas in the North Wirral domain, specifically Stanlow oil refinery in the Mersey Estuary and Connah's Quay power station & Shotton Works in the Dee Estuary are at risk of inundation under increasing SLR. Results from LISFLOOD suggest that the implementation of a tidal power lagoon on the North Wirral coastline reduces flood risk in these industrial areas up to 1.37 m at Shotton Works and 2.51 m at Stanlow oil refinery under RCP 8.5 (0.98 m SLR) (Figure 19). Modelling of a tidal lagoon in the Severn Estuary also found that maximum water levels were predicted to fall slightly by between 0.2 and 0.5 m upstream of a lagoon structure (Falconer et al., 2009). Modelling of Swansea Bay Tidal Lagoon under extreme sea-level conditions also found that the project provides flood risk benefit to onshore elements of the project, and did not increase sea-levels outside of the lagoon (URS, 2014). The presence of a lagoon can reduce the magnitude of tidal currents upstream and alter the period of submergence to reduce flood risk (Xia et al., 2010).

Protection is most likely offered in the North Wirral domain due to the size, shape and location of the tidal lagoon seawall. In the model domain, the lagoon seawall narrows the Queens Channel and creates a funnel in the Mersey, which in turn may limit the magnitude of tidal currents up the estuary. Protection is not offered by the tidal lagoon in the same manner as a seawall, by deflecting and dissipating waves, but by changing tidal hydrodynamics of the area. The result from the lower lagoon seawall in the North Wirral reiterates this; the lower wall allows the tide to propagate more easily up the Mersey estuary to create greater depth of inundation. This shows that tidal power lagoons may be able to provide flood risk benefit to areas at risk of inundation under future SLR. The effect of the structure on the North Wirral coastline is likely to be far reaching; the domain of future modelling needs to extend further inland to visualise the full extent of inundation in the Dee Estuary, and extend the impact from North Wales up to Southport or Blackpool.

The reduction of flood risk in the North Wirral domain, and reduced magnitude of tidal hydrodynamics, may be due to the size of the tidal lagoon. The North Wirral lagoon is 139.1 km^2; this is over ten times larger than the Swansea Bay tidal lagoon (TLSB, 2014a). The scale of change seen as a result of the implementation of tidal power lagoons increases with the size of the structure (Cousineau et al., 2012). The North Wirral lagoon structure is likely to be causing changes in the magnitude of tidal currents, leading to flood risk reduction and reduced water depth. This result from LISFLOOD is likely to be an accurate estimate of the change sin flood risk and inundation in the North Wirral domain. The simplified flow representation in LISFLOOD is able to capture the impact of a SLR and storm tide (Bates et al., 2005a). The model operates well over shallow coastal floodplains and has been shown to successfully handle large volumes of water in a large study domain (Bates and de Roo, 2000; Dawson et al., 2005). Future modelling may wish to simulate the impact of tidal lagoon structures more specifically on tidal currents and 3D tidal velocity profiles (Pender and Néelz, 2007; Cornett et al., 2013). This could be achieved with Telemac2D or Telemac 3D (Robins et al., 2011; Rees et al., 2014). Telemac combines ocean, terrestrial and atmospheric processes and has been used in flood inundation modelling and to also quantify potential changes in tidal hydrodynamics following the implementation of single and multiple tidal lagoons in the upper Bay of Fundy and Severn Estuary (Falconer et al.,2009; Cornett et al., 2013; Rees et al., 2014;). This will allow further investigation into how tidal lagoon structures are able to offer flood risk protection upstream of the project by altering tidal hydrodynamics.

A large tidal lagoon on the North Wirral would provide flood risk benefit and reduction in cost of damage in the Mersey and Dee Estuary up to £ 524,700,000 in suburban areas under RCP 8.5 (0.98 m SLR), by 2100. This is because fewer properties are inundated; the cost of damage is reduced as less area is inundated. However relying simply on flood extent and volume can under-predict the actual economic impact felt by a coastal community (Hunter et al., 2005;

Prime et al., 2015). Consideration must be made to indirect losses for flooded households; temporary evacuation costs, loss of utility services and loss of earnings (Penning-Roswell et al., 2013). Therefore the cost of inundation of each scenario may be higher than estimated.

The large lagoon in the North Wirral is predicted to generate more power, if it is assumed that power generation is proportional to size of lagoon (Frid et al., 2012). The North Wirral lagoon may be a cheaper strategy than offshore wind and, for larger lagoons, comparable with nuclear energy (Poyry, 2014). A lagoon on the North Wirral of this scale represents a large investment; the cost of building a seawall and a lagoon increases as water depth increases (Linham, 2007; Hogan et al, 2014). As the water depth in the North Wirral domain reaches up to 15.6 m the costs may be high. A smaller lagoon may be more financially feasible but may not provide flood risk benefit; magnitude of tidal currents are unlikely to be reduced (Xia et al., 2010a). Cornett et al. (2013) found that changes in water levels are largest near the lagoon and generally diminish with increasing distance. A smaller lagoon may not help to resolve flood risk in industrial areas of the Mersey Estuary. Further modelling of the impacts of a smaller lagoon is required.

It can be seen that the implementation of a tidal lagoon in the North Wirral may lead to the increased exposure of intertidal areas and saltmarshes at Ince Banks and reduced depth of inundation at Parkgate Marsh (Figure 19). LISFLOOD does not model morphological changes however it can be assumed that a reduction in the magnitude of tidal currents up estuary may cause a change in hydroperiod and lead to a loss or change in habitat extent (French, 2006; Shields et al., 2011; Pye, 2014). A reduction in maximum water level and flood risk can lower suspended sediment concentration to alter net accumulation (Falconer et al., 2009; TLSB, 2014e). Future modelling could assess the impact of the implementation of a tidal power lagoon on local morphological change and suspended sediment concentrations (Polagye, 2010; Cousineau et al., 2012). Finite Volume Coastal Ocean Mode (FVCOM) has been successfully applied to modelling coastal sediment transport in the past (Amoudry and Souza, 2011; Nicholls et al., 2015). Delft 3D has been applied to modelling changes in coastal morphology, flow and waves as a result of tidal and meteorological forcing (Lesser, 2004). Tailored, site specific near field and far field modelling of the geomorphological and sedimentological impact of a tidal power lagoon is required for each potential lagoon project.

Current tidal flood risk management plans in North west England and North Wales agree that action must keep pace with SLR to enable flood risk to local communities to be lowered (AECOM, 2012; EA Wales, 2013). The middle Mersey Estuary and Ince Bank have been identified as areas where flood risk will increase (EA, 2009). Properties should be protected to their current standard or better; a broader range of integrated strategies should work alongside existing natural and hard defences to reduce the likelihood of flooding (EA, 2009; 2010a). Tidal lagoons do not currently feature as options to reduce risk of inundation, but these structures may have the ability to keep pace with SLR.

Increased flood risk and inundation

The implementation of a tidal lagoon from Colwyn Bay to Kinmel Bay appears to increase flood risk in low-lying areas. These areas, including Llandudno, Prestatyn and Rhyl, were identified as areas at risk of inundation in baseline scenarios (Figure 23). The flood risk at Llandudno is significantly increased as a result of the lagoon in this location. Increased flood risk mainly impacts residential areas, transport links and leisure facilities, as this is a popular holiday destination (CBC, 2014).

The presence of a tidal lagoon seawall across Colwyn Bay is likely to mean that water is displaced; incoming tides have a smaller area to inundate (Figure 28) (Linham and Nicholls, 2010). This will cause water depths to increase in low-lying areas, such as Llandudno, and increase flood risk (French, 2001). Water displacement is also likely to affect flood risk in Abergele, Kinmel Bay and Rhyl. Increased flood risk in Llandudno would be a reason not to build a tidal power lagoon in the location modelled here. Swansea Bay Tidal Lagoon is located away from the main Bristol Channel to minimise the impact of water displacement (TLSB, 2014e). The tidal head in Swansea Bay, created to generate energy, is in response to a standing wave rather than the main progressive tidal wave, which reduces far-field changes in extreme water levels (TLSB, 2014e). Alternative locations for a tidal lagoon at Colwyn Bay should be considered to minimise flood risk in vulnerable areas.

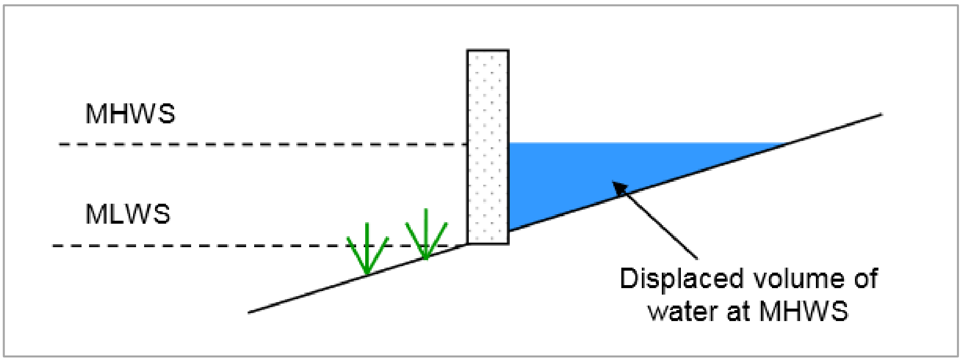

Figure 28: Illustration of the displaced volume of water at MHWS (Linham and Nicholls, 2010, pp. 65).

The tidal lagoon at Colwyn Bay also increases the extent of inundation and flood risk at Abergele, Rhyl and Prestatyn as sea-level rises. Inundation due to SLR is likely to occur in these suburban areas, most likely due to the low-lying topography (CBC, 2015a). Much of Conwy Bay consists of shallow sand banks and mudflats that presently restrict flood generation (HR Wallingford, 2008; Halcrow, 2010). These restrictions will be progressively less significant under high-end SLR, leading to increased nearshore wave height and tidal velocity (Stansby et al., 2006; Neill et al., 2012). The cost of damage of SLR scenarios remains high for urban, suburban and agricultural areas following the implementation of a tidal lagoon. The cost of damage is likely to be the same because the same areas are inundated in baseline and lagoon scenarios; no protection is offered in the areas at risk of inundation by the lagoon. The location of the lagoon modelled in these scenarios is not feasible as it increases flood risk, and does not reduce cost of damage.

LISFLOOD suggests there is a high flood risk along the North Wales coastline, from Abergele to the Point of Ayr. Strategies must be considered and implemented in the near future to mitigate the risks from extreme SLR. One option, which consists of 5 separate impounded areas, has been suggested (Figure 29). These structures would impound 700 km2 and would have a potential average generation capacity of ~ 3 GW (Houghton, 2012). These structures would provide flood risk benefit to the North Wales and North Wirral coastline, but will have far reaching impacts on hydrodynamics and habitats. Extensive inundation and morphological modelling would be required. These structures would also impound the Mersey Estuary, Dee Estuary, River Clwyd and River Conwy.

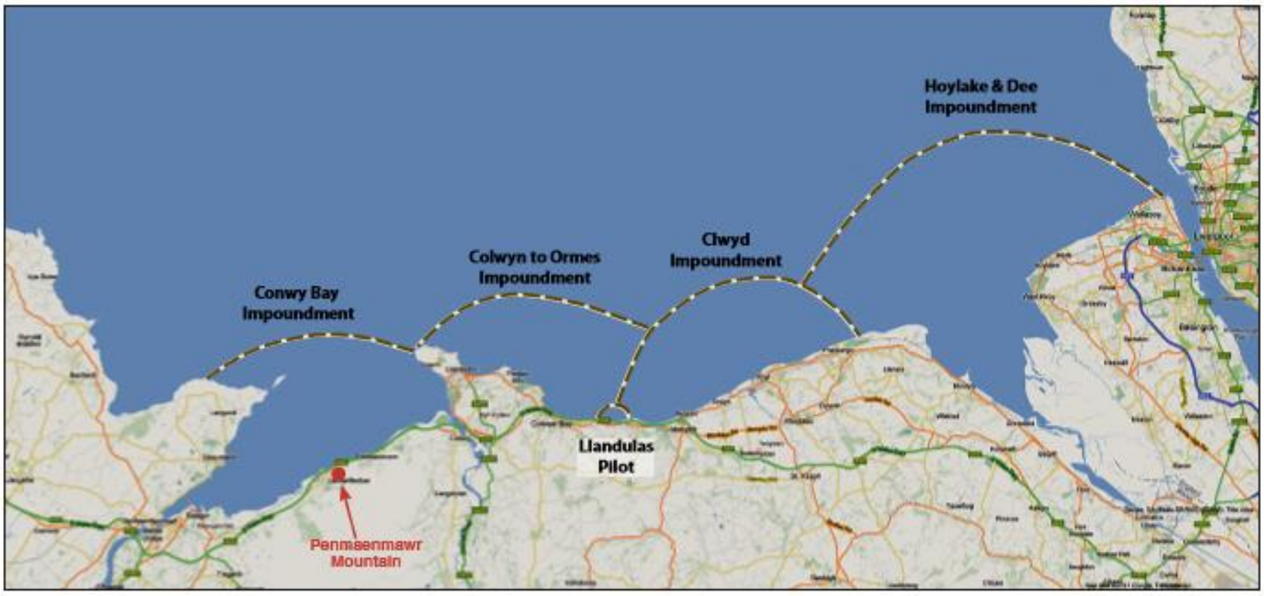

Figure 29: Five tidal impoundments along the North Wales and North Wirral coastline (Not to scale) (Anderson, 2012; Houghton, 2012).

Strategies would have to be implemented to manage fluvial flooding and monitor salinity in the lagoon. Sluices could be used to maintain water levels during fluvial flood events, and salinity of the lagoon water could be monitored (TLSB, 2014e). Salinity is currently monitored in natural lagoons to maintain suitable levels when fluvial flooding occurs, as well as in saltmarsh restoration and managed realignment projects (Esteves and Marshall, 1993; Wicklein and Gain, 1999).

A smaller, pilot tidal impoundment project has been suggested at Llandulas, and a project at Llandudno. The smaller lagoon at Llandudno would aim to provide reliable flood protection and also eliminate the current problem of erosion of the beach on the north shore (Daily Post, 2015). Many local stakeholders believed that controlling the tide through the use of a barrier is a feasible and reasonable approach (EA Wales, 2014). However the Tidal Clwyd Flood Risk Management Strategy does not support the use of barriers, due to the risk of failure, high costs and possible damage to habitats (EA Wales, 2014). Additional numerical modelling can help to eliminate potential risk and failure, and cost benefit analysis would be required to consider the investment. However adaptation measures may not prevent the eventual evacuation and loss of low-lying areas along the Conwy coast to the sea (Anderson, 2012).

Additional strategies could be implemented at Prestatyn, Rhyl and Kinmel Bay to minimise flood risk; the implementation of smaller tidal lagoons could be combined with hard and soft defence strategies (Wales Audit Office, 2009). Upgrading hard sea defences would offer protection to some areas, however this defeats the point of green, innovative adaptation strategies to minimise flood risk in the future (Linham and Nicholls, 2010). ‘Soft’ flood management solutions, e.g. public education and flood warning are also encouraged (Dawson et al., 2005). Limiting intervention would mean high risk areas are inundated more regularly and potentially lost altogether (Arnjberg-Nielsen et al., 2015). This may result in the complete relocation of towns, caravan parks, roads and the main railway (Wong et al., 2014). Tidal power lagoons may not be able to resolve all flood risk along the North Wales coastline, but will be one option available to mitigate inundation, along with retreat and accommodation adaptation options.

Additional modelling would be required in order to consider the effectiveness of a range of integrated strategies, to minimise flood risk and their ability to respond to extreme SLR.

Limitations

Model outputs from LISFLOOD are projections of how extreme SLR could impact depth and extent of inundation in the future. The projections are estimations of future scenarios, and results can also be influenced by and a result of the model setup and input data (Bates and de Roo, 2000). The methodology used in this study, in addition to the resolution of LiDAR data selected, has been guided by the desire to model large areas of the North Wales and North Wirral domain coastlines, within the limitations of available computing resources.

LISFLOOD is a powerful exploratory tool to assess flood impacts and risk (Smith et al., 2012; Quinn et al, 2013). The predictions can look realistic however there is a significant degree of uncertainty that surrounds inundation extent as there is no data against which to validate the results (Pender and Néelz, 2007). Inaccuracy of the DEM and loss of defined features can limit the observed inundation extent, which highlights the importance of accurate LiDAR data (Bates et al., 2005b). Studies of the coastline using different topographical data sets may yield different results however grid size is thought to have a limited impact (McInnes et al., 2009; Lewis et al., 2011). Results of 2D models should be used as guides and aids when planning under a range of scenarios, and should not be used solely as tools to inform decision makers (Néelz and Pender, 2009; Wadey et al., 2012).

A number of assumptions have been made, as is often the case with inundation modelling. All scenarios assume the status quo in the present-day continues up to 2100. This is unrealistic as this assumes no further intervention or development of the floodplain occurs and the friction co-efficient will remain constant (Dawson et al., 2005). It has been identified that model results are likely to be sensitive to the floodplain friction value selected and the choice of friction coefficient should be regarded as a modelling assumption (Bates et al., 2005a; Lewis et al., 2011). It is also unrealistic that only one friction co-efficient is selected across a large domain, which includes urban, intertidal and arable areas. A friction value can be applied in future modelling on a cell by cell basis, dependent on land use (Prime et al., 2015). The model also assumes that the bathymetry of the site remains constants (Dawson et al., 2009). This is a significant assumption as the shallow sandflats and mudbanks to the North of the Conwy coastline are mobile, and major changes are likely to occur over the next century. The model assumes a uniform return period of an extreme water level along the coastline, which is shown to be unlikely (Battjes and Gerritsen, 2002; McInnes et al., 2003; Lewis et al., 2011). Depth damage costs also assume one house type in suburban and urban areas (Penning-Roswell et al., 2013). The cost of damage to transport routes, roads, and caravan park homes (commonplace on the North Wales coast) are also not considered (Penning-Roswell et al., 2013). These assumptions should be considered when interpreting results, and also communicated to decision makers and stakeholders involved in planning for future SLR.

It has been identified that there is a degree of uncertainty surrounding the rate of sea-level change. The model assumes a constant rate of SLR, as predicted by the IPCC. The probability and associated time-scale for change are highly uncertain (Lewis et al., 2011). If a 1m net SLR were to occur over a long duration (the next century), then coastal communities would be able to respond in an ad hoc basis (Linham and Nicholls, 2010). However extreme, rapid change, such as the collapse of the WAIS, would result in a step change in SLR and a more reactive societal response (Dawson et al., 2005; 2009). Based on construction time of the Thames Barrier and the Eastern Schelde Barrier in the Netherlands and upgrade of current defences, new intervention and infrastructure would require upwards of 10 years to be built. Grinsted et al., (2015) also identify relative SLR in Liverpool to be 1.66 m in the 95th percentile. Therefore adaptation strategies would need to remain flexible to manage this uncertainty (Evans et al., 2004).

Conclusion

Tidal resources have the potential to secure the UK's energy demands into the future and provide secondary benefit as coastal flood protection against future sea-level rise. LISFLOOD was successfully used to model extreme flood events in the North Wirral and Colwyn, to look at changes in the extent and depth of flooding following the construction of a lagoon under present-day sea-level and future, high-end SLR.

Baseline scenarios show that there is low flood risk on the North Wirral coastline under future high-end SLR scenarios, with no tidal lagoon. Low-lying areas of the North Wirral domain, notably infrastructure at Stanlow refinery and Connah's Quay and residential areas at Prestatyn, are at a higher risk of inundation under RCP 4.5 (0.72 m SLR) and RCP 8.5 (0.98 m SLR). The construction of a tidal lagoon on the North Wirral coastline reduces flood risk under all high-end sea-level rise scenarios. The tidal lagoon provides protection to infrastructure in the North Wirral domain, and eliminates flooding at Stanlow oil refinery and Frodsham under all SLR scenarios. The tidal lagoon reduces the depth of inundation at the Point of Ayr and Prestatyn up to 0.47 m, but the extent of inundation remains the same as baseline scenarios. The cost of damage as a result of inundation is reduced in suburban areas by £1.2 billion, £156 million in urban and £1.5 million in arable areas with a tidal lagoon. Flood risk benefit in the North Wirral domain is most likely due to the size and shape of the tidal lagoon, which limits the magnitude of tidal streams up the Dee and Mersey estuary. However, the North Wirral coastline is not at high flood risk so protection here is not a priority, and the bathymetry of Liverpool Bay and size of the lagoon may mean this lagoon is not financially viable. Alternative locations for a tidal power lagoon in Liverpool Bay and the Wirral appear limited though. A smaller lagoon may provide a more financially viable option, but it remains to be seen if this will provide any form of flood risk benefit in the area. Without further study of alternative lagoon shape and size, impact on tidal currents, morphology and suspended sediment over a larger domain and cost-benefit analysis, it cannot be said if the North Wirral is a suitable location for a tidal lagoon.

Baseline scenarios show that the flood risk in Colwyn Bay and Old Colwyn does not increase under future high-end SLR scenarios due to the steep topography and existing defences. Low-lying land in the Colwyn Bay domain is at increasing flood risk as sea-level rises; residential areas, holiday parks and transport networks at Prestatyn, Rhyl, Kinmel Bay and Llandudno experience increased risk of inundation under all high-end SLR scenarios. Inundation in these low-lying areas in the Colwyn Bay domain are exacerbated following the implementation of a tidal lagoon at Colwyn Bay, under all high-end SLR scenarios. Inundation increases up to 2.44 m at Kinmel Bay and 2.66 m at Prestatyn under RCP 8.5 (0.98 m SLR). Llandudno is inundated up to 1.87 m, and becomes cut off from the mainland. Rhyl is also inundated on all sides. The cost of damage as a result of inundation is reduced by £8.1 million in suburban areas, but increased in by £5.1 million in urban areas with a tidal lagoon under RCP 8.5 (0.98 m SLR). This is a far less significant saving than in North Wirral domain. A tidal lagoon in Colwyn Bay could increase flood risk in Llandudno, Rhyl and Colwyn Bay, which is reason enough to recommend alternatives locations are sought for this project. It can be seen that tidal power lagoons that are not placed in suitable locations can increase flood risk in the near field.

All results from LISFLOOD are estimations of future scenarios, and interpretation of results should consider the assumptions and limitations of the model. The accuracy of topographic data sets and sensitivity to the model friction co-efficient are key limitations. Baseline scenarios of coastal inundation should be used to determine where tidal power lagoons are best placed to provide flood risk benefit and reduce the costs of inundation in vulnerable areas.

Tidal power lagoons may be one of many strategies for low carbon, green energy production and flood protection on the Conwy coastline and on the Wirral. These structures have the ability to keep pace with sea-level rise and could be effective in reducing flood risk as part of an integrated strategy. Following further study, flood risk management strategies could combine tidal lagoon with hard and soft defence options to provide resilience to future sea-level rise on the North Wirral and Conwy coastline.

Acknowledgements

This work would like to acknowledge the support from the EU FP7 collaborative project Responses to Coastal Climate Change: Innovative Strategies for High End Scenarios -Adaptation and Mitigation- (RISES-AM-, Grant agreement no: 603396) and the EPSRC project Adaptation and Resilience of Coastal Energy Supply (ARCoES EP/1035390/1).

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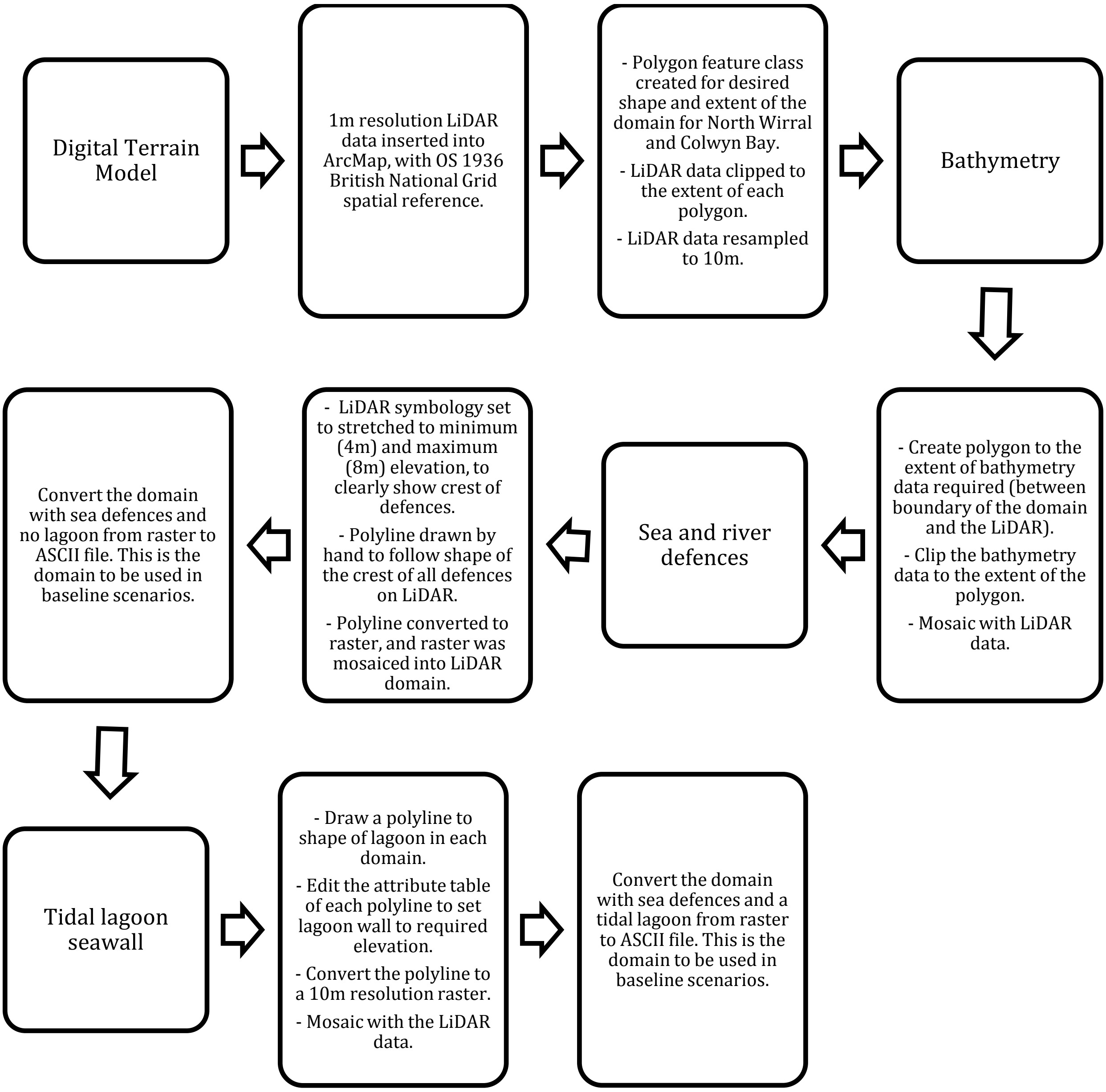
Appendix

Appendix 1: Method to create domain in Arc GIS for LISFLOOD model simulations.



Digital Terrain Model

1m resolution LiDAR data inserted into ArcMap, with OS 1936 British National Grid spatial reference.

- Polygon feature class created for desired shape and extent of the domain for North Wirral and Colwyn Bay.
- LiDAR data clipped to the extent of each polygon.
- LiDAR data resampled to 10m.

Bathymetry

- Create polygon to the extent of bathymetry data required (between boundary of the domain and the LiDAR).
- Clip the bathymetry data to the extent of the polygon.
- Mosaic with LiDAR data.

Sea and river defences

- LiDAR symbology set to stretched to minimum (4m) and maximum (8m) elevation, to clearly show crest of defences.
- Polyline drawn by hand to follow shape of the crest of all defences on LiDAR.
- Polyline converted to raster, and raster was mosaiced into LiDAR domain.

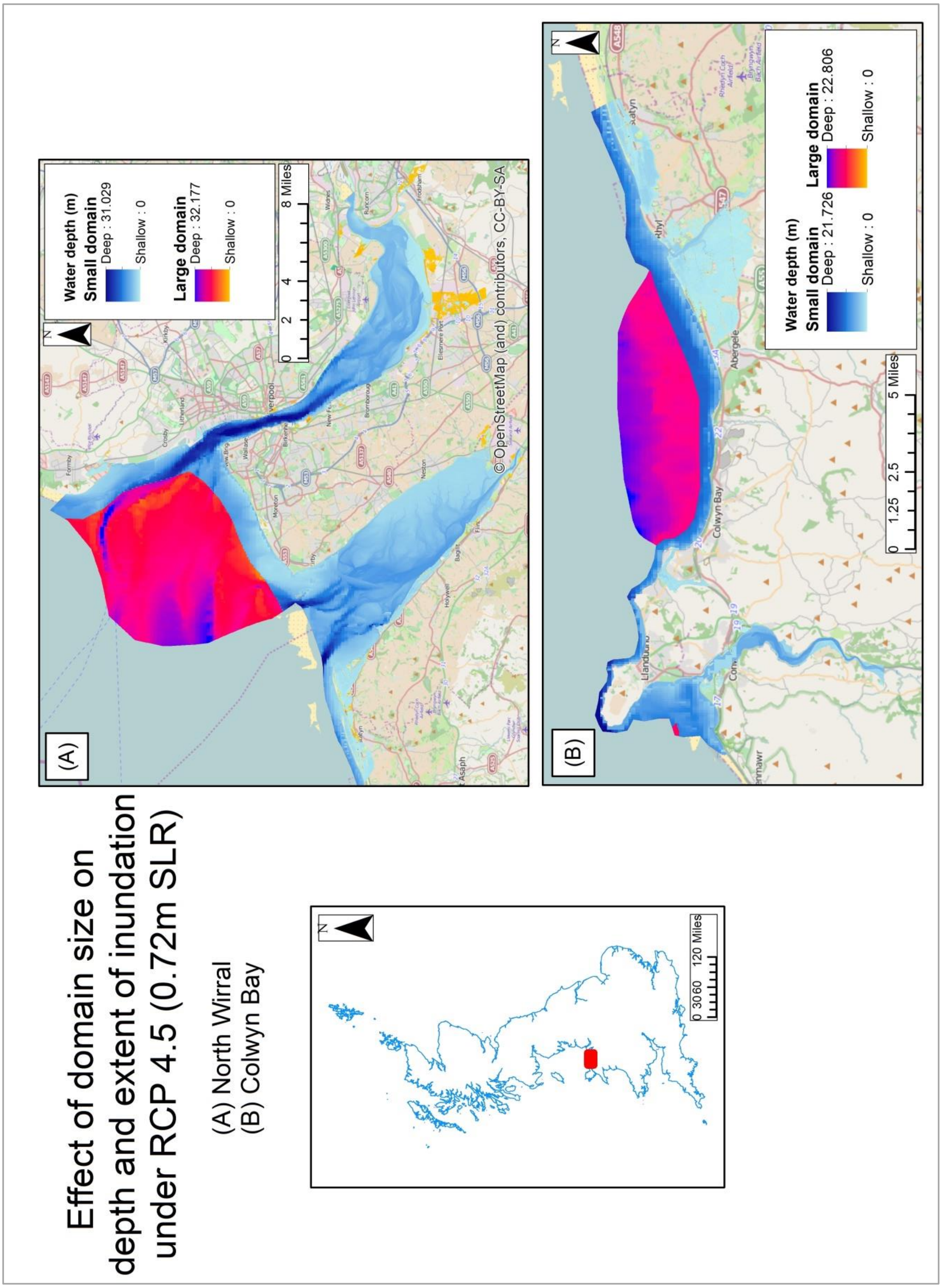
Convert the domain with sea defences and no lagoon from raster to ASCII file. This is the domain to be used in baseline scenarios.

Tidal lagoon seawall

- Draw a polyline to shape of lagoon in each domain.
- Edit the attribute table of each polyline to set lagoon wall to required elevation.
- Convert the polyline to a 10m resolution raster.
- Mosaic with the LiDAR data.

Convert the domain with sea defences and a tidal lagoon from raster to ASCII file. This is the domain to be used in baseline scenarios.

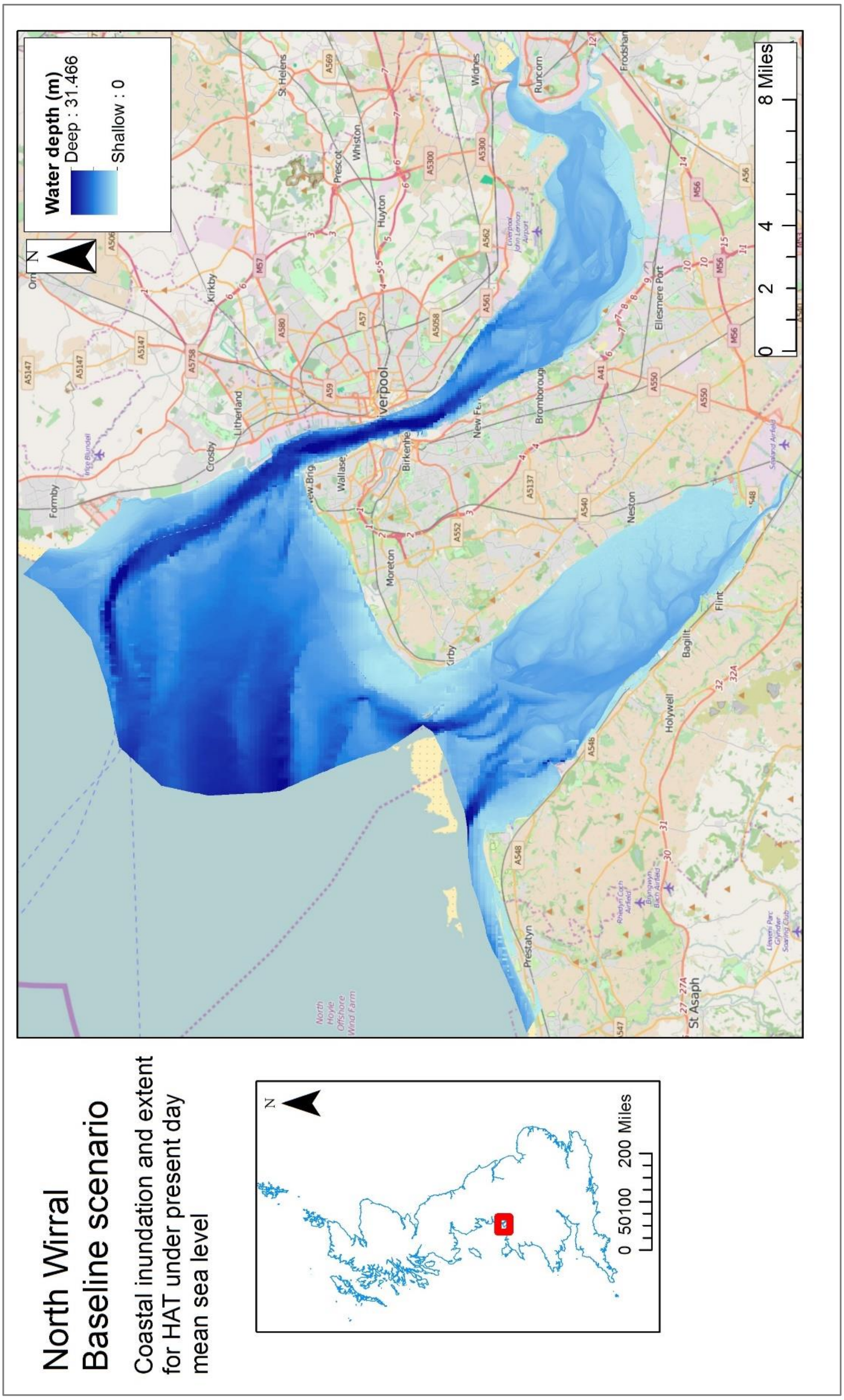
Appendix 2: The effect of domain size on depth and extent of inundation under RCP 4.5 (0.72 m SLR) in (A) North Wirral; (B) Colwyn Bay.



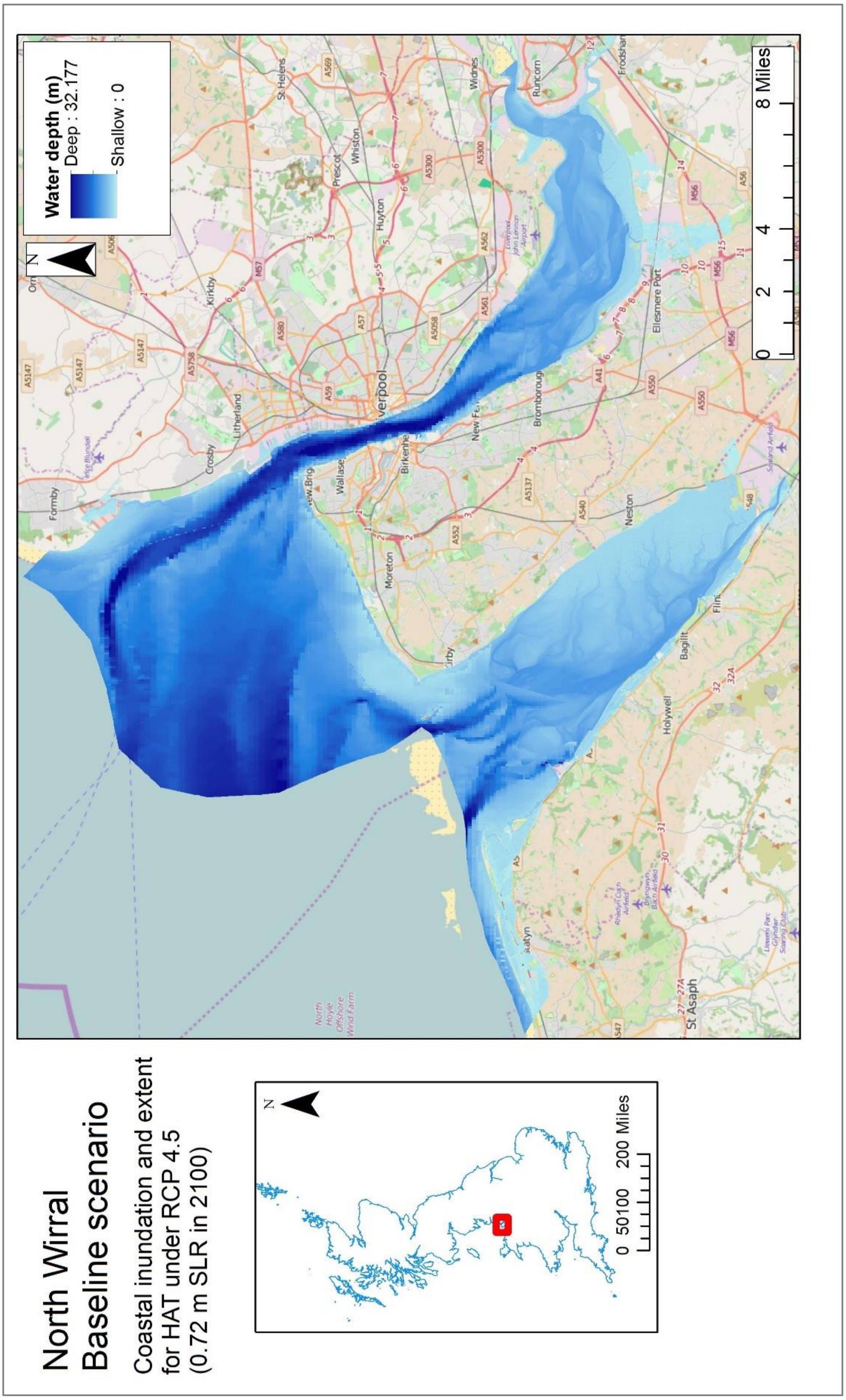
Appendix 3: Model runs to be completed in LISFLOOD.

Model run	Scenario	Location	Lagoon	Sea level (m)	DTM file	BCI file	BDY file	PAR file	Outputfile			
1	North Wirral SLR and tidal lagoon	Wirral	No	0	Wirral10m	Wirral	Wirral1	run_1	Wirral1			
2		Wirral	No	0.72	Wirral10m	Wirral	Wirral2	run_2	Wirral2			
3		Wirral	No	0.98	Wirral10m	Wirral	Wirral3	run_3	Wirral3			
4		Wirral	Yes	0	WirralLagoon10m	Wirral_Lagoon	WirralLagoon1	run_4	WirralLagoon1			
5		Wirral	Yes	0.72	WirralLagoon10m	Wirral_Lagoon	WirralLagoon2	run_5	WirralLagoon2			
6		Wirral	Yes	0.98	WirralLagoon10m	Wirral_Lagoon	WirralLagoon3	run_6	WirralLagoon3			
7	Colwyn Bay SLR and tidal lagoon	Colwyn	No	0	Colwyn10m	Colwyn	Colwyn1	run_7	Colwyn1			
8		Colwyn	No	0.72	Colwyn10m	Colwyn	Colwyn2	run_8	Colwyn2			
9		Colwyn	No	0.98	Colwyn10m	Colwyn	Colwyn3	run_9	Colwyn3			
10		Colwyn	Yes	0	ColwynLagoon10m	Colwyn_Lagoon	ColwynLagoon1	run_10	ColwynLagoon1			
11		Colwyn	Yes	0.72	ColwynLagoon10m	Colwyn_Lagoon	ColwynLagoon2	run_11	ColwynLagoon2			
12		Colwyn	Yes	0.98	ColwynLagoon10m	Colwyn_Lagoon	ColwynLagoon3	run_12	ColwynLagoon3			
13	Lower tidal lagoon seawall	Wirral	Yes	0	WirralLowLagoon10m	Wirral_Lagoon	WirralLagoon1	run_13	WirralLowLagoon1			
14		Wirral	Yes	0.72	WirralLowLagoon10m	Wirral_Lagoon	WirralLagoon2	run_14	WirralLowLagoon2			
15		Wirral	Yes	0.98	WirralLowLagoon10m	Wirral_Lagoon	WirralLagoon3	run_15	WirralLowLagoon3			
16		Colwyn	Yes	0	ColwynNoLagoon10m	Colwyn_Lagoon	ColwynLagoon2	run_16	ColwynLowLagoon1			
17		Colwyn	Yes	0.72	ColwynNoLagoon10m	Colwyn_Lagoon	ColwynLagoon2	run_17	ColwynLowLagoon2			
18		Colwyn	Yes	0.98	ColwynNoLagoon10m	Colwyn_Lagoon	ColwynLagoon3	run_18	ColwynLowLagoon3			
19	Larger domain, no lagoon	Wirral	Yes	0	WirralNoLagoon10m	Wirral_Lagoon	WirralLagoon1	run_19	WirralNoLagoon1			
20		Wirral	Yes	0.72	WirralNoLagoon10m	Wirral_Lagoon	WirralLagoon2	run_20	WirralNoLagoon2			
21		Wirral	Yes	0.98	WirralNoLagoon10m	Wirral_Lagoon	WirralLagoon3	run_21	WirralNoLagoon3			
22		Colwyn	Yes	0	ColwynLowLagoon10m	Colwyn_Lagoon	ColwynLagoon1	run_22	ColwynNoLagoon1			
23		Colwyn	Yes	0.72	ColwynLowLagoon10m	Colwyn_Lagoon	ColwynLagoon2	run_23	ColwynNoLagoon2			
24		Colwyn	Yes	0.98	ColwynLowLagoon10m	Colwyn_Lagoon	ColwynLagoon3	run_24	ColwynNoLagoon3			
25	Friction sensitivity	Wirral	Yes	0.72	WirralLagoon10m	Wirral_Lagoon	WirralLagoon2	run_25	WirralLagoonLF	Friction value	Low	0.018
26		Wirral	Yes	0.72	WirralLagoon10m	Wirral_Lagoon	WirralLagoon2	run_26	WirralLagoonHF		High	0.1
27		Colwyn	Yes	0.72	ColwynLagoon10m	Colwyn_Lagoon	ColwynLagoon2	run_27	ColwynLagoonLF		Low	0.018
28		Colwyn	Yes	0.72	ColwynLagoon10m	Colwyn_Lagoon	ColwynLagoon2	run_28	ColwynLagoonHF		High	0.1

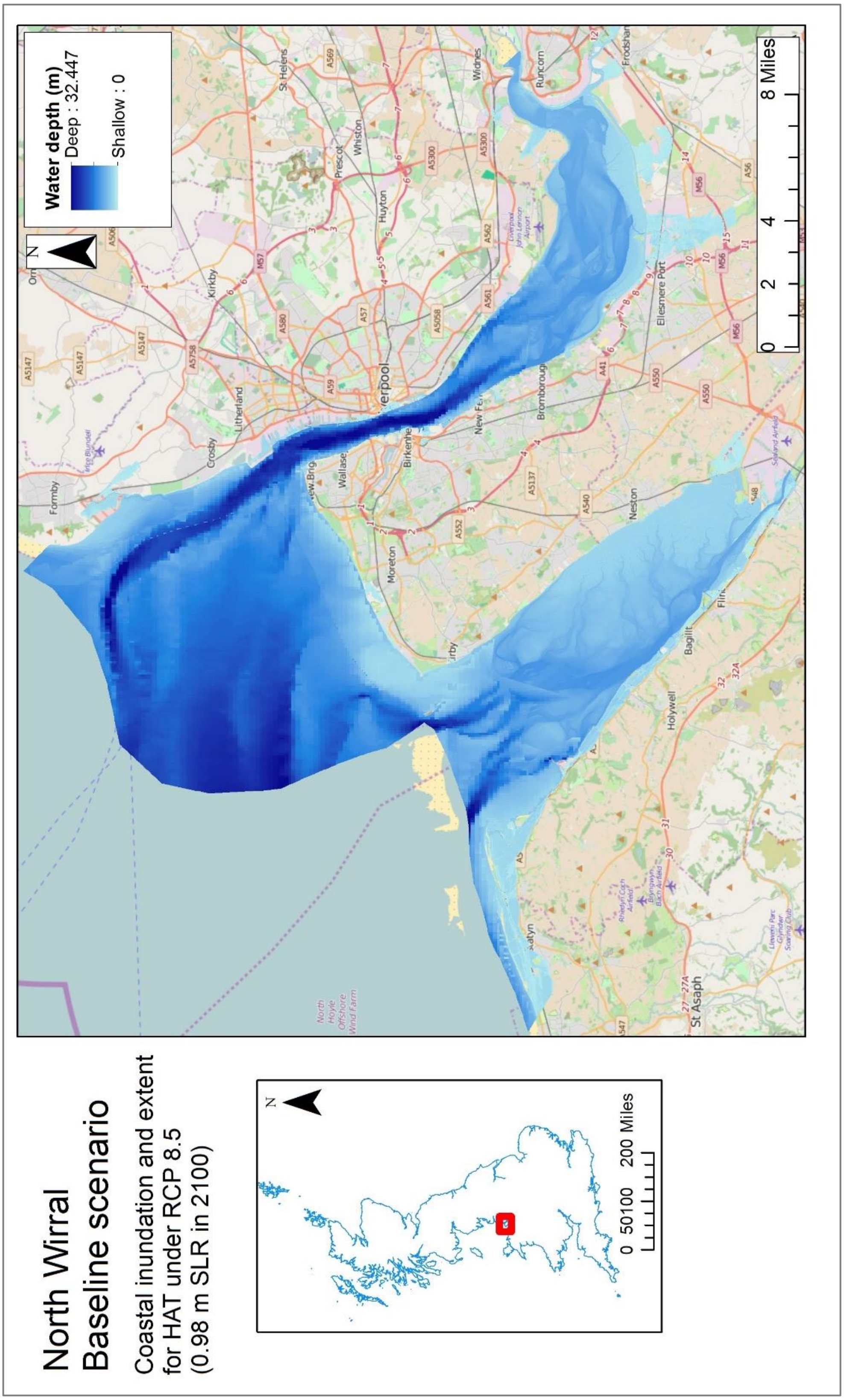
Appendix 4: Baseline coastal inundation and extent for the North Wirral under present-day mean sea-level conditions.



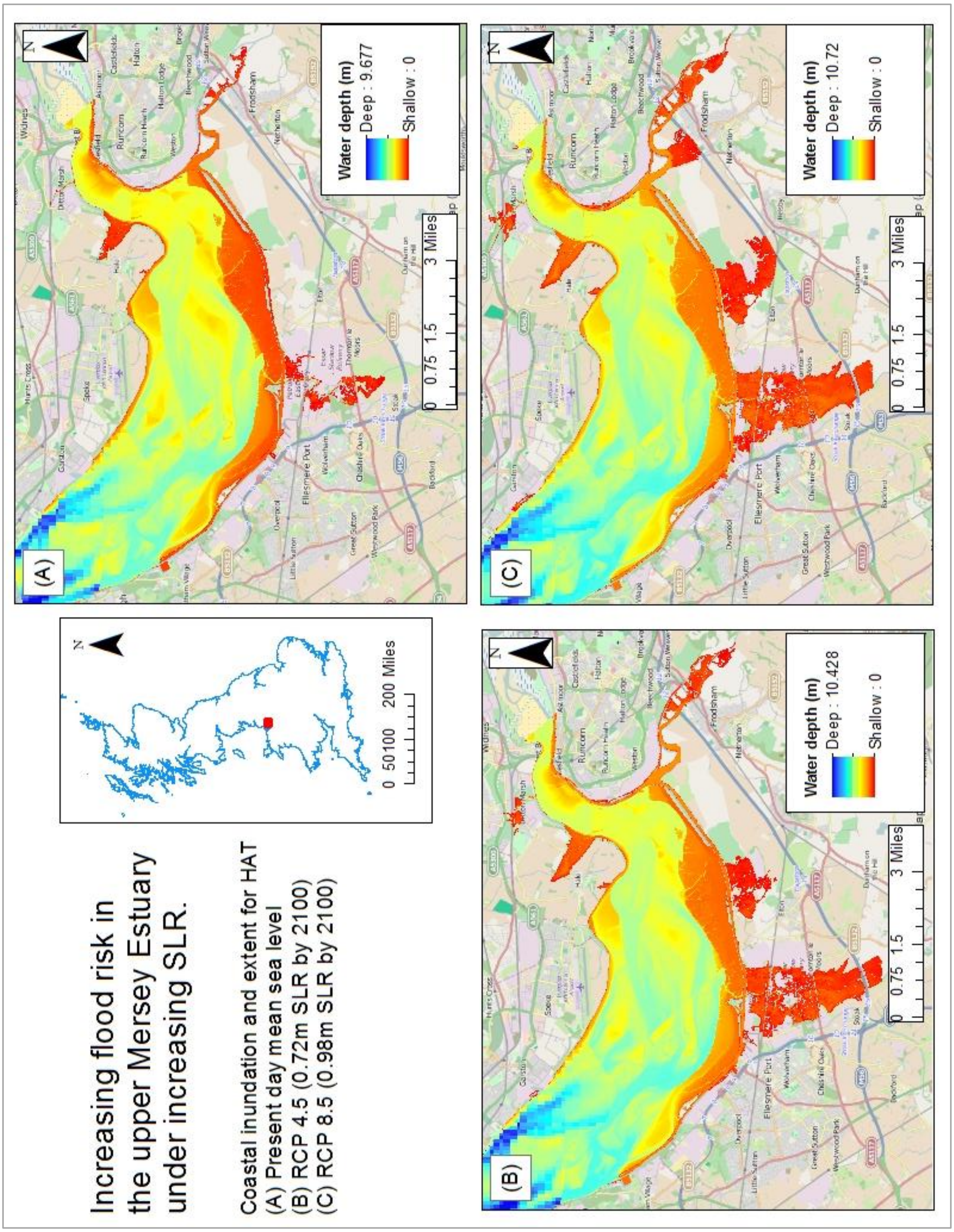
Appendix 5: Baseline coastal inundation and extent for the North Wirral under RCP 4.5 (0.72 m SLR in 2100).



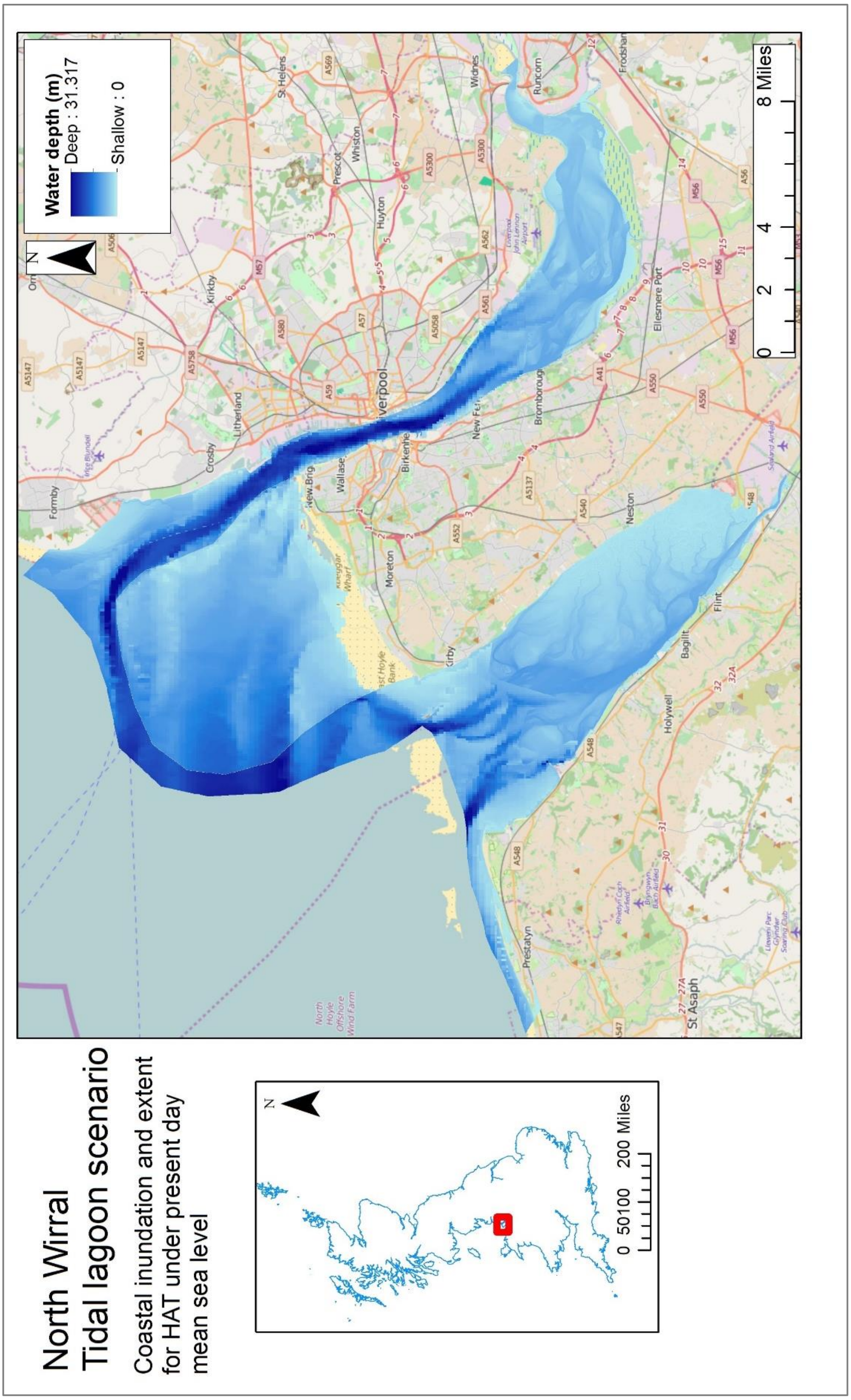
Appendix 6: Baseline coastal inundation and extent for the North Wirral under RCP 8.5 (0.98 m SLR in 2100).



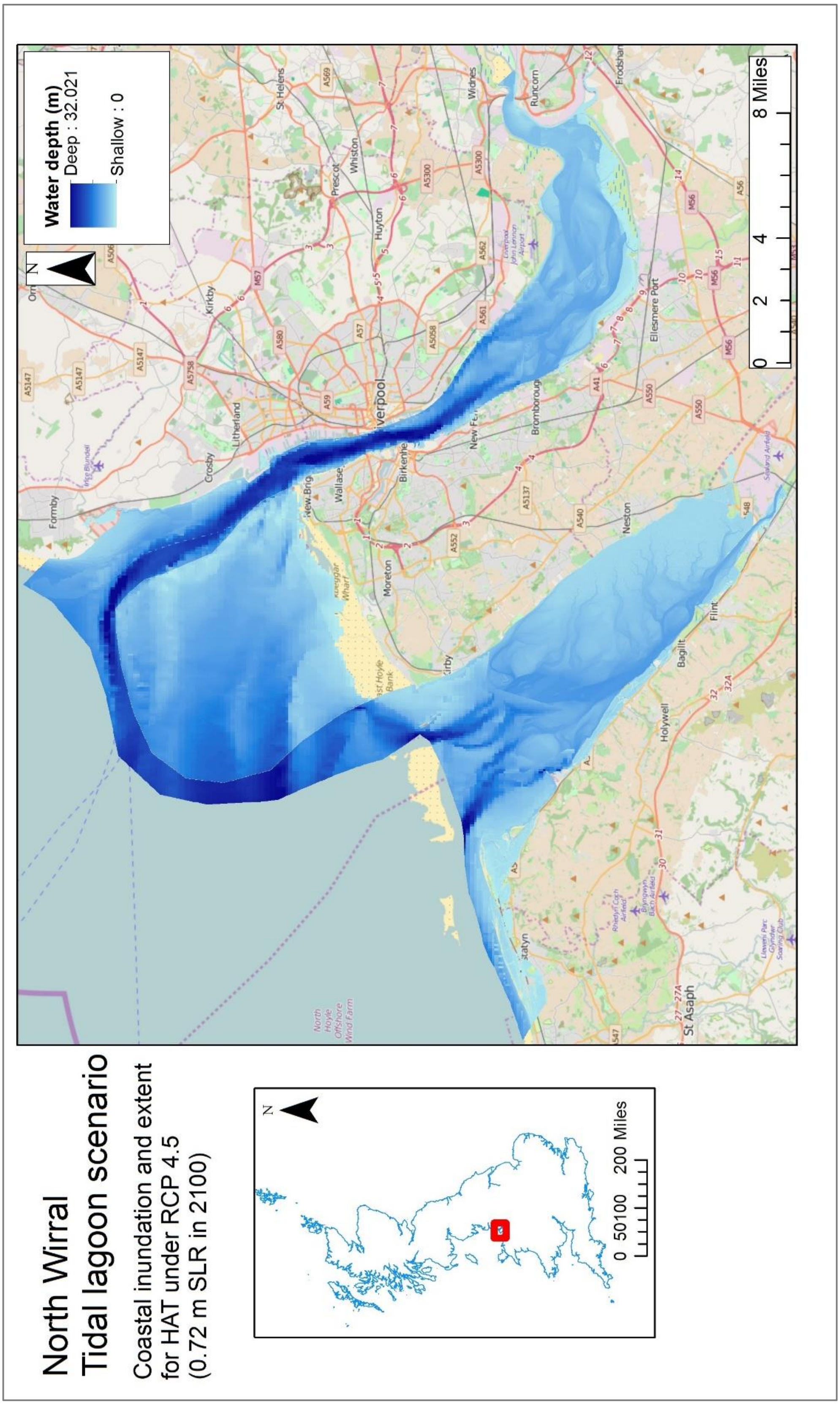
Appendix 7: Baseline coastal inundation and extent at Stanlow oil refinery and petrochemical site under (A) present-day sea-level conditions, (B) RCP 4.5 and (C) RCP 8.5.



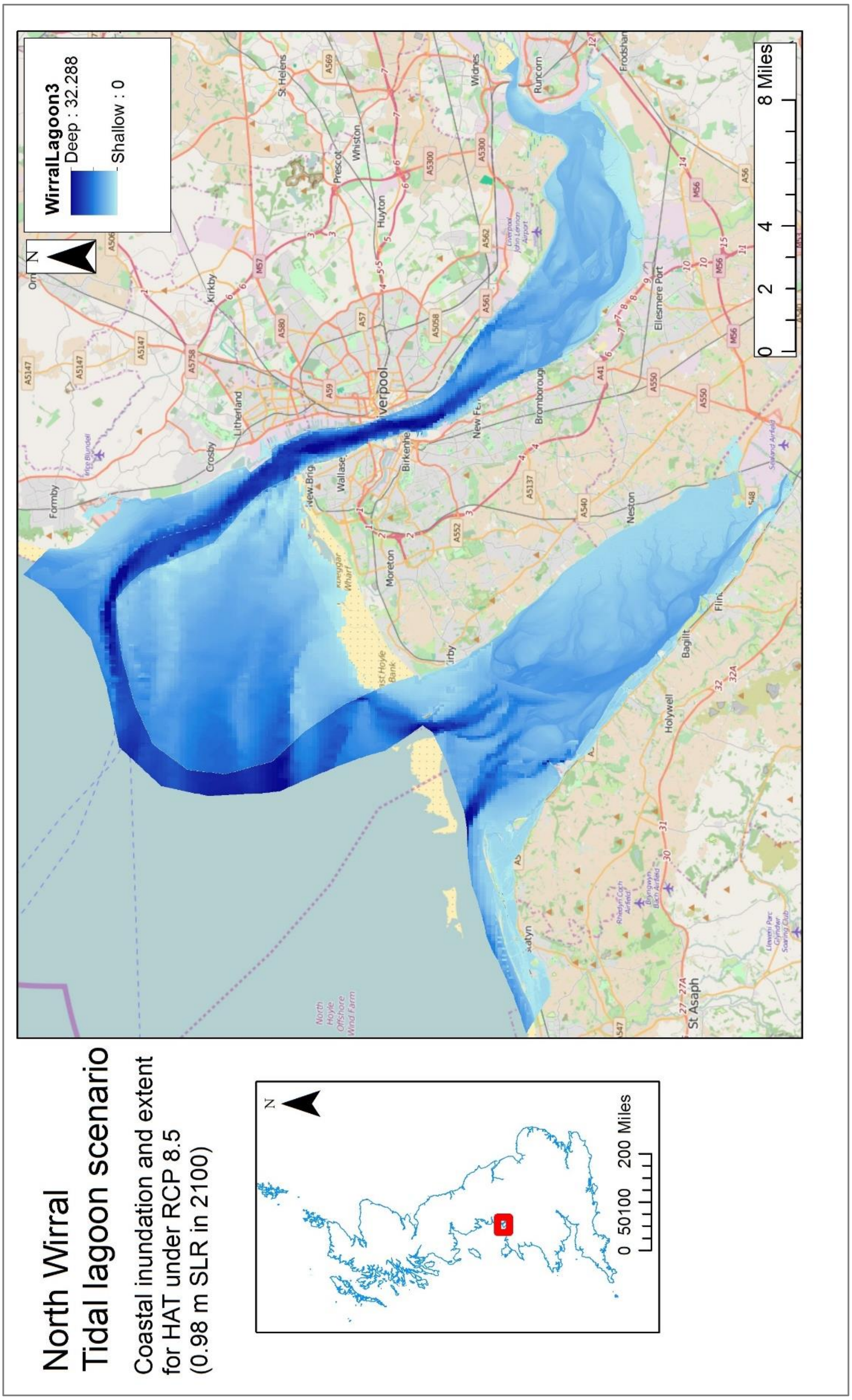
Appendix 8: Coastal inundation following the implementation of a tidal lagoon in the North Wirral under present-day mean sea-level.



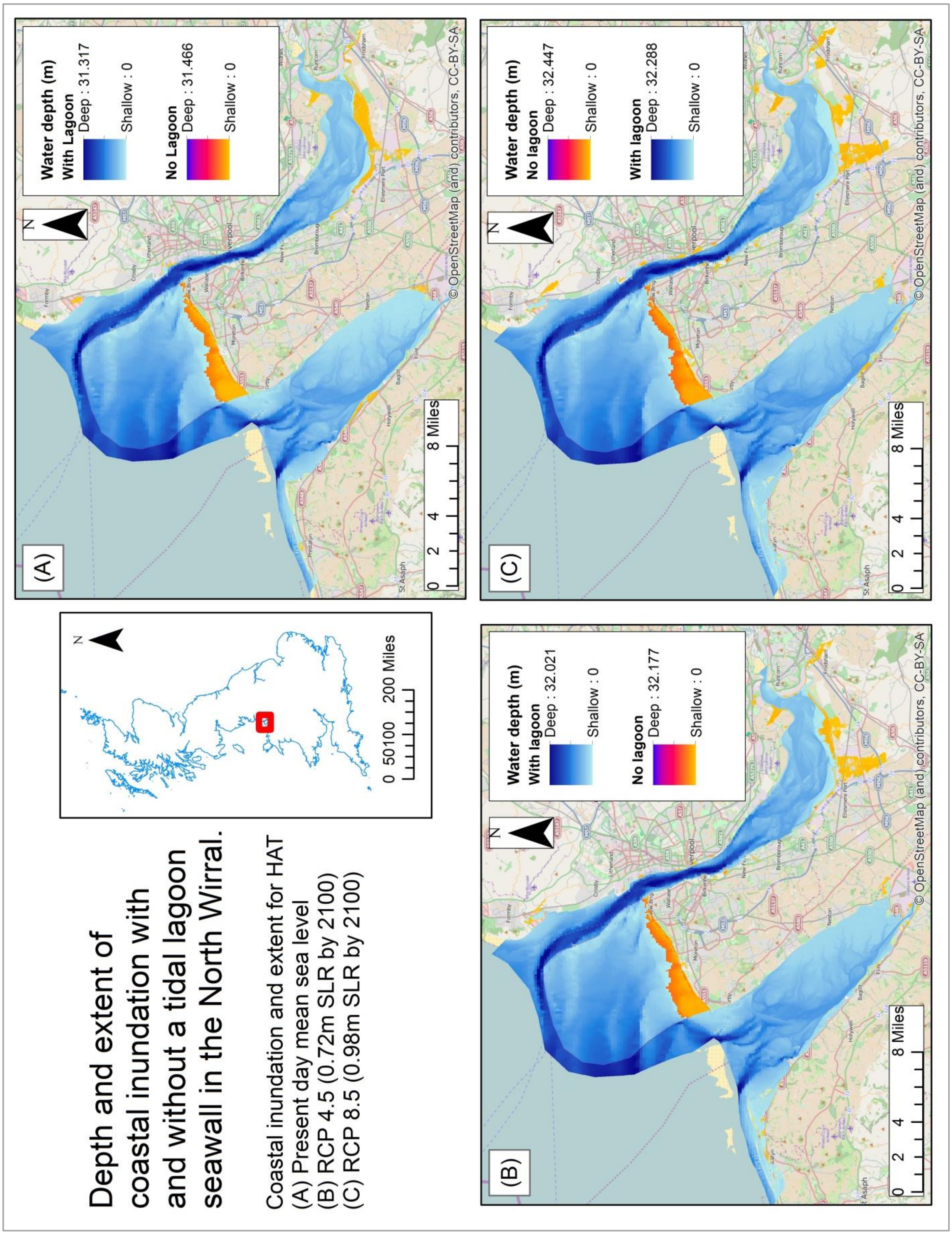
Appendix 9: Coastal inundation following the implementation of a tidal lagoon in the North Wirral under RCP 4.5 (0.72 m SLR).



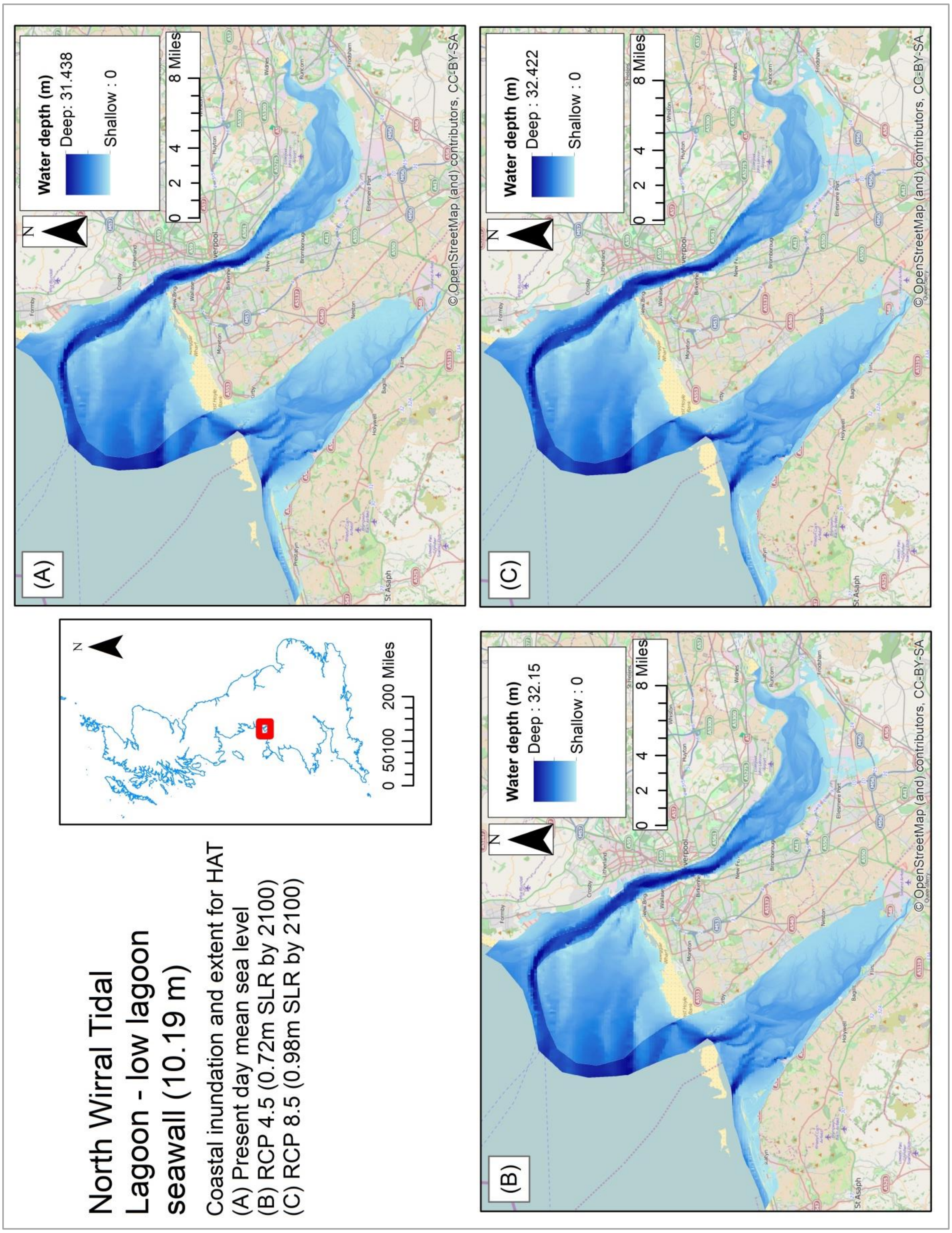
Appendix 10: Coastal inundation following the implementation of a tidal lagoon in the North Wirral under RCP 8.5 (0.98 m SLR).



Appendix 11: Comparison of depth and extent of inundation in the North Wirral with and without a tidal lagoon under (A) present-day sea-level conditions, (B) RCP 4.5 and (C) RCP 8.5.



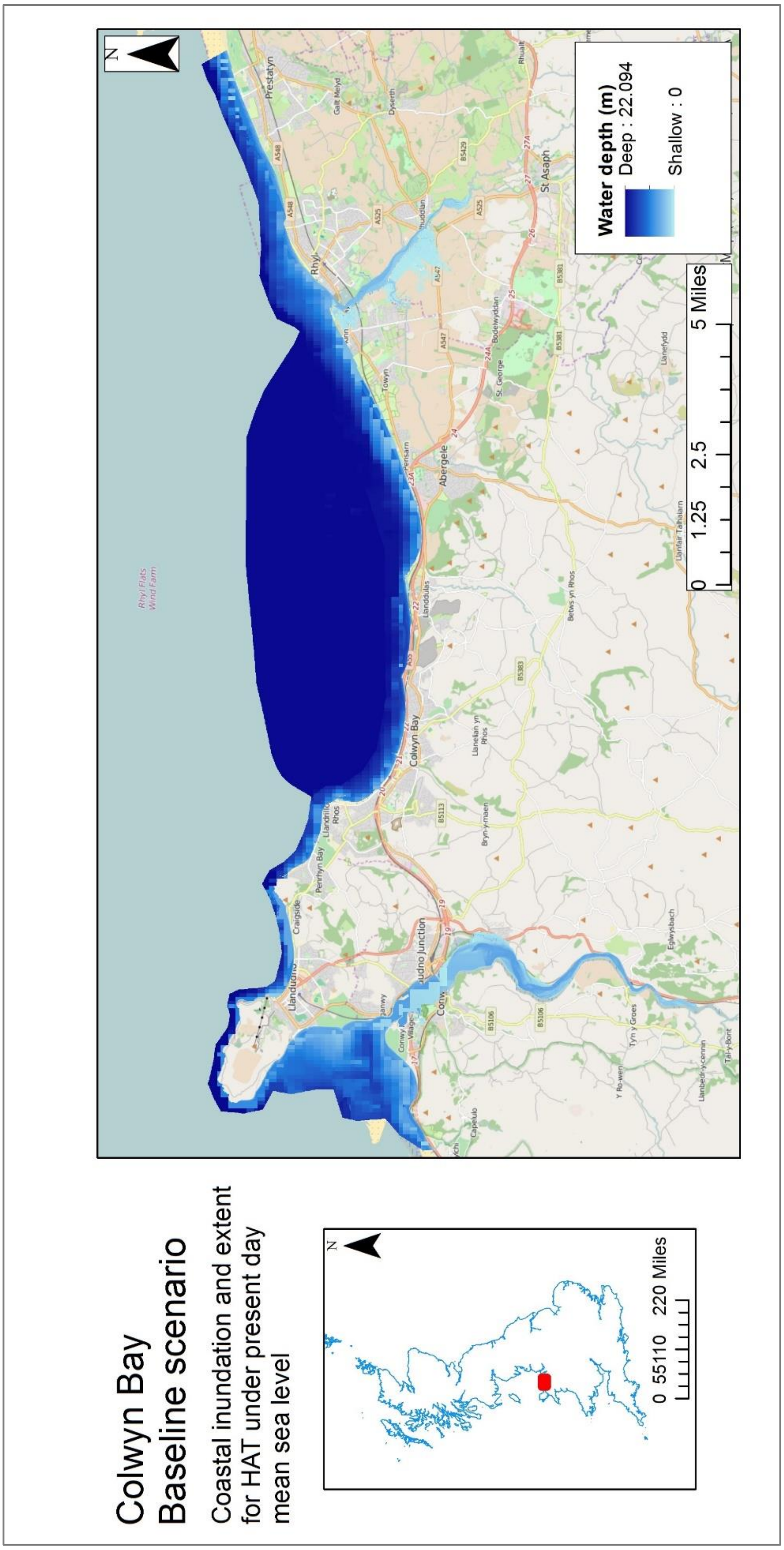
Appendix 12: Coastal inundation following the implementation of a lower tidal lagoon seawall in the North Wirral under (A) present-day sea-level conditions, (B) RCP 4.5 and (C) RCP 8.5.



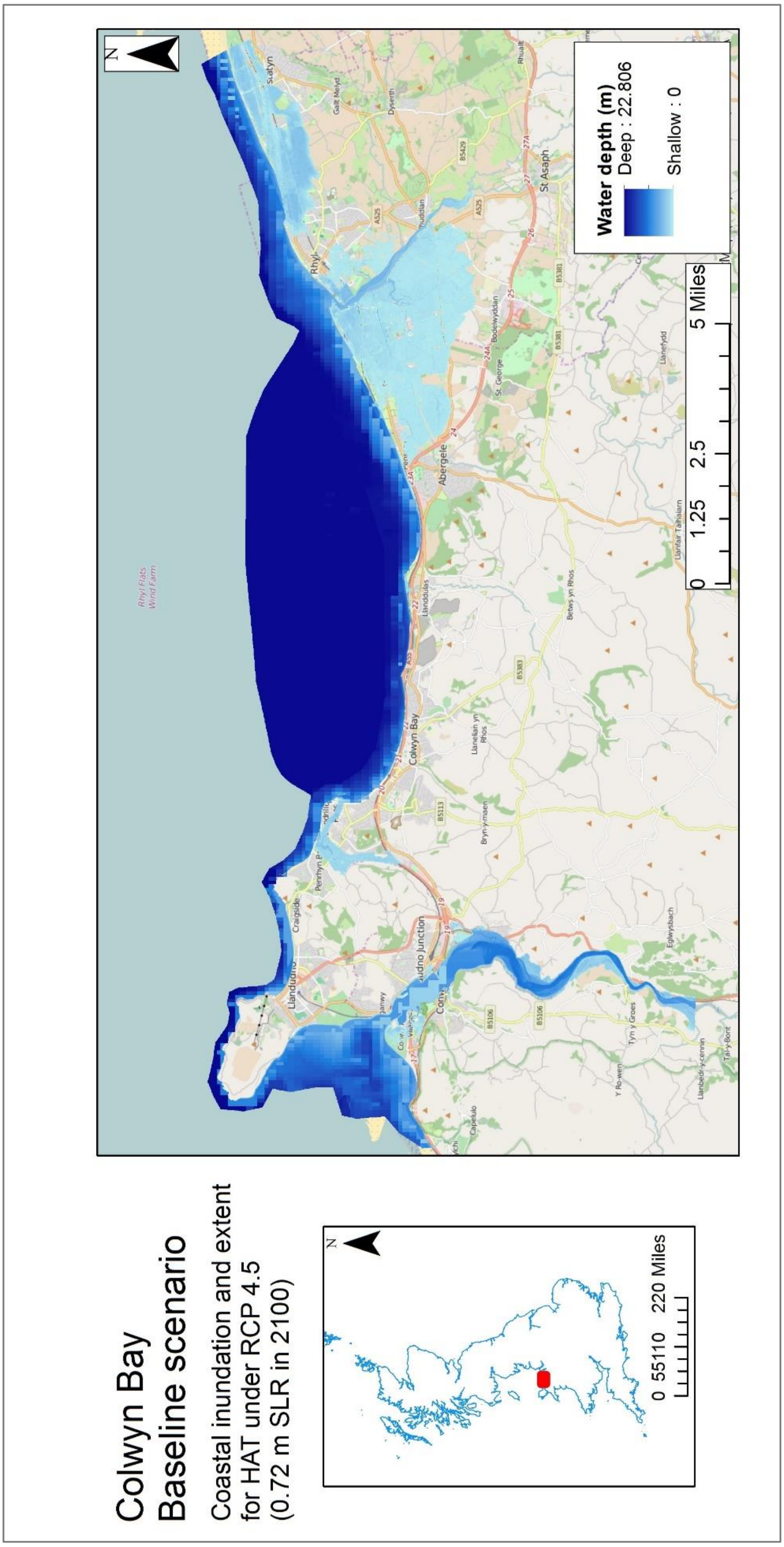
Appendix 13: Depth Damage results for North Wirral.

	Damage (£ GBP)		
Scenario	**Arable**	**Urban**	**Suburban**
Wirral1	2,893,400	2,757,300,000	5,900,800,000
Wirral2	2,991,800	2,885,800,000	6,245,200,000
Wirral3	3,047,500	2,954,000,000	6,409,300,000
WirralLagoon1	4,383,200	2,933,300,000	7,101,200,000
WirralLagoon2	4,486,500	3,047,200,000	7,419,500,000
WirralLagoon3	4,541,400	3,110,300,000	7,575,800,000
WirralnoLagoon1	4,656,600	3,134,600,000	7,526,800,000
WirralnoLagoon2	4,855,000	3,312,200,000	7,918,400,000
WirralnoLagoon3	4,931,300	3,403,500,000	8,100,500,000

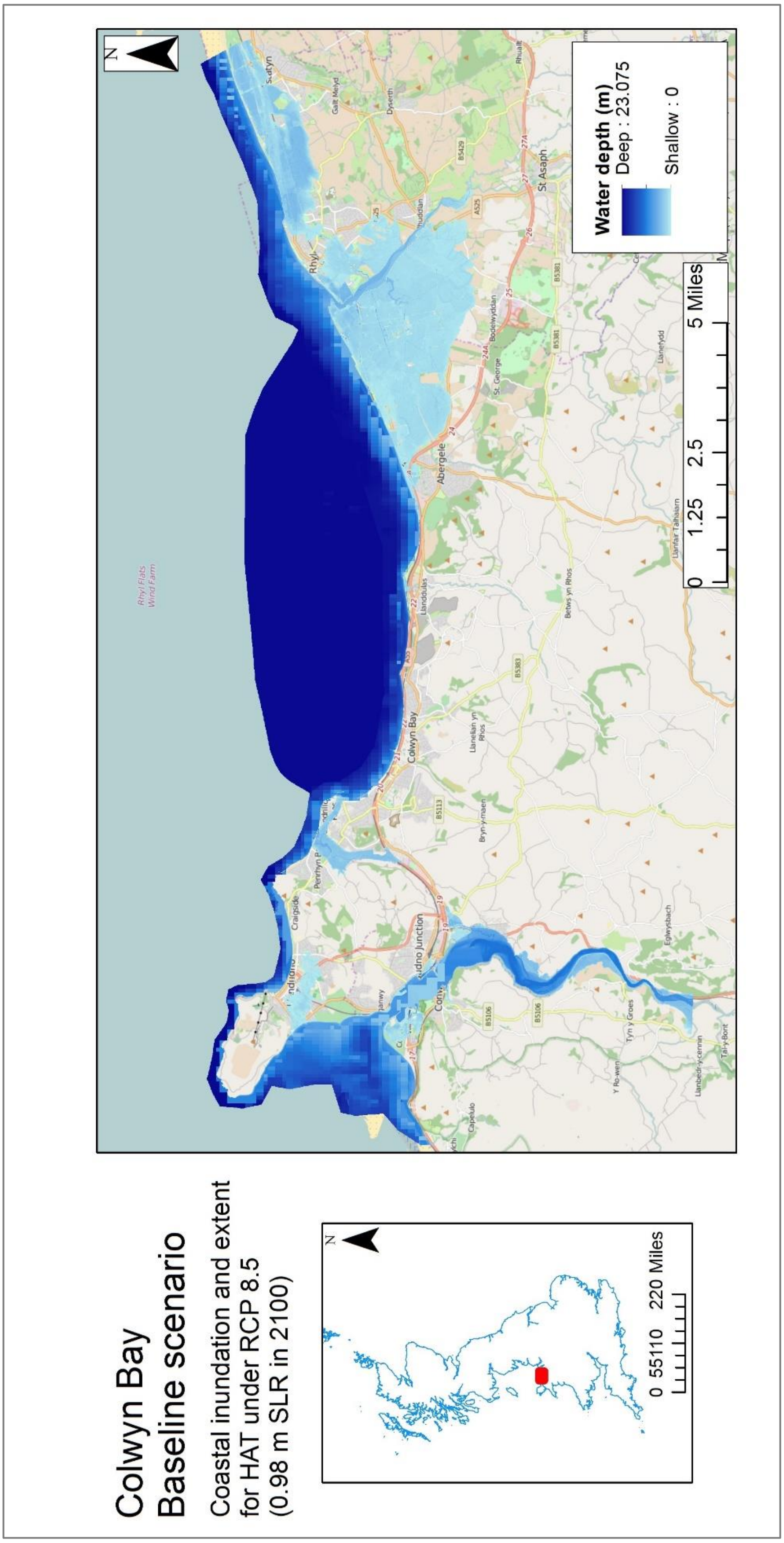
Appendix 14: Baseline coastal inundation and extent for Colwyn Bay under present-day mean sea-level conditions.



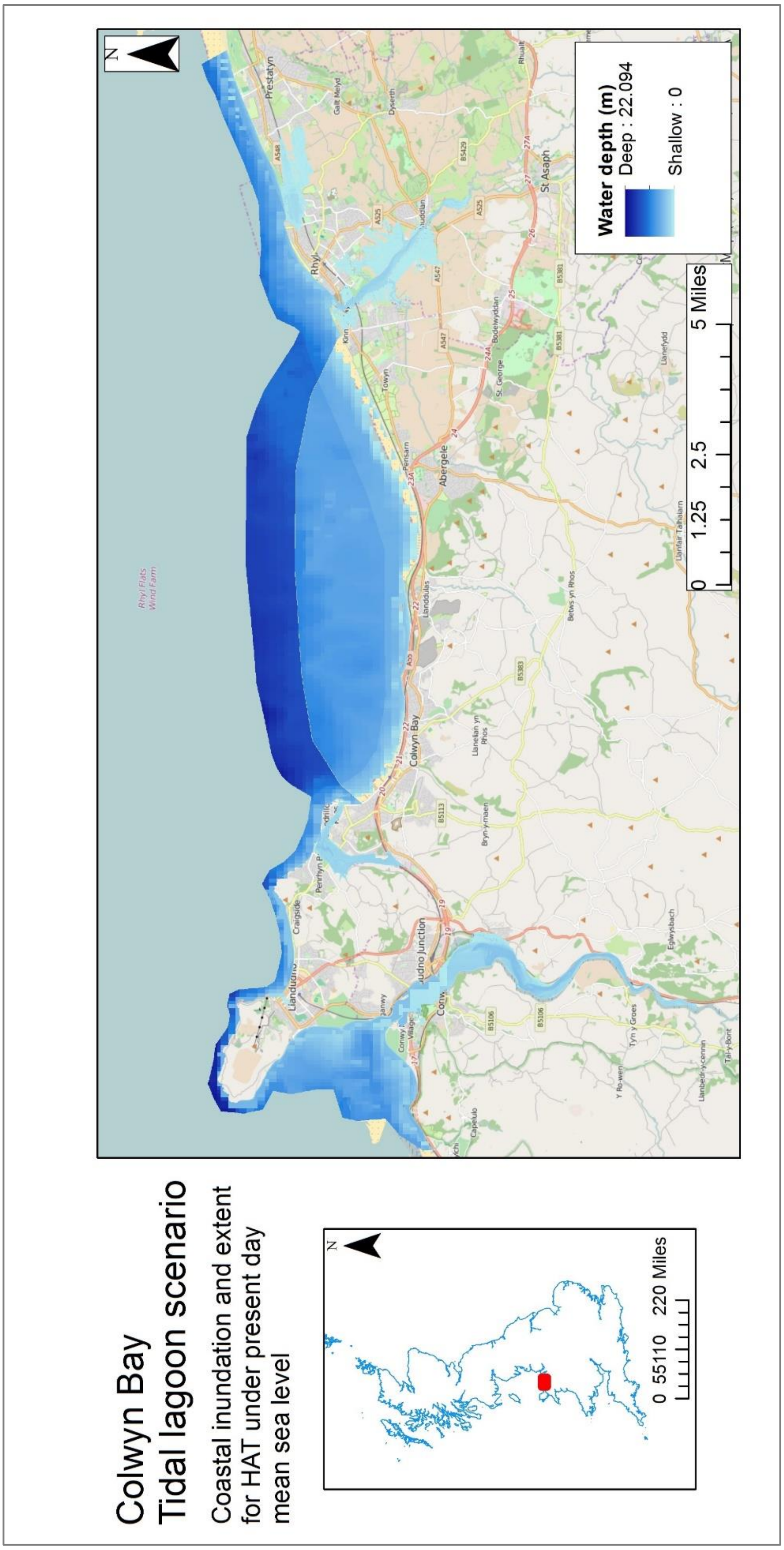
Appendix 15: Baseline coastal inundation and extent for Colwyn Bay under RCP 4.5 (0.72 m SLR in 2100).



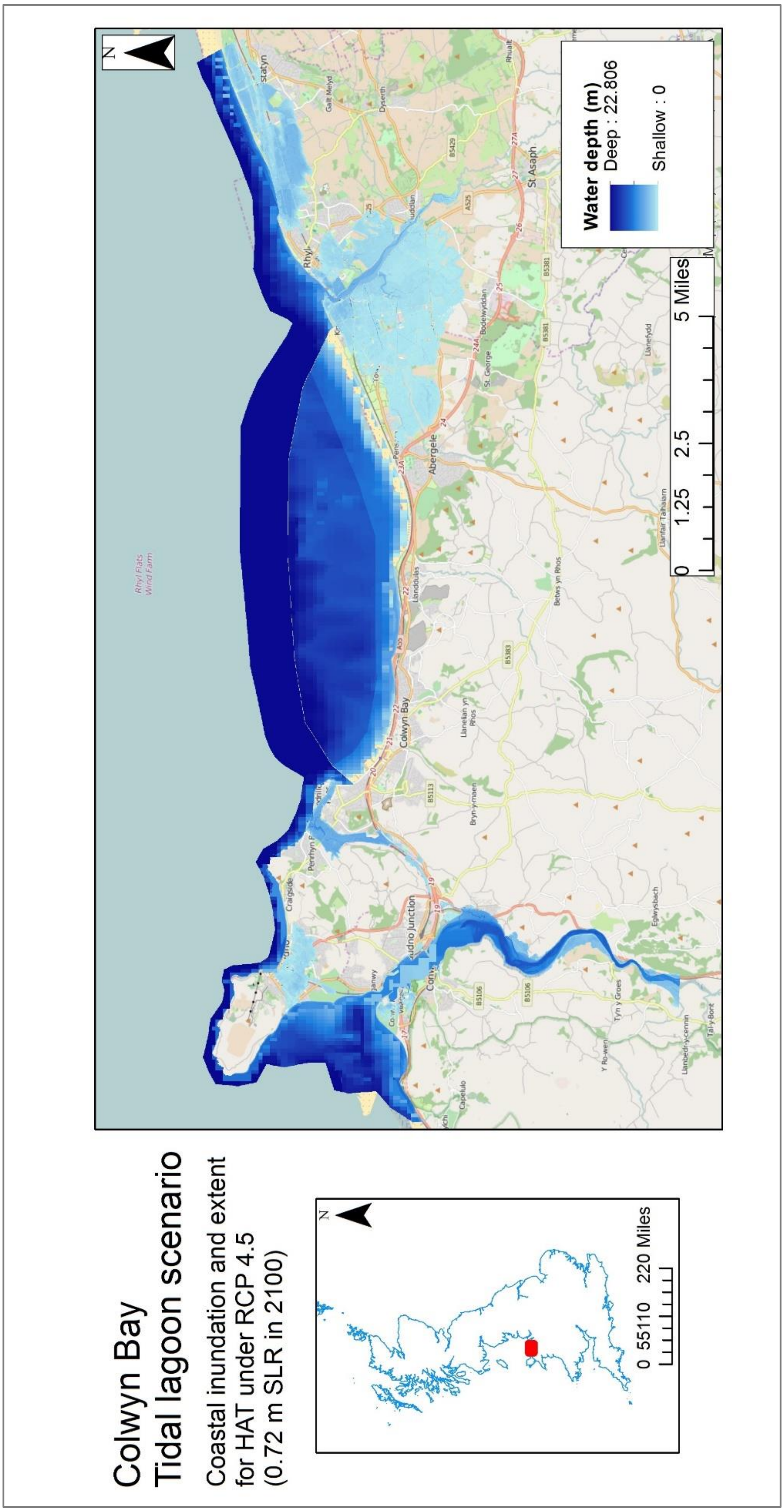
Appendix 16: Baseline coastal inundation and extent for Colwyn Bay under RCP 8.5 (0.98 m SLR in 2100).



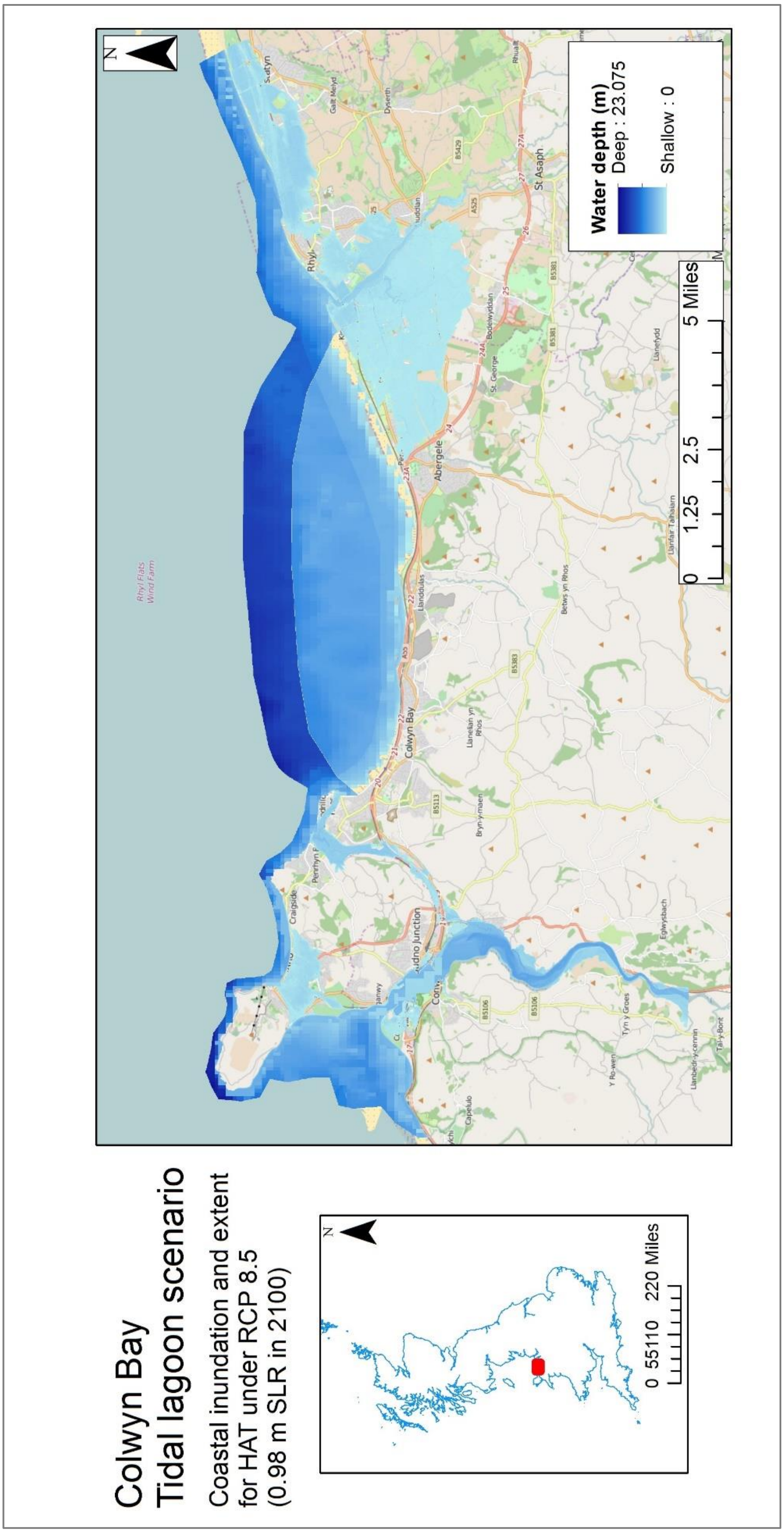
Appendix 17: Coastal inundation following the implementation of a tidal lagoon in Colwyn Bay under present-day mean sea-level conditions.



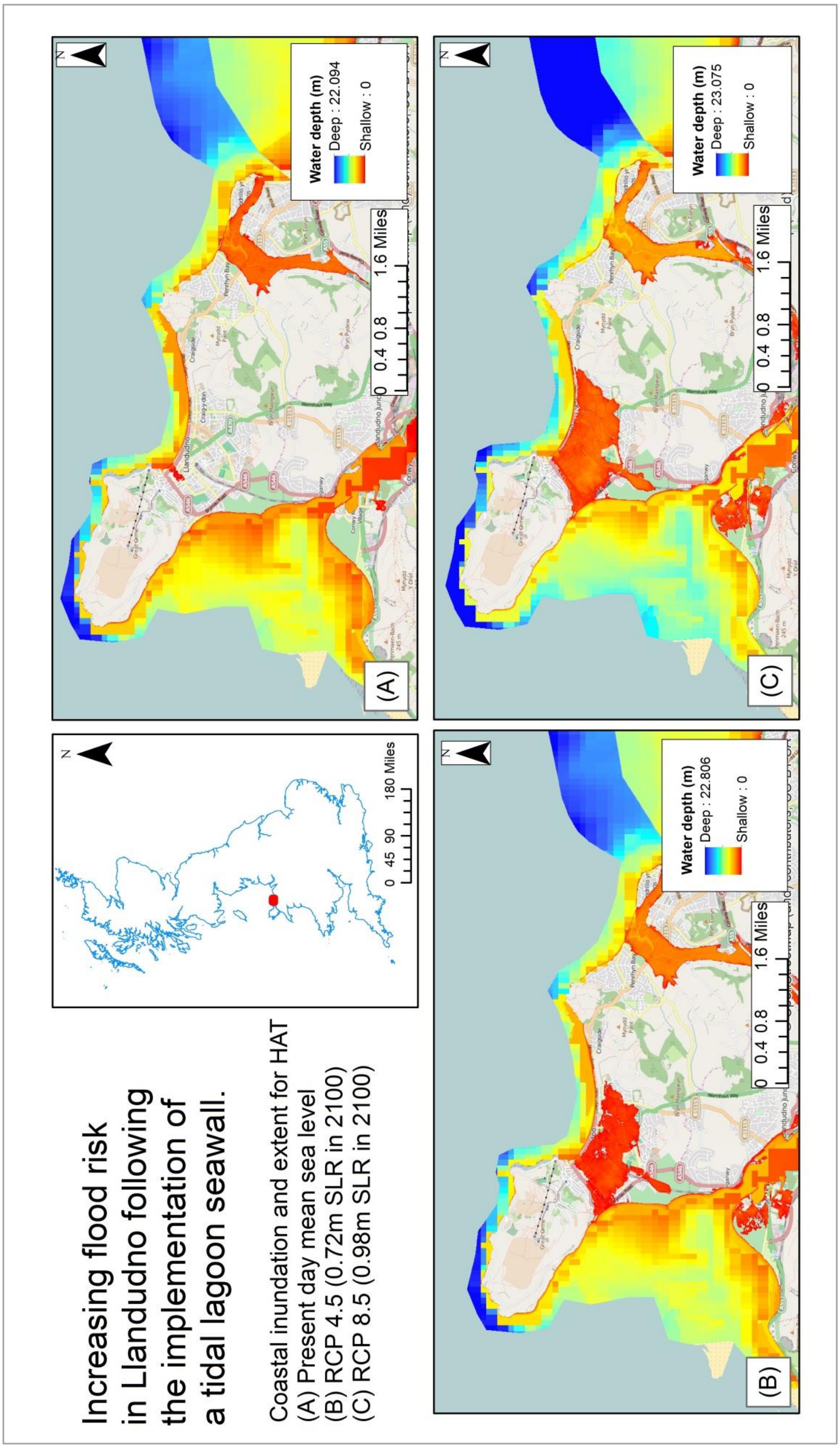
Appendix 18: Coastal inundation following the implementation of a tidal lagoon in Colwyn Bay under RCP 4.5 (0.72 m SLR in 2100).



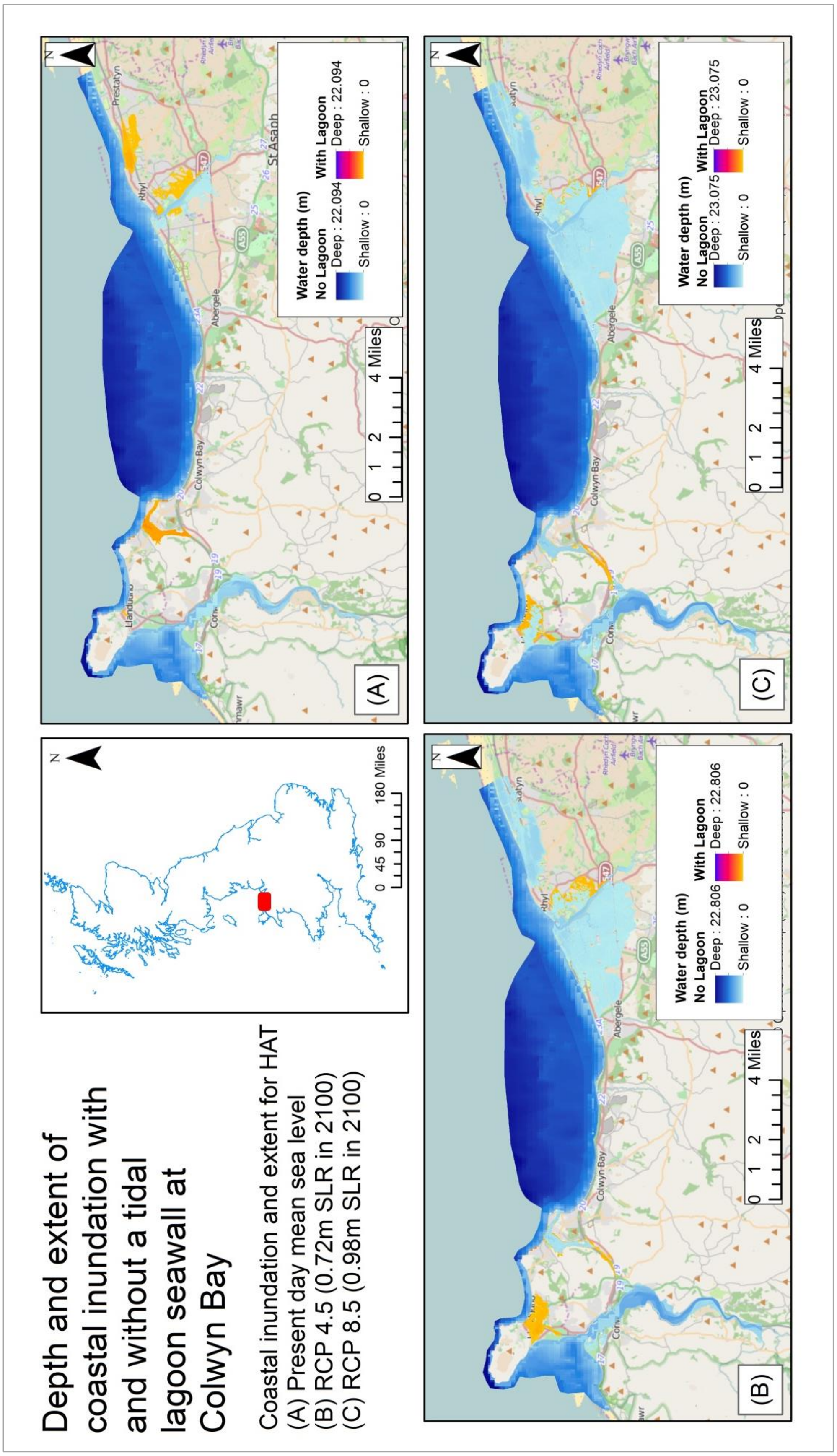
Appendix 19: Coastal inundation following the implementation of a tidal lagoon in Colwyn Bay under RCP 8.5 (0.98 m SLR in 2100).



Appendix 20: Increasing flood risk in Llandudno following the implementation of a tidal lagoon under (A) present-day sea-level conditions, (B) RCP 4.5 and (C) RCP 8.5.



Appendix 21: Comparison of depth and extent of inundation in Colwyn Bay with and without a tidal lagoon under (A) present-day sea-level conditions, (B) RCP 4.5 and (C) RCP 8.5.



Appendix 22: Depth Damage results for Colwyn Bay.

	Damage (£ GBP)		
Scenario	**Arable**	**Urban**	**Suburban**
Colwyn1	661,020	231,084,619	684,671,004
Colwyn2	1,226,200	388,550,803	869,295,005
Colwyn3	1,352,900	474,208,602	977,480,496
ColwynLagoon1	1,162,500	385,546,154	1,101,600,000
ColwynLagoon2	1,617,100	547,039,547	1,302,200,000
ColwynLagoon3	1,748,500	628,300,439	1,396,100,000
ColwynnoLagoon1	1,072,500	379,869,911	1,111,000,000
ColwynnoLagoon2	1,637,600	537,266,135	1,295,400,000
ColwynnoLagoon3	1,764,500	623,111,545	1,404,200,000