Identification of physical indicators of coastal vulnerability to impacts of climate change and sea level rise in the Dublin area

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1. Introduction

1.2 Global and local picture: Sea level changes

Global average temperature has increased by 0.74°C at an unprecedented rate over the past 100 years due to anthropogenic greenhouse emissions and it is believed this trend will continue (IPCC, 2007). The impacts of climate change, of which sea-level rise is the most apparent worldwide widespread consequence, are being felt now and will be in the longer term. As the atmosphere warms, sea level will rise because of the heat absorption by the ocean leading to thermal expansion and melting ice.

During the 20th century the average sea level rate was1.8mm/yr. Nevertheless this trend has accelerated over the last two decades to 3.2mm/yr (Church and White, 2006. Recent research global projections predict a future global SLR from 0.25-0.5 m (Church et al., 2001; Meehl et al., 2007) to 0.5 -1.4 m (Rahmstorf, 2007) or even 0.8 to 2 m by 2100 above 1990 levels (Pfeffer et al., 2008).

Closing the sea-level budget is an area of active research. Church et al. (2010) have recently updated estimates of the observed rate of rise from both satellite altimeter and in situ observations. They project a centimetric sea-level rises in future years mainly from ocean thermal expansion and glaciers with important contributions by Greenland. Antarctica terrestrial storage is also expected to undergo changes.

A change in mean sea level will be reinforced by any increase in wave energy or surge levels, also associated with the atmospheric change. In fact, changes in sea level and storm frequency and severity are among the causes for intense coastal erosion.

Impacts will be felt most acutely during extreme events. In Europe, for instance, the storm surge of 1953 had a major impact, with the loss of over 1,800 lives in the Netherlands and 300 in southeast England.

The fact that Ireland is positioned at the centre of north-west Europe's coastal margin makes it prone to impacts of storminess on coastal areas, which is where most Ireland's population lives, posing a real threat on both population and coastal ecosystems such wetlands, with only 1 m rise in sea level.

Increases in storminess over the Atlantic will likely to cause the Irish wetlands and soft-sediment along the coast being among the first in Europe to respond to storm-led sea level rise (Devoy, 2008). In particular the east coast soft and low-lying shorelines and Co. Dublin area are highly exposed and already experiencing erosion and ecosystem losses. Therefore contrary to what some European studies may suggest the Irish coast is quite vulnerable to impacts of climate change.

According to McElwain & Sweeney (2006) the potential area of inundated land in Ireland under a medium sea level scenario increase of 0.48 m by 2100 combined with extreme water level of 2.6 m is approximately 300km^2. Analysis of hindcast total water level data from Dublin Bay generated as part of the National Coastal Protection Strategy Study (DCENR), have estimated that a modest mean sea level increase of 0.4m will lead to a worsening of coastal flooding by a factor of thirty. This together with the increase on return of surge events period and increase in gale force winds will certainly displace a greater amount of land.

Unfortunately despite the extensive literature established since the 1980s concerning coastal vulnerability, there is a deficiency on coastal vulnerability studies from local to national scale that quantify the relationships between observed coastal physical changes and the driving factors. In Northern Ireland McLaughlin (2001) evaluated Northern Ireland's coastal vulnerability and developed a coastal vulnerability index for this area. Similar quantitative approaches to evaluate the possible effects of the changing climate along the Irish coats will be extremely valuable in Ireland (Devoy, 2008).

The application of vulnerability indices to coastal vulnerability assessment has proved an efficient and consistent method for characterising the relative vulnerability of different coasts (Abuodha and Woodroffe, 2006. Coastal vulnerability assessments based on methodology developed by USGS (Thieler et al., (2000); Pendleton et al., 2010)), and others (Torresan et al. (2008); Nicholls et al. (2008); Harvey and Woodroffe (2008)) are good examples of this.

In the light of the above, a primary challenge to understand the shoreline response to future water-level changes in the Dublin area would be analysing the characteristics of its shoreline that makes it susceptible to change over the next century based on its physical response to sea level rise. In order to do this physical indicators or variables, contributing to coastal evolution in this area, need to be identified.

2. Study area: Physical and weather setting

2.1 Geology-Geomorphology

The coastline of Ireland (7400 km long) can be classified as paraglacial (Carter, 1990). The Irish coast is highly variable in terms of its wave climate and energy, geomorphic development during the late Pleistocene and Holocene, and present-day morphology and coastal dynamics (Carter and Orford, 1988). In total 3,000 km is classified as 'soft' coast, of which 50% is considered to be at risk from erosion.

In contrast to the west, the eastern and south-eastern regions are composed of unconsolidated Quaternary glaciogenic sediments.

Some of the coastal systems in the Dublin area include those of cliffs, beaches, and barriers (sand and gravel types); lagoons; dunes and sand plains; and salt marshes, mudflats and other wetlands (Carter 1991b. Glacial and fluvial actions have shaped the coast into bays and estuaries sedimentary areas.

In the study area (See

Figure 1. 1) barriers (from Holocene) formed as sea levels rose during the postglacial marine transgression. Large quantities of unconsolidated glacial clays, sands and gravels were swept up and incorporated into coarse grained storm beach ridges, partly closing the bays and creating estuaries behind them (Mulrennan, 1990).

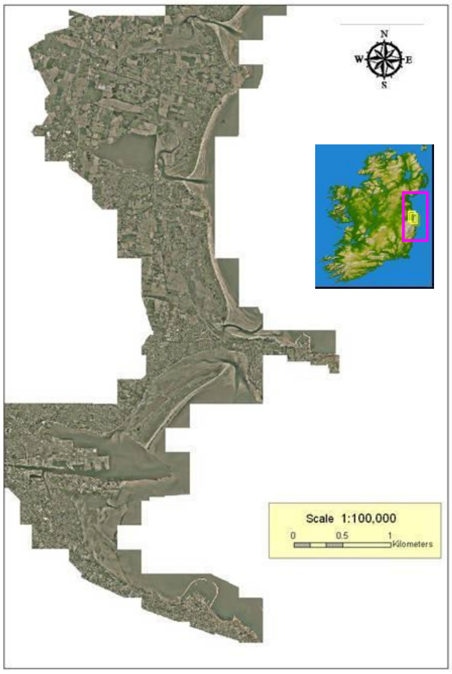


Figure 1. 1 Study area: Coastline from Malahide to Dun Laoghaire.

Particularly in North County Dublin, the coastline comprises a series of barrier-beach complexes (Mulrennan, 1990), each of which is located at the mouth of an estuary lying between two resistant headlands, sand beaches and cliffs (See Figure 1. 2). In South County Dublin, sand and gravelly beaches, rocky or unconsolidated cliffs and large intertidal areas are predominant (Figure 1. 3).

Figure 1. 2 Malahide-Corballis estuary and barrier-beach complexes (OSi oblique imagery, 2004)

Figure 1. 3 Rocky cliffs along the coast between South Co. Dublin and Co. Wicklow

Evidence of changes in the Dublin coastline since the nineteenth century have been previously detected and derived from secondary sources, including maps, charts, documents and aerial photographic surveys (Mulrennan,1990; 1993); Two estuary-barrier complexes on the north Dublin coastline have undergone considerable morphological changes such as reduction in the size of the estuaries and estuary mouths, and the accretion of beach sediments and fore dune ridges around the distal or southern ends of the barriers. Disruption of the tidal regime has led to substantial hydrodynamic and morphological changes, in some places to attempt to restore the hydraulic equilibrium of these estuary/barrier complexes (Mulrennan, 1990).

A number of zones and distinct morpho-sedimentary provinces can be recognised within each complex in the study area.

2.1.1 The onshore area

The onshore zone is subdivided into three sections: the beach or splash zone (above mean high water mark), the dunes/cliff and the hinterland (See Figure 1. 4). The part of the beach below MHW belongs to the inshore zone. The splash zone begins at the MHW and ends at either the cliff toe, dune vegetation line or, if present, at a manmade structure. The hinterland is the landward limit of the coastal zone.

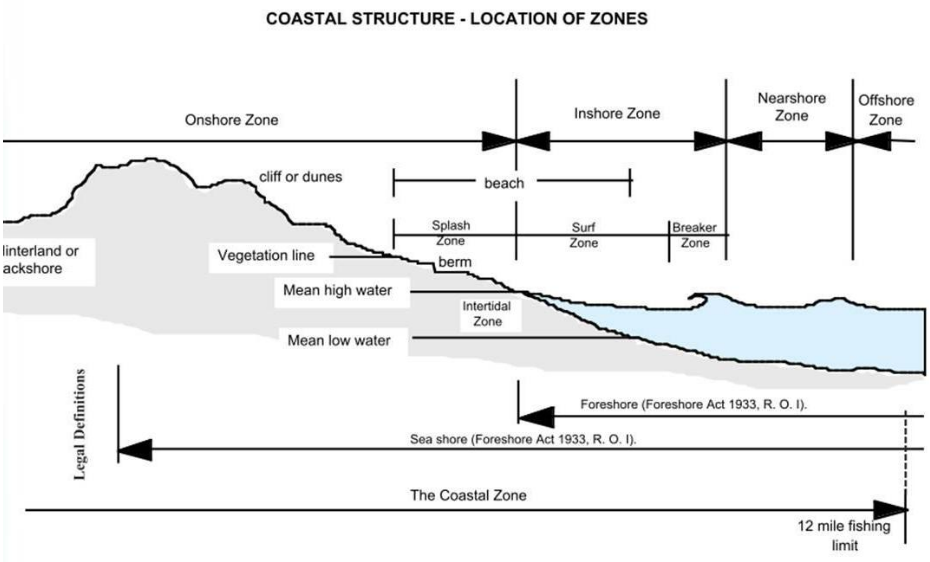


Figure 1. 4 Coastal structure. Sea shore as defined by Foreshore Act 1933 (amended 1992)

Within the onshore zone the following features can be distinguished:

-Sand Beaches: its shape is frequently defined by currents which move along the shore.

-Shingle-gravel beaches: often supplied by eroding boulder clay cliffs and gravel beaches formed from offshore gravel deposits which have been rolled onshore by rising sea levels.

-Dune Shorelines: dune developing systems and erosional forms with numerous blowouts and deflationary structures.

-Sand spits: accumulations of sand are created when the coastline veers away from the longshore current which continues in a straight line.

Tombolos: a beach formed when sediment is deposited in the slack water (caused by sheltering from waves and disruption of current patterns) between an island (or rock) and the mainland (i.e: Sutton Tombolo).

2.1.2 Inshore zone-Near shore

-Sand flats / Mudflats: This is an area of intertidal sand near the seaward end with muddier conditions further in near the river mouth, typical of estuaries and sheltered inlets.

-Saltmarsh: higher levels of mudflats or sand flats above the level of neap high tides, that the most sheltered part of estuaries and marine inlets salt marshes may develop on .

- Intertidal ridges and runnels aligned parallel to the shoreline that merge with ebb tidal deltas at the distal end of the barriers. These together with dune systems and salt marshes provide a strongly dissipative morphodynamic regime (Mulrennan, 1990, 1992).

Cliffs can be divided into

-Rocky Cliffs

-Glacial till/clay cliffs: mixture of boulders, gravel and clay and usually fronted by sand, gravel or mud beaches.

2.2 Coastal topography. Bathymetry

A wide, shallow-water inshore zone (water depths <50 m) and continental shelf coupled to wide dissipative beach systems, rock platforms, and abrasion surfaces, are also characteristic of Ireland's coastline. These features maximise wave energy absorption and reduce the impacts of wave-surge; opposing resistance to the erosion of coastal areas. Irish Sea shallow shelf amplifies tide and wave heights. In shallow continental shelves like ours, wind speed and direction greatly influences storm surges height rather than atmospheric pressure.

Seabed sediment type, sediment transport dynamics and shallow stratigraphy represent basic information to understand the coastal processes and their evolution within changeable climate change scenarios.

Therefore good quality onshore-offshore data is essential for vulnerability assessment studies. Offshore coastal high-resolution bathymetric data together with high quality tide gauge data linked with remote sensing information from satellite imagery and climate scenario generation represent essential tools to predict possible effects of climate changes and sea level rises on the coast (McFadden et al,. 2007a).

2.3 Relative sea level changes

For Ireland sea-level change will be a major environmental concern through out this century (Orford et al. 2006). In Ireland variations of these situations have been generalised by Carter (1991) into estimating annual retreat rates (See Table 2. 1) for the East of Ireland as a function of a 30 cm increase in sea level by 2040.

Potential coastal recession rates									
Location	Low SLR (9cm)			Medium SLR (18cm)			High SLR (30cm)		
	1	2	3	1	2	3	1	2	3
East of Ireland	4.50	3.75	2.25	9.00	7.50	4.50	15.04	12.53	7.5

Table 2. 1 Potential coastal recession rates (m a-1) based on the Bruun Rule as a function of varying RSL rise by AD2040 and coastal configuration of: 1=shoreline, 2= 2m high cliff and 3 = 10m high cliff (after Carter 1991)

Measurement of sea-level change requires consistent tidal level measurements from harbour-based tide-gauges; either statistical averaging of hourly measurements or averaging of high and low tidal elevations determines annual value of mean sea level. Trend analysis in MSL requires at least 30 years of data to avoid periodical trends.

Impacts of sea-level rise are determined by the relative sea-level change, reflecting not only the global-mean trend in sea level, but also regional and local variations in sea-level change and geological uplift or subsidence. Changes in the level of land relative to the sea are referred to as isostatic changes. The combination of sea level rise and vertical land movements at any one position at the coastline result in the relative sea-level (RSL) change rate.

In Ireland post glacial rebound is the main contributor to isostatic change. The "zero" or tilt line between the rising north and subsiding south runs from Galway to Dublin and continues eastwards through the United Kingdom.

Whereas eustatic effects are global in scale, isostatic and neo-tectonic effects are regional, and therefore they require local specification and interpretation (Orford, 2006). Figure below shows past and future trends in relative sea level in Ireland.

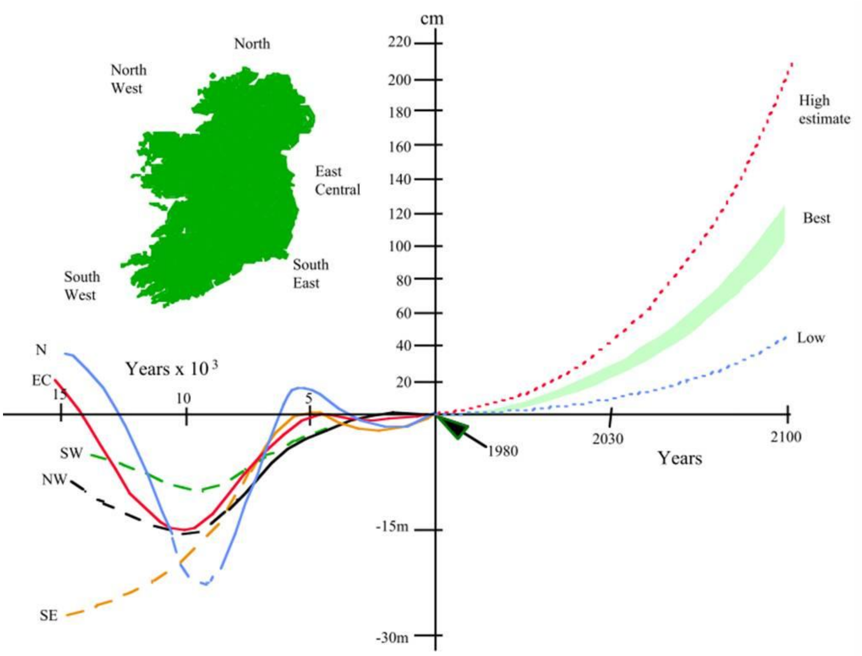


Figure 2. 1 Relative sea level rise around Ireland showing past trends and present estimates of future rise (Devoy, 1990)

Past sea-level changes in Ireland have been extrapolated from long period records from a number of tidal gauges. Table 2. 2 below reproduced from Carter (1992) shows recent sea-level changes at a number of tidal record stations in Ireland.

Tide gauge	SL change mm/year	Data Set Period	Source
Dublin	+ 0.5	1938-1951	Valentin (1953)
	+ 0.3	1938-1980	Carter (1982)
Belfast	-0.2	1917-1980	Carter (1982
Malin Head	-2.4	1960-1980	Carter (1982)

Table 2. 2 Sea-level changes at different locations in Ireland

2.4 Coastal change

Coastal erosion varies markedly according to whether coasts are fronted by bedrock or glacial sediment (Carter et al., 1992) and by the overall energy regime of the coast, as imparted by waves and tides (Carter and Bartlett, 1990).

Most of the sand and gravel found in Irish beaches have a glacial origin. The evolution of the soft coastline (i.e: sand dunes or clay cliffs) is the result of historical fluctuations in sea level rise, changing long term and short term weather patterns (storminess, wave, tide and wind actions, currents, etc) action of rivers and man influence (ECOPRO, 1996).

Any increased acceleration in coastal retreat under future sea level rises would result initially in an amplification of this Holocene pattern of coastal morphological development, tending to slow any initially enhanced erosion rates (Devoy 2008).

In Ireland erosion rates upon ‘‘soft’’ (sediment-dominated) coasts of sandy systems and glacial sediments, reach average values of 0.2–0.5 m/y, commonly rising to 1–2 m/y on southern and eastern coasts (Carter and Bartlett, 1990).

Irish hard coast (rock cliffs) is mainly determined by its geography and geology. Rocky coasts respond more slowly than soft coasts to sea-level changes. Rates may be as low as 0.01 m per century in some places although retreat commonly occurs through sudden cliff failures and catastrophic point-process operation.

The following Table 2. 3 gives the likely erosion rates of different cliff types in the study area (ECOPRO, 1996).

Lithology	Granite	Limestone	Shales	Sandstone	Glacial till
Recession rate (m per year)	0.001	0.001 - 0.01	0.01 - 0.1	0.1 - 1.0	1.0 -10

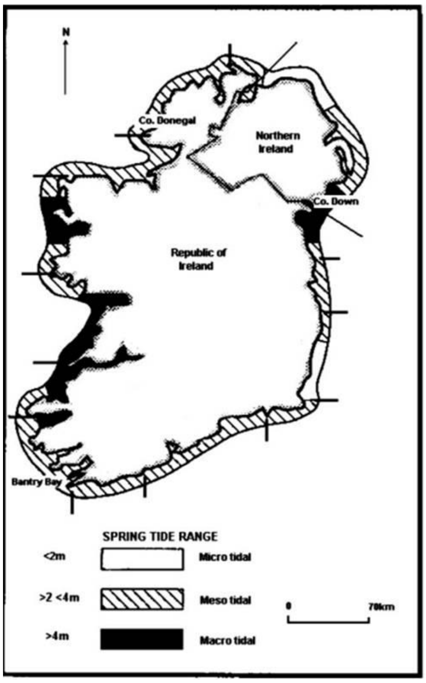
Table 2. 3 Erosion rates of different cliff types in Ireland

Coastal erosion causes the loss of 160 to 300 ha of coastline each year, especially on the south west Atlantic coast. For example, the soft cliffs across the coastal path between Bray and Greystones have been severely eroded over recent years. Average retreat measurements of 0.952 m/yr (2005-2009); 0.205m/yr (1864-2009) obtained from historical OSi maps, aerial orthophotographs, LiDAR terrestrial topography and real time GPS measurements between Dalkey and Bray, represents the most accurate indication to date of erosion retreat rates for a soft coastline in the east coast of Ireland (Robinson, 2009).

The stretch of coast from Dublin to Carnsore Point, Co Wexford which is protected by offshore banks, the increased water depths over the banks will allow increased wave energy to reach the coast and will significantly increase the rate of erosion above that predicted by the Bruun Rule.

2.5 Tidal regimes

The dynamic controls (e.g., storms surges, waves, tides, currents, and fluvial discharges) affecting the different coastal environments also vary significantly in scale around Ireland. High tide coinciding with strong meteorological conditions and wave activity increases water levels usually resulting in storm damage along the coast.



Tide raising forces generate a tidal wave of approximately 0.5m in large oceans. However, as it approaches the coast, the shallower water causes the tidal wave to shoal and increase in height and it can reach higher heights sometimes due to the existence of the continental shelf others due to the funnel-shape of the estuary (ECOPRO, 1996). Tidal regimes in Ireland range from meso to macrotidal (spring tidal range is 2 m to more than 4 m) but also include microtidal areas (spring tidal range is below 2 m) for south-east and central northern coasts (See Figure 2. 2).

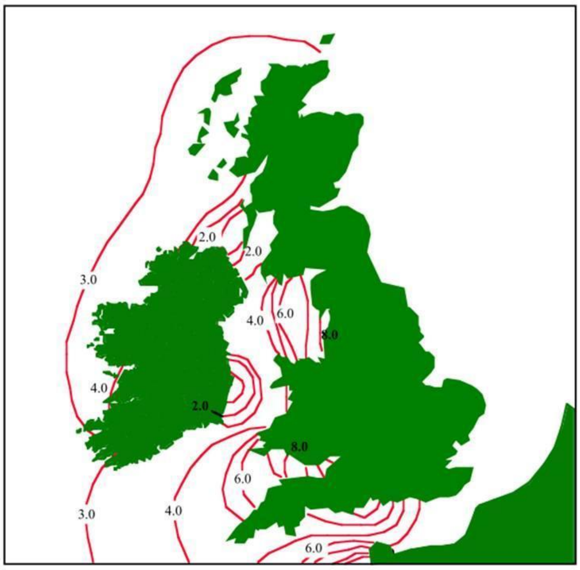
Figure 2. 2 Variation in spring tidal ranges around the Irish coastline (Carter, 1991a)

This varied tidal background is further influenced in height by major storm activity. Particularly those coasts, of western Ireland, that are exposed to eastwards-moving cyclones and swell wave energy from the North Atlantic.

From the co-tidal lines (lines joining places where tides occur at the same time) the movement of the tidal wave from the Atlantic along the south coast and up the Irish Sea as far as north Co. Dublin, where it meets the incoming tide from the north, is evident. The lack of tide elevation plays a major role in determining tidal range and tidal current velocity in the south Irish Sea. Due to the influence of the amphidromic point (zero tide) the tidal range in Arklow is lower than at Dublin which is further away from this point (See Figure 2. 3).

In the Irish Sea shallow shelf areas control the tide amplification, surge resonation and wave shoaling transformation. Most of the tidal motion at the Irish Sea comes from the Atlantic Ocean tidal, which it is, in turn, a result of gravitational planetary forces.

The structure of co-tidal elevation is virtually the same for both M2 and S2 constituents (lunar and solar forces), supporting the major influence of the amphidromic point on the Irish Sea.



Maximum tidal range on the east coast is associated with the shelf areas underlining the amplification potential of shallow waters. There is a spring elevation gradient on the Irish coast from 0.6 m at Arklow to 4.5 m in Dundalk Bay.

Figure 2. 3 Spring tidal range in the Irish Sea showing the influence of the amphidromic point

Regarding tidal current velocities, the residual direction of maximum velocity is northwards through the south Irish Sea and eastwards over Liverpool Bay. The secondary tidal flow through the North Channel meets up with the northerly low southwest of the Isle of Man (Orford, 1989).

Tidal heights refer to Chart Datum (CD). This datum varies from port to port and is usually set to, or near to, the Lowest Astronomical Tide (LAT) at the nearest port. For instance mean sea level at Dublin is 2.46m CD and 1.30m CD at Arklow. This would also affect the MSL, therefore there is small variation in mean sea level between the two ports is as a result of the influence of land masses, friction inertia etc., on tidal movements (ECOPRO, 1996).

The fact that the tidal wave from the Atlantic meets the incoming tide from the north as far as north Co. Dublin, together with shallow-wide continental shelf and the mesotidal range (2-4m), which poses a higher risk of inundation from storms (as considered in UGSS vulnerability studies by Thieler et al., (2000); Pendleton et al., 2010), makes the tidal range one of the most relevant indicators regarding coastal vulnerability studies to sea level changes.

2.6 Exposure to high wave energy

Wave climate is of particular interest as the energy imparted to waves by winds in the offshore region is finally dissipated on the coastline and used to transport and distribute sediment budget. Coasts receiving greater average annual wave energies can be expected to change most rapidly in response to sea-level rise (other factors being equal). Since wave energy is proportional to the square of wave height, then annual average wave height could be used to provide a regional semi-quantitative indicator of coastal wave energies (Sharples, 2006).

There are reports that argue that the wave climate is worsening (WASA Project, 1995). TOPEX/Poseidon and ERS-1/2 satellite imagery data (Woolf et al., 2002) have revealed that significant wave height have increased in the North Atlantic mid-latitudes from 1998-2002.

Wave heights and energy around Ireland reach maximum values along western coasts, with significant deep-water wave heights (Hsig) of 15–20 m. In the Irish Sea region the median wave height is 1-1.6m with extreme (1 in 1000) wave heights of 1.9 m (Orford, 1989).

Even though our coasts are affected by storms they only receive about 20% of the wave energy levels occurring on open Atlantic coasts. In relatively low-energy coasts of the East of Ireland deep-water waves rarely exceed 8 to 10 metres in height (Orford, 1989). While locally-generated sea waves dominate, swell waves entering the Irish Sea through St George's Channel and the North Channel, have an important role (Carter, 1983).

In general waves from 90-270 degrees, following the strong south to west air flows are predominant in the basin, and hence a high probability of waves generated in the Atlantic travel into this area (Orford, 1989).

2.7 Exposure of the coast to storms

The position and track of depression systems over Ireland greatly influences wind directions and wave heights in Irish coastal waters. Ireland lies in the path of the major east to north easterly North Atlantic storm tracks (as shown in Figure 2. 4). If these low pressure systems coincides with high water their damage on the coastline increases.

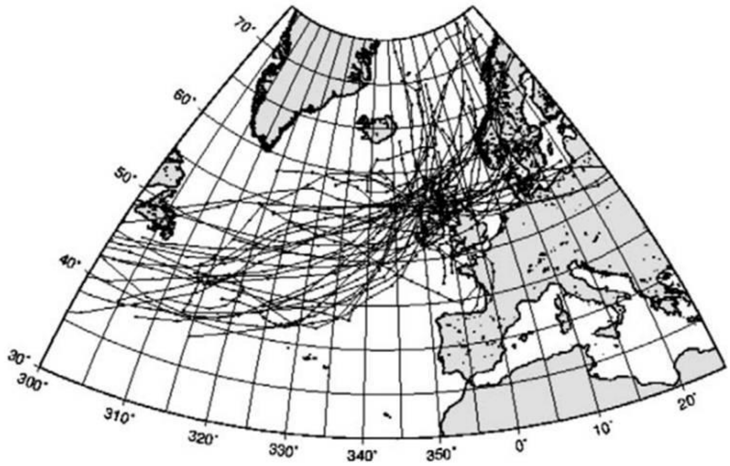


Figure 2. 4 The focus and paths of cyclones (minimum wind speed 15.3m/s) affecting Ireland and coastal Northwest Europe (record taken for the period 1973–1975) (Devoy, 2000b; Lozano et al., 2002).

Pronounced cyclical changes in frequency linked to the behaviour of the North Atlantic Oscillation (NAO) have occurred since the 1940s at a quasi-decadal (ca. 8.5 years) level (Lozano and Devoy, 2002). Future intensity and frequency of extreme coastal flooding events might increase as result of climate change (Flather and Smith 1998; IPCC 2007). Increase in the magnitude of storms affecting Ireland's coasts combined with SLR, whose potential impacts include coastal erosion and increased storm-surge flooding (Nicholls et al., 2008) will enhance coastal impacts (Carter , 1991a).

The prevalent wind in the Dublin region has a souththerly and westerly direction. Trajectory of some the most severe storms affecting the East of Ireland are given in Figure 2. 5. Westerlies increase their frequency in the summer and their intensity during the winter, although analyses of wind variations for south-east and eastern coasts may also suggest an increased occurrence of easterly winds and associated storminess in these regions, again with implications for coastal erosion. Therefore storminess represents an important factor to account for when assessing coastal vulnerability.

There is a diurnal variation in mean wind speeds in most parts of the country with nocturnal speeds typically 2-4 knots (1-2m/s) less than those of early afternoon.

Directional frequencies are often affected by nearby uplands as it can be the case at Dublin Airport where funnelling of the wind occurs around the Wicklow Mountains, situated further south.

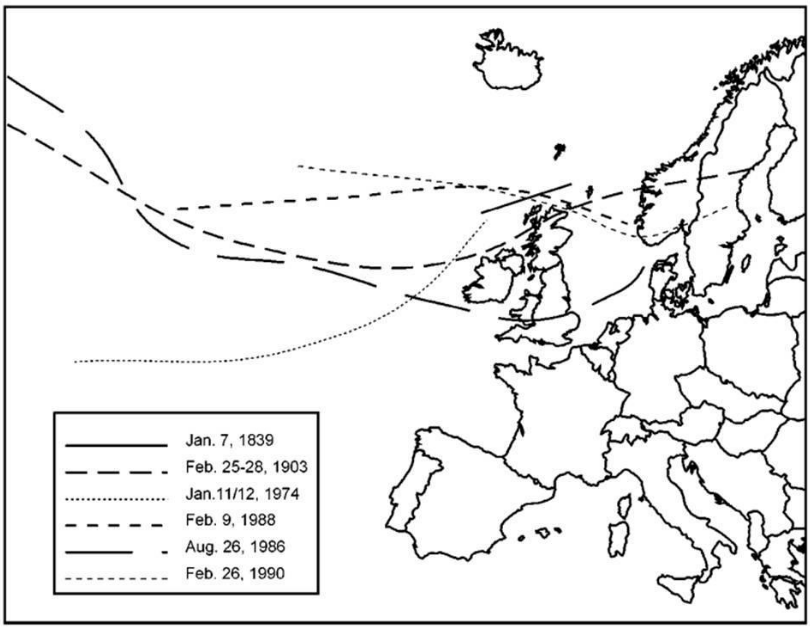


Figure 2. 5 Trajectories for six of the most severe storms in eastern Ireland (Sweeney, 2000)

A most comprehensive database of severe storm events from 1715–1999 was derived from documentary reports and newspaper coverage and compared with a database of severe storm occurrences from 1903–1999 using standard meteorological observations from stations in the Dublin region (Sweeney, 2000). This analysis considered the occurrence of events selecting wind/speeds over 58 kts as threshold. 578 storms were found over a 285 period (average of approx 2 events/yr) with 1920's, 1960's and 1990's being the windiest decades in eastern Ireland. See Figure 2.6 and Figure 2. 7.

Gales, defined as a period of not less than ten minutes during which mean wind speed exceeds 34 knots (17.5m/s), are experienced on about eight days per year in the Dublin region. Gusts are reported at wind observing stations when the wind speed in the gust exceeds the mean wind speed being observed by more than 10knots (5m/s).

From analysing past storms in Ireland it can be noticed that is the rapidly developing secondary depression that usually does the damage. The storm that occurred on Christmas Eve in 1997 produced the highest wind gust of the 1990s at

Dublin Airport (76 knots/39m/s) exemplifies this process. This 'secondary-low' mechanism could have been frequent in the past (Lamb, 1991). It remains uncertain how surface temperature changes may affect cyclogenesis and Irish storm climatology (Sweeny, 2000).

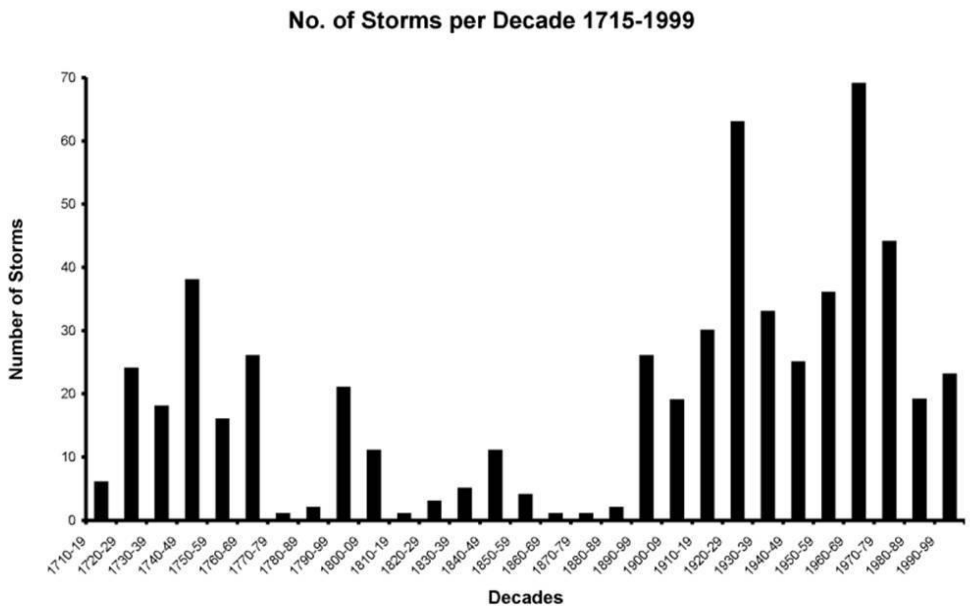


Figure 2.6 Storm frequency at Dublin 1715-1999 as inferred from documentary sources (Sweeney, 2000).

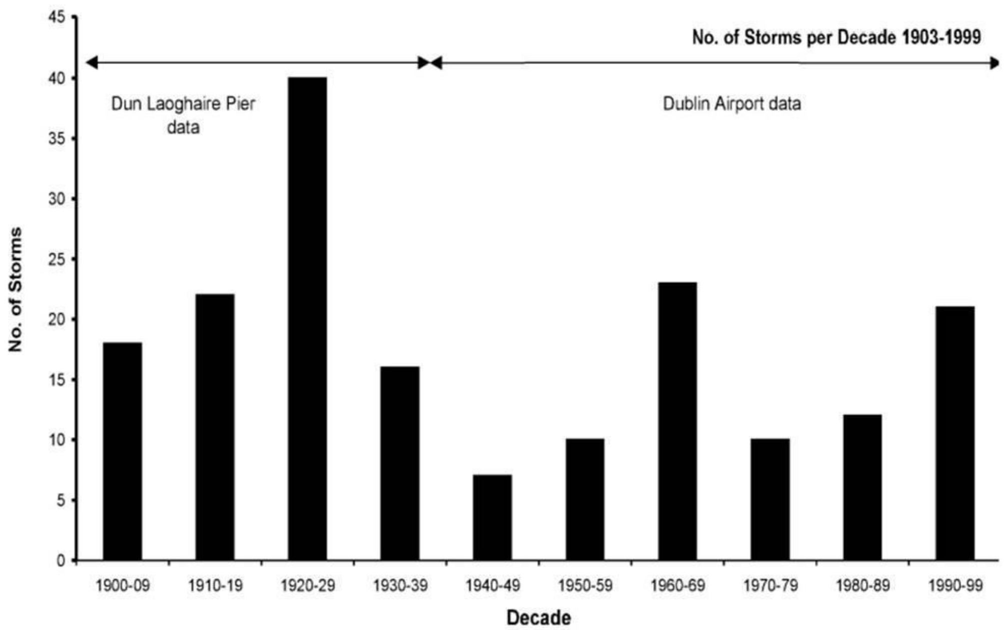


Figure 2. 7 Storm frequency at Dublin from 1903-1999 as inferred from instrumental sources (Sweeney, 2000)

2.7.1 Storm Surges

Storm surges are sea level rises associated with strong or prolonged winds, wave activity exerted by wind stress in the surface and low pressure systems moving at the same speed as the tidal wave in the open sea. They can also be defined as the difference between the predicted tide and the real water level observed usually measured at high tide. Surges in water level of this nature may take a number of days to disappear and for the tide to return to predicted levels. When they coincide with high spring tides, high winds and high wave activity, their impacts on vulnerable coastal areas are noticeable, increasing the risk of lowland coastal flooding and drastic changes to coastal geomorphology. A likely increase in the number of intense cyclones and associated strong winds, particularly in winter over the North Atlantic together with a slight pole ward shift of the storm tracks projected (IPCC, 2007) will have a direct impact on storm surges. In shallow waters like those in the eastern coast of Ireland, bathymetric changes would influence the impact of future sea level rise in surges heights (Lowe, 2001).

In the Irish Sea, surges are associated with major Atlantic depressions. Surge strength depends on the speed, intensity and size of the depression, usually from a westerly direction, as it travels over the British Isles (Orford, 1989).

Surges are significant when they coincide with a high spring tide, as happened on the East coast of Ireland in February 2002 when a surge of about one metre coincided with one of the highest spring tides of the year, causing intense flooding. That is why estimates of the probability of occurrence of these increases in water level are necessary for coastal protection.

The effect of wind on sea level largely depends on the topography of the area as a storm surge entering shallow water also increases.

Atmospheric pressure will also influence the water level. An area of low pressure will tend to raise the sea level and an area of high pressure will tend to depress the level. In general a barometric pressure of 1mb below the average will result in a increase of 10mm of sea level.

A measurement of coastal susceptibility would imply an analysis of de-trended (for relative sea level) historical hourly recorded positive surges (difference between observed and predicted tidal levels) as measured at different tide gauges across the study area. However, where recorded sea level data is not of a sufficient length of time to carry out extreme value analysis, joint probability analysis of tide and surge data can provide estimates of extreme sea levels (ECOPRO, 1996).

In the light of the above, low, soft coasts of less than 5 m above mean sea level (msl) in Ireland are susceptible to surge and storm activity (EUROSION, 2004). Particularly susceptible are low, embayed, and estuary-type coasts, like those in the study area and also those adjacent to the coast. These contain fine sediments in marsh and mudflat systems that are vulnerable to wave energy. Deep water storm waves at the coast may result in barrier over-washing, changes in sediment distribution, barrier erosion, and breakdown (Carter, 1983).

3. Methodologies

The methodology employed to assess coastal vulnerability is based on a methodology developed by USGS (Thieler et al., 2000; Pendleton et al., 2010). In order to assess the physical vulnerability of the coast regarding potential susceptibility to physical change as sea level rises, coastal vulnerability indicators need to be firstly identified. These factors that are important to coastal change and shoreline evolution are typically the same (EUROSION, 2004) but some of them have been selected according to coast characteristics in the study area (Devoy, 2008; Mulrennan, 1990; Orford, 1989). According to this the following variables were considered: geomorphology, coastal slope, elevation, shoreline changes, mean tidal range, wave height and direction, storminess and wind speed and direction and relative sea level rise.

3.1 Geomorphology

The geomorphology of the coast is a physical expression of how energy is being mitigated. Shorelines attempt to absorb the energy entering the coastal zone by redistributing sediment. Therefore any change in the point of energy application will change its configuration. Soft rock substrate would have an increased sensitivity for erosion; a sedimentary coast would be highly sensitive to both erosion and flooding. Quaternary geological maps from the Geological Survey of Ireland and high resolution digital terrain models (0.25m) and aerial photography (OPW, 2006) and data from the EUROSION Project (2004) have been used to refine geomorphology along the coast by integrating and digitising new coastal features, particularly in the intertidal zone (See Figure 4. 1).

In the future, geomorphological seabed classification will be integrated with coastal geomorphology, using as a base map a high resolution integrated onshore-offshore topography.

This sets the basis for the second phase of the vulnerability assessment on which different coastal feature units will be can be ranked according to its relative resistance of a given landform to erosion. Geomorphological units can be ranked according to established classifications (Gornitz and Kancirik's classification 1989; Gornitz et al. (1994)). It can also be classified as erodible and non erodible, soft or hard (ECOPRO, 1996) and where erosion is happening. This can in turn be ranked regarding its viability for inland migrating (Torresan et al., 2008). The event frequency and relaxation time together with coastal type can also be taken in account when ranking this variable (Pethic and Crooks, 2000).

3.2 Coastal slope

This variable would be indicative of risk of inundation and shoreline retreat as low-lying sloping areas retreat faster. Bathymetry and subtidal substrate slope of the near shore zone strongly influence the wave activity and exposure of the coastline and therefore the physical response of sandy barriers to sea-level rise.

The Intertidal zone slope is the angle of a line drawn from high water mark to low water mark irrespective of intervening irregularities (Sharples, 2006). Steeper offshore gradients absorb less wave energy than gentle (dissipative) gradients; Although gentler gradients may also result in increased storm surge heights. These characteristics may locally determine shoreline responses to sea-level rise.

Ideally an intertidal slope should have been incorporated into this study. Unfortunately there is a gap between the high resolution bathymetry compiled by INFOMAR (2010) and Terrestial LiDAR topography that has obstructed an accurate integration of offshore–onshore high resolution topographic data. Therefore the slope was only calculated from LiDAR digital terrestrial models (See Figure 4. 2).

3.3 Elevation. Topographic Integration between bathymetric and LiDAR terrestrial data

Low-lying low profile land immediately landwards of the mean high water mark is very vulnerable to future sea-level rises and storm surge events.

High resolution topography should be the base for any coastal vulnerability study and represents a necessary input for storm surge climate models.

Two datasets were used in this study:

- Digital elevation Model (OPW/Dept Agriculture 2006): OPW LIDAR survey digital datasets (DTM, DSM, Ground Only Point Cloud and Ortho-photography from Skerries to Dalkey Island) surveyed during autumn 2006 by BLOM Aerofilms. The LiDAR DTM and DSM has a spatial resolution of 2m (x,y) and was generated from LiDAR point data with a spatial resolution of approximately 1m. The classified ground point data was generated with a spatial resolution of approximately 1m. All data is presented in Irish Grid projection. All LiDAR elevation data is shown in meters relative to OD Malin.

-The second dataset was Multibeam bathymetry data acquired by INFOMAR in 2010. These data was cleaned using HIPS 7.0 software. Then gridded (2m x 2m) using DMagic IVS Package and it was finally integrated together with terrestrial topography in ArcGIS 9.3 as presented in Figure 4. 3.

3.4 Coastal change

According to some studies much of our coast is susceptible to erosion. In particular 54 km out of 99 km of the Dublin coast, have been classified as soft and 12km at risk (The County and City Engineers Association, 1992).

For this study it is assumed that when the shoreline has been eroding in 1985-1990 (former CORINE Costal erosion database) nor recently (according to the EUROSION database), this factor will add to the risk of erosion or flooding (EUROSION, 2004). Therefore the aim of this work is to identify areas that are undergoing eroding/accreting changes.

In carrying out this survey, Ordnance Survey (OSi) maps and aerial photography from both OSi and OPW are analysed to detect the historical changes in the coastline as it is evident from observing Figure 3. 1.

Figure 3. 1 Aerial photographs showing changes in coastal dune systems and intertidal areas in Mahalide-Corballis estuary (North Dublin)

In order to do this, first of all the coastline needs to be identified; The s.85 (1) of Sea-Fisheries and Maritime Jurisdiction Act (2006) establishes the low-water mark as the baseline on the coast of the mainland or of any island, or on any low-tide elevation situated wholly or partly at a distance not exceeding 12 miles from the mainland or an island.

The low-water line is the line along a coast to which the sea recedes at low-water. Although identifying what constitutes the low-water mark is not a straightforward exercise as there are different low-water marks during the course of different tidal cycles and as a result of variation in the gravitational pull of the moon, Earth and Sun. Not all states use the same low-water line as chart datum on navigation charts. Many states use mean low-water springs (MLWS) as the datum which is the average height of all recorded low-water spring tides. Therefore this line is difficult to determine in places such as coasts with a large tidal range and a gentle shelving foreshore such as Dublin Bay.

Identifying the low water mark is often not possible and defining a specific low-water line from with aerial photographs may not prove to be reliable. Therefore it is the High Water Mark that agencies such as the Ordnance Survey use. Sometimes changes in the vegetation line along the coast can be used when reliance on high water marks (or the water line in aerial photographs) leads to inaccuracies. Although in the case of sea walls or revetments, it is the position of the HMW that should be noted (ECOPRO, 1996).

For this particular study, the present position of the vegetation line was accurately mapped using the most recent O.S. maps and aerial photographs available. This was then compared with the vegetation lines obtained from as many maps and aerial photographs as possible. Comparing the position of the coastline at various times in the past gives a comprehensive view of the evolution of the coast. The survey started from mapping the most critical features regarding vegetation line in dune areas. The cliff base line or cliff top (from field surveys in local studies) can be the preferred reference line in cliffed areas and can be related to O.S maps and aerial photographs. The advantage of using these features as opposed to tidal lines i.e. HWM, LWM, is that the information can be derived from both maps and aerial photographs. Although the use of HWM and LWM obtained from O.S maps can considered unreliable for accurate coastline change analysis, the well defined HWM from the 1st edition of the 25'' maps has been used (See image Figure 4. 4).

Therefore coastal change analysis has been divided be divided into two steps:

-Comparing of water marks between the old 25' and 6'' Osi maps and the new aerial photographs (OPW, 2006) datasets where HWM or LWM can be easily identified (Figure 4. 5).

- Comparing the aerial photographs from 1970's, 2000, 2004 and 2006 using the vegetation line and baseline of cliff (Figure 4. 6).

Georeferencing images can also lead to inaccuracies and therefore influence coastal evolution analysis. OSi 1:30,000 sterophotographs (1971) where georeferenced using OPW (2006) aerial photographs. In this process control points were chosen with special care in order to minimise distortions, especially along the coast.

Once changes are identified, the next phase of the vulnerability assessment will be calculating erosion and accretion rates for different coastal units and the percentage of coastline undergoing erosion. In the same way, a radius of influence of coastal areas prone to erosion and flooding will be created.

3.5 Mean Tidal Range (m)

Tidal range allows us to determine how much the tides vary over the course of one cycle each day**.** As this is not constant it is usually quoted as the Mean Spring Tidal Range. For instance (the maximum spring tidal range), is defined as the average difference between Mean of predicted High Water Springs (MHWS) and Mean Low

Water Springs (MLWS) tides over 18.6 years, when the sun and moon are so aligned that their forces result in the highest and lowest astronomical tides known as HAT and LAT.

The sun has a similar effect as the moon and it is the combination of these variables which causes the tides to vary from day to day as can be seen from the tidal predictions. From analysis of tidal data a mean value of the spring tide levels is calculated, so that reliable and accurate tidal predictions for at least one year are given from Admiralty charts and Almanacs tide tables at hourly intervals for standard or primary ports such as Dublin (North Wall) and secondary ports (i.e: Malahide).

The alternative to the above is to use a numerical method using all the harmonic constituents obtained from either the Hydrographer of the Navy or from The Proudman Oceanographic Laboratory (POL). To compute and visualise tidal levels and currents, Contour lines of a tidal regime were obtained from POLPREDS for Windows 2.0 numerical model, which is an offshore tide and current computation system for PCs developed by the Proudman Ocean Laboratory (See http://www.pol.ac.uk/appl/polpred.html).

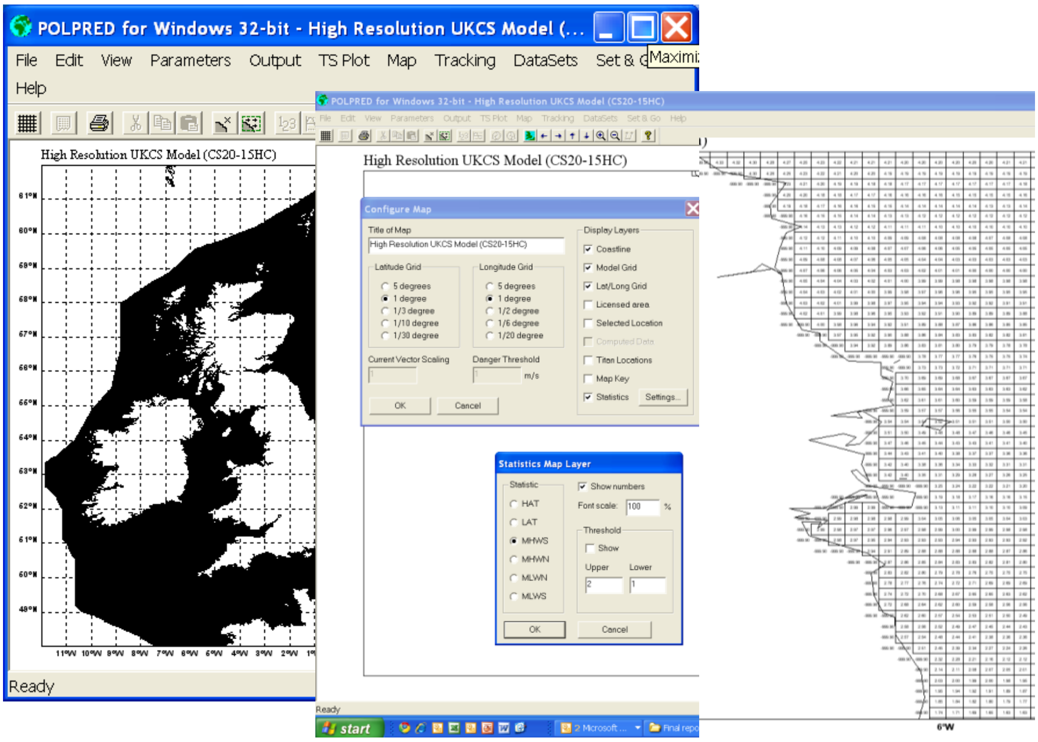


Figure 3. 2 Mean High and Low Water Spring Predicted tide generated by POLPREDS in the Dublin area

MHWS and MLWS were obtained for every single cell (at 1 degree resolution) across the area of interest (See Figure 3. 2) and data were exported into an excel spread sheet where tidal range was calculated subtracting the low tide from the high tide to determine tidal range.

Geodetic coordinates where converted into Irish Grid Cartesian coordinates using the OSi co-ordinate converter. Then tidal range data were downloaded into ArcGIS 9.3 where **c**ontour lines of a tidal regime were interpolated and plotted (See .

A comparison of predicted tidal data using VORF and POPRED softwares at Dun Laoghaire port is displayed in Table 3. 1 below. VORF modelling software can sometimes produce better results than POLPRED when compared to actual tide observations on the ground. This is due to the fact that POLPRED can be used to model tides, but its accuracy begins to break down coming closer to the coast as weather, morphology and interactions with the coast begins to make an influence. In the future values from both softwares will be compared and those values that best fits the actual tidal regime at a particular site will be considered.

POLPRED				VORF		
MHWS	MLWS	Spring Range (m)		MHWS	MLWS	Spring Range (m)
2.94	0.5	2.44		4.034	0.780	3.254

Table 3. 1 Difference in tidal regimes generated by VORF and POLPREDS at Dun Laoghaire Port ((53.297039, -6.131404); Ellipsoid Height (m) = 60.056))

Tidal ranges can now be divided and ranked according to Haye’s (1979) tidal range classification: 1. Microtidal <1metres; 2. Low-mesotidal 1-2 metres; 3. High-mesotidal 2-3.5 metres; 4. Low-macrotidal 3.5-5 meters; 5. Macrotidal >5 metres (less vulnerable than micro tidal regimes).

3.6 Mean wave height (m)

This is an indicator of the total average annual swell and storm wave energy received over time, and also of wave energy that drives the coastal sediment budget. Coasts receiving greater than average annual wave energies can be expected to change most rapidly in response to sea-level rise. Because of the orientation of particular shores to the wave approach direction, and the presence or absence of features such as sheltering headlands or other barriers, certain shoreline segments will be more exposed to wave energy (Sharples, 2006). Where long term water level and near shore wave data are available it is possible to ascertain whether the occurrences of large waves and high water levels are correlated (joint probability analysis). But for most of the coastline of Ireland this analysis is not possible as there is little wave and water level data.

Since wave energy is proportional to the square of wave height, it is envisaged that this annual average wave height model could be used to provide a more detailed and regionally variable semi-quantitative indicator of the east of Ireland coastal wave energies. However, a quantitative annual average wave height, frequency (or period) and direction data hourly wave forecasts (using WAM) for a grid of points located off the Irish coast with corresponding records from a number of buoys installed in recent years for the Dublin area is needed so the wave contour lines can be built and the exposure regarding the orientation of particular area to the wave heights and direction can be assessed. Despite the fact that wave height data is not yet available, the annual average of theoretical wave energy, a factor related to wave height, is being displayed below in Figure 3. 3 semi-quantitative indicator of the east of Ireland coastal wave energy.

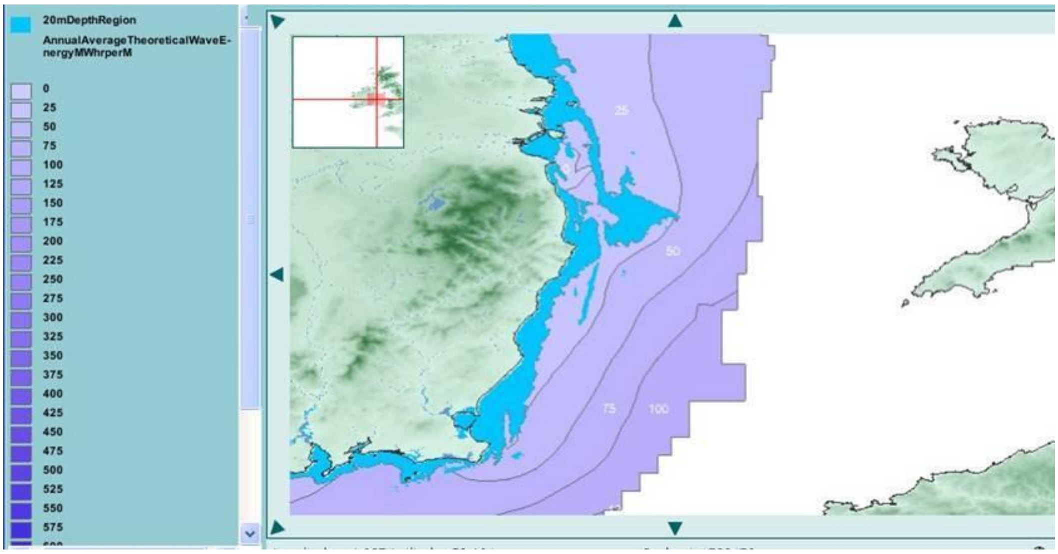


Figure 3. 3 Annual average theoretical Wave energy (MWhrperM) from Marine institute map viewer (www.marine.ie)

3.7 Wind/ Storm Frequency

Storminess is normally defined in terms of the number of days with strong winds of force 10 (from 24.5 to 28.4m s^{-1}) on the Beaufort wind scale for one or more measurements during a 6-h period over the course of any single day.

Storm frequency can be measured from analysis of the records of gale days (days where the 10-minute mean wind speed exceeded 34 knots (17.5m/s) (Met Eireann, 1996)). For this particular study, storm frequency was calculated analysing mean wind speed that exceeded 48-55 knots (24.5-28.4 m/s or 89-102km/hr) from instrumental records corresponding to mid range force 10 on the Beaufort scale, which is the speed at which structural damage, seldom experienced inland and trees uprooted can be expected.

Storm frequency from 1961 to the 1990´s was derived from available instrumental recorded data at three weather stations within our study area are displayed in Figure 4. 9, Figure 4. 10 and Figure 4. 11.

Nevertheless there are different ways of characterising storminess using extreme wind velocities, storm surge heights and also by analysing sea level pressure. Thus storminess can also be characterised by making use of the gridded wind speed data sets downscaled from regional climate models.

As both wind speed and direction vary over short time intervals the wind reported at weather stations is an average of the winds over ten minutes preceding the hour. At the weather stations, mean hourly wind speeds and directions along with gusts (short increases in wind speed) are also recorded. Regarding wave generation at sea, it is the longer and slowly varying mean hourly wind speeds which are of interest.

Three hourly wind speed modelled data at a 14 km resolution horizontal grid was derived from the Hirlam weather forecasting model, driven at the boundary using the HadCM3L_A1B GCM from 1961-2000 and ECHAM5_A2 GCM outputs and a boundary driver ECMWF ERA data from Hirlam (used as a regional climate model. Annual values of mean hourly wind speed data was downloaded into ArcGIS and interpolated using Kriging interpolation method for different locations along my study area to show the distribution of winds along coastal areas (See Figure 4. 8).

Although it would be interesting to calculate number of hours where the mean wind speed of easterly winds (NE, E, and SE) was greater than or equal to 17 knots at all points across my study area since 1960's.

In latter phases of this vulnerability assessment, past storm surge data will be used combined with the presence of significant areas of low-lying land immediately landwards of the mean high water mark or likely to do so as a result of projected future sea-level rises using high resolution topography and historically recorded year return period of storm surge event water levels.

3.8 Rate of relative sea level rise (mm/yr)

Past sea levels increased the amount of time the coast is exposed to extreme storm surges and therefore its vulnerability. Therefore historical record of sea-level change can be combined with other variables e.g: elevation, geomorphology, wave characteristics, erosion rates, etc to assess the relative coastal vulnerability to future sea level change.

Ireland has a poor and incomplete tide-gauge system by which relative sea level change can be determined. Tidal data are recorded by a variety of agencies such as the Marine Institute and port authorities. There is a need to consolidate our analysis of existing long-term sea level data (Orford, 2006) and there are a number of projects undertaking this task at the moment.

Values of relative sea-level change data from historical records (past 50-100 yr) were obtained for the Dublin area. Raw data for modern for the 20th century RSLC determination are virtually always obtained from tide-gauges, which is recorded on paper charts as an analogue signal, then reduced to given an annual MSL time series. A long term trend was then derived from annual mean values of sea level given by the Permanent Service for Mean Sea Level (PSMSL) at Dublin Port from 1938 to 2001. Then a trend line fitted via linear least squares regression specifies a value of RSLR rate from the slope regression coefficient (See Figure 4. 12). The value of the trend line as a stable estimate for future change depends on the length of the time series. The same procedure will be applied to other locations long-term data in the future.

3.8.1 Sea level scenarios

In considering future changes at the local level where vulnerability and adaptation assessments are required, account needs to be taken of the long-term, non-climate change-related trend, which is usually associated with vertical land movement that affect relative sea level.

Scenarios of future sea level changes have been generated using the Sea Level Scenario Generator from Sim CLIM software (http://www.simclim.com/) taking into account global, regional and local components and expressing as yearly changes in sea level (in cm) from 1990 to 2100.

This data includes global eustatic sea-level rise as well as local isostatic or tectonic land motion. This is ranked using modern rate of eustatic rise (approx 1.8mm/yr) as very low risk. Since this is global or background rate equal to all shorelines, the relative sea level rise ranking reflects primarily regional to local isostatic or tectonic effects.

For generating regionally-varying, time-dependent scenarios of sea-level change, the underlying method used in SimCLIM is that of pattern scaling (Hulme et al., 2000). Initially, seven normalised patterns have been created and stored in SimCLIM. The SimCLIM Sea Level Scenario Generator has the capacity to take account of local trends, that it is the rate of "vertical land movement rate" (non-climate- change-related trend). If the value is known, this rate can be entered. In this case the vertical land movement trend is not known, so the value for the overall (unadjusted) recent sea-level trend, in mm/year, as estimated from tide-gauge data is then input into the system so the SimCLIM can adds this trend to the regional component, but only after subtracting an estimate of the climate-change-related portion of that trend in order to avoid "double-counting" the climate-related influences and inflating the future projected rise.

SimCLIM adjusts the locally observed trend by subtracting the estimated global-mean trend, as derived from observational data (Church et al., 2001). However, in order to be consistent with the regional pattern-scaling, the global-mean value is initially multiplied by the proportion of the model-based, current global sea-level change due to thermal expansion (from MAGICC, which, for historical greenhouse forcing and three sets of model sensitivity values, gives: low, 0.61; mid, 0.68; and high, 0.73) and then scale the location-specific value derived from the chosen GCM pattern:

$$OBS_{ncc} = OBS_L – OBS_g \, [GCM*TE + (1-TE)]$$

Equation 3. 1 SIMCLIM Method to calculate the non-climate-change local trend in sea-level (mm/yr)

OBS_{ncc} is the non-climate-change local trend in sea-level (mm/yr)

OBS_L is the local observed trend, as typically derived from tide gauge data (mm/yr)

OBS_g is the estimated observed global-mean sea-level trend (1.0, 1.5 and 2.0 mm/yr, for the low, mid and high estimates, respectively) .

GCM is the value of the GCM-specific normalised value of sea-level change, relating to thermal expansion only.

TE is the proportion of the model-based, global sea-level change due to thermal expansion, as generated by MAGICC.

The non-climate-related trend, OBS_{ncc}, which is often due to vertical land movement, is then added on to the regional pattern-scaled projection of sea-level changes.

Altogether, the global, regional and local components are combined in the SIMCLIM Sea Level Scenario Generator (See Figure 4. 13) and expressed as yearly changes in sea level (in cm), from 1990 to 2100 as it is illustrated in Figure 4. 14 to Figure 4. 26 using several SRES scenarios ((AR4) IPCC, 2007). SRES scenarios are based on projections of climate change depending on future human activity, greenhouse emissions, land-use and other driving forces. There are more than forty different and they can be grouped into families; for instance those including A1 (i.e: A1T; A1B; A1Fl) represent the worse case scenario: rapid economic growth, globalised world and increased on temperature of 1.4 - 6.4 °C.

4. Results

4.1 Refined geomorphological map

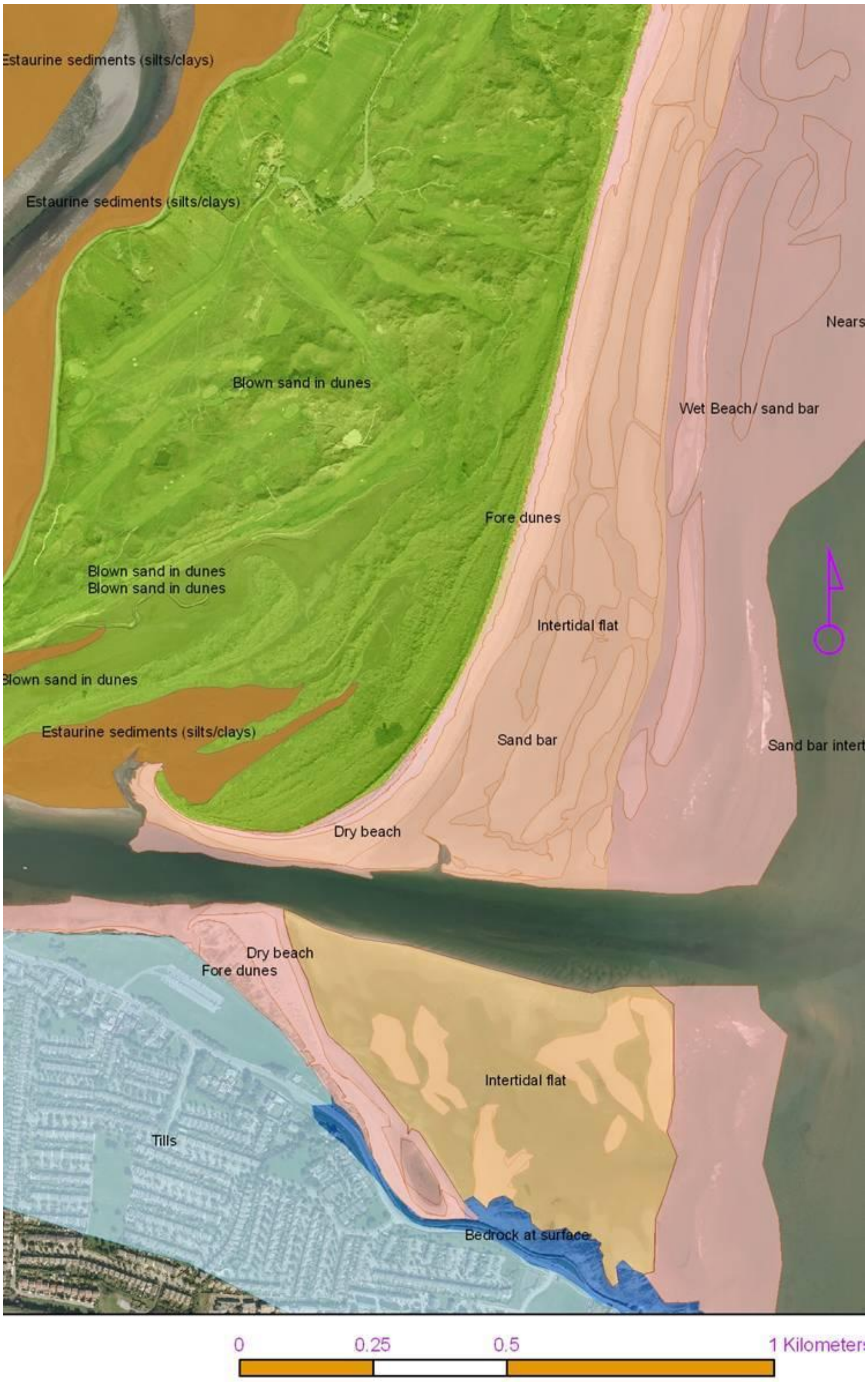


Figure 4. 1 Geomorphological map in the Malahide- Corballis estuarine area

Figure 4. 1 shows a zoomed into the Malahide estuarine area displaying new coastal features identified and digitised from orthophotographs (OPW, 2006) and field

surveys such as cliffs, beaches, and barriers (sand and gravel types); lagoons; dunes and sand plains; and salt marshes, mud flats, Intertidal flats, ridges and runnels, etc.

4.2 Coastal Slope

Figure 4. 2 below shows an example of the slope range in the Malahide- Corballis estuarine area calculated from digital Terrestial elevation data generated by OPW in 2006. In the future the intertidal slope will be calculated from integrated elevation data from generated from Multibeam bathymetry data and LiDAR terrestial data.

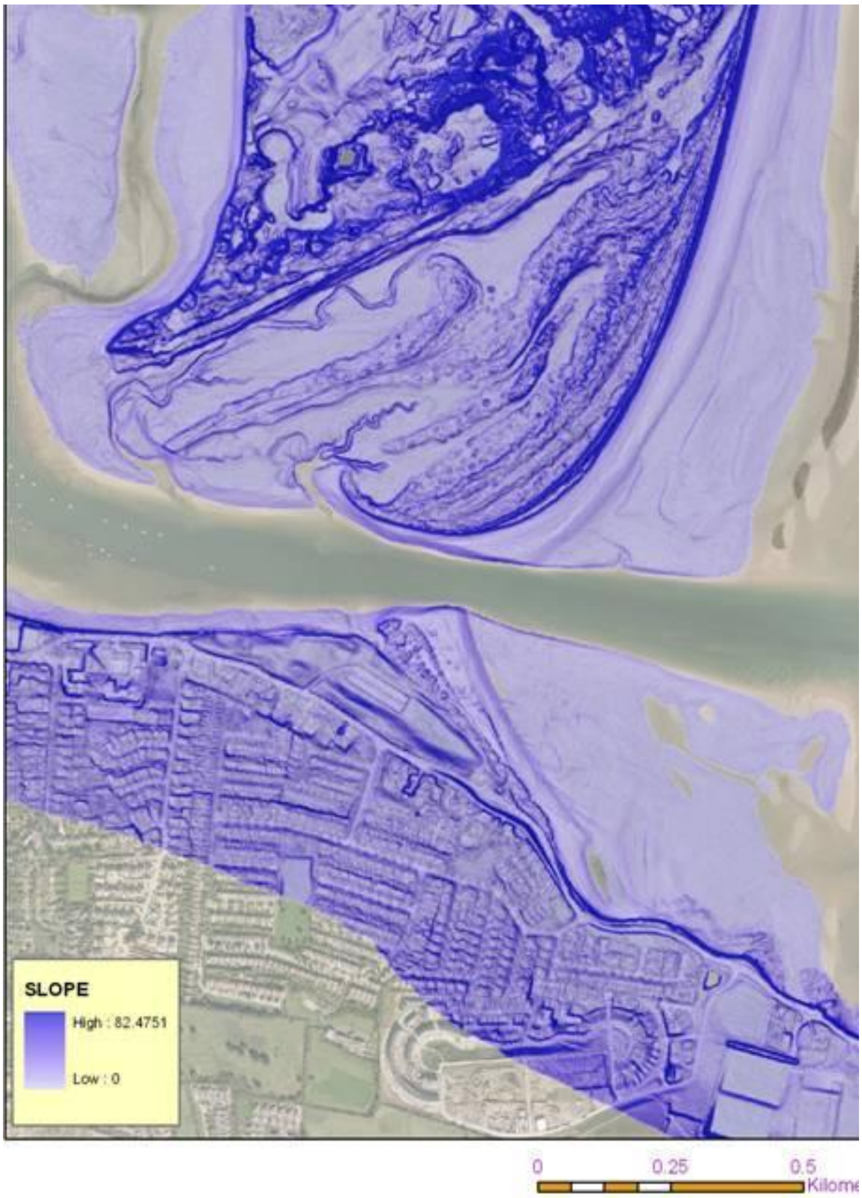


Figure 4. 2 Slope in the Malahide-Corballis estuarine area

4.3 Bathymetry-Terrestial topography integration in Dublin Bay

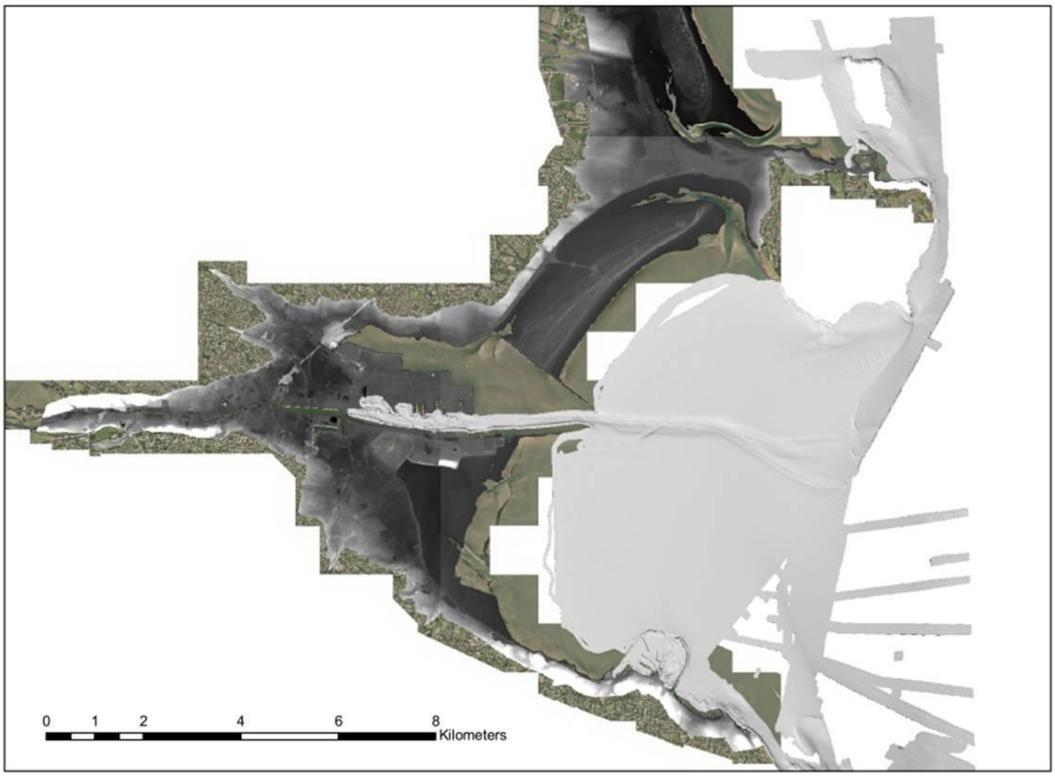


Figure 4. 3 Integration of LiDAR digital terrestrial topography and Multibeam bathymetry in Dublin Bay

4.4 Shoreline changes

High and low water marks shown in Figure 4. 4 from OSi 25´´ historical maps last revised in 1969-70 have been digitised along the coast of the Dublin. Then high water marks have been compared with coastline extracted fom OSi 6´´ historical maps from 1935-1938 and (OPW, 2006) orthoimagery in Figure 4. 5. Changes in the vegetation line extracted from stereophotographs from 1971 and orthoimagery obtained in 2000, 2004, and 2006 are illustrated in Figure 4. 6; this Figure shows areas where accretion of beach sediments and fore dune ridges extension around ends of the barriers have taken place since 1971. Similarly in other areas are experiencing erosion processes.

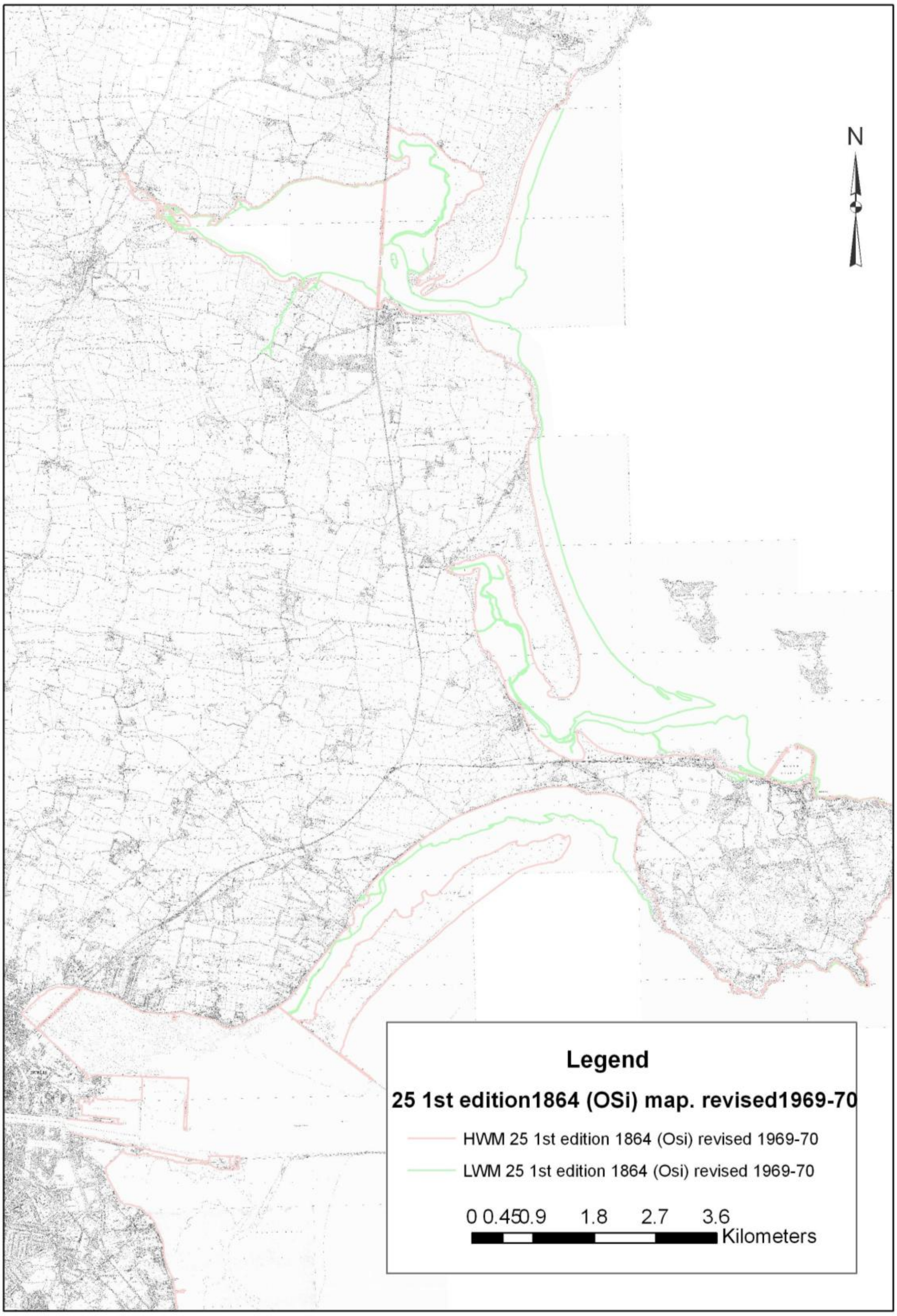


Figure 4. 4 High and low water mark lines extracted from Osi historical marks in the Dublin area

Figure 4. 5 Changes in the evolution of the high water mark at the Corballis Barrier and Broadmeadow Estuary between from 1935-1938 and 1969-1970 (OSi Maps) and orthoimagery from 2006

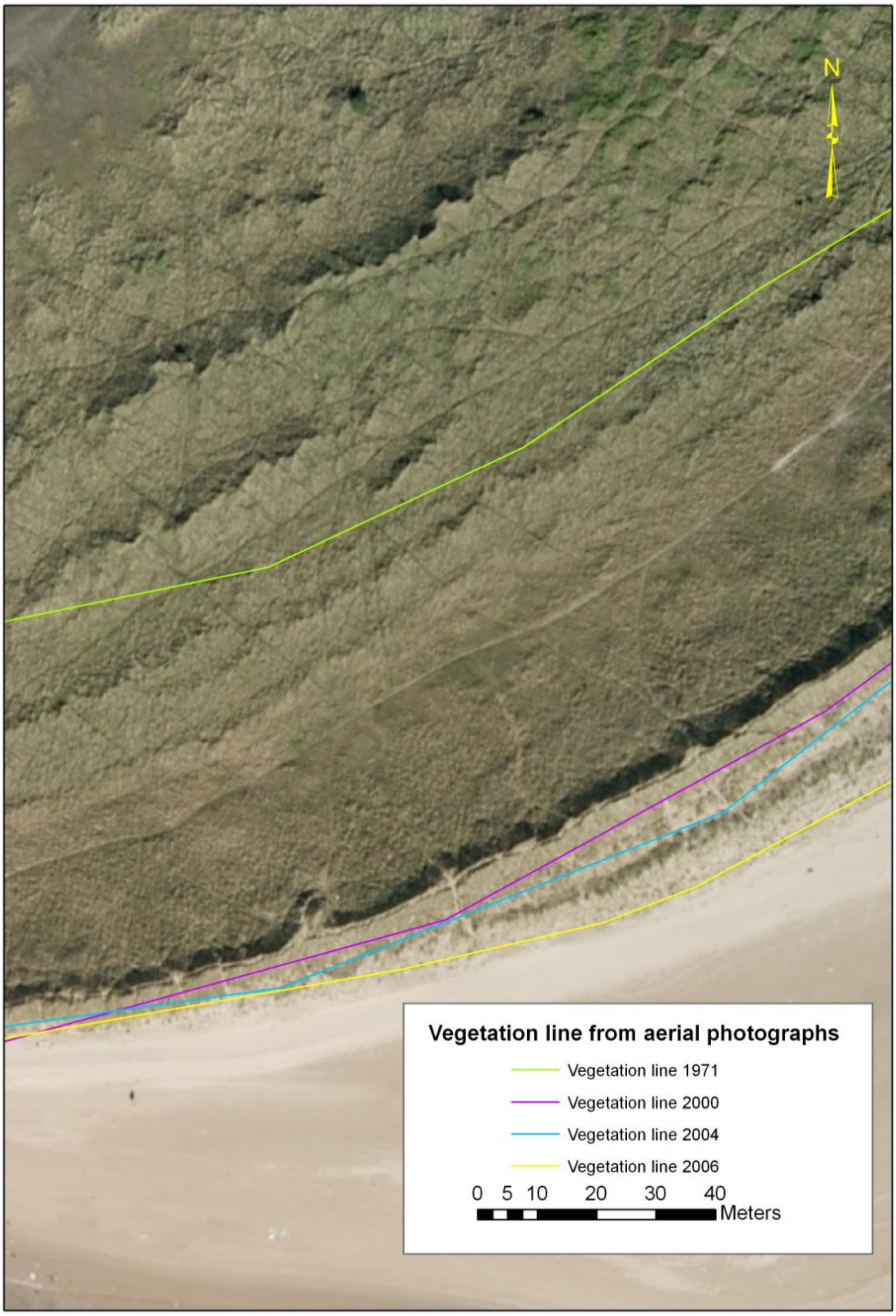


Figure 4. 6 Changes in the evolution of the vegetation line at the Corballis Barrier and Broadmeadow Estuary between from 1971 stereophotographs and orthophotographs from 2000, 2004, 2006

4.5 Mean tidal range (m)

In Arklow the tidal range is lower than at Dublin (See Figure 4.7) which is further away from the amphidrome point. The range of the tides increases southwards from Larne and northwards from Wicklow and attains a maximum of about 4.9 metres at spring tides near Dundalk.

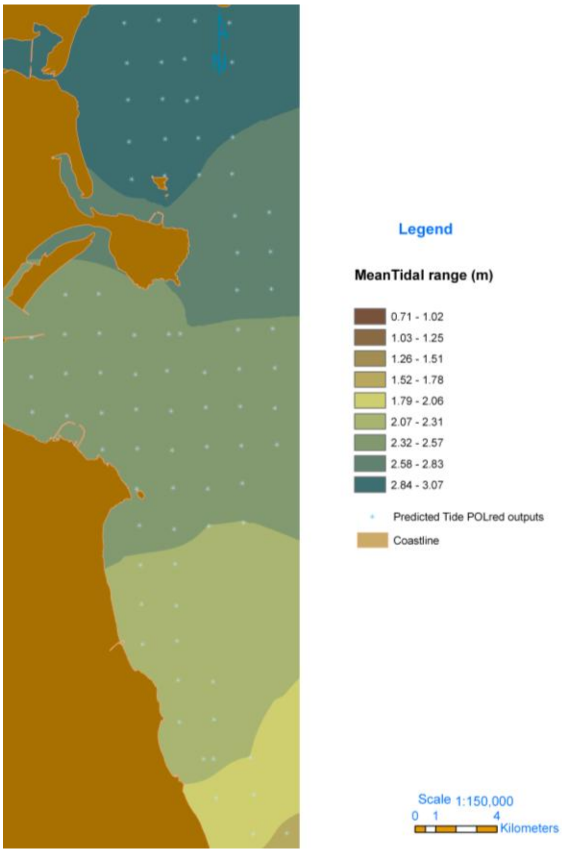


Figure 4. 7 Variations of the spring tidal range in the Dublin area

Some studies have classified the microtidal coasts as low risks and macrotidal as high considering that the strong tidal currents are associated to large tide range. Following USGS (Thieler et al., 2000; Pendleton et al., 2010) vulnerability ranking of tidal ranges, adopted in this study the opposite has been considered. This is because given a 50% chances of a storm occurring at high tide, if our study area has, for example, a 4m of tide range, this represents that a storm with 3m surge height is still up to 1 below the elevation of high tide for ½ of the tidal cycle; However a microtidal coastline, is nearly always high tide, so there is a higher risk of inundation from storms for a wider period of time.

In this regard the mesotidal range in the Dublin area of 2-4m poses a higher risk than macrotidal ranges to coastal inundation in event of storms.

4.6 Wind contour map

Modelled three hourly wind speed data (10m above sea level) was derived at a 14 km resolution horizontal grid from the Hirlam weather forecasting model, driven at the boundary using the HadCM3L_A1B GCM from 1961-2000 and ECHAM5_A2 GCM outputs and a boundary driver ECMWF ERA data from Hirlam. These data was later downloaded and interpolated using the kriging method (ArcGIS 9.3.1). Figure 4. 8 illustrates the annual mean 3h wind distribution in the Dublin area.

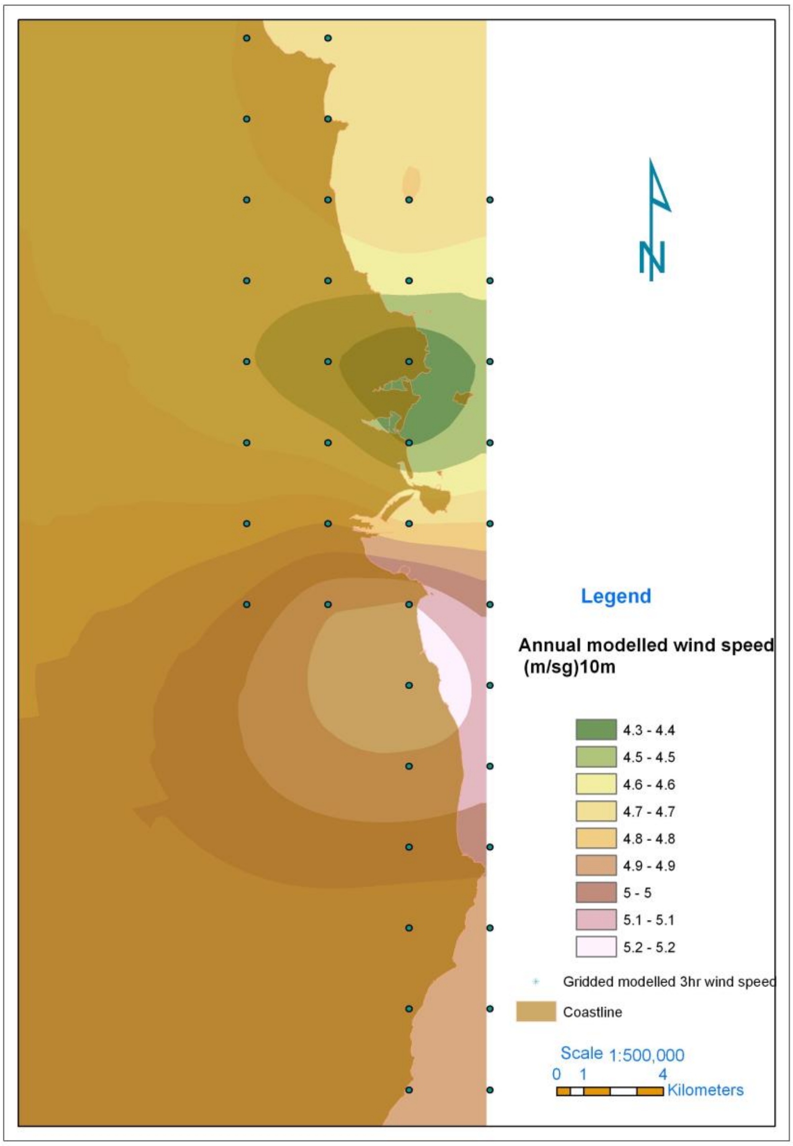


Figure 4. 8 Annual mean wind speed in the Dublin area interpolated from three hourly modelled downscaled data

4.6.1 Storm Frequency

Figure 4. 9, Figure 4. 10 and Figure 4. 11 show the storm frequency from 1961-1990´s as inferred from instrumental data provided from different weather stations at Dublin, Casement and Rosslare determined by the number of days with strong winds of force 10 (from 24.5 to 28.4m s−1) on the Beaufort wind scale.

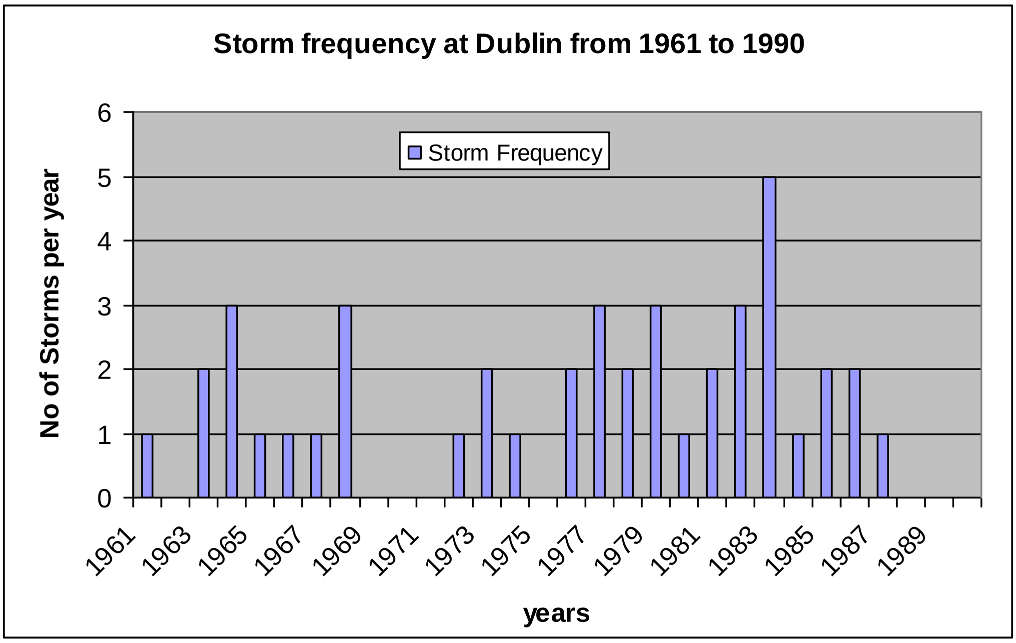


Figure 4. 9 Storm frequency per year at Dublin from 1961-1990´s as inferred from instrumental sources

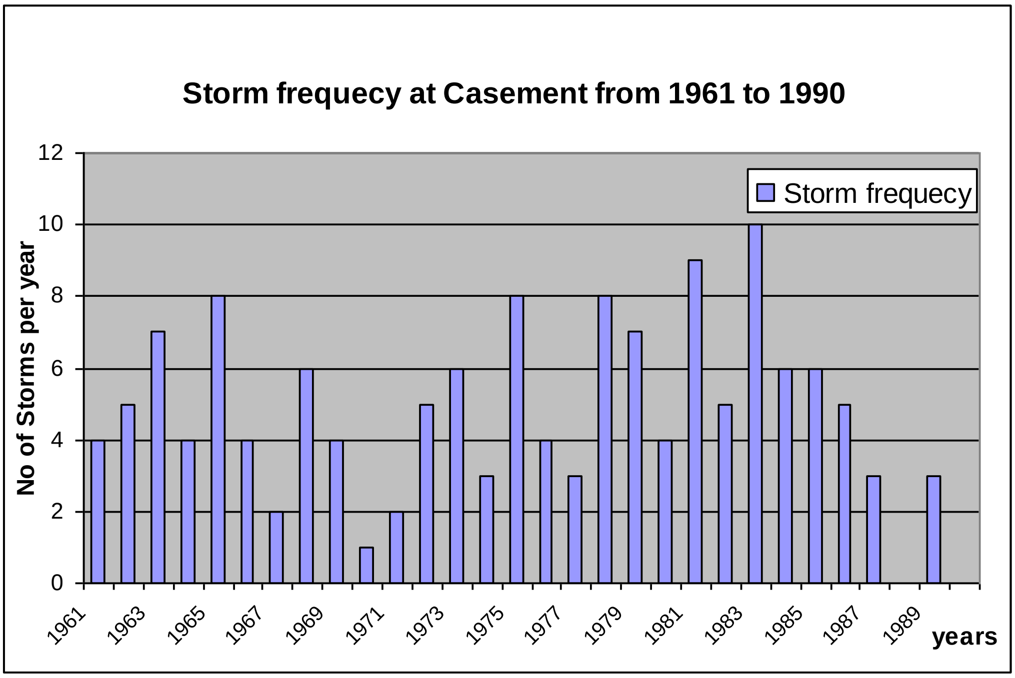


Figure 4. 10 Storm frequency per year at Casement from 1961-1990´s as inferred from instrumental sources

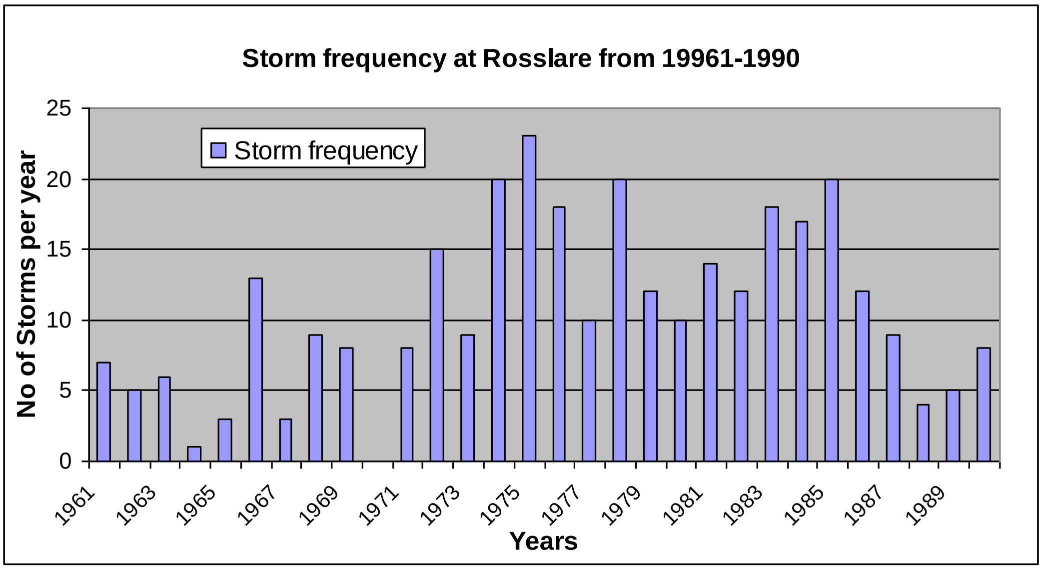


Figure 4. 11 Storm frequency at Rosslare from 1961-90´s as inferred from instrumental sources

4.7 Sea level rise rates

A long term annual mean values of sea level given by the Permanent Service for Mean Sea Level (PSMSL) at Dublin Port from 1938 to 2001 have been used to calculate the specific RSLR. A value of 1.68 mm/yr is then extrapolated from the slope regression coefficient (See Figure 4. 12).

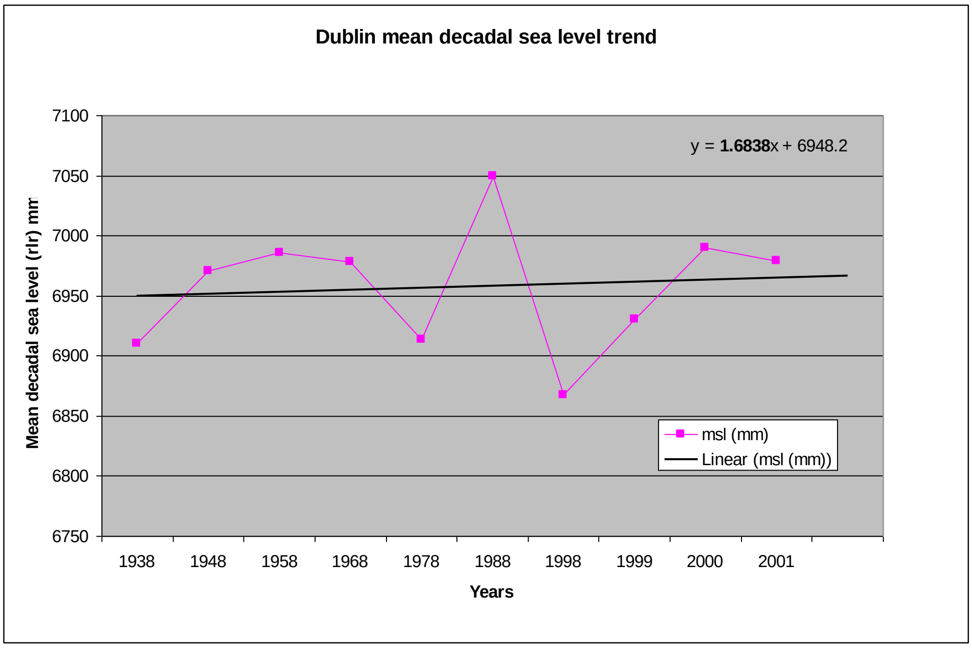


Figure 4. 12 Relative mean sea-level change at Dublin obtained from historical records from 1938 to 2001

4.7.1 Future Sea level scenarios in the Dublin area

Several sea level scenarios have been generated for Dublin expressed as yearly changes in sea level (in cm), from 1990 to 2100 including global, regional and local components combined using the SimCLIM Sea Level Scenario Generator (Figure 4. 13). A local observed sea-level trend of 1.68mm/yr previously obtained from mean sea-level trends at Dublin from historical records from 1938 to 2001 is been entered.

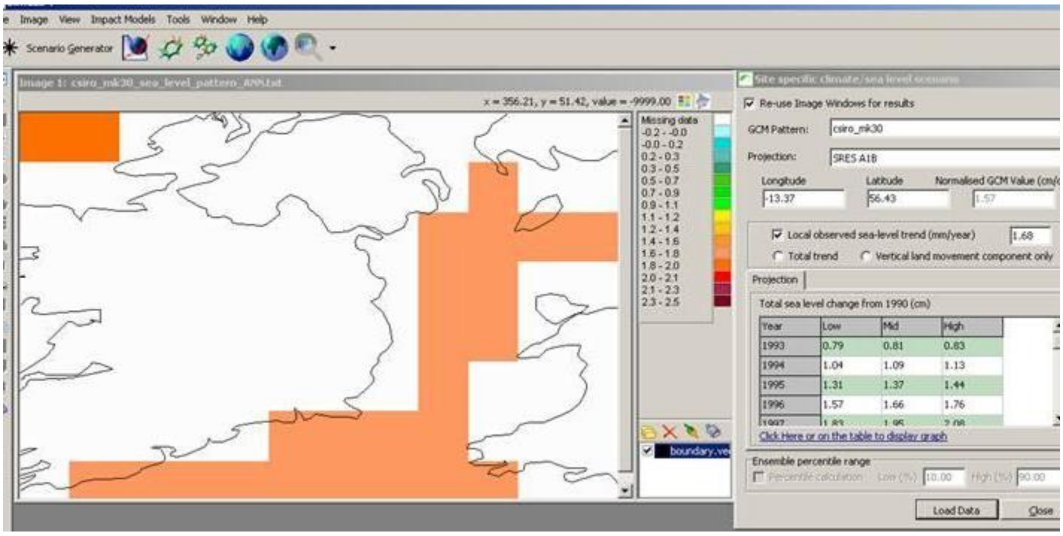


Figure 4. 13 Site specific climate/Sea level scenarios using SIMCLIM software

By looking at Figures 4.14 to Figure 4.26 it can be seen that the highest increases in sea level are given by SRES projections that include groups containing A1 or A2.

Figure 4. 14 Sea level scenarios using CSIRO_MK30 Global Climate Model and balanced across energy sources SRES A1B projections

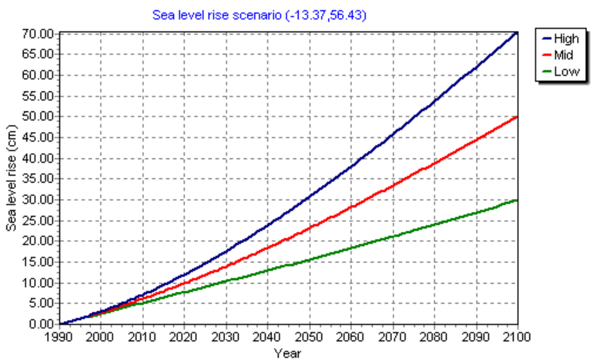
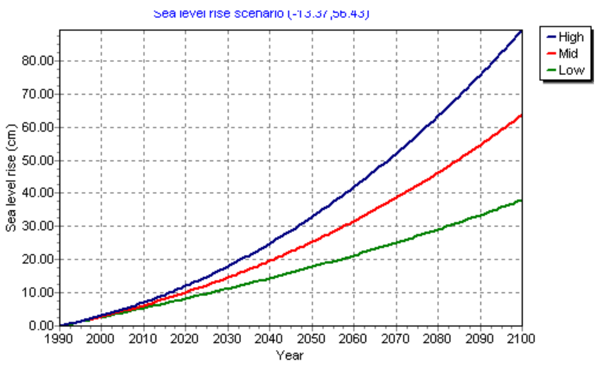


Figure 4. 15 Sea level scenarios using CSIRO_MK30 Global Climate Model and A1FI fossil intensive SRES A1F1 projections



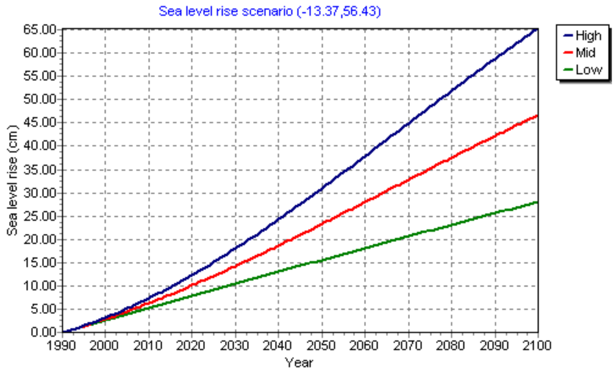


Figure 4. 16 Sea level scenarios using CSIRO_MK30 Global Climate Model and predominantly non-fossil SRES A1T projections

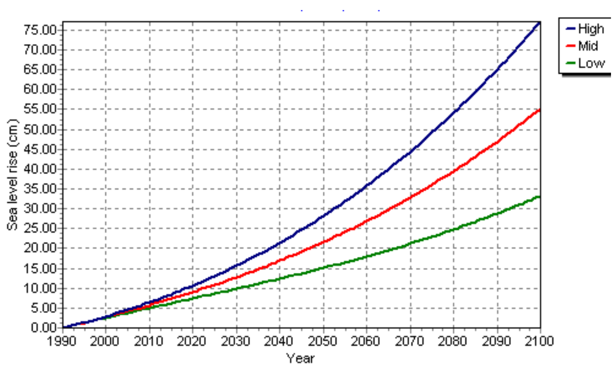


Figure 4. 17 Sea level scenarios using CSIRO_MK30 Global Climate Model and SRES A2 projecting global population and regionally oriented economic growth

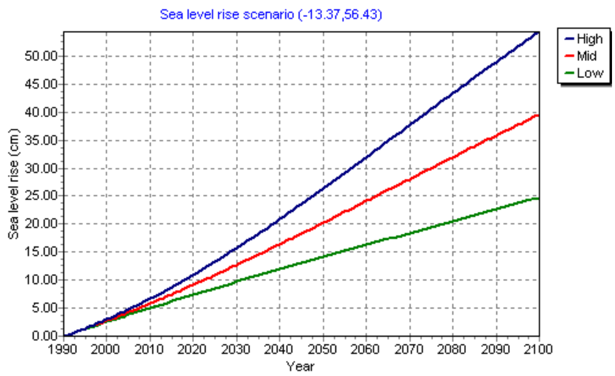


Figure 4. 18 Sea level scenarios using CSIRO_MK30 Global Climate Model and SRES B1 projections

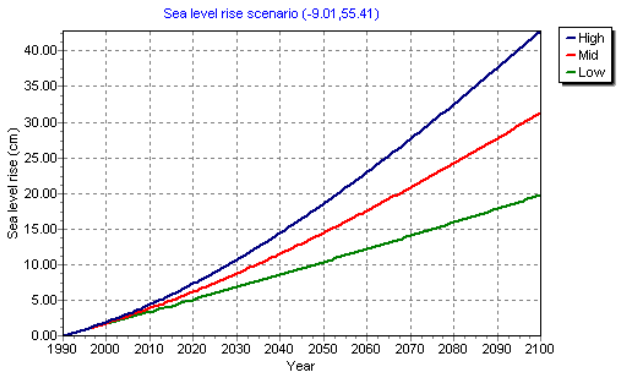


Figure 4. 19 Sea level scenarios using CSIRO_MK30 Global Climate Model and SRES B2 projections

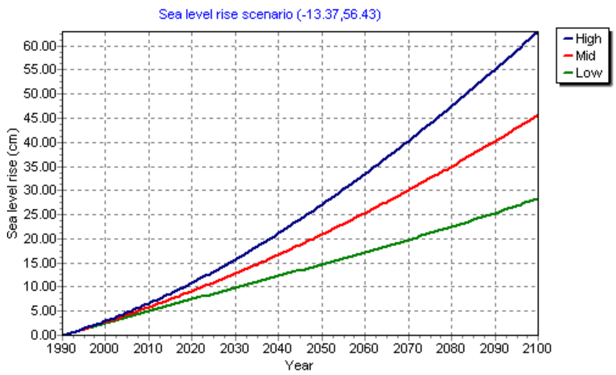


Figure 4. 20 Sea level scenarios using CCCMA_CGCM and SRES B2 projections

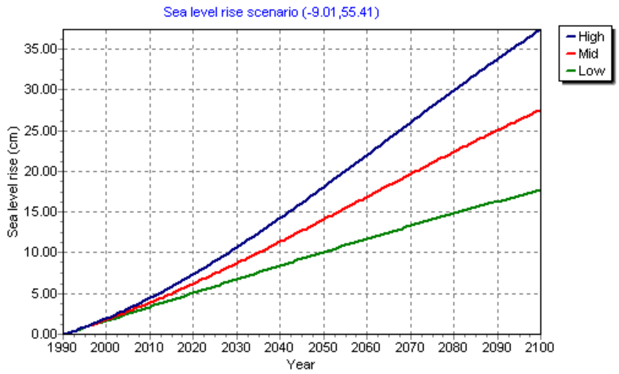


Figure 4. 21 Sea level scenarios using CCCMA_CGCM and SRES B1 projections

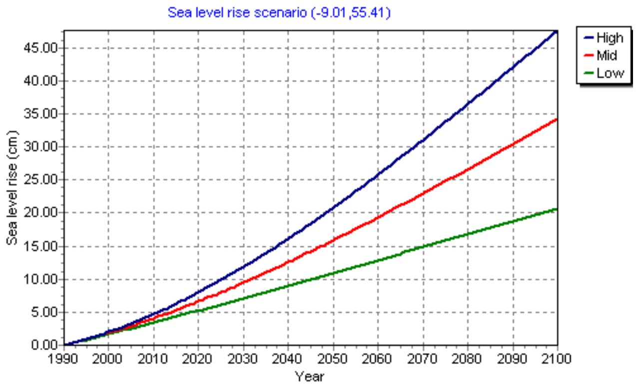


Figure 4. 22 Sea level scenarios using CCCMA_CGCM and balanced across energy sources SRES A1B projections

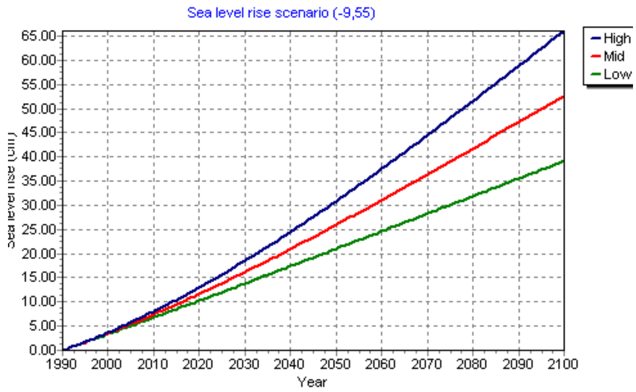


Figure 4. 23 Sea level scenarios using Giss_e_h Global Climate Model and balanced across energy sources SRES A1B projections

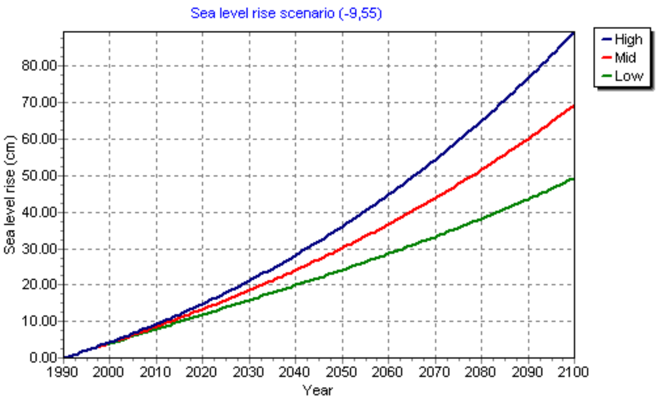


Figure 4. 24 Sea level scenarios using Giss_e_h Global Climate model and continuously increasing global population and regionally oriented economic growth SRES A2 projections

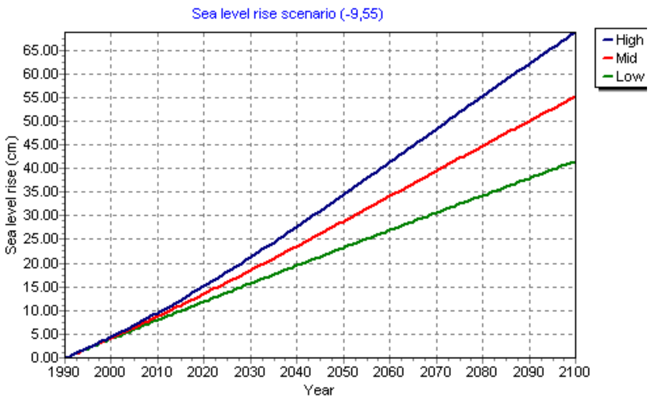


Figure 4. 25 Sea level scenarios using Giss_e_h Global Climate model and same global population SRES B1 projections

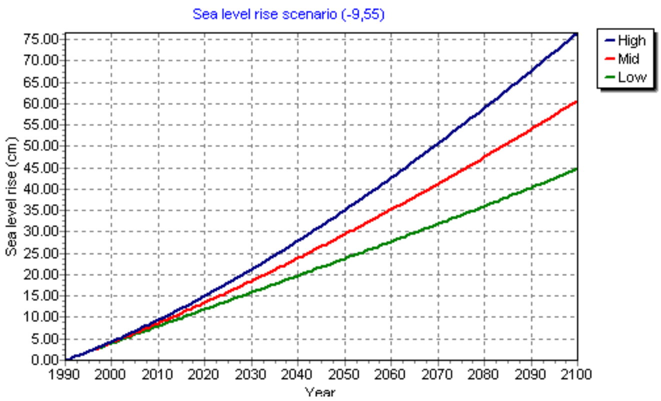


Figure 4. 26 Sea level scenarios using Giss_e_h Global Climate model and SRES B2 projections

5. Future work

Regarding the second phase of the vulnerability mapping, indicators or variables identified and compiled in this study will be divided into quintiles and a ranking based on their values distribution will be assigned. After shorelines will be divided into segments and for each shoreline segment a coastal vulnerability index based on methodology developed by USGS (Thieler et al., (2000); Pendleton et al., (2010)) will be applied. This CVI will assign a range of vulnerability (low to very high) regarding coast's potential susceptibility to physical change as sea level rises.

Finally the vulnerability of the coast to storm surges will be assed. For this storm vulnerability modelling will be undertaken in order to investigate how the surge component is modified under future scenarios by analysing the impact of enhanced wind velocities and increased sea levels on the peak surge elevation.

Probability of occurrence of a storm surge coinciding with high tide caused by Easterly wind gales under future climate conditions will also be investigated.

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