Irish Coastal Protection Strategy Study Phase 4 - South West Coast

Work Packages 2, 3 & 4A - Technical Report

IBE0388/December 2013

The Office of Public Works
Oifig na nOibreacha Poiblí

Office of Public Works

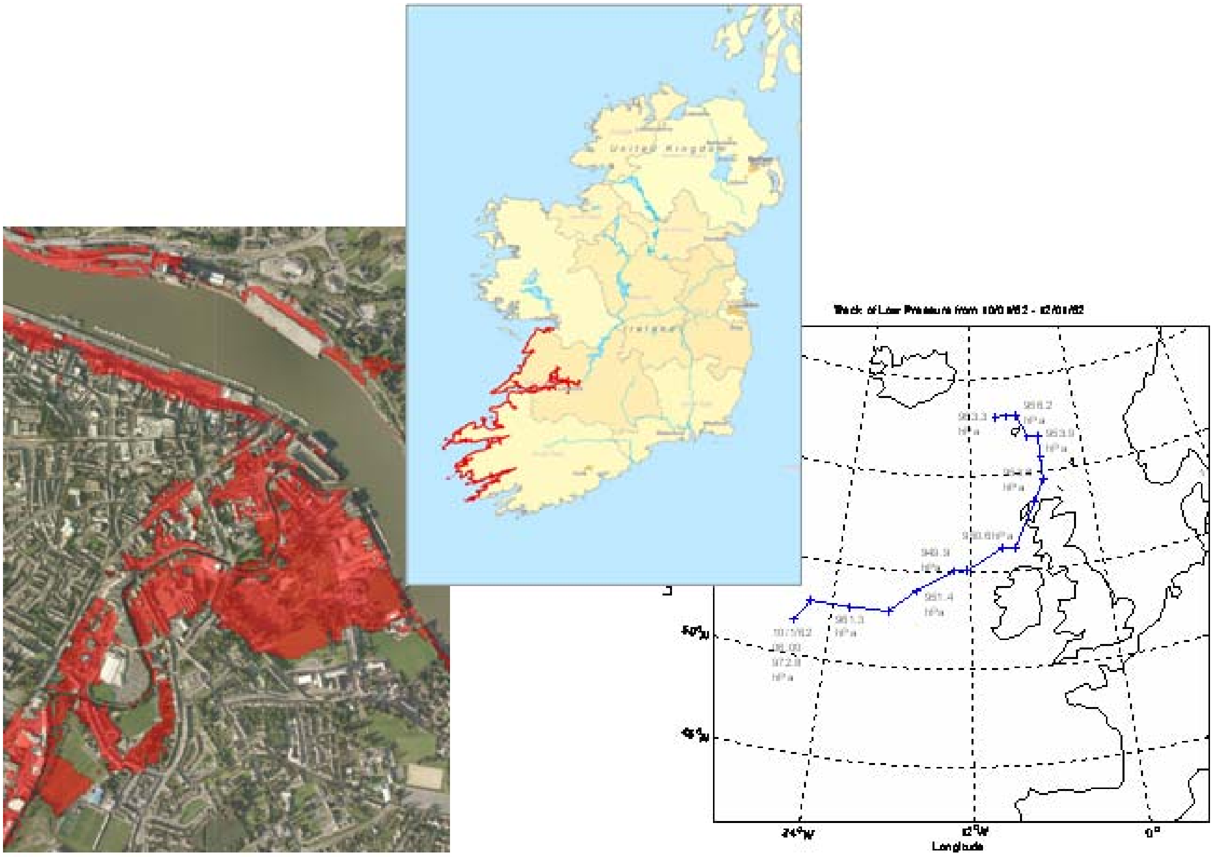
Irish Coastal Protection Strategy Study - Phase IV

Work Packages 2, 3 & 4A

Strategic Assessment of Coastal Flooding and Erosion Extents

South West Coast - Bantry Bay to Ballyvaghan Bay

Technical Report – December 2013



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Technical Report

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Schedule of Included Digital Data (Refer Appendix 5)

Flood Related

0.1 % AEP Flood Extent	ESRI Shapefile	Extreme Flood Extent
0.5 % AEP Flood Extent	ESRI Shapefile	Indicative Flood Extent
1 % AEP Flood Extent	ESRI Shapefile	
2 % AEP Flood Extent	ESRI Shapefile	
5 % AEP Flood Extent	ESRI Shapefile	
10 % AEP Flood Extent	ESRI Shapefile	
20 % AEP Flood Extent	ESRI Shapefile	
50 % AEP Flood Extent	ESRI Shapefile	
0.5% AEP Flood Depth	ESRI Grid	

Erosion Related

Erosion 2030	ESRI Shapefile
Erosion 2050	ESRI Shapefile

1.0 Executive Summary

This report presents the work undertaken and the findings of Phase 4 of the Irish Coastal Protection Strategy Study (ICPSS), Work Packages 2, 3 and 4A for the south west coast of Ireland. Work Packages 2 and 3 essentially comprise an assessment of the hazard and potential risk from coastal flooding at a strategic level, whilst Work Package 4A comprises a strategic level assessment of erosion hazard and potential risk.

The knowledge of extreme water levels along the coast is a key element in the development of coastal protection strategy. Consequently a series of studies were commissioned to establish extreme flood extents around the Irish coastline. The first of these was a pilot study which focussed on the south east coast between Dalkey Island and Carnsore Point. The next phase of the study extended the geographic coverage to include establishing extreme tidal flood extents for the section of coastline between Dalkey Island and Omeath i.e. the North East Coast, followed by the South Coast between Carnsore Point and Bantry Bay. The study outlined in this report is the first part of a three part commission for the western coast of Ireland, and establishes the extreme flood outlines for the section of coastline between Bantry Bay and Ballyvaghan Bay, i.e. the South West Coast. The Shannon Estuary is also included within this study in respect of flood hazard only.

In all of these studies predictive coastal flood extent maps for a range of probabilities, particularly for the 0.1 % and 0.5 % annual exceedance probabilities (AEP's) were derived. In addition, predictive coastal flood depth maps were produced for the 0.5% AEP. For the purposes of these studies, the flood extent and flood depth maps are broadly classified as flood hazard maps.

The studies used numerical modelling of total water levels (tides and surge) to derive extreme water levels along this particular stretch of coastline. The application of extreme value analysis to data generated by the numerical model allowed an estimation of the extreme water levels of defined exceedance probability to be established along the relevant sections of coastline.

Where available a detailed Digital Terrain Model (DTM) derived from LiDAR data was used in this study to define the extent of the predicted floodplain. The predicted flood extents were calculated by combining the results of the surge and tidal modelling, the statistical analysis, and the DTM using GIS technology. The high resolution DTM existed for only a small number of areas along the south western coastline, and thus low resolution data from the National Digital Height Model (NDHM) was used to cover the remaining length of the coastline between Bantry Bay and Ballyvaghan Bay.

The resulting predicted coastal flood extent and flood depth maps are presented in this report (Refer Appendix 3A, Appendix 3B and Section 5.0). A review of the predicted floodplain maps generated throughout the study area showed that coastal flood hazard existed predominantly in or near coastal settlements with four primary areas of potential coastal flood hazard identified for the south west coast as follows: Castlemaine Harbour, Tralee to Derrymore, Ballyheige to Barrow and Moneycashen to Finuge. A further five areas were identified for the Shannon estuary, Foynes to

Aughinish, Newtown to Adare, Limerick City, Shannon to Portdrine and Ennis to Newmarket on Fergus. The extent of the predicted floodplain for each of these primary areas of potential coastal flood risk is shown in detail in Section 5.0 from Figure 5.2 to Figure 5.10.

The hazard and potential risk associated with changes in the coastline resulting from coastal erosion is also an important consideration in the development of a coastal protection strategy. A strategic level erosion assessment was therefore undertaken along the study coastline, excluding the Shannon Estuary, to estimate the likely future position of the coastline in the years 2030 and 2050. This assessment was based on the comparison of the best available current and historical mapping and aerial photography.

Aerial photographic records of the coastline from 1973, 2000 and 2005 were used as the primary basis for the erosion assessment. The coastlines as depicted by the seaward limit of vegetation were digitised from each photographic series and a GIS system used to compare these and establish the extent of coastal change over the intervening time period. From this information an annualised rate of erosion was derived and used to project where the coastline could potentially retreat to by 2030 and 2050 assuming the rate of retreat remained constant.

The resulting erosion maps are presented in this report (Refer Appendix 4 and Section 6.0). A review of the erosion maps generated throughout the study area showed that there were seven primary areas of potential coastal erosion risk identified as follows: Waterville to Ballinskelligs, Rossbehy to Cromane, Fermoyle to Tonakilly, Ballyheige to Banna, Ballybunnion, Seafield to Quilty and Lehinch. The extent of the predicted erosion for each of these primary areas of potential coastal erosion is shown in detail in Section 6.0, from Figure 6.8 to Figure 6.14.

The analysis of coastal erosion along the south west coast indicated that there was generally little potential risk associated with coastal erosion particularly in the urban areas, primarily due to the fact that these areas are either naturally resilient or protected by man-made defences. The mean annualised erosion rate of all areas along the study coastline where an erosion hazard was identified was approximately 0.5 metres. The maximum annualized erosion rate identified throughout the study coastline occurred at Ventry Strand, County Kerry and equated to a rate of 3.12 metres. However the mean annualised erosion rate at Ventry Strand was 0.71 metres. The highest mean annualised erosion rate of 1.03 metres occurred at Beale, County Kerry. The maximum annualized erosion rate in County Clare was 3.11 metres and occurred at Kilcredaun. The highest mean annualised erosion rate in County Clare was 0.57 metres at Seafield.

It was concluded, that the approach of using synthesised data from the tidal and storm surge model for extreme value analysis worked well in the study area in respect of the assessment of the hazard and potential risk associated with coastal flooding. Similarly the analysis of historical aerial photography also provided a reliable means of estimating the hazard and potential risk from coastal erosion.

It is anticipated that the strategic flood and erosion maps produced in this study will be of particular interest to local authority planners in considering the coastal flood and erosion hazard associated with future proposed development (both strategic

and non-strategic) at the planning stage. It is further anticipated that these maps will be of assistance to local authorities and emergency services generally in respect of the management of such hazards and their likely social, economic and environmental impacts.

These maps may also be used to undertake strategic assessment of the economic value of assets at potential risk from both coastal flooding and erosion.

Whilst every effort has been taken throughout this study to optimise the accuracy of the flood and erosion maps produced, there are unavoidable inaccuracies and uncertainties associated with these maps. These uncertainties are discussed and highlighted throughout the report and in the disclaimer and guidance notes appended to this report. All mapping presented in this report should be read in conjunction with these appended disclaimers and guidance notes.

2.0 Introduction

This report presents the work undertaken and the findings of Phase 4 of the Irish Coastal Protection Strategy Study (ICPSS), Work Packages 2, 3 and 4A from Bantry Bay to Ballyvaghan Bay, including the Shannon Estuary in respect of flood hazard only. It follows on from an earlier Phase 1 study involving a general overview of coastal protection in Ireland which was concluded in October 2004, and also the Phase 2/Phase 3, south east, north east and south coast studies. Work Packages 2 and 3 essentially comprise the assessment of extreme coastal water levels and flood hazard at a strategic level, whilst Work Package 4A comprises a strategic level assessment of the erosion hazard.

The prediction of extreme water levels and the assessment of both coastal flood and erosion hazard is a key element in developing any coastal protection strategy. Typically this information is derived from the analysis of long term historical tidal records, mapping and/or ortho-photography. Unfortunately this kind of data is not widely available in Ireland.

Due to the shape of the coastline and the presence of shallow basins, both the tidal regime and the effects of wind on the south west coast and Shannon estuary water levels are complex. As such simple interpolation of water levels along the coast and extrapolation to higher return period events is not applicable or will lead to inaccurate results. Therefore the combination of analytical and numerical modelling techniques as developed and proven capable of accurately predicting extreme tidal levels of various return periods in the original pilot study (Reference 1) were applied for this study.

The objective of Work Package 2 was to establish an extreme coastal flood extent for the area from Bantry Bay to Ballyvaghan Bay, including the Shannon Estuary. Following consultation with the Client and a review of the best practice in other, mostly European countries, the extreme coastal flood extent was taken to be the flood outline associated with a water level with a 0.1% annual exceedance probability (AEP) (Reference 2). Thus, the present likelihood of flooding from coastal waters is less than 0.1% each year for areas outside the extreme coastal flood extent and therefore no further consideration of coastal flood hazard is required.

In Work Package 3, coastal flood extent and flood depth maps were derived primarily for the 0.5% AEP. This is considered to be an indicative flood standard, thus any development of areas defined to lie within this flood extent would at least require further investigation of the coastal flood hazard at planning stage. Predicted coastal flood extent maps were also derived however for a range of additional exceedance probabilities ranging between 50% and 1.0% AEP. These maps are broadly classified as flood hazard maps for the purposes of this study.

In Work Package 4A, the hazard and potential risk posed by coastal erosion was assessed and quantified by estimating the potential future position of the coastline in the years 2030 and 2050.

It is important to note that the flood mapping undertaken in this study is for strategic purposes. Furthermore, any defence works potentially protecting the floodplain are

not taken into account. This means that areas may be shown to flood in this document, even though at present a flood defence is protecting them. In addition the flood extent mapping only takes into account coastal flooding; any significant impact from fluvial or other sources (sewers etc.) is not accounted for and needs to be considered separately.

Similarly the erosion mapping undertaken in this study is also for strategic purposes. In contrast to the flood extent mapping, it was not possible to eliminate the effect of existing coastal defence structures from the erosion assessment. Consequently there will be areas where no erosion line is shown that would be vulnerable should the present defences fail or not be maintained in the future. Equally there may be potential erosion shown in areas that are now adequately defended by coastal protection structures that were introduced during the assessment period. No erosion assessment has been carried out for the Shannon Estuary.

This report outlines how the extreme water levels for a range of locations over the assessment area were derived, how the coastal flood extent maps and flood depth maps for this area were derived and also how the hazard and potential risk from coastal erosion was assessed. However this report does not include the consideration of any impacts or effects due to climate change or other long term changes, as the primary purpose was to establish the current level of hazard.

It is anticipated that the strategic flood and erosion maps produced in this study will be of particular interest to local authority planners in considering such potential coastal flood and erosion hazard associated with future proposed development (both strategic and non-strategic) at the planning stage. It is further anticipated that these maps will be of assistance to local authorities and emergency services generally in respect of the management of such hazards and their likely social, economic and environmental impacts.

These maps may also be used to undertake strategic assessment of the economic value of assets at potential risk from both coastal flooding and erosion.

3.0 Storm Surge Modelling and Analysis

3.1 Numerical Modelling

In the absence of long term, historic, time series of water levels along the coast of Ireland, computational modelling was used to simulate historic water levels for a range of extreme conditions.

To simulate the development of storm surges around the main coastline of Ireland a dedicated model was developed using some of the latest technology in tidal modelling. The storm surge model, referred to as the Irish Seas Tidal Surge Model (ISTSM) covers the whole of Ireland using mesh cells of varying sizes. This model was extensively tested and calibrated prior to the simulation of storm surges to obtain a good correlation with tidal water levels along the coast. Model extent and input bathymetry to the model are described in Section 3.1.1.

A separate more detailed rectangular grid model was used to simulate historic water levels in the Shannon Estuary, as described in Section 3.1.2.

For this study both models were used to simulate storm surge events relevant to the study area, which occurred in the past 50 years.

3.1.1 Irish Seas Tidal Surge Model Extent and Calibration

Bathymetric information for the model area and tidal records at a large number of locations within the model domain were obtained (see Table 3.1). The tidal surge model used in this study covers an area of 18° longitude and 13.5° latitude as shown in Figure 3.1. Overall the model covers the Northern Atlantic Ocean up to a distance of 600km from the Irish Coast.

Table 3.1: List of locations used in tidal model for calibration

Ardrossan	Holyhead	Port Oriel
Arklow	Howth	Portpatrick
Ballyglass	Isle d'Oessant	Portrush
Bangor	Jersey	Roberts Cove
Belfast	Kilkeel	Rockall
Bristol	Killybegs	Roscoff
Castlemaine	Kinlochbervie	Rosslare
Castletownbere	Knightstown	Sligo
Cobh	Liverpool	St. Kilda
Courtown	Malin Head	St. Marys
Devenport	Moneycashen	Stornoway
Dublin	Mumbles	Tobermory
Dun Loaghaire	Newhaven	Wexford
Dunmore East	Newlyn	Weymouth
Fishguard	Porcubine Bank	Wicklow Harbour
Galway	Port Ellen	Workington
Heysham	Port Erin	

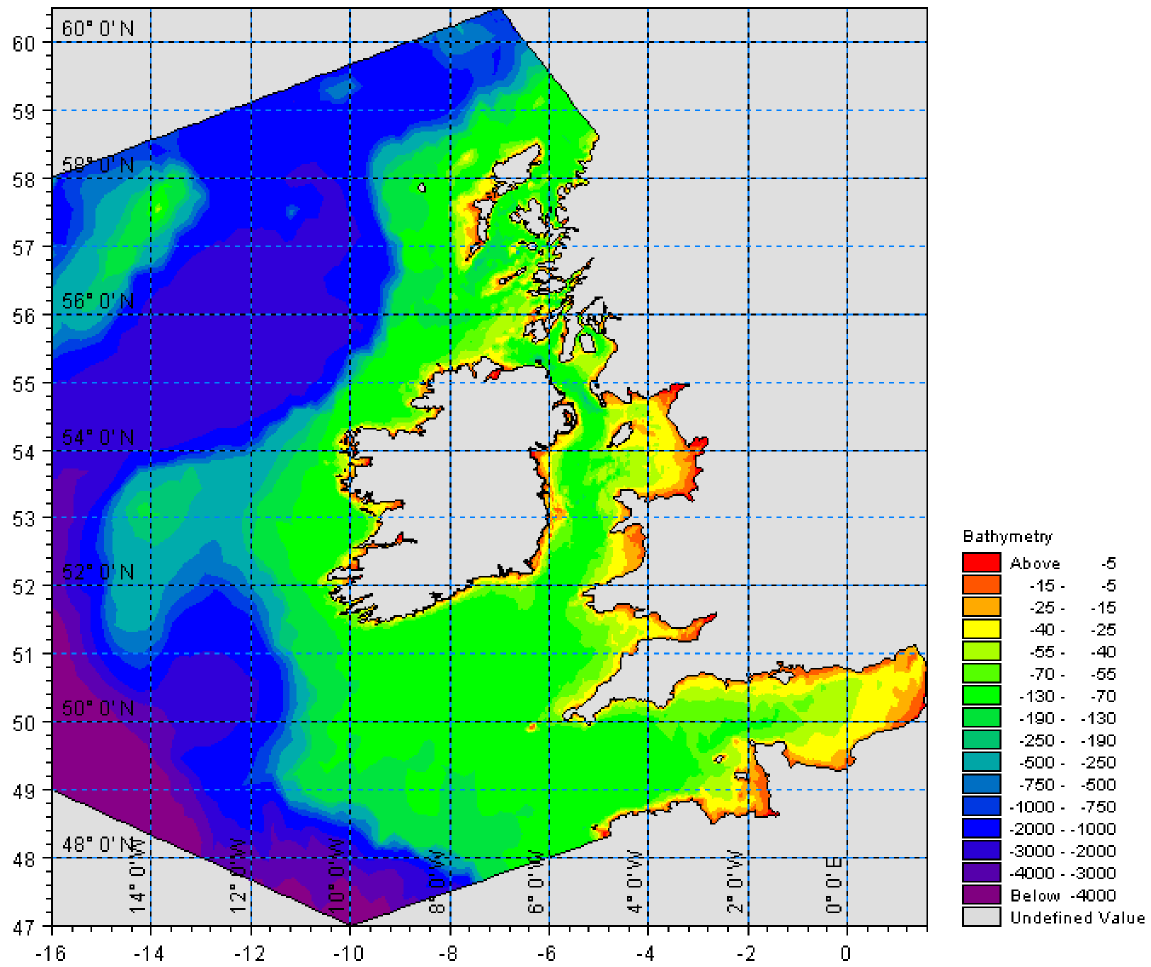

Figure 3.1: Extent of Irish Seas Tidal Surge Model (ISTSM)

The Irish Seas Tidal Surge Model utilises flexible mesh technology allowing the size of the computational cells to vary, depending on user requirements. To adequately represent the variable bathymetry, the model mesh was generated and refined in regions of most importance to satisfactory model performance. Thus the model provides greater detail along the shoreline and over banks in the study area when compared to other parts of the model domain. Along the Atlantic boundary, the model features a mesh size of 13.125' (24km), whilst along the west coast, which is of primary interest at this stage, the cell size is on average 150-200m adjacent to the shoreline, increasing to 1-2km at circa 10km offshore.

The bathymetry for the model was generated using a number of different sources. Large amounts of the bathymetric information were obtained from Admiralty Charts, as digitally supplied by C-Map of Norway. Recent surveys undertaken by the Geological Survey of Ireland (GSI) and the Marine Institute under the Irish National Seabed Survey (INSS) and the Infomar project have also been included in the bathymetry of the model.

Both survey data obtained by RPS and digitised charts were quality checked by RPS engineers and compared with Admiralty data and known benchmarks, before being corrected to mean sea level (MSL) using over 490 reference levels.

The initial base model was calibrated against a set of tidal predictions over a period of more than 30 days. A detailed description of the model set-up, the boundary conditions, model constraints and the calibration and validation with tidal events can be found in the calibration report, Calibration of tidal surge model with astronomic tides, January 2006 (Reference 3). This base model was adjusted to focus on the western coastline, including more detail in the study area and less in the Irish Sea. A further validation exercise was carried out on completion of the adjustment, and is outlined in Section 3.3.2 and Appendix 1.

3.1.2 Shannon Model Extent and Calibration

As the Shannon Estuary is relatively more complex than the outer south western coastline, a more detailed analysis was performed in this area, using a separate more detailed rectangular mesh model specifically created for this purpose. Suitable boundary conditions for this model were obtained by extracting the surface elevations from the ISTSM for the south west coast and applying them as boundary conditions in the Shannon Estuary model.

Most events simulated for the south west coast were also simulated for the Shannon, with the exception of a small number of events which didn't yield particularly large water levels at the boundary of the Shannon Estuary model. An additional 26 extraction points were created within the estuary and extreme water levels determined based on further statistical analysis undertaken on completion of the simulations, as per the main south west coastline.

The Shannon Estuary model used in this study covers an area from west of Carrigaholt to Limerick, as shown in Figure 3.2. The grid resolution of the model is 45 metres.

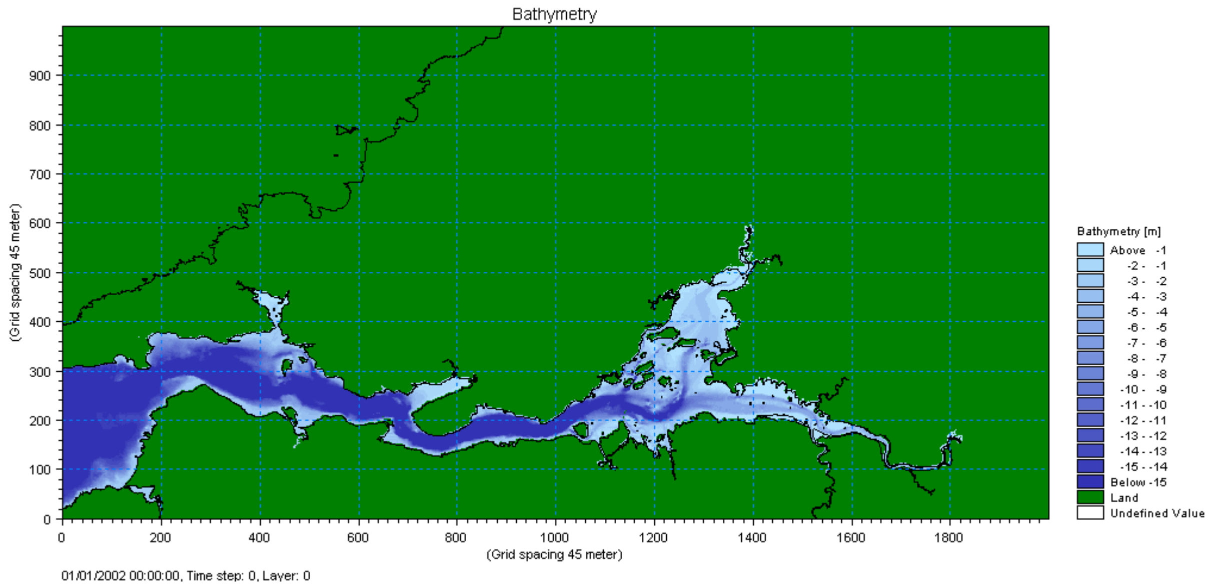

Figure 3.2: Extent of Shannon Estuary Model

The bathymetry for the model was generated using a number of different sources. Large amounts of the bathymetric information were obtained from Admiralty Charts, as digitally supplied by C-Map of Norway. Recent surveys undertaken by the Geological Survey of Ireland (GSI) and the Marine Institute under the Infomar project have also been included in the bathymetry of the model, along with local surveys provided by Hydrographic Surveys, Irish Hydrodata and Direct Route Limerick. All survey data and digitised charts were quality checked by RPS engineers and compared with Admiralty data and known benchmarks, before being corrected to mean sea level (MSL).

It should be noted that there were areas of significant extent and influence missing from the bathymetry database in the Shannon, namely the Fergus Estuary. However, RPS have used all available information, including Admiralty Charts and aerial imagery to manually digitise the bathymetry in this area to the best accuracy possible. It should be noted however that all prediction points east of the Fergus Estuary hold less reliability than those to the west.

The Shannon Estuary model was calibrated and validated as far as possible using a limited database of information from the UK Admiralty Tide Tables, as described in Appendix 1. On completion of the validation exercise, the model was deemed suitable for predicting the extreme water levels within the estuary, with all results within the expected tolerance for this study.

3.1.3 Historic Storm Surge Selection

In order to simulate historic storm surges (hindcasting) which are relevant to the study area, the water level records from gauges at Balls Bridge, Capeclear, Carrigaholt, Castlemaine, Castletownbere, Doon Bay, Foyle, Galway, Killybegs, Kilronan, Malin Head, Moneycashen, Portrush, Rossaveel and Tarbert were reviewed. Initially, all events with a recorded tidal level above a critical threshold at each gauge were identified. The dates of these events were then compared and

significant surge events identified as those occasions when multiple gauges showed elevated water levels.

In order to model the full development of the storm surge, a period of approximately 4 days prior to each of the identified events and an additional 2 days after the event was simulated. Therefore at least 7 days of simulation was carried out per surge event.

In a number of cases the surge event lasted a number of days or one low pressure field was followed immediately by another storm, also causing extreme water levels. In these cases the simulation period was extended to suit the combined event. A list of all storm surge runs used for this study is given in Table 3.2. The duration listed in the table is the duration of the modelling sequence and is in general considerably longer than the duration of the actual storm. The 'met grid' resolution referred to in column number five refers to the resolution of the meteorological data used in the simulation of the storm surge and is given in degrees.

Table 3.2: Overview of surge model runs, duration and grid resolution

Run No.	Start date and time	End date and time	Duration (Days)	Met grid resolution
1	26/11/1959 00:00	03/12/1959 00:00	7	1.125
2	19/10/1961 18:00	26/10/1961 18:00	7	1.125
3	12/01/1965 21:00	19/01/1965 21:00	7	1.125
4	22/02/1967 09:00	02/03/1967 09:00	8	1.125
5	17/12/1968 06:00	24/12/1968 09:00	7	1.125
6	06/01/1974 06:00	14/01/1974 09:00	8	1.125
7	04/02/1974 06:00	11/02/1974 06:00	7	1.125
8	06/10/1974 06:00	13/10/1974 06:00	7	1.125
9	28/10/1974 09:00	04/11/1974 09:00	7	1.125
10	09/11/1974 00:00	16/11/1974 00:00	7	1.125
11	25/01/1975 00:00	31/01/1975 18:00	7	1.125
12	19/10/1976 00:00	26/10/1976 00:00	7	1.125
13	06/11/1977 18:00	13/11/1977 18:00	7	1.125
14	02/01/1978 18:00	09/01/1978 18:00	7	1.125
15	01/10/1979 00:00	08/10/1979 00:00	7	1.125
16	16/01/1980 00:00	23/01/1980 00:00	7	1.125
17	03/03/1981 09:00	10/03/1981 09:00	7	1.125
18	08/12/1981 06:00	15/12/1981 06:00	7	1.125
19	12/10/1982 06:00	19/10/1982 06:00	7	1.125
20	17/01/1984 00:00	23/01/1984 21:00	7	1.125
21	19/10/1984 00:00	26/10/1984 00:00	7	1.125
22	21/11/1984 18:00	28/11/1984 18:00	7	1.125
23	02/04/1985 00:00	09/04/1985 00:00	7	1.125
24	11/09/1985 00:00	18/09/1985 00:00	7	1.125
25	23/03/1986 00:00	30/03/1986 00:00	7	1.125
26	28/11/1986 00:00	05/12/1986 00:00	7	1.125
27	27/12/1986 00:00	03/01/1987 00:00	7	1.125
28	21/03/1987 00:00	28/03/1987 21:00	8	1.125
29	02/10/1987 00:00	09/10/1987 00:00	7	1.125

Run No.	Start date and time	End date and time	Duration (Days)	Met grid resolution
30	26/01/1988 00:00	02/02/1988 18:00	8	1.125
31	22/09/1988 18:00	29/09/1988 21:00	7	1.125
32	04/02/1989 00:00	10/02/1989 18:00	7	1.125
33	04/03/1989 06:00	11/03/1989 21:00	7.5	1.125
34	12/12/1989 00:00	19/12/1989 00:00	7	1.125
35	25/01/1990 06:00	01/02/1990 06:00	7	1.125
36	22/02/1990 09:00	01/03/1990 09:00	7	1.125
37	31/12/1990 00:00	07/01/1991 00:00	7	1.125
38	12/03/1991 00:00	19/03/1991 00:00	7	1.125
39	11/08/1991 00:00	18/08/1991 00:00	7	1.125
40	20/10/1992 00:00	27/10/1992 00:00	7	0.5
41	06/01/1993 06:00	13/01/1993 06:00	7	0.5
42	07/01/1994 03:00	14/01/1994 00:00	7	0.5
43	22/02/1994 00:00	01/03/1994 00:00	7	0.5
44	28/11/1994 06:00	05/12/1994 06:00	7	0.5
45	12/01/1995 18:00	19/01/1995 18:00	7	0.5
46	19/10/1995 18:00	26/10/1995 18:00	7	0.5
47	19/11/1995 06:00	26/11/1995 18:00	7.5	0.5
48	02/01/1996 00:00	09/01/1996 00:00	7	0.5
49	23/09/1996 18:00	01/10/1996 09:00	7.5	0.5
50	23/10/1996 00:00	30/10/1996 00:00	7	0.5
51	05/02/1997 06:00	12/02/1997 09:00	7	0.5
52	11/10/1997 18:00	19/10/1997 18:00	8	0.5
53	29/12/1997 00:00	05/01/1998 00:00	7	0.5
54	03/09/1998 18:00	10/09/1998 18:00	7	0.5
55	20/12/1998 00:00	06/01/1999 00:00	17	0.5
56	21/11/1999 00:00	28/11/1999 00:00	7	0.5
57	18/12/1999 00:00	26/12/1999 18:00	9	0.5
58	23/09/2000 18:00	30/09/2000 18:00	7	0.5
59	20/11/2000 00:00	27/11/2000 00:00	7	0.5
60	07/12/2000 18:00	14/12/2000 18:00	7	0.5
61	05/03/2001 06:00	12/03/2001 06:00	7	0.5
62	19/04/2001 18:00	26/04/2001 18:00	7	0.5
63	19/05/2001 18:00	26/05/2001 18:00	7	0.5
64	12/10/2001 18:00	19/10/2001 18:00	7	0.5
65	23/01/2002 03:00	03/02/2002 09:00	11	0.5
66	22/02/2002 18:00	01/03/2002 18:00	7	0.5
67	23/04/2002 06:00	30/04/2002 06:00	7	0.5
68	03/10/2002 09:00	10/10/2002 09:00	7	0.5
69	31/10/2002 18:00	07/11/2002 18:00	7	0.5
70	26/11/2002 15:00	03/12/2002 15:00	7	0.5
71	14/02/2003 00:00	21/02/2003 00:00	7	0.5
72	22/10/2004 18:00	29/10/2004 18:00	7	0.5
73	06/01/2005 21:00	12/01/2005 21:00	6	0.5
74	29/10/2005 06:00	05/11/2005 09:00	7	0.5
75	25/03/2006 00:00	01/04/2006 00:00	7	0.5
76	04/09/2006 18:00	11/09/2006 18:00	7	0.5
77	03/10/2006 18:00	10/10/2006 18:00	7	0.5
78	29/11/2006 18:00	09/12/2006 09:00	9.5	0.5
79	15/02/2007 09:00	22/02/2007 09:00	7	0.5

Run No.	Start date and time	End date and time	Duration (Days)	Met grid resolution
80	22/10/2007 18:00	29/10/2007 18:00	7	0.5
81	05/03/2008 09:00	12/03/2008 09:00	7	0.5
82	08/01/2009 09:00	16/01/2009 09:00	8	0.5

3.2 Boundary Conditions

3.2.1 Tidal Boundary

The tidal boundary conditions for the model simulations were derived from a global tidal model (GTM) developed by Kort and Matrikelstryrelsen (KMS) Denmark, as detailed in the calibration report (Reference 3). This model allows the calculation of tidal elevation based on a set of harmonics which are given at a spatial resolution of 0.5° which RPS further supplemented with additional data from GLOSS and PSMSL from the British Oceanographic Data Centre. Thus for the simulation of the actual storm surges seasonal components have been included to account for the normal seasonal variation of the water level, with the mean water level being generally higher during the period of October – January when compared to the May – August period.

3.2.2 Meteorological Boundary

At the beginning of the project, sources for meteorological data such as wind speeds, directions and air pressure were researched. Virtually all European meteorological organisations operate atmospheric models which cover the extent of the Irish Seas Tidal Surge Model. A number of other organisations also hold this information. For example, the American Meteorological service (NOAA) operates a global atmosphere model (GFS) from which forecast data is freely available (this model used to be referred to as the Medium Range Forecast (MRF)). Recently the resolution of this model has been significantly improved and the simulations are started four times a day, however older data is only available for 12 hourly analysis fields and a charge is made for retrieval of these archived data sets.

In Europe only a limited number of organisations have archived historic model simulations covering a sufficient extent and with adequate spatial and time resolution. One of these organisations is the European Centre for Medium Range Weather Forecasts (ECMWF). The ECMWF is an international organisation supported by 34 European states. ECMWF data is used by a large number of the European meteorological organisations for data analysis and as boundary conditions for their own models. The ECMWF holds analysis fields at sufficient resolution, which are assimilated forecasts using observed conditions of the atmosphere.

For the simulation of the storm events, two different data sources were used, both obtained from the ECMWF. The parameters applied to generate surge within the model are mean sea level atmospheric pressure and the 10 minute averaged 10m wind speeds (u and v component). An atmospheric model with analysis running at 6 hourly intervals and 0.5° resolution has been operational at ECMWF since 1991. In

addition a re-analysis project was completed in 2003, which included the simulation of the meteorological conditions since 1957 at 6 hourly intervals and 1.125° resolution (ERA 40). Thus for all periods prior to 17th September 1991 the ERA 40 re-analysis data set was available.

Both the operational model and the re-analysis model used all available meteorological data to assimilate a best fit of the measured data to the numerical simulation. Therefore physically impossible values due to errors in the measurements and processing are eliminated and the meteorological conditions are captured on a standard grid. It was decided to use the ECMWF data, since these two data sets covered the period of historic tidal records and provided a reasonably consistent data source. The mean sea level air pressure and the u and v component of the 10m wind speed were obtained at the analysis time steps of 00, 06, 12 and 18 hours from either the ERA 40 data set or the operational surface model depending on the date of the event. These data sets cover the following area: 27°W to 45°E and 33°N to 73.5°N, approximately, which comfortably exceeds the boundaries of the tidal surge model. The data sets were obtained as GRIB files and converted to dfs2 files for model input.

While these six hourly data sets provide a good representation of the wind and pressure field on a large scale, they do not provide sufficient information to simulate the water level variation in the surge model at the required scale. In order to improve the model prediction additional wind and pressure data were acquired from the ECMWF. These data sets are taken from various forecast simulations and correspond to the periods 03, 09, 15 and 21 hours.

The forecast and the analysis data was then combined into a single data set which covered a 24 hour period with 8 time steps, providing sufficient information to simulate the development and progression of the storm surges.

Originally there was concern regarding the use of forecast data in the simulations. However comparisons showed that the improvement from the use of a 3 hourly time step is greater than the error induced by using data which has not been assimilated with measured values.

3.2.3 Other Boundary Conditions and Adjustments

The contribution to storm surge from beyond the surge model boundary was considered, for example from elements such as the Northern Atlantic oscillation (NAO). However even under extreme wind conditions, the Ekman layer, which drives the water along the surface, does not penetrate to a depth greater than 200m, and since the model extends beyond the continental shelf into water depths of more than 1000 metres along most parts of the Atlantic boundary, it was not considered necessary to add any additional surge components, as their influence would be rather small (<20mm). In addition, the model adjusts the tidal boundary for any change of air pressure imposed by the meteorological boundary condition in relation to a reference pressure, which was set to 1013hPa. Thus, the most significant part of the NAO is already included in the model. The model also takes account of Coriolis effects along the boundary and within the model domain.

3.3 Storm Surge Simulations

3.3.1 Calibration of Wind Parameters

Using the meteorological conditions, a number of initial simulations were carried out to tune the wind friction factor used in the model to simulate the transfer of energy from the wind field to the water. A variable wind friction approach was used in the model, with a constant friction value below a lower limit wind speed, and then increasing friction to an upper wind speed limit above which a second constant value was used. This is illustrated in Figure 3.3, where the friction coefficient is shown in blue and the corresponding wind friction is shown by the red trace.

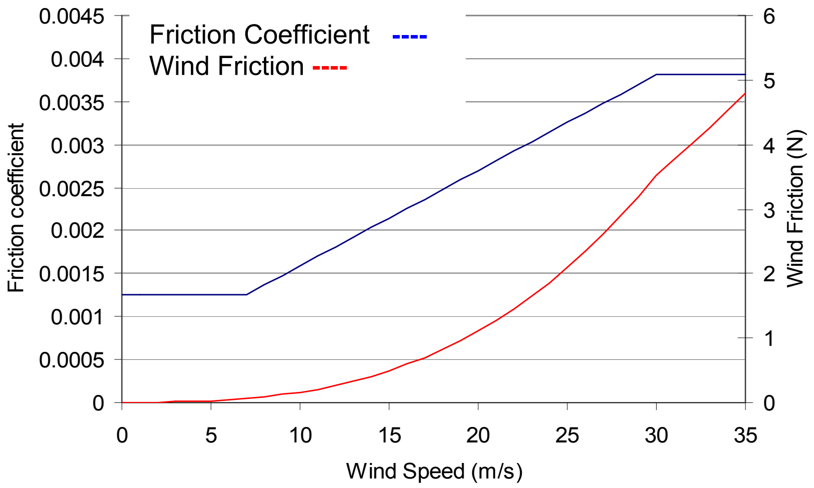

Figure 3.3: Friction coefficient used in the surge model

The lower wind speed limit was set at 7m/s and the upper wind speed limit at 30m/s. This was compared to the Charnock parameter, which is often used to simulate the wind reduction over open water as well as in wave hindcasting. In addition the Charnock parameter is used in meteorological models to calculate the loss of energy into the ocean surface from wind / wave interaction. Comparison was made to the ECMWF meteorological model and it was found that the values were of the same order of magnitude as the standard Charnock parameter of 0.0185 which is generally assumed for fully developed seas.

Using the above friction parameter description, a number of storm surge periods were simulated, with the data received from ECMWF used to validate the model. These runs were assessed and it was found that the storm surges observed in the Irish Sea were lower in virtually all instances when compared to the measured events. Consequently, a comparison of the ECMWF data with wind data from the UK Met Office was carried out to assess the quality of the input data. The UK Met Office wind data originates from a metocean hindcast model provided for coastal application. Following the comparison it was discovered that the wind speeds in the Irish Sea from the ECMWF data were around 10% lower when compared to the 10m wind speeds given by the UK Met Office model, as illustrated in Figure 3.4. Such deviation would invariably result in a significant change in the surge, since the wind speed is squared in the friction term.

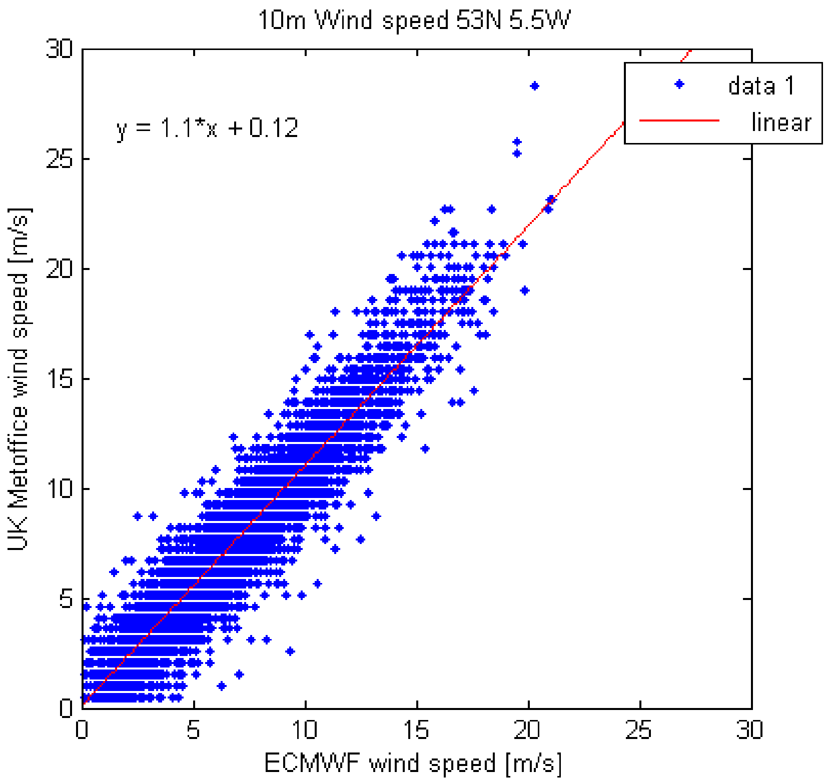

Figure 3.4: Correlation between wind velocities from the UK Met Office wave data set and ECMWF operational atmospheric analysis model for a location in the Irish Sea

This is further illustrated by Figure 3.5, which shows the average wind speed during a storm surge event using the ECMWF operational surface analysis with a grid resolution of 0.5°. It can be seen, that the wind speed increases in the Irish Sea when compared to the speeds over land in England, Wales and Ireland, however the wind speeds in the entrance to the Irish Sea and in the St. Georges Channel are lower when compared to surrounding 'over water' areas.

In order to resolve this problem RPS contacted ECMWF and detailed discussions were held with their Head of Ocean and Wave Modelling. It was established that the decrease in wind speed was, in part, due to the resolution of the atmospheric model used by ECMWF, which makes the effect of land more pronounced in the Irish Sea when compared with other coastal areas. In addition, the advection term in the atmospheric model can result in a further decrease in wind speeds on the land/water boundaries. The wind fields in the ECMWF data sets were thus modified to take account of the under prediction in the model based on this correspondence with ECMWF. The factor map used to adjust the wind speeds is given in Figure 3.6.

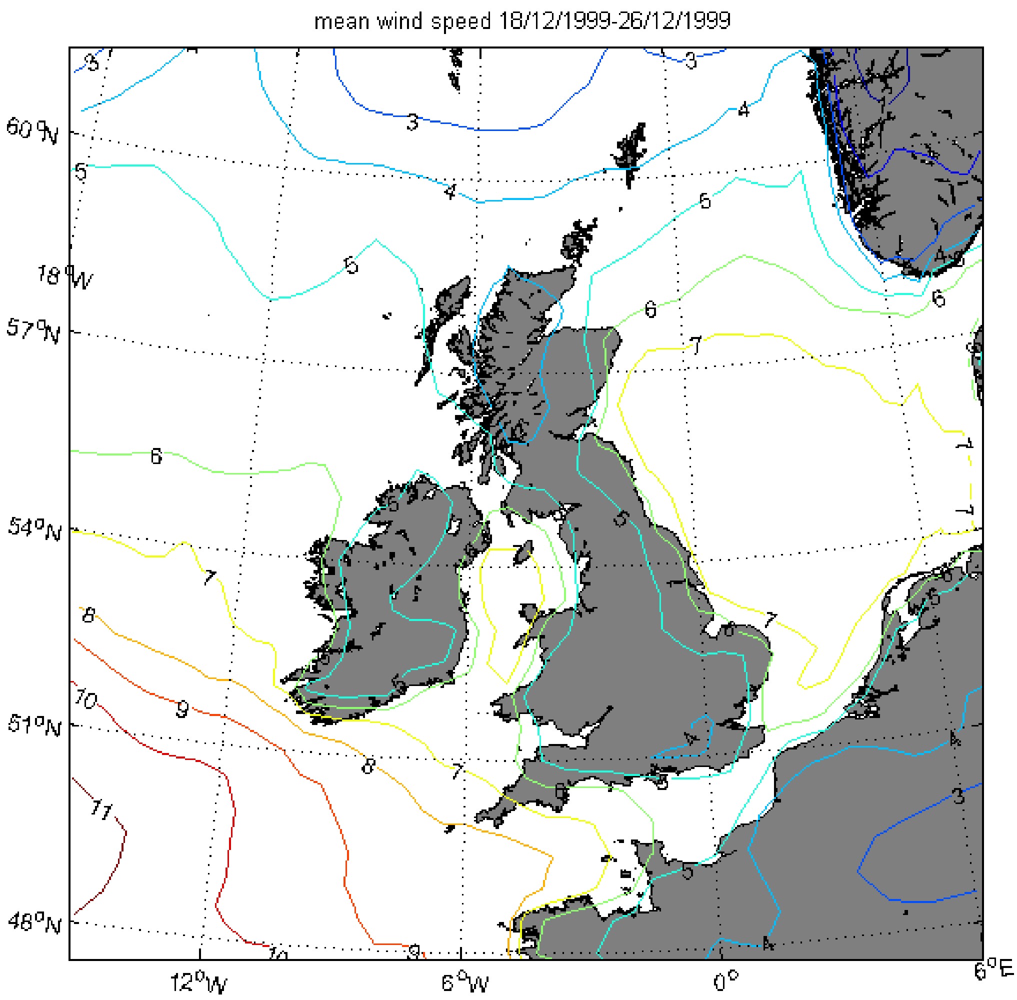

Figure 3.5: Mean wind speeds from operational surface analysis, wind speeds in m/s

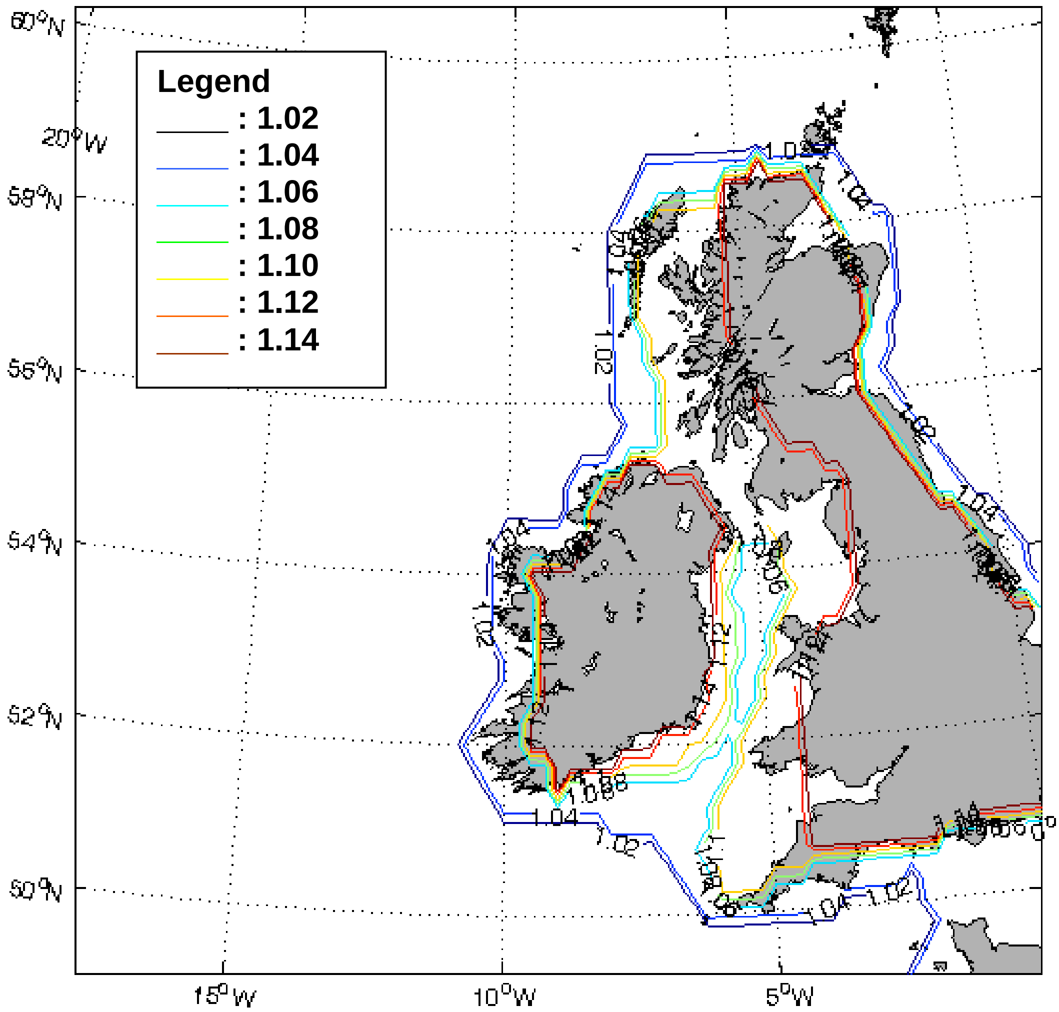

Figure 3.6: Factor map used for adjusting wind speeds to "over sea" velocities

3.3.2 Storm Surge Modelling - Validation

After successful calibration of the model using a limited number of storm surge events, more simulations were undertaken and the results were validated against measured data, mostly from UK NTSLF and Marine Institute tide gauges. A number of examples of surge model simulated total water levels compared with measured total water levels are shown in the calibration report produced specifically for the south west, west and north west model (Appendix 1).

The model produced for the south west coast storm surge simulations gave good correlation with the majority of the tide gauge data at the various locations where records were suitable for comparison. The model was therefore considered successfully calibrated and fit for the purpose of simulating storm surge water levels along the south west coast of Ireland and for predicting extreme water levels required for the production of coastal flood extent maps.

3.3.3 Effects from Seiching/Local Wind Set-up and Gusts on South West Coast

The results of the basic surge model simulations did not show any seiching effects or local wind set-up in the bays on the south west coast, however seiching/local wind set-up effects generally cannot be simulated using the 3 hourly met data set. This is principally due to the lack of any information on gust speeds or variation in wind speeds due to gusts within the three hourly datasets.

In order to investigate the significance of these effects along the south west coast, additional model simulations with pseudo random variation of wind speed and direction were carried out to derive an estimate of typical seiching/local wind set-up amplitude, which needs to be added to the numerical modelling results. Some typical results of the simulations are shown in Figure 3.7, which shows tidal elevation at a point within the Kenmare River, as well as combined tide and surge with and without gusts, taken from the numerical model.

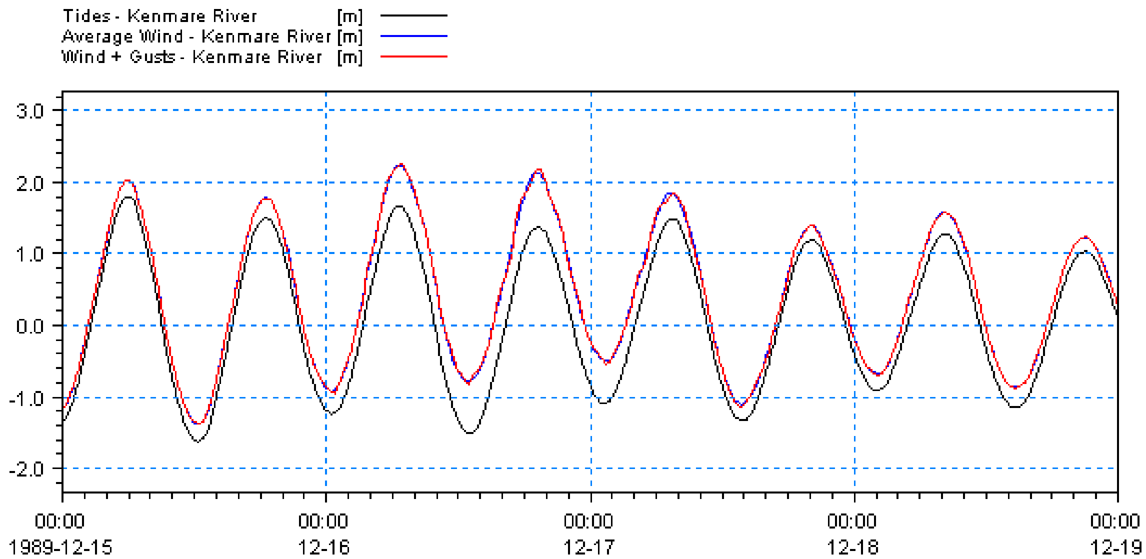

Figure 3.7: Seiching/Local wind set-up in the Kenmare River, tidal elevations and combined tidal and surge elevations with average wind and with gusts

Figure 3.8 shows a comparison of the seiching/local wind set-up at three locations along the western coastline of Ireland. As can be seen, the water level varies with the oscillation in this case due to the variation in wind speed and direction on a sub-hourly basis. Figure 3.9 shows the effect of seiching/local wind set-up within the Kenmare River by comparing the surge residual with and without the influence of gusts.

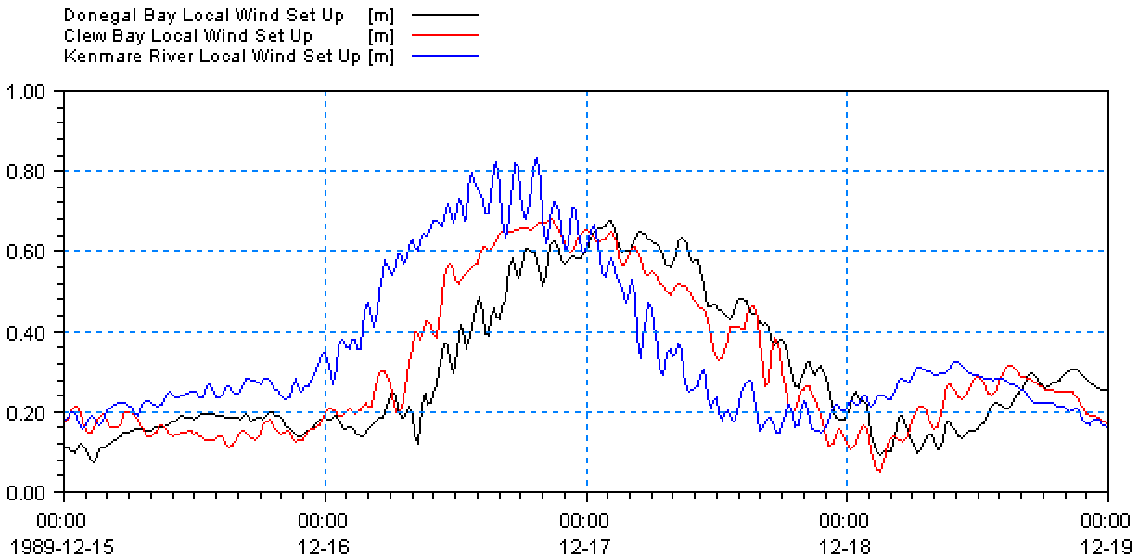

Figure 3.8: Comparison of seiching/local wind set-up in Donegal Bay, Clew Bay and Kenmare River

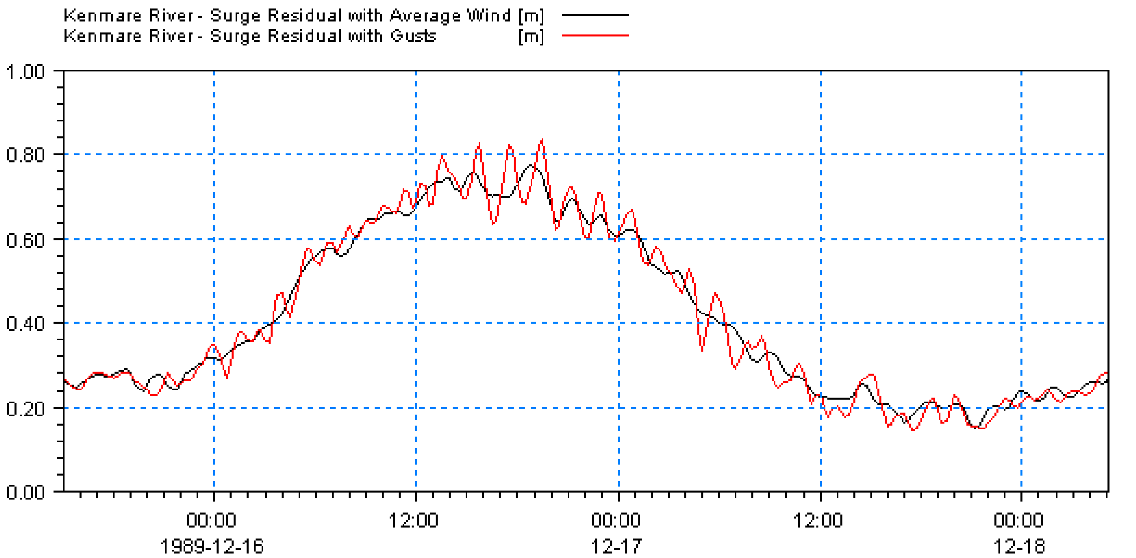

Figure 3.9: Seiching/local wind set-up in the Kenmare River, surge residual with and without the influence of gusts

Table 3.3 shows the maximum seiching/local wind set-up allowance assumed for each location although it must be noted that seiching/local wind set-up is not a major issue on the south west coast compared to other coastlines.

Table 3.3: Seiching/local wind set-up allowance for each point in the study area

Point	Average seiche/local wind set-up from modelling	Estimated seiche/local wind set-up
SW1	0.034	**0.05**
SW2	0.038	**0.05**
SW3	0.041	**0.05**
SW4	0.043	**0.05**
SW5	0.053	**0.05**
SW6	0.074	**0.05**
SW7	0.101	**0.10**
SW8	0.117	**0.10**
SW9	0.060	**0.05**
SW10	0.048	**0.05**
SW11	0.041	**0.05**
SW12	0.054	**0.05**
SW13	0.040	**0.05**
SW14	0.033	**0.05**
SW15	0.031	**0.05**
SW16	0.038	**0.05**
SW17	0.045	**0.05**
SW18	0.054	**0.05**
SW19	0.081	**0.10**
SW20	0.085	**0.10**
SW21	0.065	**0.05**
SW22	0.050	**0.05**
SW23	0.044	**0.05**
SW24	0.039	**0.05**
SW25	0.034	**0.05**
SW26	0.026	**0.05**
SW27	0.026	**0.05**
SW28	0.027	**0.05**
SW29	0.028	**0.05**
SW30	0.032	**0.05**
SW31	0.043	**0.05**
SW32	0.044	**0.05**
SW33	0.041	**0.05**
SW34	0.076	**0.10**
SW35	0.086	**0.10**
SW36	0.108	**0.10**
SW37	0.100	**0.10**
SW38	0.055	**0.05**
SW39	0.051	**0.05**
SW40	0.038	**0.05**
SW41	0.039	**0.05**
SW42	0.042	**0.05**
SW43	0.039	**0.05**
SW44	0.038	**0.05**
SW45	0.033	**0.05**
SW46	0.032	**0.05**
SW47	0.033	**0.05**
SW48	0.034	**0.05**
SW49	0.036	**0.05**
SW50	0.039	**0.05**

Point	Average seiche/local wind set-up from modelling	Estimated seiche/local wind set-up
SW51	0.038	**0.05**
SW52	0.038	**0.05**
SW53	0.057	**0.05**
SW54	0.038	**0.05**
SW55	0.042	**0.05**
SW56	0.061	**0.05**
SW57	0.083	**0.10**
SW58	0.096	**0.10**

3.4 Output from the Storm Surge Simulations

In order to minimise the combined error from tidal and storm surge simulations, for example, due to timing differences, it would be ideal to run two simulations for each storm surge period; one with tidal components only and one with both tidal and storm surge components. While this approach was adopted for the north east and south east coasts, it was not feasible for the south west coast simulations, due to the lack of sufficient digital tide gauge information along this stretch of coastline to allow an accurate assessment to be made of the joint probability of occurrence of tidal and surge events. Therefore, one simulation was run for each storm surge period, incorporating both tidal and storm surge components with the extreme water levels being the direct output of these simulations.

From the various storm simulations, time series of the surface elevations were extracted at 58 points as shown in Figure 3.10 to Figure 3.12. The position of the extraction points was selected based on consideration of the shape of the coastline, which might affect surge levels, in addition to the proximity to vulnerable areas. In order to gain more accurate water levels in the Shannon Estuary, an additional detailed model was set up over this area, and the relevant water levels extracted at twenty six points. Figure 3.13 and Figure 3.14 show the additional extraction points for the more detailed Shannon Estuary model.

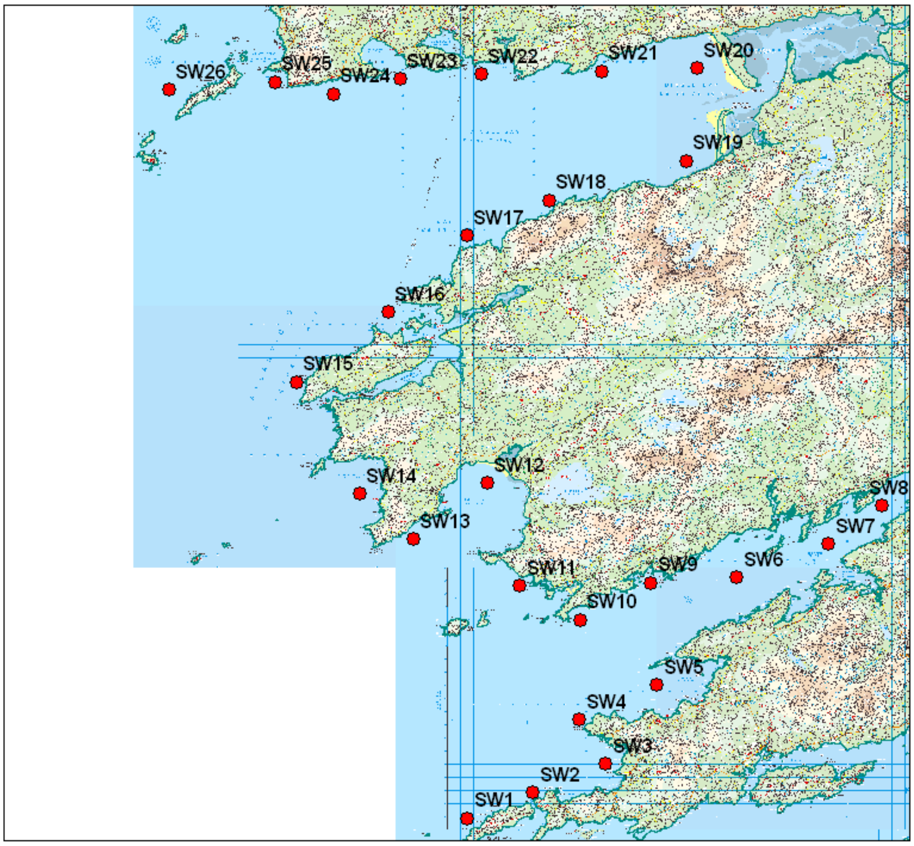

Figure 3.10: Location of extraction points SW1 – SW26 along the study area

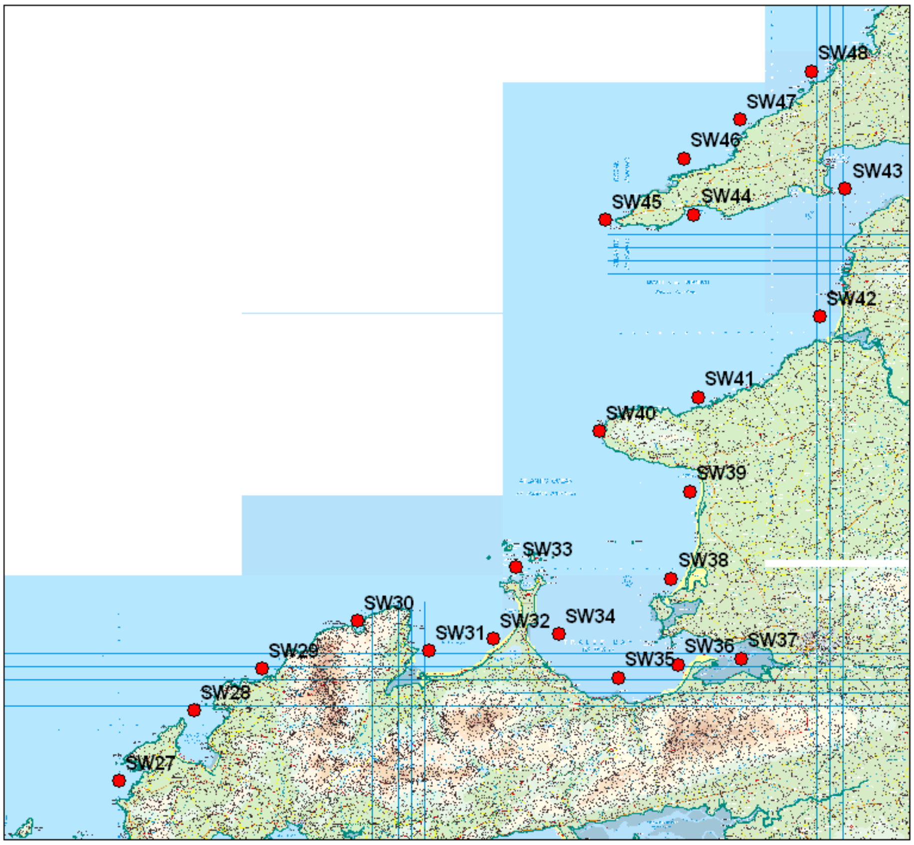

Figure 3.11: Location of extraction points SW27 – SW48 along the study area

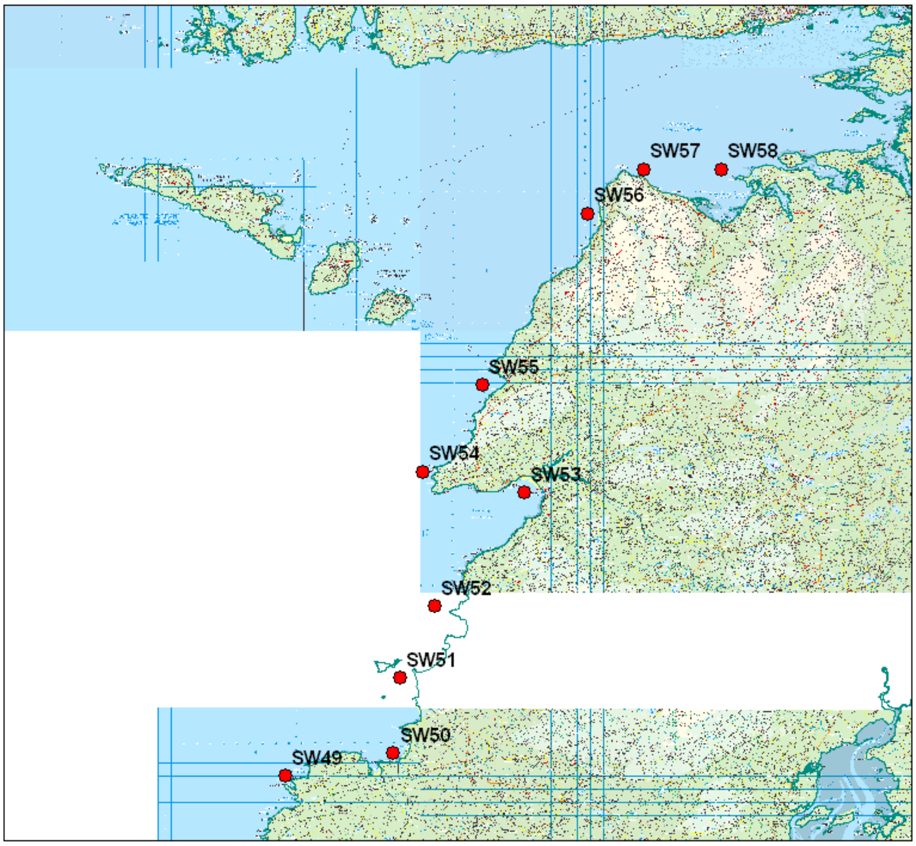

Figure 3.12: Location of extraction points SW49 – SW58 along the study area

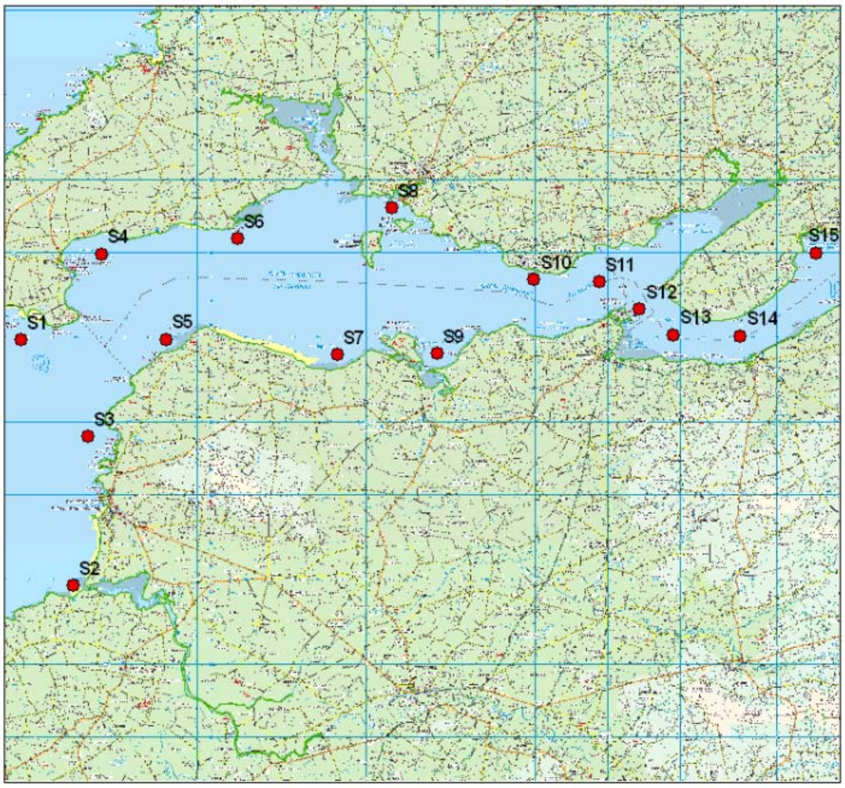

Figure 3.13: Location of extraction points S1 to S15 in the Shannon Estuary

Figure 3.14: Location of extraction points S16 to S26 in the Shannon Estuary

Following the simulation of all 82 storm events, subsequent analysis indicated that the predicted surges at the extraction points during a number of events were considered to be too small to be of importance. After histogram analysis, the top tidal levels at each point were selected for the subsequent Extreme Value Analysis detailed in Section 4.0.

4.0 Extreme Value Analysis of Water Levels

4.1 Introduction

Extreme value analysis (EVA) was undertaken by fitting theoretical probability distributions to the water level values extracted from the results of the model simulations. A partial duration series, also known as peak over threshold model, was used to select the largest events which occurred within the dataset. The selection can be made on the basis of a fixed number of the largest values or by applying a threshold level over which the events are selected for inclusion into the data series.

Candidate probability distributions were fitted to the data, with several distributions being investigated as follows:

- Weibull,
- Generalised Pareto,
- Gamma/Pearson Type 3,
- Log-Pearson Type 3,
- Log-normal,
- Exponential and
- Truncated Gumbel.

For the estimation of the parameters relating to the probability distributions generally three methods can be applied; the method of moments, the method of L-moments and maximum likelihood method.

The goodness of fit of the resulting distributions was tested using five statistical methods; Chi-squared, Kolmogorov-Smirnov test, standardised least squares criterion, probability plot correction co-efficient and Log-likelihood measure.

The uncertainty of these distributions was also evaluated by application of the Jackknife re-sampling technique. With this technique the entire data set of n events is re-sampled n-1 times. Each time one of the events is excluded and the distribution is fitted to the remaining n-1 events using the same method. From the resulting distributions the values for given return periods are derived and the average and standard deviation determined. These values are referred to as the averaged estimates and the standard deviation of the estimates. The difference of the averaged estimate and the estimated value initially derived provides a measure of the convergence of the statistical analysis (i.e. if the analysis covered a long enough period) and the confidence limits of the values are given by the standard deviation.

Extreme value analysis can be carried out on the statistical data in several ways. In principle the entire process can be considered as random, in which case the probability functions are fitted to the entire set as a whole. In the case of extreme coastal water levels, two physical processes are more or less coupled but are often initially considered independent. In this case the probability of occurrence or exceedance can be derived for each process separately and through a correlation

factor, the two are combined. This allows the fitting of separate and possibly different probability distributions to each parameter.

For the south west coast the extreme value analysis was carried out on total water level at each of the 58 data points, in contrast to the south east and north east coasts where surge and tide were considered separately. This was due to a lack of available historic tide gauge data required to accurately separate surge and tidal levels for individual surge events. Therefore no combined probability analysis was required for the south west coast water levels.

4.2 Analysis of Extreme Events: Points SW1 – SW58 and S1 – S26

Extreme value analysis of total water level

The extreme value analysis of total water level was undertaken as described in the previous section. The best fitting results were obtained by using the threshold or fixed location parameter method for selecting data. The most successful candidate distributions and respective method used to evaluate the parameters are given below.

- Truncated Gumbel method - maximum likelihood
- Two parameter Weibull - method of L-moments
- Gamma - method of L-moments

At all points the Truncated Gumbel method was found to give the best estimation of probability distribution, as illustrated in Figure 4.1. The parameters were evaluated for each point using the maximum likelihood method. The extreme water levels were evaluated for return periods ranging from <1 year to 1 in 1000 year. The relevant water level values are shown for 0.1% and 0.5% annual exceedance probability in Table 4.1. The table also provides the averaged estimates based on the Jackknife sampling technique and the standard deviation as discussed in the previous section. It can be seen that the averaged estimates are very similar to the estimates initially derived (less than 15mm difference) and the standard deviation is in the order of 51 to 101mm. All results are given in Appendix 2.

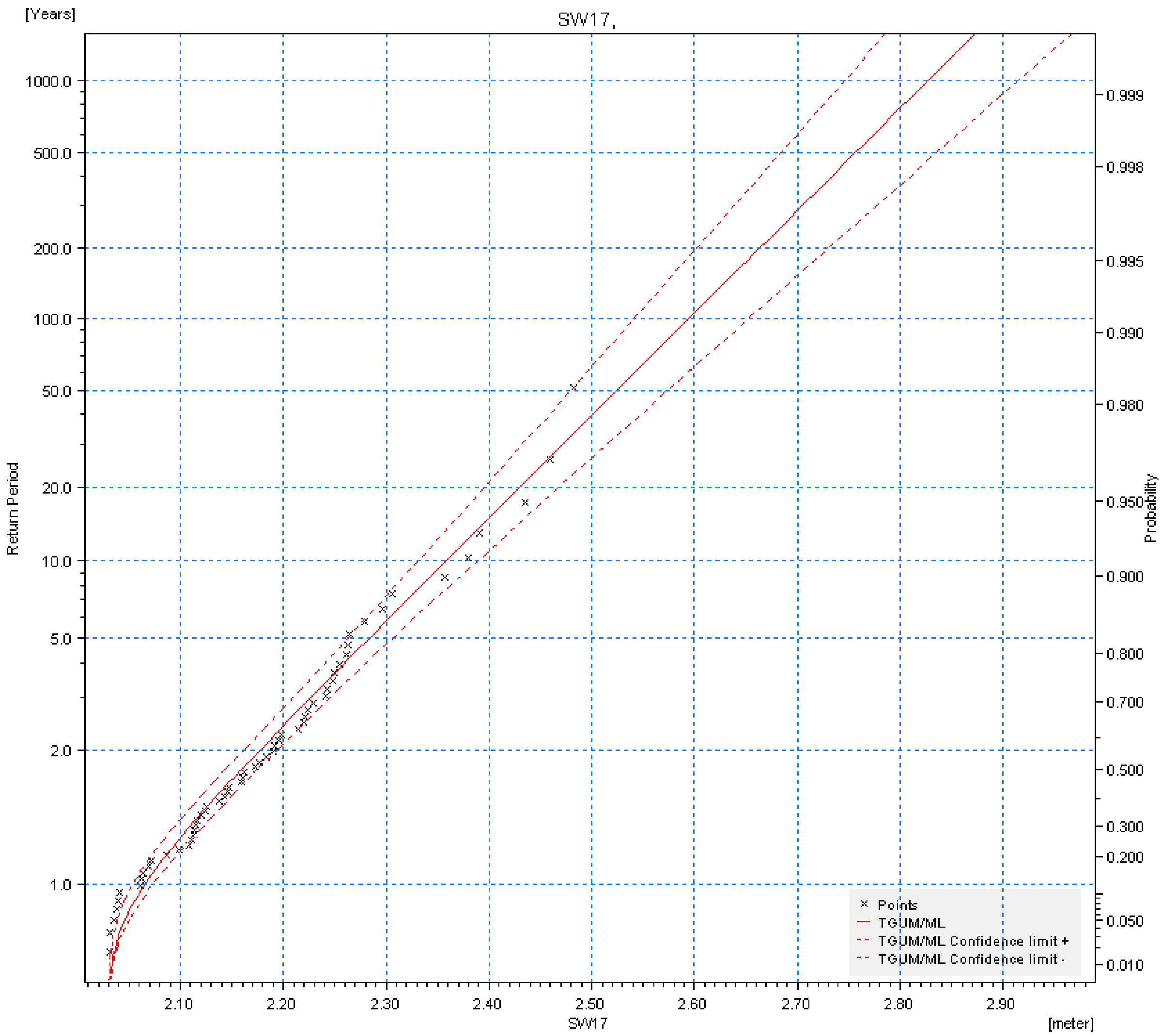

Figure 4.1: Simulated water levels and fitted truncated Gumbel distribution with confidence limits

Table 4.1: Total Water Level values for 0.1% & 0.5% AEP events (MSL)

	Coordinate		0.5% exceedance value			0.1% exceedance value		
	Longitude	Latitude	estimated value [m]	averaged value [m]	st.dev [m]	estimated value [m]	averaged value [m]	st.dev [m]
SW1	-10.230	51.600	2.565	2.568	0.055	2.711	2.715	0.072
SW2	-10.159	51.619	2.580	2.583	0.054	2.721	2.725	0.071
SW3	-10.080	51.640	2.549	2.551	0.053	2.675	2.678	0.069
SW4	-10.110	51.670	2.570	2.573	0.057	2.702	2.706	0.075
SW5	-10.025	51.695	2.557	2.559	0.051	2.679	2.683	0.065
SW6	-9.940	51.770	2.645	2.647	0.054	2.789	2.792	0.070
SW7	-9.840	51.795	2.668	2.671	0.053	2.810	2.813	0.069
SW8	-9.782	51.822	2.705	2.707	0.055	2.849	2.852	0.071
SW9	-10.035	51.765	2.627	2.630	0.056	2.771	2.774	0.073
SW10	-10.112	51.738	2.616	2.619	0.056	2.763	2.766	0.073
SW11	-10.180	51.760	2.622	2.625	0.058	2.772	2.775	0.076

	Coordinate		0.5% exceedance value			0.1% exceedance value		
	Longitude	Latitude	estimated value [m]	averaged value [m]	st.dev [m]	estimated value [m]	averaged value [m]	st.dev [m]
SW12	-10.220	51.830	2.674	2.677	0.064	2.835	2.839	0.085
SW13	-10.300	51.790	2.664	2.667	0.064	2.826	2.829	0.084
SW14	-10.360	51.820	2.692	2.695	0.062	2.852	2.855	0.081
SW15	-10.435	51.895	2.760	2.763	0.059	2.911	2.914	0.078
SW16	-10.335	51.945	2.794	2.797	0.056	2.937	2.941	0.073
SW17	-10.251	51.999	2.836	2.839	0.057	2.984	2.988	0.075
SW18	-10.160	52.025	2.851	2.854	0.057	2.994	2.997	0.075
SW19	-10.009	52.054	2.914	2.916	0.057	3.058	3.061	0.075
SW20	-10.000	52.118	3.021	3.024	0.063	3.195	3.198	0.081
SW21	-10.106	52.114	2.938	2.941	0.061	3.100	3.103	0.079
SW22	-10.240	52.110	2.894	2.896	0.060	3.057	3.060	0.077
SW23	-10.330	52.105	2.891	2.894	0.061	3.058	3.062	0.078
SW24	-10.404	52.093	2.881	2.884	0.063	3.049	3.052	0.082
SW25	-10.470	52.100	2.892	2.895	0.064	3.061	3.065	0.081
SW26	-10.588	52.092	2.914	2.916	0.059	3.081	3.084	0.076
SW27	-10.476	52.165	2.962	2.965	0.063	3.115	3.119	0.083
SW28	-10.395	52.215	3.049	3.052	0.059	3.215	3.219	0.075
SW29	-10.320	52.245	3.090	3.093	0.061	3.260	3.263	0.078
SW30	-10.215	52.280	3.143	3.147	0.068	3.313	3.318	0.090
SW31	-10.135	52.261	3.161	3.164	0.065	3.321	3.325	0.087
SW32	-10.063	52.270	3.158	3.162	0.065	3.314	3.318	0.087
SW33	-10.040	52.320	3.228	3.231	0.065	3.403	3.407	0.083
SW34	-9.989	52.275	3.244	3.246	0.062	3.398	3.401	0.081
SW35	-9.922	52.246	3.263	3.266	0.057	3.425	3.428	0.073
SW36	-9.855	52.256	3.312	3.314	0.059	3.479	3.482	0.075
SW37	-9.785	52.261	3.450	3.455	0.060	3.632	3.639	0.076
SW38	-9.865	52.315	3.268	3.271	0.067	3.434	3.437	0.089
SW39	-9.847	52.375	3.302	3.305	0.072	3.481	3.484	0.094
SW40	-9.950	52.415	3.267	3.270	0.071	3.442	3.446	0.094
SW41	-9.840	52.440	3.297	3.301	0.075	3.473	3.477	0.101
SW42	-9.706	52.497	3.385	3.389	0.062	3.575	3.579	0.078
SW43	-9.680	52.585	3.407	3.410	0.069	3.611	3.615	0.087
SW44	-9.850	52.565	3.359	3.362	0.066	3.556	3.560	0.083
SW45	-9.950	52.560	3.289	3.292	0.072	3.479	3.483	0.093
SW46	-9.863	52.603	3.299	3.301	0.070	3.486	3.490	0.089
SW47	-9.801	52.631	3.309	3.312	0.067	3.497	3.500	0.085
SW48	-9.721	52.665	3.338	3.341	0.070	3.530	3.534	0.089
SW49	-9.633	52.735	3.366	3.368	0.071	3.562	3.566	0.090
SW50	-9.512	52.752	3.410	3.414	0.067	3.614	3.619	0.085
SW51	-9.507	52.804	3.423	3.427	0.068	3.628	3.632	0.085
SW52	-9.469	52.853	3.426	3.430	0.067	3.630	3.635	0.084
SW53	-9.370	52.932	3.496	3.501	0.071	3.712	3.718	0.089
SW54	-9.485	52.945	3.459	3.463	0.069	3.669	3.674	0.088
SW55	-9.420	53.005	3.475	3.480	0.069	3.682	3.688	0.087
SW56	-9.304	53.124	3.617	3.625	0.074	3.843	3.854	0.094
SW57	-9.241	53.155	3.652	3.657	0.074	3.874	3.881	0.094
SW58	-9.152	53.156	3.680	3.686	0.070	3.901	3.909	0.089

5.0 Floodplain Mapping

5.1 Creating Flood Heights for the Floodplain Mapping

The total water level modelling and subsequent extreme value analysis were conducted using water levels primarily referenced to mean sea level (MSL). In order to carry out the required flood mapping process, the resulting extreme water levels had to be referenced to OD Malin. OD Malin is defined as the Mean Sea Level at Portmore Pier, Malin Head, County Donegal, between 1960 and 1969. Thus the OD Malin Geoid is a model of the level surface which is closest to mean sea level over the oceans. This surface is continued landward as the fundamental reference surface for height measurement. However due to errors in the levelling system as well as changes in land levels, the OD Malin Geoid does not exactly follow the mean sea level surface around Ireland.

Initially RPS attempted to convert from MSL via a nautical Datum (Chart Datum) to the land based datum (Poolbeg) using the conversion given by the Admiralty Tide Tables and then to OD Malin using information provided by Ordnance Survey Ireland (OSI). However during previous phases of this study this methodology was found to be inaccurate, as with each conversion a certain degree of error was introduced. Furthermore, the Chart datum and OD Poolbeg surfaces are not separated by a constant height difference relative to the OD Malin Geoid, thus some interpolation and in some places extrapolation was required.

As a result of these datum conversion issues alternative techniques were researched and a new analysis technique, which is currently being tried by other agencies such as Geological Survey of Ireland (GSI) and OSI was used. In a joint project with Ordnance Survey UK and Ordnance Survey Northern Ireland, OSI has established the height difference between orthometric height (the height given by ETRS89) and OD Malin. This was carried out by establishing the constant gravity surface through gravimetric measurements and establishing a secondary corrective surface based on 183 primary reference stations covering all of Ireland. This conversion model, also referred to as OSGM02, represents a best fit to all primary archived benchmarks in Ireland for the conversion between geocentric orthometric height defined by ETRS89 and the OD Malin Geoid.

For this study the mean sea level calculated by the ISTSM model can be regarded as equivalent to the constant or iso-gravity surface mentioned above. Thus to convert from this surface to OD Malin a secondary corrective surface needed to be applied. OSI provided details on how to obtain this secondary corrective surface, which is shown in Figure 5.1. It should be noted, that this corrective surface is extended in this diagram significantly seaward and beyond the true validity of the OD Malin datum. Furthermore the diagram covers Northern Ireland, where OD Malin is not applicable, thus the information is only for illustrative purpose in those areas. It should also be noted, that the corrective surface is not identical to OD Malin at Malin, which was also taken into account in the subsequent analysis.

The derived corrective surface was checked against known or measured MSL values in the study area. In each case the MSL was determined relative to OD Malin, this value was then compared against the level of MSL derived from the secondary

corrective surface. Comparisons were made against known conversions at Cobh, Castletownbere, Ballycotton and Rosslare, resulting in a maximum difference of circa 100mm between observed MSL and the secondary corrective surface.

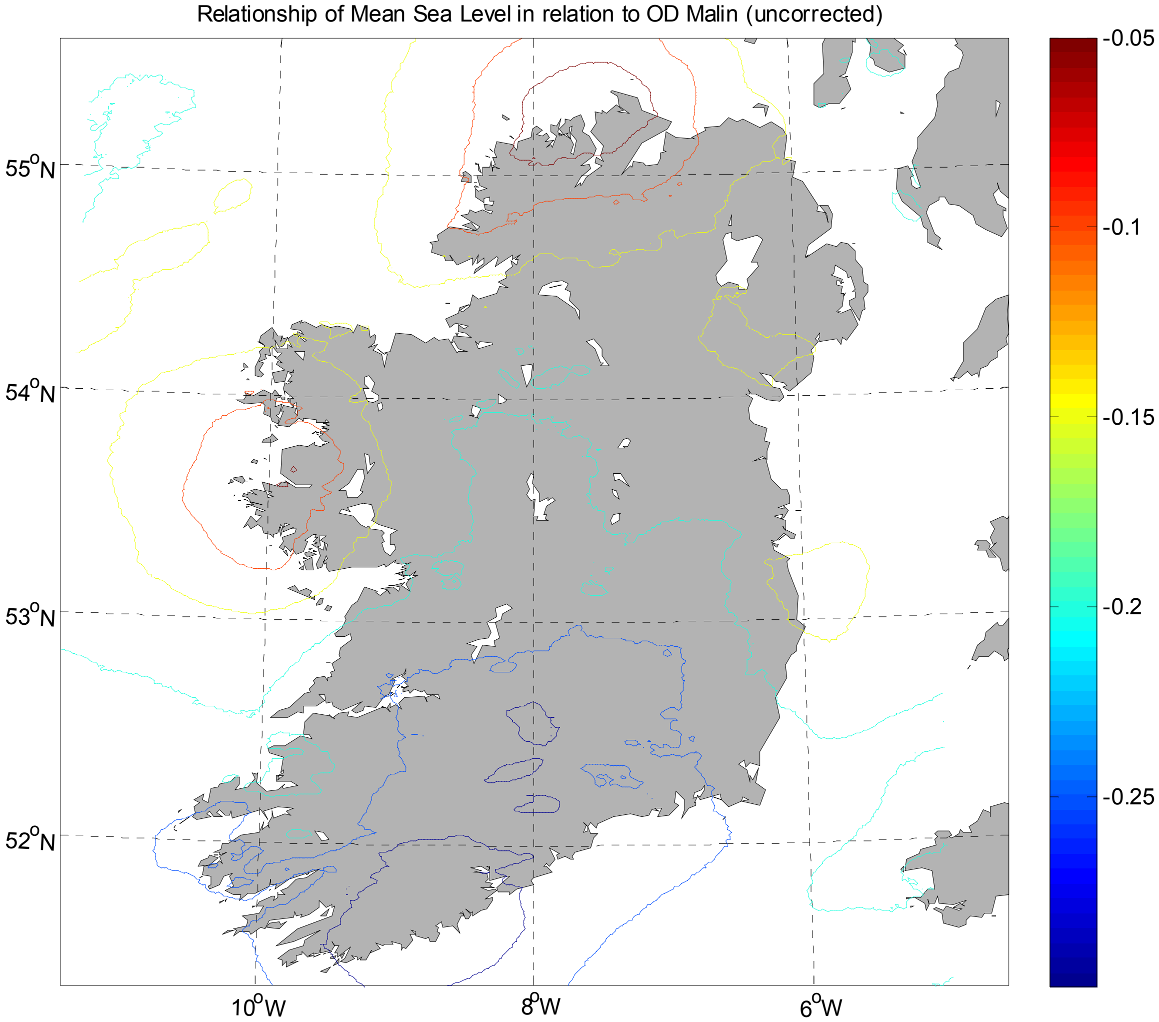

Figure 5.1: Secondary corrective surface between OSGM02 gravity and OSGM02 OD Malin

The detailed conversions for each of the extreme value analysis points are shown in the following tables.

Table 5.1 gives the results of the extreme value analysis of total water level events for all locations excluding the Shannon Estuary, which is shown in Table 5.2. In both tables, the levels are shown both relative to MSL and OD Malin. The coordinates of each point are given in Latitude and Longitude to ETRS89 Datum and are identical to those shown in Figure 3.10 to Figure 3.14.

Table 5.1: Extreme Water Level Table showing Total Water Levels in Study Area for Points SW1 – SW58 (all heights in metres)

		Point SW1	Point SW2	Point SW3	Point SW4	Point SW5	Point SW6	Point SW7	Point SW8	Point SW9	Point SW10
Coordinate	**Longitude**	**-10.230**	**-10.159**	**-10.080**	**-10.110**	**-10.025**	**-9.940**	**-9.840**	**-9.782**	**-10.035**	**-10.112**
	Latitude	**51.600**	**51.619**	**51.640**	**51.670**	**51.695**	**51.770**	**51.795**	**51.822**	**51.765**	**51.738**
Height to mean sea level for different AEP	50%	2.12	2.15	2.16	2.17	2.18	2.21	2.24	2.27	2.19	2.18
	20%	2.22	2.25	2.25	2.26	2.27	2.31	2.34	2.37	2.29	2.27
	10%	2.29	2.31	2.31	2.32	2.33	2.37	2.40	2.43	2.36	2.34
	5%	2.36	2.38	2.37	2.38	2.38	2.44	2.46	2.50	2.42	2.41
	2%	2.44	2.46	2.44	2.46	2.45	2.52	2.55	2.58	2.50	2.49
	1.00%	2.50	2.52	2.49	2.51	2.50	2.58	2.61	2.64	2.57	2.55
	0.50%	2.57	2.58	2.55	2.57	2.56	2.65	2.67	2.71	2.63	2.62
	0.10%	2.71	2.72	2.68	2.70	2.68	2.79	2.81	2.85	2.77	2.76
MSL to OD Malin		-0.240	-0.244	-0.242	-0.243	-0.242	-0.242	-0.244	-0.250	-0.249	-0.249
seich / set-up allowance		0.050	0.050	0.050	0.050	0.050	0.050	0.100	0.100	0.050	0.050
Height to OD Malin for different AEP	**50%**	**1.93**	**1.96**	**1.97**	**1.98**	**1.99**	**2.02**	**2.10**	**2.12**	**1.99**	**1.98**
	20%	**2.03**	**2.05**	**2.06**	**2.07**	**2.08**	**2.12**	**2.19**	**2.22**	**2.09**	**2.08**
	10%	**2.10**	**2.12**	**2.12**	**2.13**	**2.13**	**2.18**	**2.26**	**2.28**	**2.16**	**2.14**
	5%	**2.17**	**2.18**	**2.18**	**2.19**	**2.19**	**2.25**	**2.32**	**2.35**	**2.22**	**2.21**
	2%	**2.25**	**2.26**	**2.25**	**2.26**	**2.26**	**2.33**	**2.40**	**2.43**	**2.30**	**2.29**
	1.00%	**2.31**	**2.33**	**2.30**	**2.32**	**2.31**	**2.39**	**2.46**	**2.49**	**2.37**	**2.35**
	0.50%	**2.38**	**2.39**	**2.36**	**2.38**	**2.37**	**2.45**	**2.52**	**2.56**	**2.43**	**2.42**
	0.10%	**2.52**	**2.53**	**2.48**	**2.51**	**2.49**	**2.60**	**2.67**	**2.70**	**2.57**	**2.56**

Table 5.1 continued (all heights in metres)

		Point SW11	Point SW12	Point SW13	Point SW14	Point SW15	Point SW16	Point SW17	Point SW18	Point SW19	Point SW20
Coordinate	Longitude	-10.180	-10.220	-10.300	-10.360	-10.435	-10.335	-10.251	-10.160	-10.009	-10.000
	Latitude	51.760	51.830	51.790	51.820	51.895	51.945	51.999	52.025	52.054	52.118
Height to mean sea level for different AEP	50%	2.17	2.19	2.18	2.21	2.30	2.36	2.39	2.42	2.48	2.50
	20%	2.27	2.30	2.28	2.32	2.41	2.46	2.49	2.52	2.58	2.62
	10%	2.34	2.37	2.36	2.39	2.48	2.52	2.56	2.58	2.64	2.70
	5%	2.41	2.44	2.43	2.46	2.54	2.59	2.62	2.65	2.71	2.77
	2%	2.49	2.54	2.52	2.56	2.63	2.67	2.71	2.73	2.79	2.87
	1.00%	2.56	2.61	2.59	2.62	2.70	2.73	2.77	2.79	2.85	2.95
	0.50%	2.62	2.67	2.66	2.69	2.76	2.79	2.84	2.85	2.91	3.02
	0.10%	2.77	2.84	2.83	2.85	2.91	2.94	2.98	2.99	3.06	3.20
MSL to OD Malin		-0.251	-0.254	-0.252	-0.251	-0.254	-0.259	-0.260	-0.256	-0.230	-0.237
seich / set-up allowance		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.100	0.100
Height to OD Malin for different AEP	**50%**	**1.97**	**1.99**	**1.98**	**2.01**	**2.10**	**2.15**	**2.18**	**2.21**	**2.35**	**2.37**
	20%	**2.07**	**2.09**	**2.08**	**2.12**	**2.20**	**2.25**	**2.28**	**2.31**	**2.45**	**2.48**
	10%	**2.14**	**2.17**	**2.16**	**2.19**	**2.27**	**2.32**	**2.35**	**2.38**	**2.51**	**2.56**
	5%	**2.21**	**2.24**	**2.23**	**2.26**	**2.34**	**2.38**	**2.41**	**2.44**	**2.58**	**2.63**
	2%	**2.29**	**2.33**	**2.32**	**2.35**	**2.43**	**2.46**	**2.50**	**2.52**	**2.66**	**2.73**
	1.00%	**2.36**	**2.40**	**2.39**	**2.42**	**2.49**	**2.52**	**2.56**	**2.58**	**2.72**	**2.81**
	0.50%	**2.42**	**2.47**	**2.46**	**2.49**	**2.56**	**2.59**	**2.63**	**2.65**	**2.78**	**2.88**
	0.10%	**2.57**	**2.63**	**2.62**	**2.65**	**2.71**	**2.73**	**2.77**	**2.79**	**2.93**	**3.06**

Table 5.1 continued (all heights in metres)

		Point SW21	Point SW22	Point SW23	Point SW24	Point SW25	Point SW26	Point SW27	Point SW28	Point SW29	Point SW30
Coordinate	Longitude	-10.106	-10.240	-10.330	-10.404	-10.470	-10.588	-10.476	-10.395	-10.320	-10.215
	Latitude	52.114	52.110	52.105	52.093	52.100	52.092	52.165	52.215	52.245	52.280
Height to mean sea level for different AEP	50%	2.46	2.41	2.39	2.38	2.39	2.41	2.50	2.55	2.59	2.64
	20%	2.56	2.51	2.50	2.49	2.50	2.52	2.60	2.66	2.70	2.75
	10%	2.63	2.59	2.58	2.57	2.57	2.60	2.67	2.74	2.77	2.82
	5%	2.71	2.66	2.65	2.64	2.65	2.67	2.74	2.81	2.85	2.90
	2%	2.80	2.75	2.75	2.74	2.75	2.77	2.83	2.91	2.95	3.00
	1.00%	2.87	2.82	2.82	2.81	2.82	2.84	2.90	2.98	3.02	3.07
	0.50%	2.94	2.89	2.89	2.88	2.89	2.91	2.96	3.05	3.09	3.14
	0.10%	3.10	3.06	3.06	3.05	3.06	3.08	3.12	3.22	3.26	3.31
MSL to OD Malin		-0.250	-0.260	-0.258	-0.262	-0.258	-0.251	-0.234	-0.227	-0.217	-0.212
seich / set-up allowance		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050
Height to OD Malin for different AEP	**50%**	**2.26**	**2.20**	**2.18**	**2.17**	**2.18**	**2.21**	**2.32**	**2.38**	**2.42**	**2.47**
	20%	**2.36**	**2.30**	**2.29**	**2.28**	**2.29**	**2.32**	**2.42**	**2.48**	**2.53**	**2.58**
	10%	**2.43**	**2.38**	**2.37**	**2.35**	**2.37**	**2.40**	**2.49**	**2.56**	**2.61**	**2.66**
	5%	**2.51**	**2.45**	**2.44**	**2.43**	**2.44**	**2.47**	**2.56**	**2.63**	**2.68**	**2.74**
	2%	**2.60**	**2.54**	**2.54**	**2.52**	**2.54**	**2.57**	**2.65**	**2.73**	**2.78**	**2.84**
	1.00%	**2.67**	**2.61**	**2.61**	**2.60**	**2.61**	**2.64**	**2.71**	**2.80**	**2.85**	**2.91**
	0.50%	**2.74**	**2.68**	**2.68**	**2.67**	**2.68**	**2.71**	**2.78**	**2.87**	**2.92**	**2.98**
	0.10%	**2.90**	**2.85**	**2.85**	**2.84**	**2.85**	**2.88**	**2.93**	**3.04**	**3.09**	**3.15**

Table 5.1 continued (all heights in metres)

		Point SW31	Point SW32	Point SW33	Point SW34	Point SW35	Point SW36	Point SW37	Point SW38	Point SW39	Point SW40
Coordinate	Longitude	-10.135	-10.063	-10.040	-9.989	-9.922	-9.855	-9.785	-9.865	-9.847	-9.950
	Latitude	52.261	52.270	52.320	52.275	52.246	52.256	52.261	52.315	52.375	52.415
Height to mean sea level for different AEP	50%	2.68	2.69	2.71	2.78	2.78	2.81	2.91	2.77	2.77	2.74
	20%	2.79	2.79	2.82	2.88	2.89	2.92	3.03	2.88	2.89	2.86
	10%	2.86	2.87	2.90	2.95	2.96	3.00	3.11	2.96	2.97	2.94
	5%	2.93	2.93	2.98	3.02	3.03	3.07	3.19	3.03	3.05	3.02
	2%	3.02	3.02	3.08	3.11	3.12	3.17	3.29	3.13	3.15	3.12
	1.00%	3.09	3.09	3.15	3.18	3.19	3.24	3.37	3.20	3.23	3.19
	0.50%	3.16	3.16	3.23	3.24	3.26	3.31	3.45	3.27	3.30	3.27
	0.10%	3.32	3.31	3.40	3.40	3.43	3.48	3.63	3.43	3.48	3.44
MSL to OD Malin		-0.210	-0.205	-0.203	-0.197	-0.196	-0.191	-0.186	-0.195	-0.197	-0.201
seich / set-up allowance		0.050	0.050	0.050	0.100	0.100	0.100	0.100	0.050	0.050	0.050
Height to OD Malin for different AEP	**50%**	**2.52**	**2.53**	**2.56**	**2.68**	**2.69**	**2.72**	**2.83**	**2.63**	**2.63**	**2.59**
	20%	**2.63**	**2.64**	**2.67**	**2.79**	**2.79**	**2.83**	**2.94**	**2.74**	**2.74**	**2.71**
	10%	**2.70**	**2.71**	**2.75**	**2.86**	**2.86**	**2.91**	**3.02**	**2.81**	**2.82**	**2.79**
	5%	**2.77**	**2.78**	**2.82**	**2.93**	**2.94**	**2.98**	**3.10**	**2.89**	**2.90**	**2.86**
	2%	**2.86**	**2.87**	**2.92**	**3.01**	**3.03**	**3.08**	**3.21**	**2.98**	**3.00**	**2.97**
	1.00%	**2.93**	**2.94**	**3.00**	**3.08**	**3.10**	**3.15**	**3.29**	**3.05**	**3.08**	**3.04**
	0.50%	**3.00**	**3.00**	**3.08**	**3.15**	**3.17**	**3.22**	**3.36**	**3.12**	**3.16**	**3.12**
	0.10%	**3.16**	**3.16**	**3.25**	**3.30**	**3.33**	**3.39**	**3.55**	**3.29**	**3.33**	**3.29**

Table 5.1 continued (all heights in metres)

		Point SW41	Point SW42	Point SW43	Point SW44	Point SW45	Point SW46	Point SW47	Point SW48	Point SW49
Coordinate	Longitude	-9.840	-9.706	-9.680	-9.850	-9.950	-9.863	-9.801	-9.721	-9.633
	Latitude	52.440	52.497	52.585	52.565	52.560	52.603	52.631	52.665	52.735
Height to mean sea level for different AEP	50%	2.78	2.82	2.80	2.78	2.72	2.74	2.75	2.77	2.78
	20%	2.89	2.94	2.93	2.90	2.85	2.86	2.87	2.89	2.91
	10%	2.97	3.03	3.02	2.99	2.93	2.95	2.96	2.98	3.00
	5%	3.05	3.11	3.11	3.08	3.02	3.03	3.04	3.06	3.08
	2%	3.15	3.22	3.23	3.19	3.12	3.14	3.15	3.17	3.20
	1.00%	3.22	3.30	3.32	3.27	3.21	3.22	3.23	3.26	3.28
	0.50%	3.30	3.39	3.41	3.36	3.29	3.30	3.31	3.34	3.37
	0.10%	3.47	3.58	3.61	3.56	3.48	3.49	3.50	3.53	3.56
MSL to OD Malin		-0.200	-0.206	-0.212	-0.205	-0.201	-0.203	-0.207	-0.210	-0.214
seich / set-up allowance		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050
Height to OD Malin for different AEP	50%	2.63	2.67	2.64	2.62	2.57	2.59	2.60	2.61	2.62
	20%	2.74	2.79	2.77	2.75	2.69	2.71	2.72	2.73	2.74
	10%	2.82	2.87	2.86	2.83	2.78	2.79	2.80	2.82	2.83
	5%	2.90	2.96	2.95	2.92	2.86	2.88	2.88	2.90	2.92
	2%	3.00	3.07	3.07	3.03	2.97	2.98	2.99	3.01	3.03
	1.00%	3.07	3.15	3.16	3.12	3.06	3.07	3.07	3.10	3.12
	0.50%	3.15	3.23	3.25	3.20	3.14	3.15	3.15	3.18	3.20
	0.10%	3.32	3.42	3.45	3.40	3.33	3.33	3.34	3.37	3.40

Table 5.1 continued (all heights in metres)

		Point SW50	Point SW51	Point SW52	Point SW53	Point SW54	Point SW55	Point SW56	Point SW57	Point SW58
Coordinate	Longitude	-9.512	-9.507	-9.469	-9.370	-9.485	-9.420	-9.304	-9.241	-9.152
	Latitude	52.752	52.804	52.853	52.932	52.945	53.005	53.124	53.155	53.156
Height to mean sea level for different AEP	50%	2.81	2.82	2.83	2.86	2.84	2.87	2.95	3.00	3.03
	20%	2.94	2.95	2.95	2.99	2.97	3.00	3.09	3.14	3.17
	10%	3.03	3.04	3.05	3.09	3.07	3.09	3.19	3.24	3.27
	5%	3.12	3.13	3.13	3.19	3.16	3.18	3.29	3.33	3.36
	2%	3.24	3.25	3.25	3.31	3.28	3.30	3.42	3.46	3.49
	1.00%	3.32	3.34	3.34	3.40	3.37	3.39	3.52	3.56	3.59
	0.50%	3.41	3.42	3.43	3.50	3.46	3.48	3.62	3.65	3.68
	0.10%	3.61	3.63	3.63	3.71	3.67	3.68	3.84	3.87	3.90
MSL to OD Malin		-0.222	-0.218	-0.218	-0.213	-0.197	-0.192	-0.176	-0.175	-0.182
seich / set-up allowance		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.100	0.100
Height to OD Malin for different AEP	**50%**	**2.64**	**2.65**	**2.66**	**2.70**	**2.69**	**2.72**	**2.82**	**2.92**	**2.94**
	20%	**2.77**	**2.78**	**2.79**	**2.83**	**2.82**	**2.85**	**2.97**	**3.06**	**3.08**
	10%	**2.86**	**2.87**	**2.88**	**2.93**	**2.92**	**2.95**	**3.07**	**3.16**	**3.18**
	5%	**2.95**	**2.96**	**2.97**	**3.02**	**3.01**	**3.04**	**3.17**	**3.26**	**3.28**
	2%	**3.06**	**3.08**	**3.08**	**3.15**	**3.13**	**3.16**	**3.30**	**3.39**	**3.41**
	1.00%	**3.15**	**3.17**	**3.17**	**3.24**	**3.22**	**3.24**	**3.39**	**3.48**	**3.50**
	0.50%	**3.24**	**3.26**	**3.26**	**3.33**	**3.31**	**3.33**	**3.49**	**3.58**	**3.60**
	0.10%	**3.44**	**3.46**	**3.46**	**3.55**	**3.52**	**3.54**	**3.72**	**3.80**	**3.82**

Table 5.2: Extreme Water Level Table showing Total Water Levels in the Shannon Estuary for points S1 – S26 (all heights in metres)

		Point S1	Point S2	Point S3	Point S4	Point S5	Point S6	Point S7	Point S8	Point S9
Coord-inate	**Longitude**	**-9.731**	**-9.696**	**-9.689**	**-9.683**	**-9.643**	**-9.600**	**-9.538**	**-9.506**	**-9.477**
	Latitude	**52.575**	**52.484**	**52.540**	**52.607**	**52.576**	**52.614**	**52.572**	**52.627**	**52.573**
Height to mean sea level for different AEP	50%	2.80	2.82	2.83	2.82	2.83	2.85	2.89	2.88	2.86
	20%	2.92	2.93	2.96	2.94	2.95	2.97	3.01	3.01	2.98
	10%	3.01	3.02	3.04	3.03	3.04	3.06	3.10	3.10	3.07
	5%	3.10	3.10	3.13	3.12	3.12	3.15	3.19	3.19	3.16
	2%	3.22	3.21	3.24	3.24	3.23	3.27	3.30	3.32	3.27
	1.00%	3.31	3.29	3.33	3.32	3.32	3.35	3.39	3.41	3.36
	0.50%	3.39	3.37	3.41	3.41	3.40	3.44	3.47	3.50	3.45
	0.10%	3.59	3.55	3.60	3.61	3.59	3.63	3.67	3.71	3.65
MSL to OD Malin		-0.210	-0.210	-0.209	-0.212	-0.213	-0.216	-0.220	-0.224	-0.223
seich / set-up allowance		0.050	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.150
Height to OD Malin for different AEP	**50%**	**2.64**	**2.71**	**2.73**	**2.71**	**2.72**	**2.74**	**2.77**	**2.76**	**2.79**
	20%	**2.76**	**2.82**	**2.85**	**2.83**	**2.84**	**2.86**	**2.89**	**2.89**	**2.91**
	10%	**2.85**	**2.91**	**2.93**	**2.92**	**2.92**	**2.95**	**2.98**	**2.98**	**3.00**
	5%	**2.94**	**2.99**	**3.02**	**3.01**	**3.01**	**3.03**	**3.07**	**3.07**	**3.09**
	2%	**3.06**	**3.10**	**3.13**	**3.12**	**3.12**	**3.15**	**3.18**	**3.19**	**3.20**
	1.00%	**3.15**	**3.18**	**3.22**	**3.21**	**3.20**	**3.24**	**3.27**	**3.28**	**3.29**
	0.50%	**3.23**	**3.26**	**3.30**	**3.30**	**3.29**	**3.32**	**3.35**	**3.37**	**3.37**
	0.10%	**3.43**	**3.44**	**3.49**	**3.50**	**3.48**	**3.52**	**3.55**	**3.58**	**3.57**

Table 5.2 continued (all heights in metres)

		Point S10	Point S11	Point S12	Point S13	Point S14	Point S15	Point S16	Point S17	Point S18
Coord-inate	Longitude	-9.419	-9.379	-9.354	-9.333	-9.292	-9.247	-9.207	-9.165	-9.127
	Latitude	52.601	52.601	52.591	52.582	52.582	52.613	52.600	52.615	52.618
Height to mean sea level for different AEP	50%	2.88	2.90	2.85	2.83	2.85	2.91	2.94	2.97	3.03
	20%	3.00	3.02	2.97	2.96	2.98	3.05	3.08	3.12	3.18
	10%	3.09	3.12	3.06	3.05	3.07	3.15	3.18	3.23	3.30
	5%	3.18	3.21	3.15	3.14	3.16	3.25	3.29	3.35	3.42
	2%	3.30	3.33	3.26	3.26	3.28	3.39	3.43	3.50	3.57
	1.00%	3.39	3.42	3.34	3.34	3.37	3.49	3.53	3.61	3.69
	0.50%	3.47	3.51	3.42	3.43	3.46	3.59	3.64	3.72	3.81
	0.10%	3.68	3.72	3.61	3.63	3.66	3.82	3.88	3.98	4.08
MSL to OD Malin		-0.226	-0.230	-0.230	-0.232	-0.233	-0.239	-0.238	-0.242	-0.245
seich / set-up allowance		0.100	0.100	0.100	0.100	0.100	0.050	0.050	0.050	0.050
Height to OD Malin for different AEP	**50%**	**2.75**	**2.77**	**2.72**	**2.70**	**2.72**	**2.72**	**2.75**	**2.78**	**2.83**
	20%	**2.87**	**2.89**	**2.84**	**2.83**	**2.85**	**2.86**	**2.89**	**2.93**	**2.99**
	10%	**2.96**	**2.99**	**2.93**	**2.92**	**2.94**	**2.96**	**3.00**	**3.04**	**3.11**
	5%	**3.05**	**3.08**	**3.02**	**3.01**	**3.03**	**3.06**	**3.10**	**3.16**	**3.22**
	2%	**3.17**	**3.20**	**3.13**	**3.12**	**3.15**	**3.20**	**3.24**	**3.30**	**3.38**
	1.00%	**3.26**	**3.29**	**3.21**	**3.21**	**3.24**	**3.30**	**3.34**	**3.42**	**3.50**
	0.50%	**3.35**	**3.38**	**3.29**	**3.30**	**3.33**	**3.40**	**3.45**	**3.53**	**3.62**
	0.10%	**3.55**	**3.59**	**3.48**	**3.50**	**3.53**	**3.63**	**3.69**	**3.79**	**3.89**

Table 5.2 continued (all heights in metres)

		Point S19	Point S20	Point S21	Point S22	Point S23	Point S24	Point S25	Point S26
Coord-inate	Longitude	-9.093	-9.074	-9.019	-8.958	-8.906	-8.879	-8.821	-8.745
	Latitude	52.630	52.660	52.633	52.678	52.669	52.686	52.682	52.677
Height to mean sea level for different AEP	50%	3.08	3.13	3.18	3.28	3.33	3.38	3.45	3.52
	20%	3.24	3.29	3.35	3.46	3.53	3.58	3.66	3.76
	10%	3.36	3.42	3.48	3.59	3.67	3.73	3.82	3.94
	5%	3.48	3.54	3.60	3.73	3.82	3.88	3.97	4.11
	2%	3.64	3.71	3.77	3.91	4.01	4.07	4.18	4.35
	1.00%	3.77	3.83	3.89	4.04	4.15	4.22	4.33	4.53
	0.50%	3.89	3.96	4.01	4.17	4.30	4.37	4.49	4.70
	0.10%	4.17	4.25	4.30	4.49	4.64	4.71	4.84	5.11
MSL to OD Malin		-0.248	-0.251	-0.251	-0.252	-0.254	-0.256	-0.258	-0.261
seich / set-up allowance		0.050	0.050	0.100	0.100	0.100	0.100	0.100	0.150
Height to OD Malin for different AEP	**50%**	**2.89**	**2.93**	**3.03**	**3.12**	**3.18**	**3.22**	**3.29**	**3.40**
	20%	**3.04**	**3.09**	**3.20**	**3.31**	**3.37**	**3.42**	**3.50**	**3.64**
	10%	**3.17**	**3.22**	**3.32**	**3.44**	**3.52**	**3.57**	**3.66**	**3.82**
	5%	**3.29**	**3.34**	**3.45**	**3.58**	**3.66**	**3.72**	**3.81**	**4.00**
	2%	**3.45**	**3.51**	**3.61**	**3.75**	**3.86**	**3.92**	**4.02**	**4.24**
	1.00%	**3.57**	**3.63**	**3.74**	**3.89**	**4.00**	**4.07**	**4.17**	**4.41**
	0.50%	**3.69**	**3.76**	**3.86**	**4.02**	**4.15**	**4.21**	**4.33**	**4.59**
	0.10%	**3.97**	**4.05**	**4.15**	**4.33**	**4.48**	**4.56**	**4.68**	**5.00**

5.2 Accuracy of Predicted Total Water Levels

The accuracy of the predicted annual exceedance probability (AEP) of total water levels is dependent on the accuracy of the various components used in deriving these levels i.e. the accuracy of the tidal and surge model, the accuracy of the statistical data and the accuracy for the conversion from marine datum to land levelling datum. The output of the water level modelling, combined with the extreme value analysis undertaken as detailed above is generally expected to be within ±180mm for confidence limits of 95% at the 0.1% AEP. Lower return period events are expected to have tighter confidence limits. This includes any systematic errors in surge modelling as well as error relating to the statistical analysis for example due to the number of events used in the EVA. The error of the conversion between the marine datum (MSL) and the land levelling system (OD Malin Geoid) is also included in this tolerance.

5.3 Flood Mapping Methodology

In accordance with the project objectives, coastal flood extent maps were prepared for the 0.1% AEP and 0.5 % AEP events, denoting the Extreme Flood Extent and Indicative Flood Extent. Additionally coastal flood depth maps were prepared in respect of the 0.5% AEP event. Flood extent maps for less extreme events associated with exceedance probabilities of 50%, 20%, 10%, 5%, 2% and 1% were also prepared and are appended to this report in a digital format. These flood maps are broadly classified as flood hazard maps in this study.

The flood extent maps and flood depth maps, were prepared by combining the extreme total water levels outlined in Table 5.1 and Table 5.2 with the OPW south west coast digital terrain model (DTM) in the limited areas where this was available, or otherwise with the lower resolution National Digital Height Model (NDHM).The water levels were assumed to remain constant between the coast and the landward limit of the floodplain. No allowance for climate change has yet been made, although a further series of climate change maps will follow this report.

The data for analysis initially comprised two layers, a point layer containing spot heights for extreme water levels with values for each of the following exceedance probabilities, 50%, 20%, 10%, 5%, 2%, 1%, 0.5% (indicative flood extent) and 0.1% (extreme flood extent), and a raster layer of gridded NDHM elevation data for the Irish coastline, or high resolution LiDAR data where available. Firstly the water level point data was converted to a 100m gridded surface, using the Inverse Distance Weighted method. This raster surface covered such a large area that a 2m grid could not easily be created and manipulated. The output raster was then broken down into smaller units that were of the same extent as the NDHM units, to make them easier to work with.

Using the ArcGIS software (Spatial Analyst Raster Calculator) the water level raster, for each specific return period, was subtracted from the corresponding NDHM layer. The output from this exercise gave a raster with positive and negative values. All negative values showed the areas that would potentially flood for that exceedance probability. The raster was then reclassified to remove all the areas that were above the flood level, leaving an output of only potential flooded areas. Potential flood

areas of the same exceedance probability were converted to polygons and merged to create one polygon layer that covered the entire area of investigation.

The raster surface areas with negative values in the above process were then used to create a surface indicative of the potential flood depths for the 0.5% AEP event. This surface was also used to create an interval raster (0.25m intervals) using ArcGIS, Spatial Analyst Raster Calculator software.

5.4 Accuracy of the Digital Terrain Model

Data was acquired for the NHDM from September to October 2007, providing a grid with a resolution of 5m. The vertical datum of the grid was Malin Head Ordnance Datum, with ING Ireland 1965 for the horizontal datum. The vertical accuracy of the data was specified to ±1.4m at the 95% confidence limit and ±2.1m at the 99% Confidence Limit, while the RMSE on slopes at an angle of less than 20 degrees was ±0.70m. With regard to the horizontal accuracy of the data, a value of ±4.0m was specified at the 95% confidence limit, while the RMSE on slopes at an angle of less than 20 degrees was ±2.0m.

Only limited use was made of a LiDAR based DTM and as such a detailed accuracy assessment of this was not undertaken. However as this DTM was derived from the same LiDAR survey as that of the North East and South coast DTMs, then a general indication of accuracy may be found in the North East and South coast ICPSS, WP2, 3 & 4A technical reports (Reference 4 and 5).

5.5 Uncertainty and Limitations of Flood Extent Maps

The level of confidence assigned to the flood extents should reflect the reliability of the input data, together with any discrepancies in the methodology of determining the flood extents. Data used in the production of any flood map is rarely of consistent accuracy and may vary depending on location.

The accuracy of the flood maps depends largely on the accuracy of the predicted extreme water levels and the Digital Terrain Model. While the water levels are produced to high accuracy (+/- 180mm, 95% confidence interval), the resulting flood hazard maps have lower accuracy due to the accuracy of the Digital Terrain Model, as described in Section 5.4. In general higher confidence in the resulting flood extents can be gained by supplementing the digital terrain models with detailed surveys of the relevant areas. However at a national strategic level this is not feasible.

In addition the flooding was assumed to occur at a fixed level over the entire flooded area. The approach adopted in this case does not consider flood paths and shows any area below the flood level as flood plain. This is a common approach adopted in other countries and in general provides a good strategic overview of flood hazard and potential risk for coastal areas. In addition it is the worst case scenario and includes for example for failure of defences or valves on sewers.

In order to more accurately assess the confidence in the flood extents, a confidence

analysis was developed and applied on the east and south coasts. It involved the collation of qualitative and quantitative information into one overall quantitative database. This was based on a scoring and weighting system, establishing five confidence classifications based on various parameters in the flood extent determination.

Results of the analysis for various confidence parameters were brought together on a raster grid, allowing the combined overall confidence to be established for each section of the east and south coastline. The results were classified into five groups in terms of very high, high, medium, low and very low confidence. Very high confidence represents a score of over 70%, with high confidence between 60-70%, medium confidence between 50-60%, low confidence between 40-50% and very low confidence being less than 40%. When this methodology was applied on the south coast using the DTM derived from the NDHM a very low confidence score was assigned (less than 40%).

On this basis it was not deemed necessary to undertake a detailed confidence analysis for the south west coast (including the Shannon estuary) as the results were likely to be the same. For the purposes of the flood extents shown in Appendices 3A and 3B a very low confidence (less than 40%) may therefore be assumed, at least for those flood extents not derived from LiDAR DTM data. The flood extents which have been derived from LiDAR DTM data are shown on the flood depth maps in Appendices 3A and 3B.

5.6 Presentation of Floodplain Maps – Extreme Flood Extent, Indicative Flood Extent and Flood Depths

The flood maps for the 0.5% AEP (indicative flood extent) and 0.1% AEP, (extreme flood extent) for the entire south west coast study area, being the primary outputs of the tidal flood hazard assessment, are presented in Appendix 3A, with the Shannon specific maps presented in Appendix 3B. There are 76 south west coast plans and 28 Shannon Estuary plans illustrating the flood extent for the two AEP events and these are displayed at a scale of 1:25,000 relative to OSI discovery series raster maps and the high water mark. In addition, the associated flood depth maps for the 0.5% AEP are presented at a similar scale.

The flood depth maps also show the limited extent of the LiDAR DTM used in this flood assessment. Where no LiDAR DTM was available, NDHM data has been used.

These datasets are also presented on CD in digital form (ArcGIS shape files) together with further flood extents associated with the 50%, 20%, 10%, 5%, 2% and 1% AEP (Refer Appendix 5).

A review of the flood maps, including flood depth maps, in Appendices 3A and 3B, showed that there were a number of primary areas of potential coastal flood risk based on the geographic extent of floodplain and proximity to urban centres. These primary areas are presented in Figure 5.2 to Figure 5.5 for the south west coast and Figure 5.6 to Figure 5.10 for the Shannon estuary in respect of the 0.5% AEP event. They are all shown relative to the OSI six inch series raster map and high water mark.

The primary areas of potential coastal flood risk for the south west coast are as follows:-

- Castlemaine Harbour, Co. Kerry,
- Tralee to Derrymore, Co. Kerry,
- Ballyheige to Barrow, Co. Kerry,
- Moneycashen to Finuge, Co. Kerry.

The primary areas of potential coastal flood risk for the Shannon estuary are as follows:-

- Foynes to Aughinish, Co. Limerick,
- Newtown to Adare, Co. Limerick,
- Limerick City, Co. Limerick,
- Shannon to Portdrine, Co. Clare,
- Ennis to Newmarket on Fergus, Co. Clare.

Whilst every effort has been made throughout this study to optimise the accuracy of these coastal floodplain maps, there are unavoidable inaccuracies and uncertainties associated with these maps. These uncertainties are discussed in this report and are highlighted in the disclaimer and guidance notes appended to this report. All flood mapping presented in this report should be read in conjunction with these appended disclaimers and guidance notes (Refer Appendices 3A and 3B).

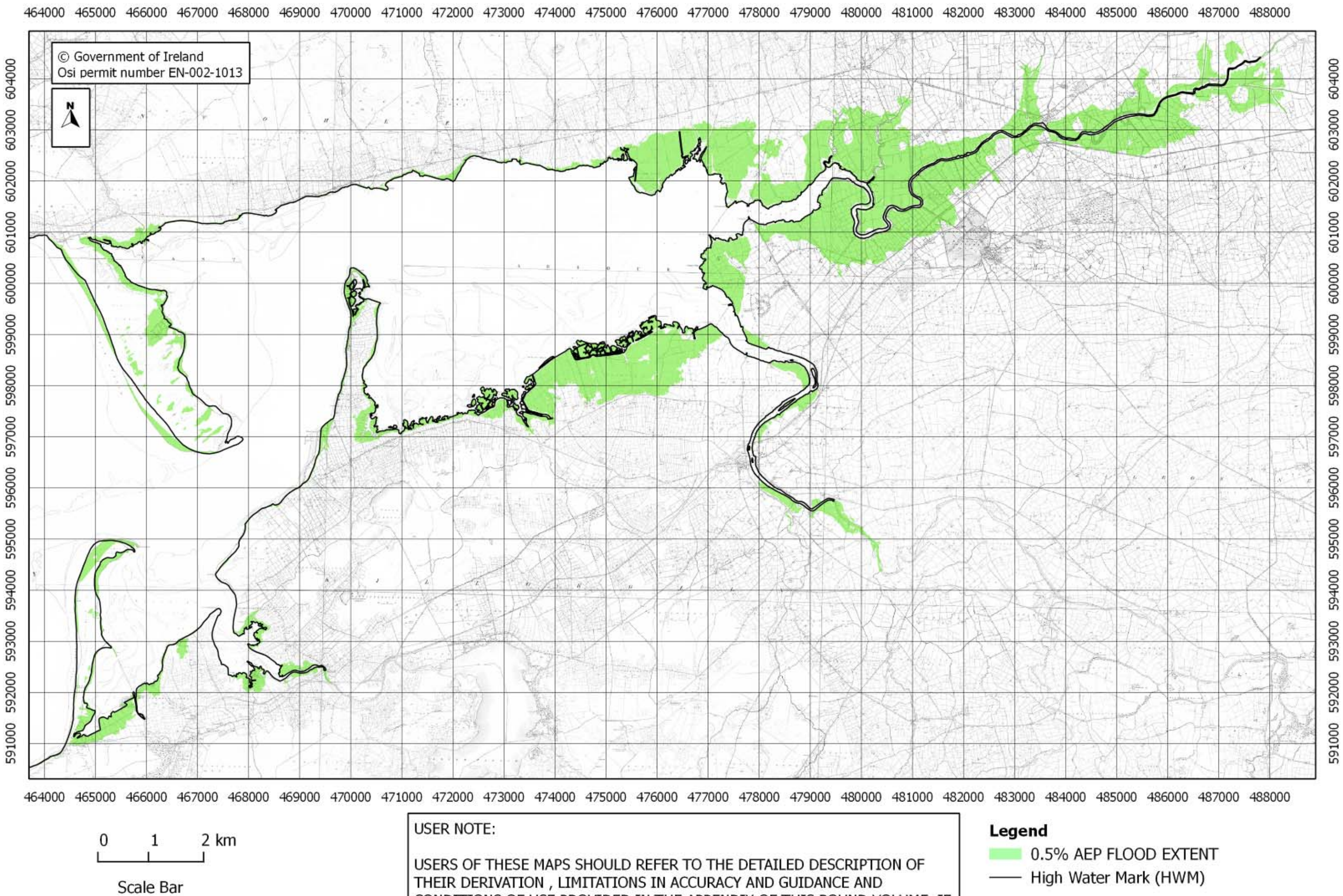

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Figure 5.2: Castlemaine Harbour Predictive Flood Extent Map, 0.5% AEP

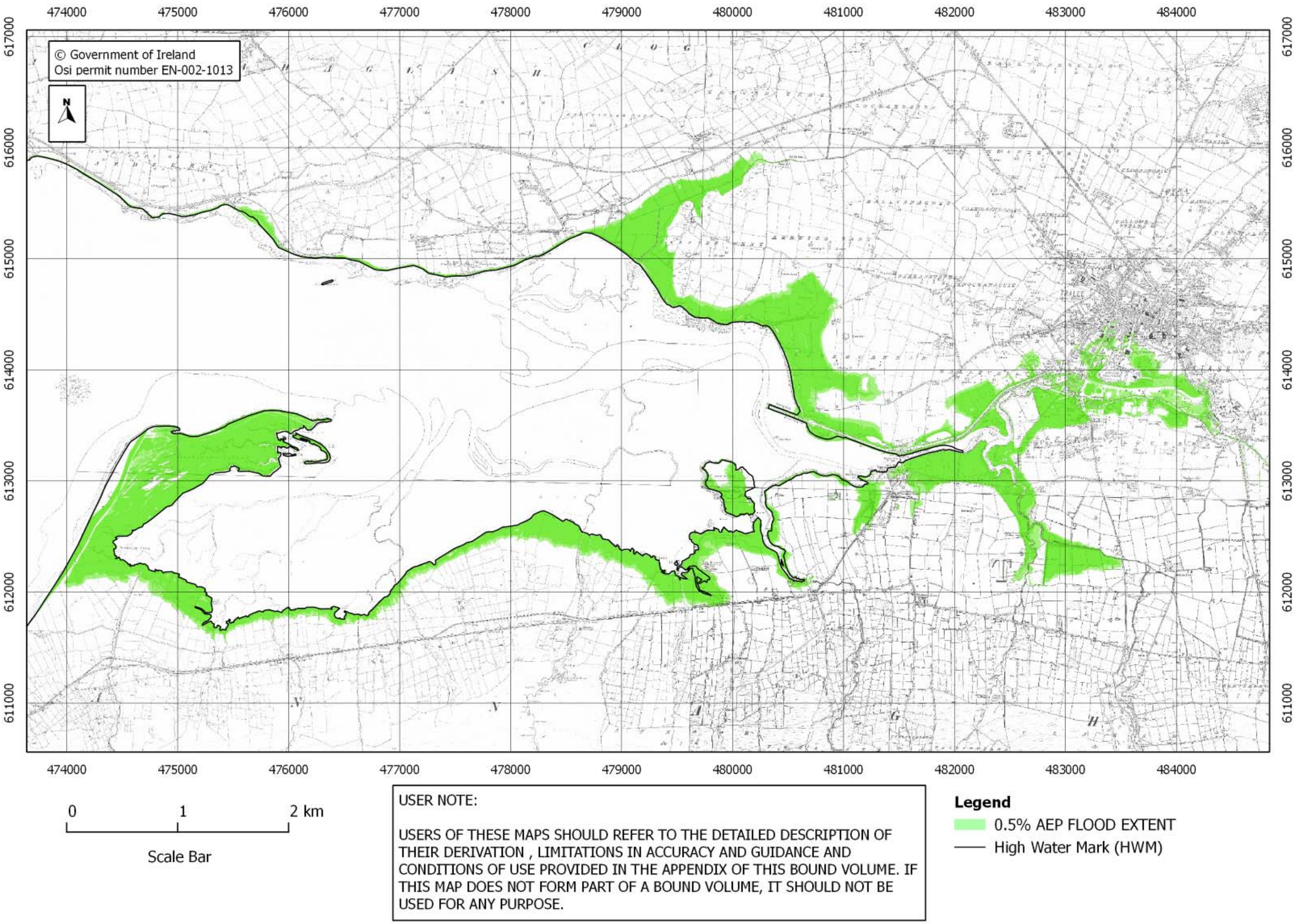


Figure 5.3: Tralee to Derrymore Predictive Flood Extent Map, 0.5% AEP

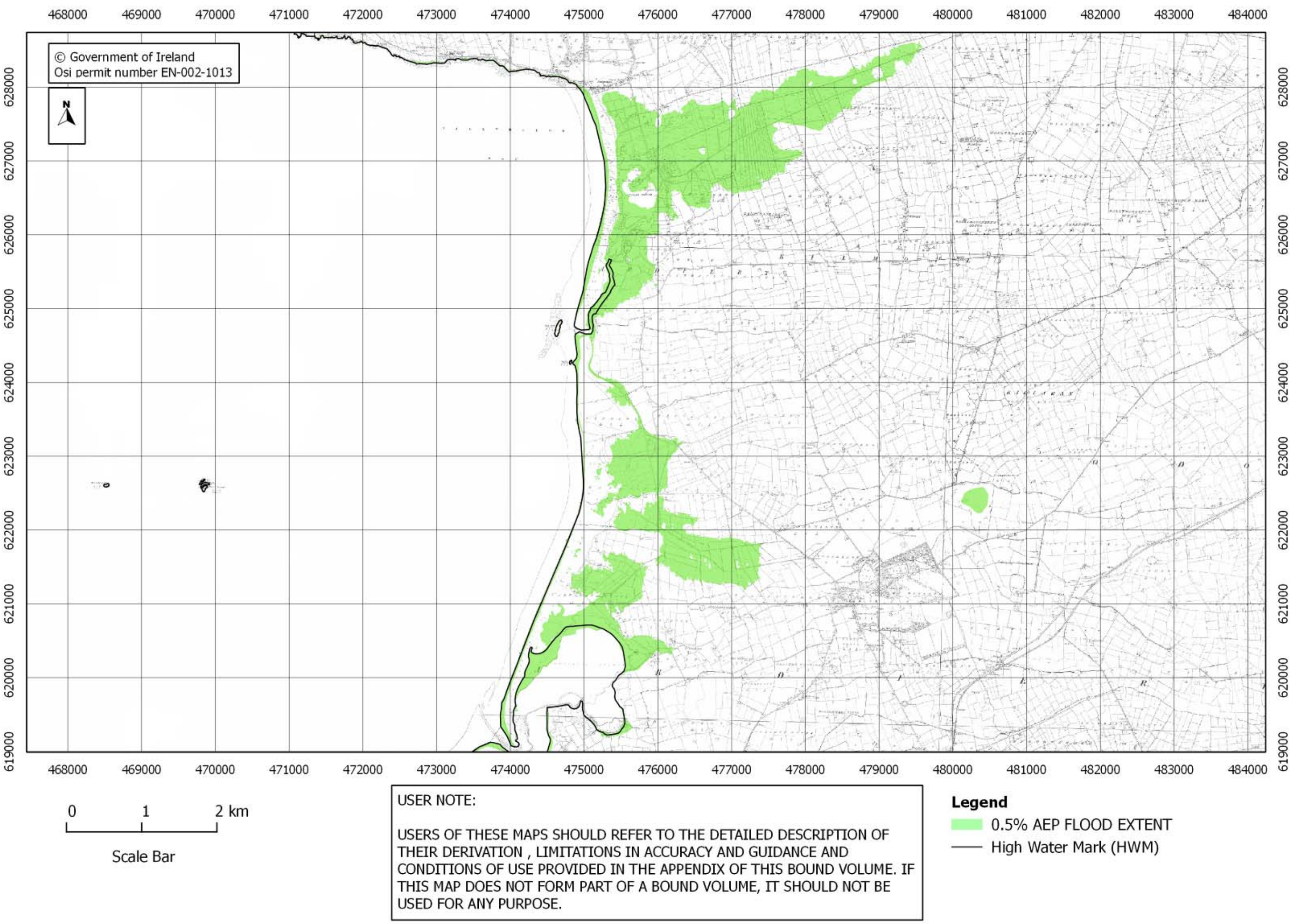
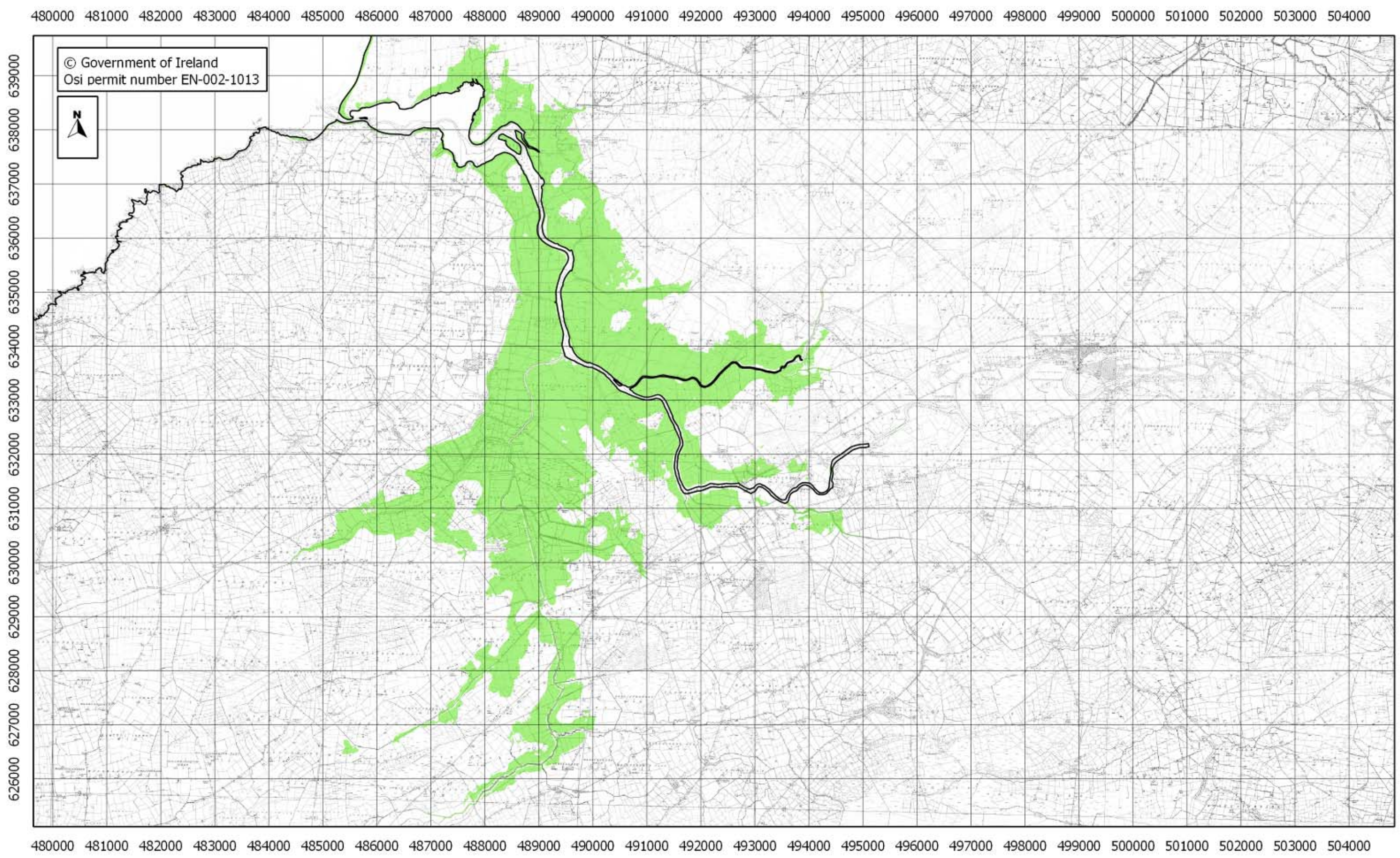


Figure 5.4: Ballyheige to Barrow Predictive Flood Extent Map, 0.5% AEP



0 1 2 km

Scale Bar

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Legend
- 0.5% AEP FLOOD EXTENT
- High Water Mark (HWM)

Figure 5.5: Moneycashen to Finuge Predictive Flood Extent Map, 0.5% AEP

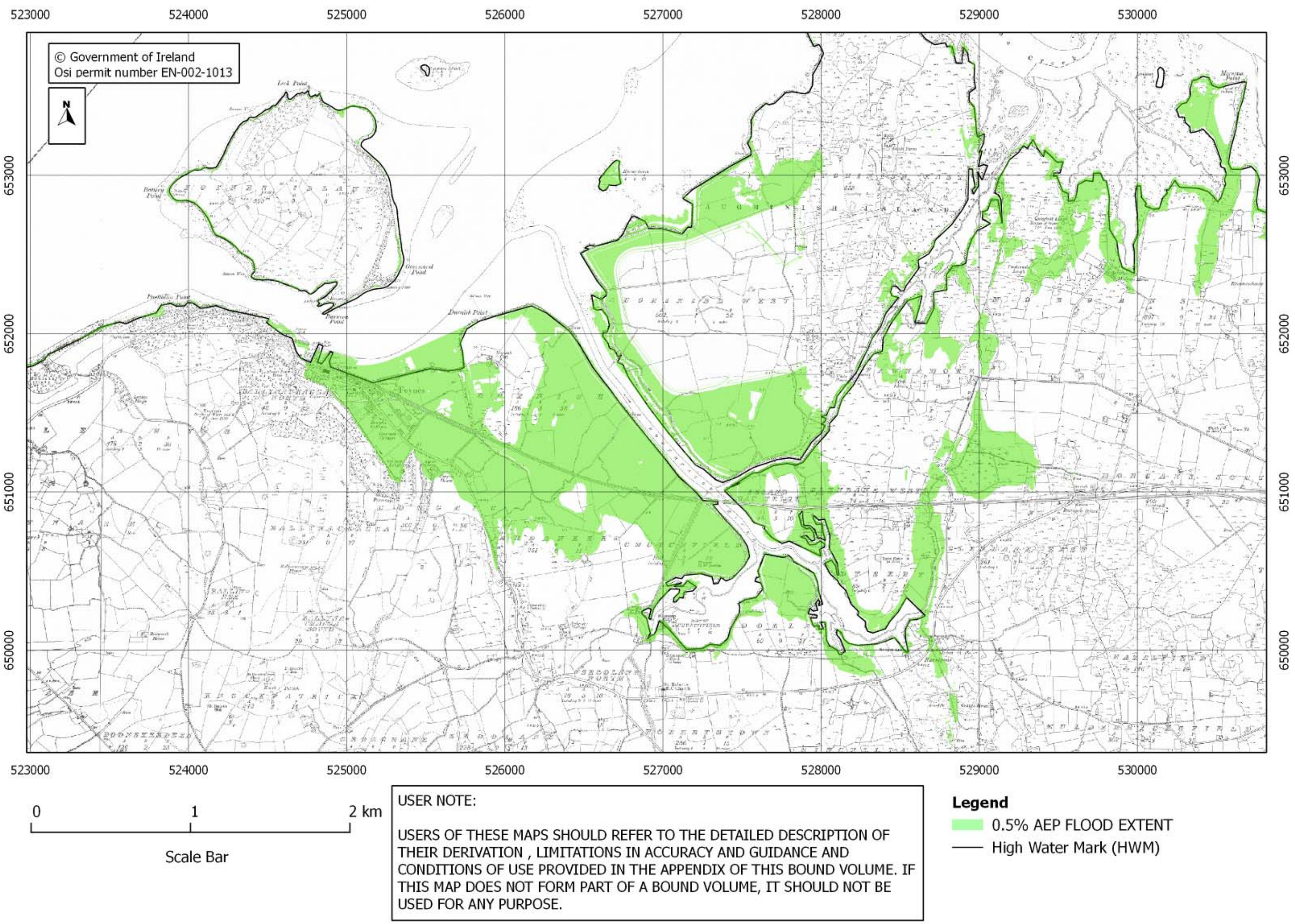


Figure 5.6: Foynes to Aughinish Predictive Flood Extent Map, 0.5% AEP

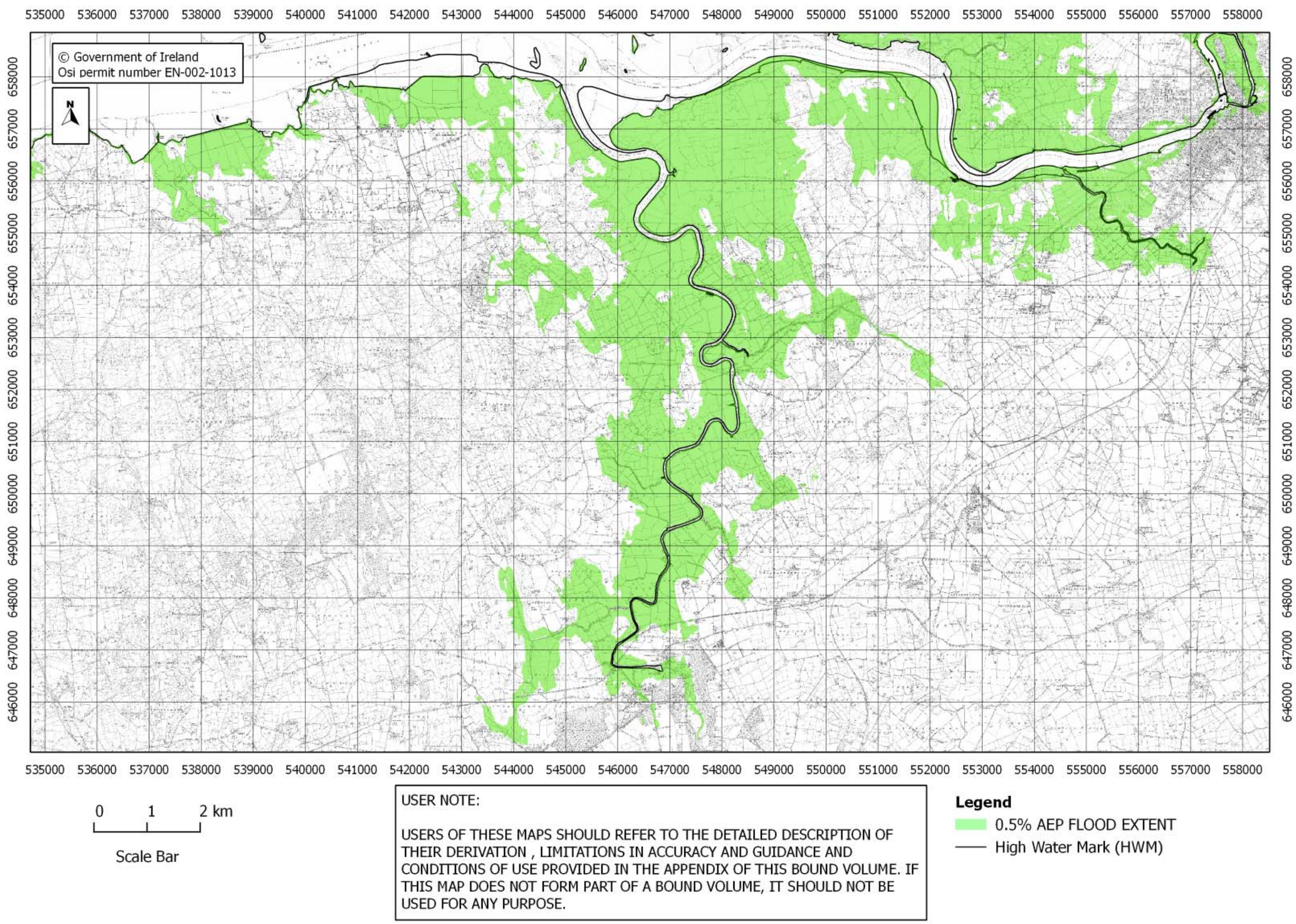


Figure 5.7: Newtown to Adare Predictive Flood Extent Map, 0.5% AEP

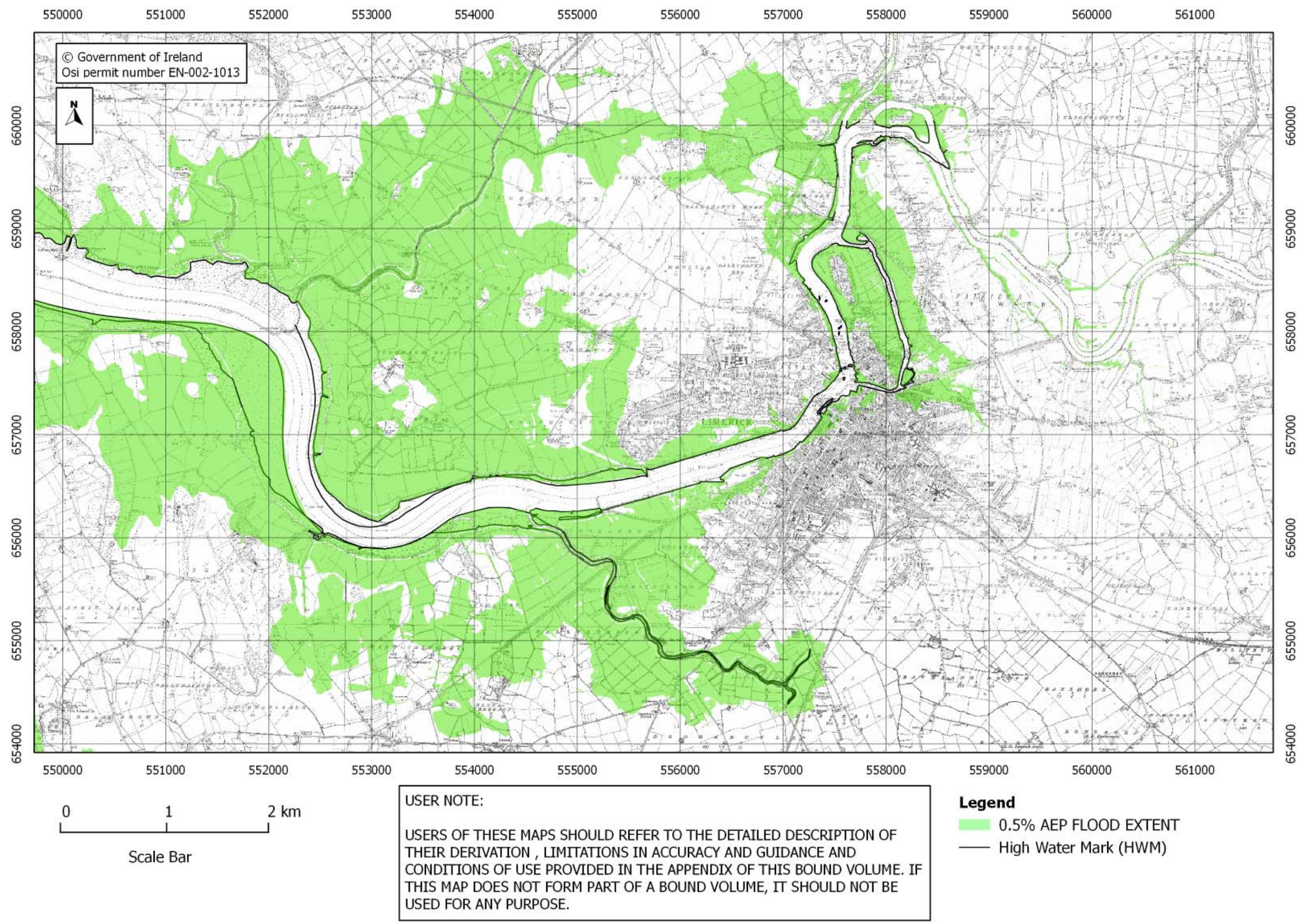


Figure 5.8: Limerick City Predictive Flood Extent Map, 0.5% AEP

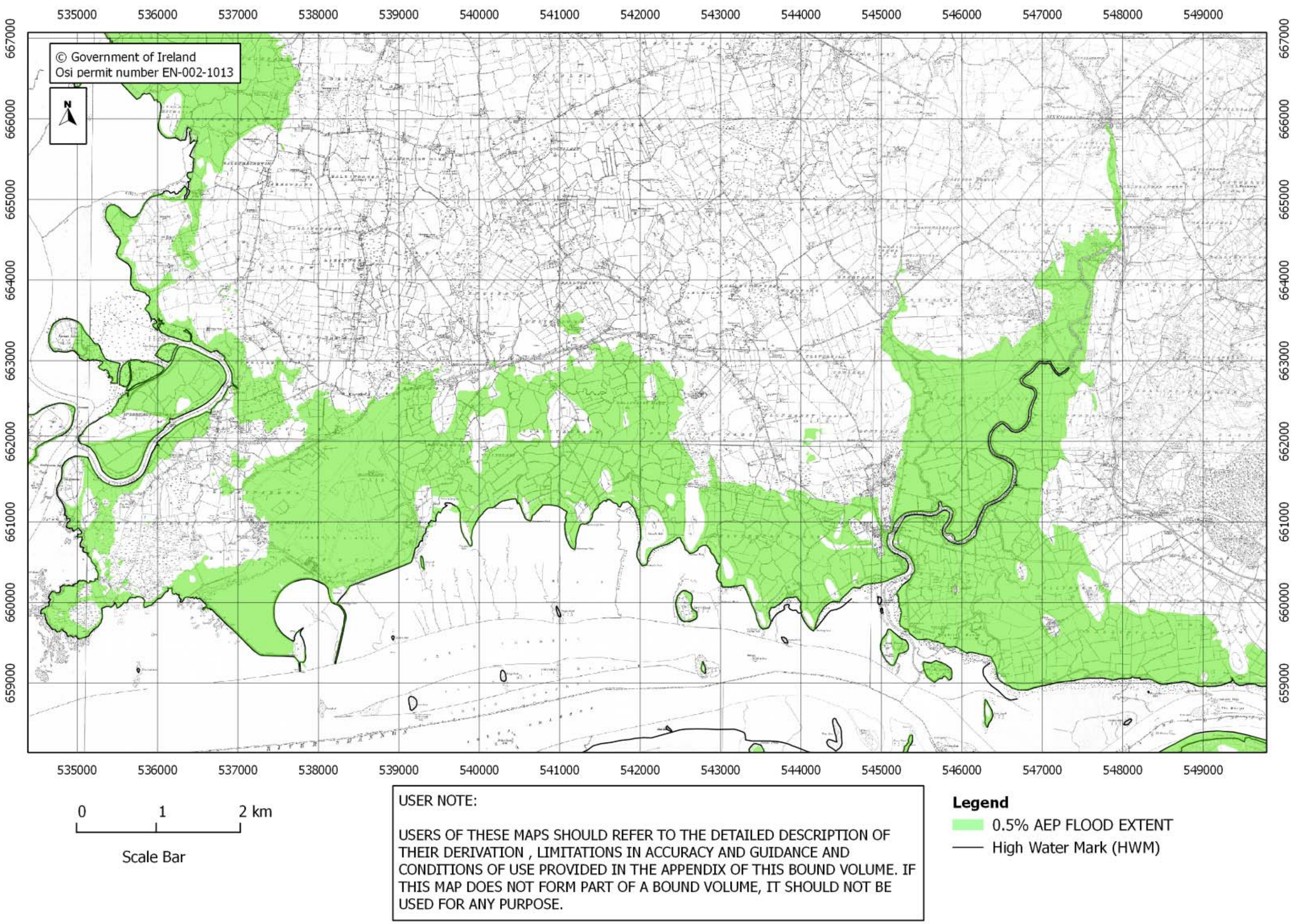


Figure 5.9: Shannon to Portdrine Predictive Flood Extent Map, 0.5% AEP

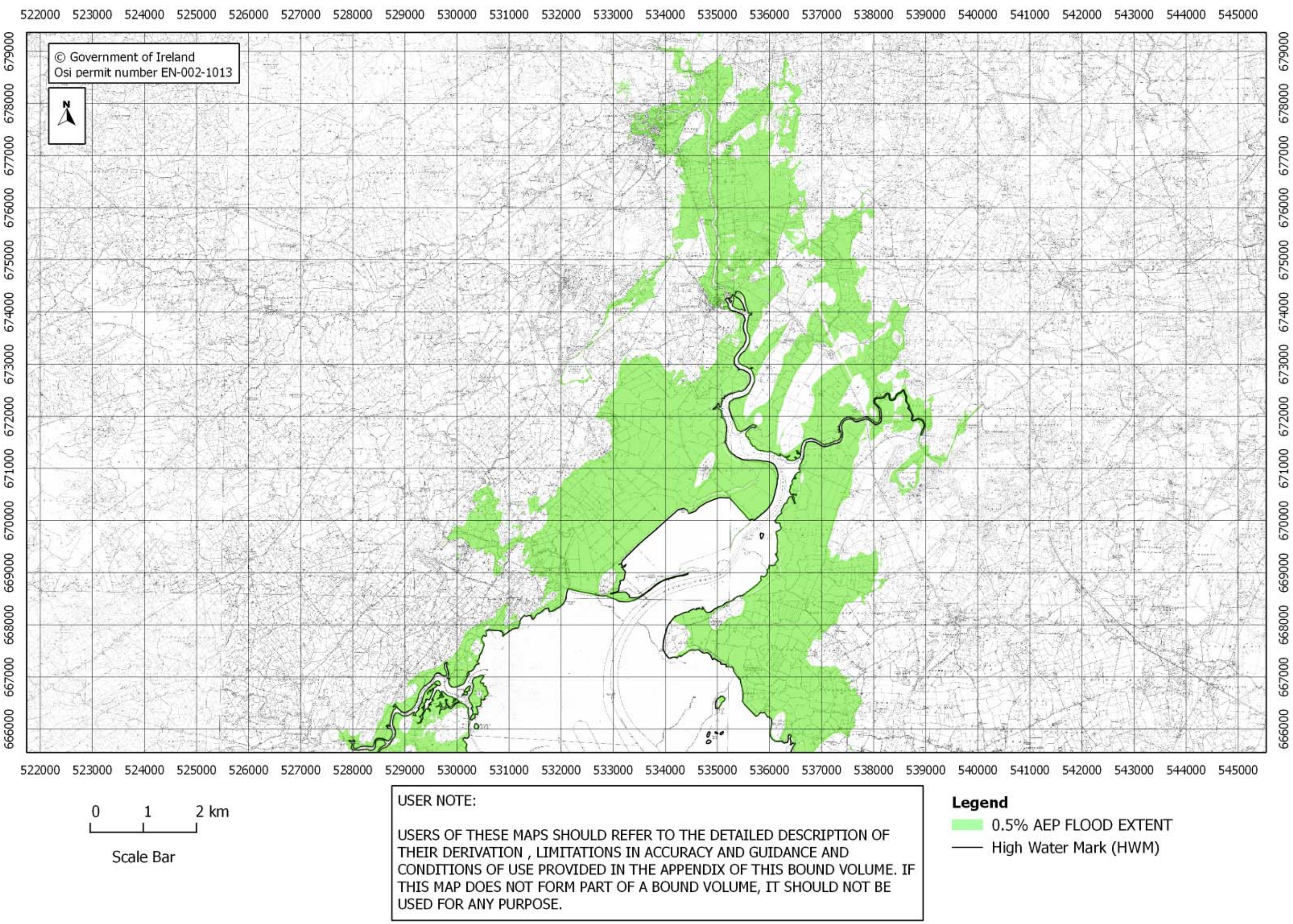


Figure 5.10: Ennis to Newmarket on Fergus Predictive Flood Extent Map, 0.5% AEP

6.0 Erosion Risk Assessment

6.1 Introduction

The work undertaken in Work Package 4A comprised a strategic level erosion hazard and potential risk assessment. The objective of this assessment was to estimate the future likely position of the coastline in the years 2030 and 2050 in areas considered to be vulnerable to erosion based on comparison of the best available current and historical mapping and aerial photography.

Such assessment was necessary to produce erosion maps to facilitate a strategic assessment of the erosion hazard and will provide valuable information for assessment of the economic value of assets at potential risk from erosion. The erosion mapping will also facilitate consideration by planners of the hazard and potential risks to future proposed development near the coastline (both strategic and non-strategic) at the planning stage.

It is also expected that the erosion maps will be of assistance to local authorities in respect of the management of the erosion hazard and potential risk and consequent social, economic and environmental impacts.

As the assessment is based entirely on the comparison of current and historical information it does not, at this stage, include a consideration of future climate change scenarios and the likely impact on erosion hazard and potential risk.

There were twelve separate Stages to the erosion risk assessment mostly involving work undertaken with the aid of a geographical information system (GIS). A brief description of the various tasks associated with and the outputs from each of these Stages is presented in the following sections.

6.2 Initial Screening of Potential Erosion Hazard Areas – Stage 1

To assist with the identification of potential erosion hazard areas the following datasets were collated, reviewed and compared:

- OSi 6 inch Scale Raster Map Series
- OSi 1: 5,000 Scale Raster Map Series
- OSi 1: 50,000 Scale Raster Map Series
- OSi 1995 ortho-photography
- OSi 2000 ortho-photography
- OSi 2005 ortho-photography
- The Coast of Ireland Aerial Oblique Imagery Survey, 2003
- The GSI Quaternary (Subsoil) Geological Mapping

The OSi 6 inch and 1:5,000 scale map series were reviewed and compared using a GIS. A significant change in the location of the high water mark (HWM) between the two datasets was used as a potential indicator of erosion. Similarly significant changes in coastal vegetation lines from a comparison of the available OSi ortho-

photography surveys (1995, 2000 and 2005) were used as a further potential indicator of erosion.

The Geological Survey Ireland (GSI) quaternary (subsoil) mapping was reviewed to identify soft geological subsoil or sediment types (e.g. sand beaches) that were potentially vulnerable to erosion and the OSi 1:50,000 scale, raster mapping was also reviewed to identify soft coastal areas e.g. sand beaches.

The coast of Ireland aerial oblique imagery survey 2003, (Reference 6) was reviewed to identify coastal areas and forms that showed evidence of erosion at the time of survey.

Coastal areas showing significant change based on the above assessment or potential for change were selected for further analysis. These areas of potential erosion hazard were defined spatially by 'clipping' the relevant sections of the HWM (vector dataset) whilst allowing a suitable tolerance or buffer at either end.

The output **coastal areas potentially at risk from erosion** were stored in GIS shape file format. A sample of this output is shown in Figure 6.1.

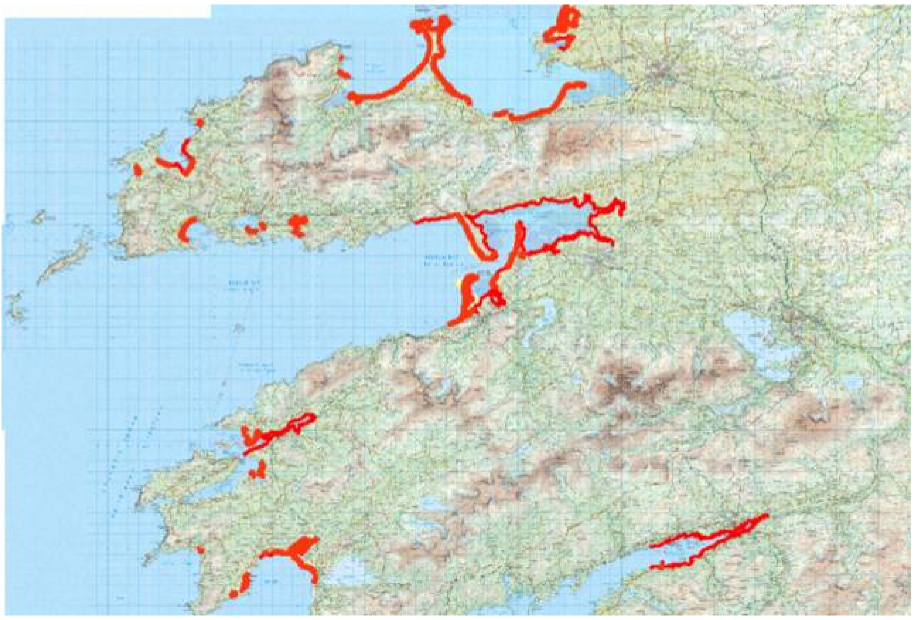


Figure 6.1: Sample Coastal Areas Potentially at Risk from Erosion

6.3 Selection and Georectification of OSi 1970's Aerial Photography – Stage 2

Based on the outputs from Stage 1, the required extent of the OSi 1970's aerial photography and the associated image tiles was identified using an OSi index of images (see Figure 6.2). As these image tiles were only available from OSi in a scanned raster (.tif) format and therefore had no assigned coordinate reference system, they required georectification for use on this project. The relevant images were carefully selected so as to cover all areas potentially at risk from erosion

(identified in Stage 1) and to achieve optimum accuracy in the georectification process.

Georectification requires access to a reference survey that has a known coordinate/geographic reference system. The reference survey has to be accurate and have similar spatial coverage to that of the 1970's aerial photography survey to allow comparison and to facilitate proper georectification. For this purpose a combination of the OSi 2000 and 2005 ortho-photography was used.

To georectify the 1970's survey images, common point locations on both survey images were selected and linked using GIS. Such common points were generally those associated with man made structures or locations that have not moved between surveys and are clearly and precisely identifiable in both surveys. Typically these points would include the intersection of roads and/or intersection of boundary walls. Residential properties generally do not provide ideal common points, as they are not always clearly visible on survey imagery.

In less developed or rural areas, field corners can offer the best available common points. Areas with less frequent common points may therefore be less accurate in their georectification relative to those with more frequent common points. Once sufficient common points had been identified and selected the survey images were processed using a GIS transformation to calculate the coordinate for each image pixel and the output data was saved in a useable format e.g. ERDAS .IMG format file.

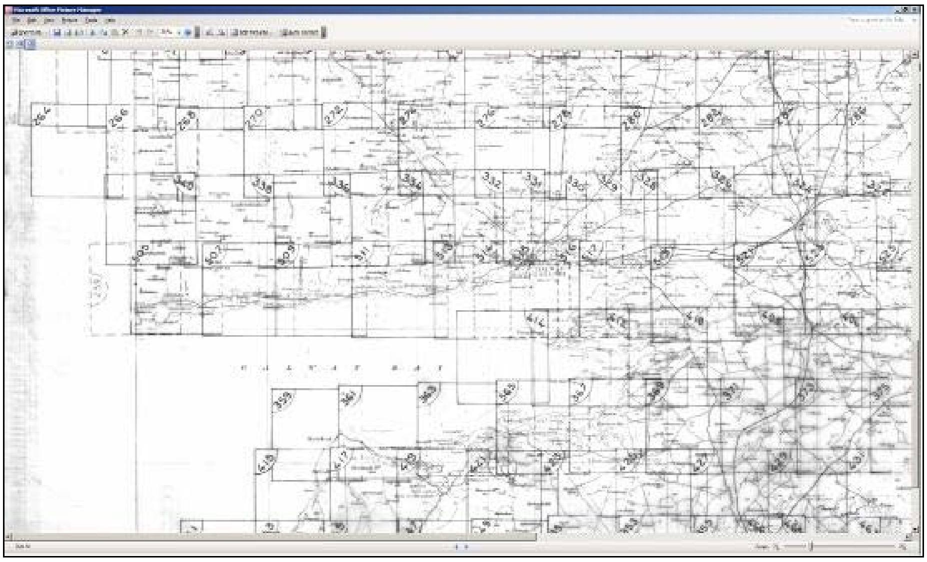


Figure 6.2: Sample OSi Index of Images

A sample of georectified OSi 1970's aerial photography from the south west coast relative to the OSi 1:50,000 scale raster map is shown in Figure 6.3.

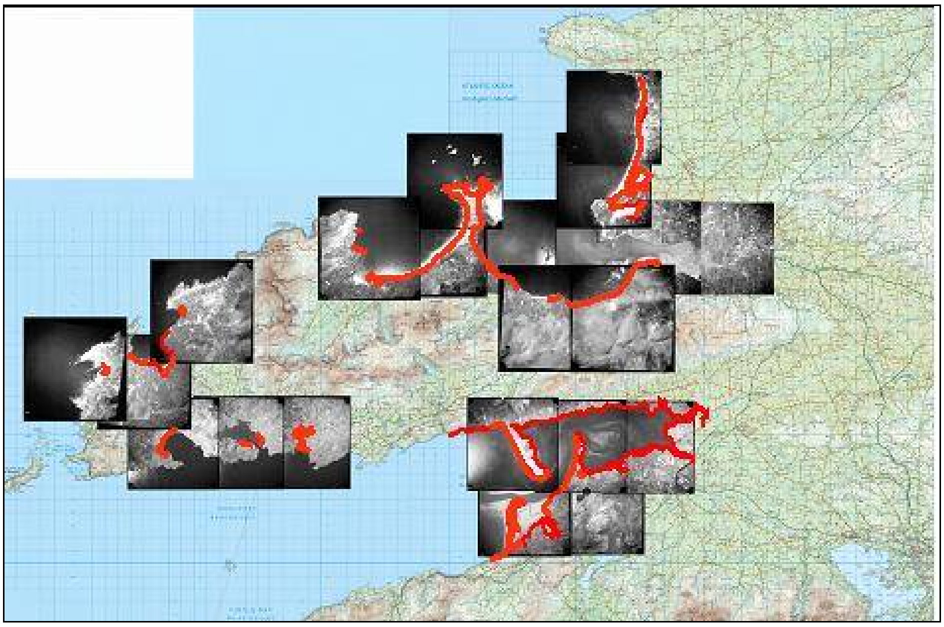


Figure 6.3: Sample Georectified OSi 1970's Aerial Photography

6.4 Digitising the 2000 Coastal Vegetation Line (Baseline) – Stage 3

The coastal vegetation line from the OSi 2000 ortho-photography survey was digitised for the entire length of the south west coastline using GIS. The line was identified visually by following the seaward limit of coastal vegetation (or man made structure if prominent on the coastline) as accurately as possible. The digitisation was generally undertaken at a scale of 1:2,000 in order to obtain sufficient accuracy.

A sample of the 2000 coastal vegetation line (baseline) derived from Stage 3 is shown in red outline in Figure 6.4 for part of the Dingle Bay coastline.

Figure 6.4: Sample OSi 2000 Ortho-Photography with Digitised Coastal Vegetation Line (shown red)

6.5 Digitising the 1970s Coastal Vegetation Line – Stage 4

The coastal vegetation line from the OSi 1970's aerial photography survey was similarly digitised following georectification of this imagery as outlined in Stage 2. The same digitisation method as for the 2000 vegetation line was generally used. However some reference to OSi raster maps and more recent colour ortho-photography was necessary to verify some of the coastal features in the monochromatic (black & white) 1970's images.

6.6 Digitising the 2005 Coastal Vegetation Line – Stage 5

The coastal vegetation line from the OSi 2005 ortho-photography survey was also digitised as per the method used for the 2000 vegetation line, described in Stage 3. The geographic coverage of this line, however, is the same as that of the 1970's vegetation line.

This 2005 vegetation line can be used to estimate more recent erosion rates, e.g. based on comparison of the 2000 and 2005 surveys, and can assist in highlighting any significant change (either increase or decrease) in the rate of erosion when compared to that derived from the 1970's and 2000 surveys. This may in some cases highlight anomalies that need further consideration in the determination of the final predictive erosion lines.

6.7 Preparation for Erosion Rate Calculation – Stage 6

To facilitate automated calculation of the "Annual" erosion rate the 2000 coastal vegetation line (baseline) was 'split' into smaller line segments of approximately 25m length. This was done automatically using the GIS, ET Geo Wizard tools. Each of these 25m line segments were then transformed to generate a single point that was located midway along the line segment. These points had the same identity (ID) and attributes as the original line segment from which they were derived. A separate GIS point shape file was thus generated.

These points were then subsequently used to compute the shortest distance between the 2000 and 1970's vegetation lines or other vegetation lines as required (e.g. between 2000 and 2005 vegetation lines). The ET Geo Wizard tools were used, as there were no such tools available within the ArcGIS software.

The primary outputs from Stage 6 were a GIS shape file 'split' into 25m length segments (2000 segmented vegetation line shape file) and a further GIS point shape file at approximately 25m intervals (2000 vegetation line point shape file).

6.8 Creation of Distance Raster(s) for Erosion Rate Calculation – Stage 7

To calculate historical erosion rates based on a comparison of the 2000 and 1970's coastal vegetation lines or surveys, it was first necessary to generate a distance raster associated with and referenced to the 1970's vegetation line. A second distance raster associated with and referenced to the 2005 coastal vegetation line was also required to facilitate calculation of historical erosion rates between the 2005 and 2000 ortho-photography surveys.

These distance rasters (1970's & 2005) were created using the distance tools in ArcGIS, Spatial Analyst software. The 1970's distance raster cells had a value based on their distance from the 1970's vegetation line and the raster extended for a distance of 100m either side of the reference vegetation line (this was deemed sufficient to encompass all observed positions of the various survey vegetation lines).

As these distance rasters had large storage requirements they were 'split' into manageable units to facilitate the distance calculations e.g. the raster covering the south west coast was sub-divided into four separate geographic units. The raster produced for one such unit, having a grid resolution of 0.5m (square), was approximately 30GB in size but was compressed to 1.5GB in a geo-database.

As the minimum raster grid resolution was 0.5m this also defined the accuracy of the distance calculation between coastal vegetation lines. A sample of the 1970's distance raster for the 1970's coastal vegetation line is presented in Figure 6.5.

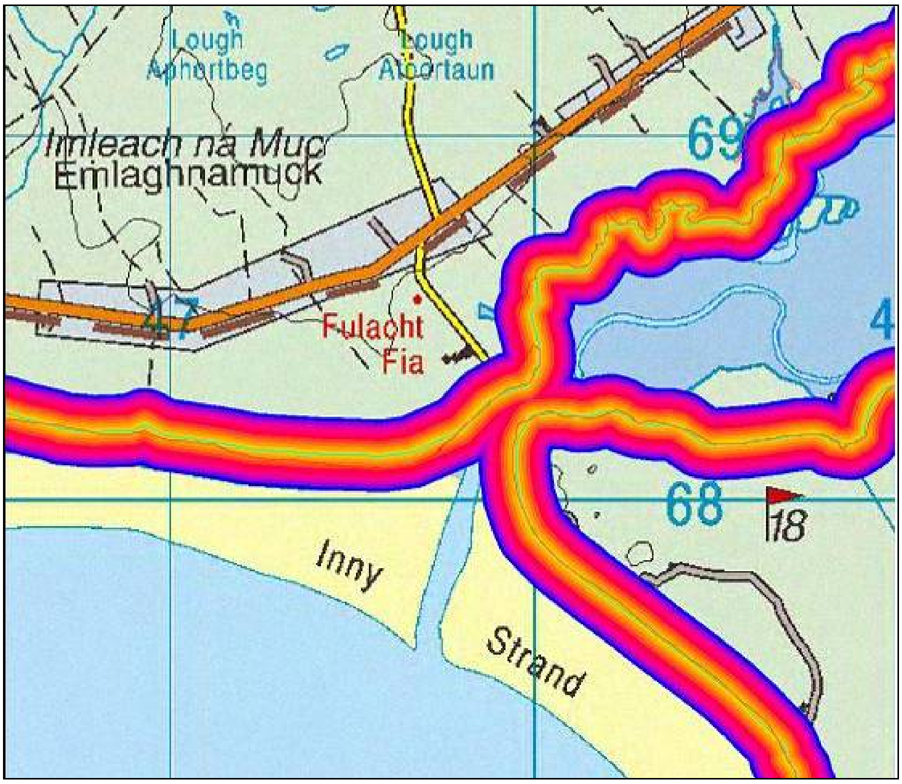


Figure 6.5: Sample of Distance Raster for 1970's Coastal Vegetation Line

6.9 Erosion Rate Calculations – Stage 8

The calculation of erosion rate was undertaken by combining the outputs from Stage 6 (2000 vegetation line point shape file) and Stage 7 (distance raster) using the surface tools in ArcGIS 3D Analyst software.

The distance values between the 2000 and 1970's coastal vegetation lines were thus calculated at 25m intervals and added as an attribute to a new 2000 vegetation line point shape file table. This distance value was then subsequently divided by the number of years between the vegetation line surveys (27 years in the case of the 1970's/2000 surveys comparison) to calculate the historical "annual" erosion rate at each point.

The first output from Stage 8 was therefore an updated 2000 vegetation line point shape file with additional attributes of distance and more significantly "annual" erosion rates for each 25m segment of the coastline considered in the analysis.

This information was then joined back to a revised 2000 segmented vegetation line (from Stage 6) using a table join GIS functionality based on a common line segment identity (ID). The updated 2000 segmented vegetation line so produced incorporated the erosion rate and accretion rate information. This line could then be classified to show the variation in erosion or accretion rates along the coastline as calculated. As this shape file included both erosion and accretion, some further analysis was required to isolate the areas of erosion from those of accretion.

Two erosion rate values were calculated for each line segment based on comparison of the 2000 coastal vegetation line (baseline) with both the 1970's and 2005 lines. Whilst these could be used to check and compare the results and to identify possible localised anomalies, it was the erosion rates based on the comparison of the 1970's and 2000 vegetation lines which were generally considered the more reliable and representative.

The primary output from Stage 8 included a rate of coastal change shape file (both erosion and accretion) that was geographically referenced to the 2000 coastal vegetation line (baseline) as shown in Figure 6.6.

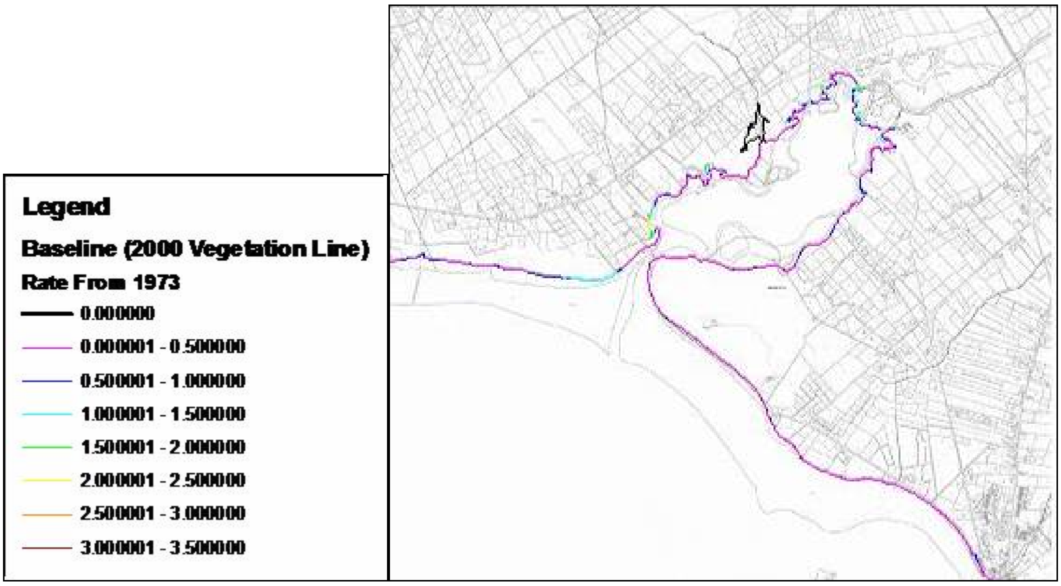


Figure 6.6: Sample of Calculated Erosion Rates Line

6.10 Erosion Set Back Calculations for 2030 and 2050 – Stage 9

The rate of coastal change shape file from Stage 8 was adapted to produce set back distance attributes associated with both the 2030 and 2050 coastlines in erosion areas only. This was achieved by simply multiplying the previously calculated "annual" erosion rates by 30 (years) and 50 (years) respectively.

The output from this Stage 9 was an erosion shape file similar to that from Stage 8 but with additional set back distance attributes.

6.11 Creation of 2030 and 2050 Draft Erosion Lines – Stage 10

The draft 2030 and 2050 predictive erosion lines were generated from the output shape file from Stage 9 using the ArcGIS, Buffer Wizard tool. This tool gives the option of creating a buffer to the Stage 9 output shape file based on the set back distance attributes calculated in that Stage.

The buffer tool generated a polygon surrounding both sides of the Stage 9 shape file i.e. landward and seaward. This polygon was then converted to a polyline by deleting the information seaward of the reference baseline from Stage 9.

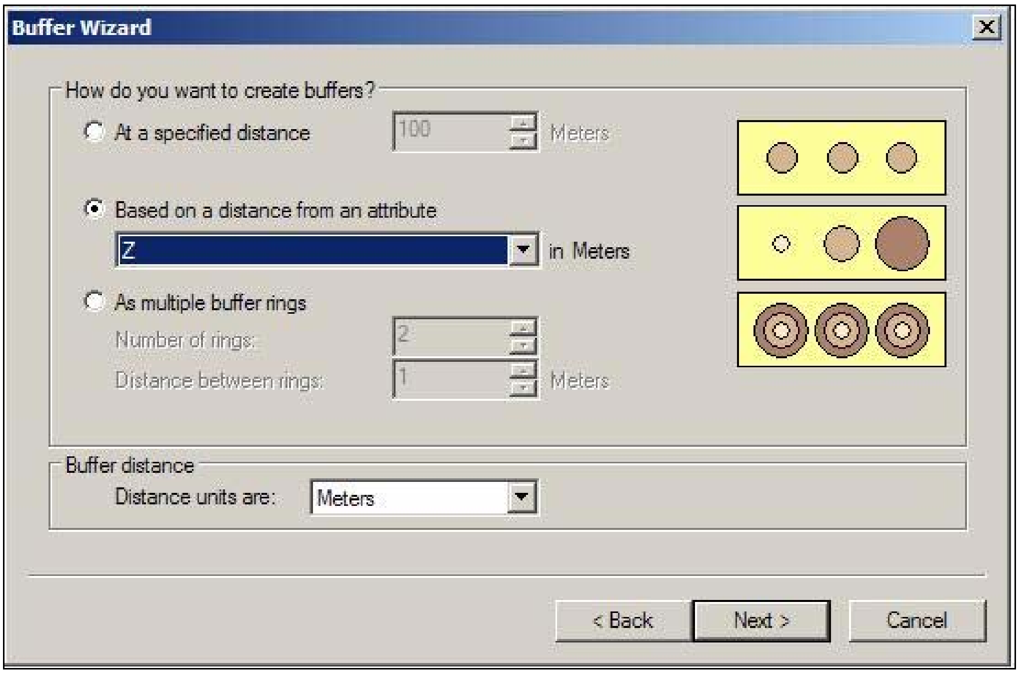


Figure 6.7: Example of Buffer Menu Used to Produce Erosion Lines

The output from this Stage 10 included two separate draft predictive erosion lines in GIS shape file format, one for 2030 and the other for 2050.

6.12 Final 2030 and 2050 Erosion Lines – Stage 11

The 2030 and 2050 draft predictive erosion lines produced in Stage 10 were subsequently reviewed and quality controlled. In particular the transitions between adjacent coastal locations that had significantly different erosion rates or perhaps no historic erosion were reviewed and amended.

Firstly the calculated "Annual" erosion rates shape file was interrogated to establish all locations where the calculated "Annual" erosion rate was less than 0.1m i.e. there had been approximately less than 3m of "observed" movement in the position of the coastal vegetation line between the 1970's and 2000. Any 2030 and 2050 erosion setback lines shown in locations corresponding to "Annual" erosion rates of <0.1m were deleted as the amount of coastal change required to produce this was considered within the probable error margin of the geo-rectification.

The remaining draft predictive erosion lines were then reviewed in conjunction with the available GSI quaternary (subsoil) geological mapping to see if any changes in geology landward of the 2000 coastal vegetation line (baseline) would impact upon the draft erosion lines or associated erosion rate(s) and adjustments made. Transitions between areas of different erosion rate were also reviewed at this time

based on consideration of the natural coastal form and changes in underlying geology.

The outputs from this Stage 11 were the final 2030 and 2050 predictive erosion lines all in GIS shape file format.

6.13 Final Erosion Hazard Map Production – Stage 12

Once the final erosion lines shapefiles were created in Stage 11, ArcGIS was used to batch produce pdf format maps for the south west coast using the Data Driven pages tool. The templates used for previous ICPSS erosion hazard map production were adapted to facilitate this process. Once the maps were produced they were subject to final review and checking.

6.14 Summary of Primary Outputs

A summary of the staged outputs from the erosion risk assessment methodology is given below: -

- Coastal areas potentially at risk from erosion (Stage 1)
- 1970's georectified coastal aerial photography (Stage 2)
- Digitised 1970's, 2000 and 2005 coastal vegetation lines (Stages 3 - 5)
- 2000 segmented vegetation line and associated point shape file (Stage 6)
- Distance rasters for 1970's and 2005 coastal vegetation lines (Stage 7)
- Rate of coastal change shape file relative to 2000 baseline (Stage 8)
- Erosion setback shape file (Stage 9)
- Draft 2030 and 2050 predictive erosion lines (Stage 10)
- Final 2030 and 2050 predictive erosion lines (Stage 11)
- Complete set of predictive erosion maps, in GIS shape file and pdf formats, for each study area (Stage 12)

6.15 Discussion of Results

The erosion maps were produced primarily as a tool to identify any assets which were likely to be affected by coastal erosion by 2030 and 2050. In developing the erosion lines the coast was divided into nominal lengths, of circa 25m and an annualised average rate of coastal retreat applicable to each sector established using GIS techniques. The resulting draft erosion lines were reviewed by an experienced Coastal Engineer and the transitions between the various sectors modified based on an assessment of coastal form and underlying geology as derived from the GSI quaternary (subsoil) geological mapping. The GSI data was also used to refine the spatial extent of the erosion maps by ensuring that no known non-erodible areas were included with the area identified as being vulnerable to erosion.

The analysis of coastal erosion along the south west coast indicated that there was generally little potential risk associated with coastal erosion in the urban areas, primarily due to the fact that the urbanised areas are mostly located on naturally resilient coastline or protected by man-made defences.

The mean annualised erosion rate of all areas along the study coastline where an erosion hazard was identified was approximately 0.5 metres. The maximum annualized erosion rate identified throughout the study coastline occurred at Ventry Strand, County Kerry and equated to a rate of 3.12 metres. However the mean annualised erosion rate at Ventry Strand was 0.71 metres. The highest mean annualised erosion rate of 1.03 metres occurred at Beale, County Kerry. The maximum annualized erosion rate in County Clare was 3.11 metres and occurred at Kilcredaun. The highest mean annualised erosion rate in County Clare was 0.57 metres at Seafield.

The highest annual rates of erosion i.e. greater than 2 metres occurred in rural areas. Additionally the mean annualised erosion rate in rural areas was approximately 0.5 metres against 0.3 metres in urban areas. The urban areas identified at potential risk of coastal erosion mostly have sea defences protecting them. The primary areas of potential coastal erosion risk are mostly rural with a few exceptions.

Rural areas without sea defences are considered to be at most risk from coastal erosion.

6.16 Uncertainty and Limitations of Erosion Lines

Where the coastline was defended at the time of the original aerial survey and is still protected today no erosion lines were produced as it was not possible to quantify the erosion rate. Also no specific consideration was taken of defences introduced since the original aerial survey i.e. if the comparison of the 1970's and later coastlines showed a detectable change in the position of the coastline, an erosion rate was established and erosion lines produced. Thus in some areas erosion lines may be shown where there are presently coastal protection works in place. In these areas the extent of the erosion hazard is likely to be an under-estimation of the potential area vulnerable to erosion due to the influence of the introduction of coastal protection works at some time during the assessment period on the derivation of the annual erosion rate. At the same time the present actual erosion hazard and potential risk is possibly over-predicted since the coastal defence structures will prevent or reduce the rate of coastal change for some time.

The erosion lines also do not take any account of future variation in erosion rates due to climate change, planned coastal protection or dredging works, failure of coastal defence works or other potential changes of a geological nature.

A confidence analysis of the erosion lines, similar to that on the east and south coast, was not undertaken on the south west coast.

6.17 Presentation of Erosion Maps

Due to the spatial extent of the study area and the number of datasets derived during the course of the erosion assessment it was not practical to present all of this information pictorially in this report. However the primary outputs, being the 2030 and 2050 estimated erosion extents, are presented completely in Appendix 4. These

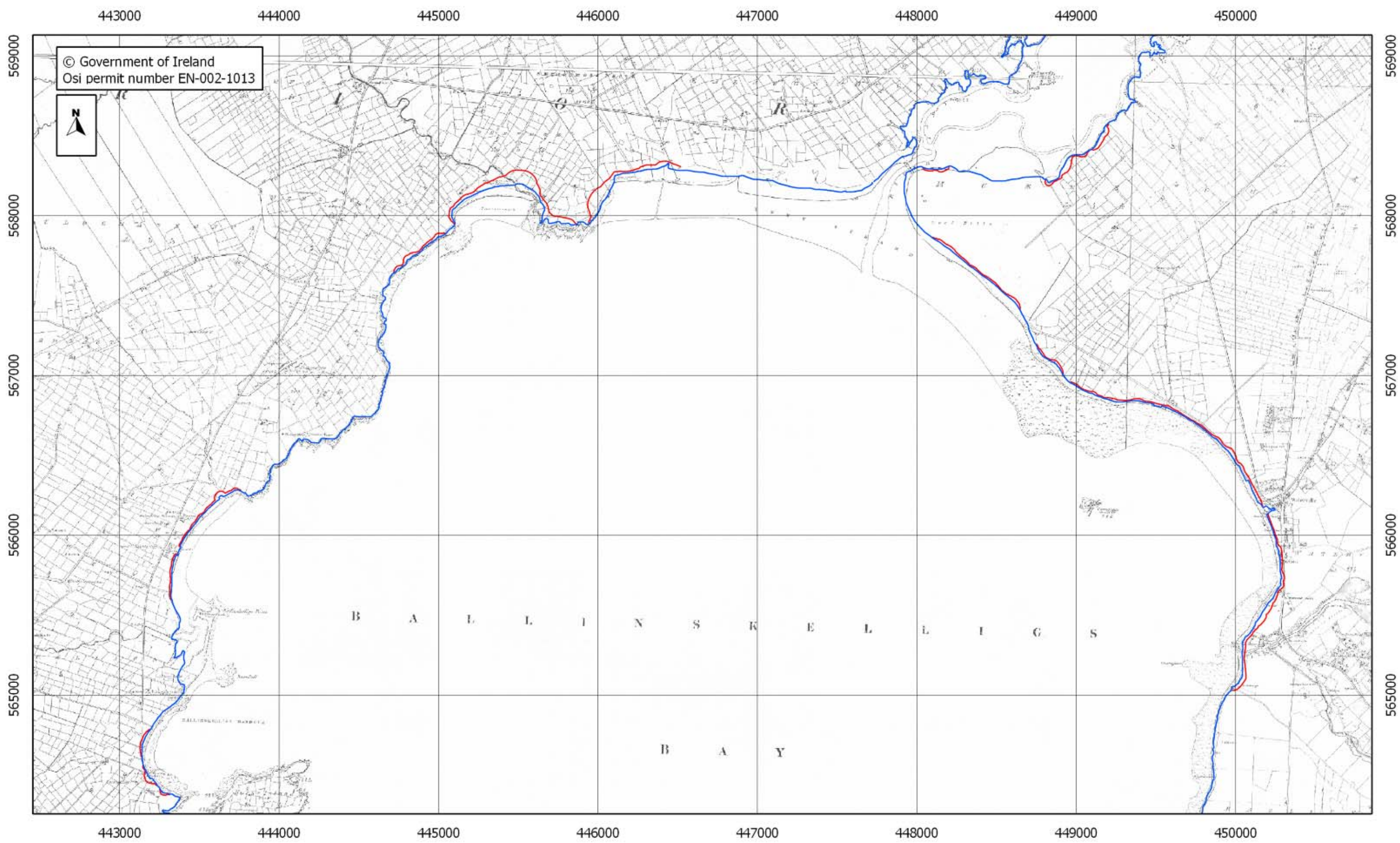
datasets are also presented on CD in digital form (ArcGIS shape files) as Appendix 5 of this report.

A review of the erosion maps generated throughout the study area showed that there were seven primary areas of potential significant coastal erosion hazard as follows:

- Waterville to Ballinskelligs, Co. Kerry
- Rossbehy to Cromane, Co. Kerry
- Fermoyle to Tonakilly, Co. Kerry
- Ballyheige to Banna, Co. Kerry
- Ballybunnion, Co. Kerry
- Seafield to Quilty, Co. Clare
- Lehinch, Co. Clare

Erosion maps for each of these seven primary areas of potential coastal erosion hazard were prepared and are shown on Figure 6.8 to Figure 6.14 for the year 2050. These primary areas of potential coastal erosion hazard were selected on the basis of the substantial geographic extent of the erosion threat identified, the rate of erosion and the lack of existing coastal protection structures evident from a review of the available mapping and aerial photography.

Whilst every effort has been made throughout this study to optimise the accuracy of the erosion hazard maps, there are unavoidable inaccuracies and uncertainties associated with these maps. These uncertainties are discussed in this report and are highlighted in the disclaimer and guidance notes appended to this report. All mapping presented in this report should be read in conjunction with these appended disclaimers and guidance notes (Refer Appendix 4).



0 0.5 1 km

Scale Bar

USER NOTE:

USERS OF THESE MAPS SHOULD REFER TO THE DETAILED DESCRIPTION OF THEIR DERIVATION , LIMITATIONS IN ACCURACY AND GUIDANCE AND CONDITIONS OF USE PROVIDED IN THE APPENDIX OF THIS BOUND VOLUME. IF THIS MAP DOES NOT FORM PART OF A BOUND VOLUME, IT SHOULD NOT BE USED FOR ANY PURPOSE.

Legend
- Denotes 2050 Erosion Lines
- Denotes 2000 Baseline / Vegetation Line

Figure 6.8: Waterville to Ballinskelligs, 2050 Erosion Map

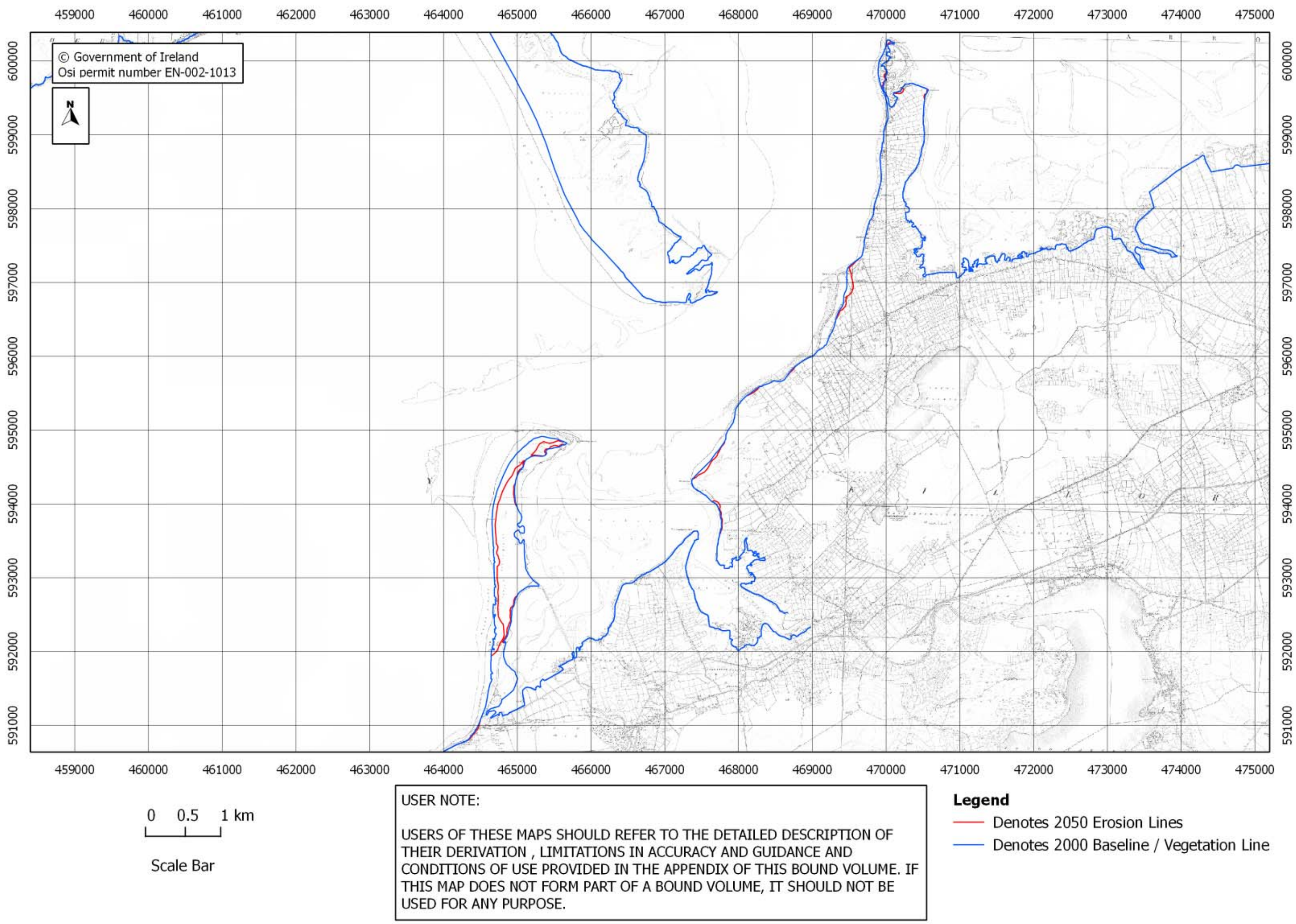


Figure 6.9: Rossbehy to Cromane, 2050 Erosion Map

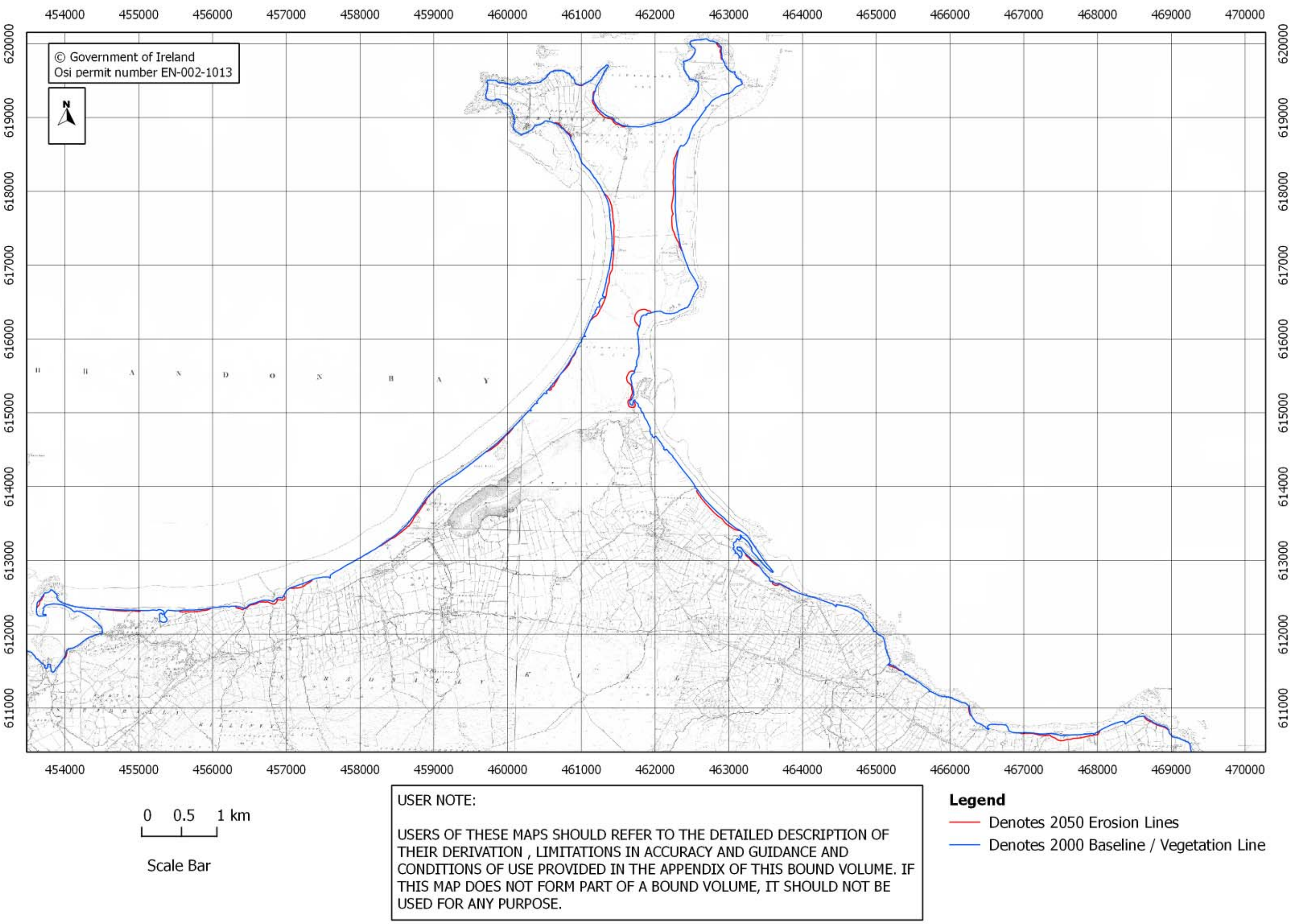


Figure 6.10: Fermoyle to Tonakilly, 2050 Erosion Map

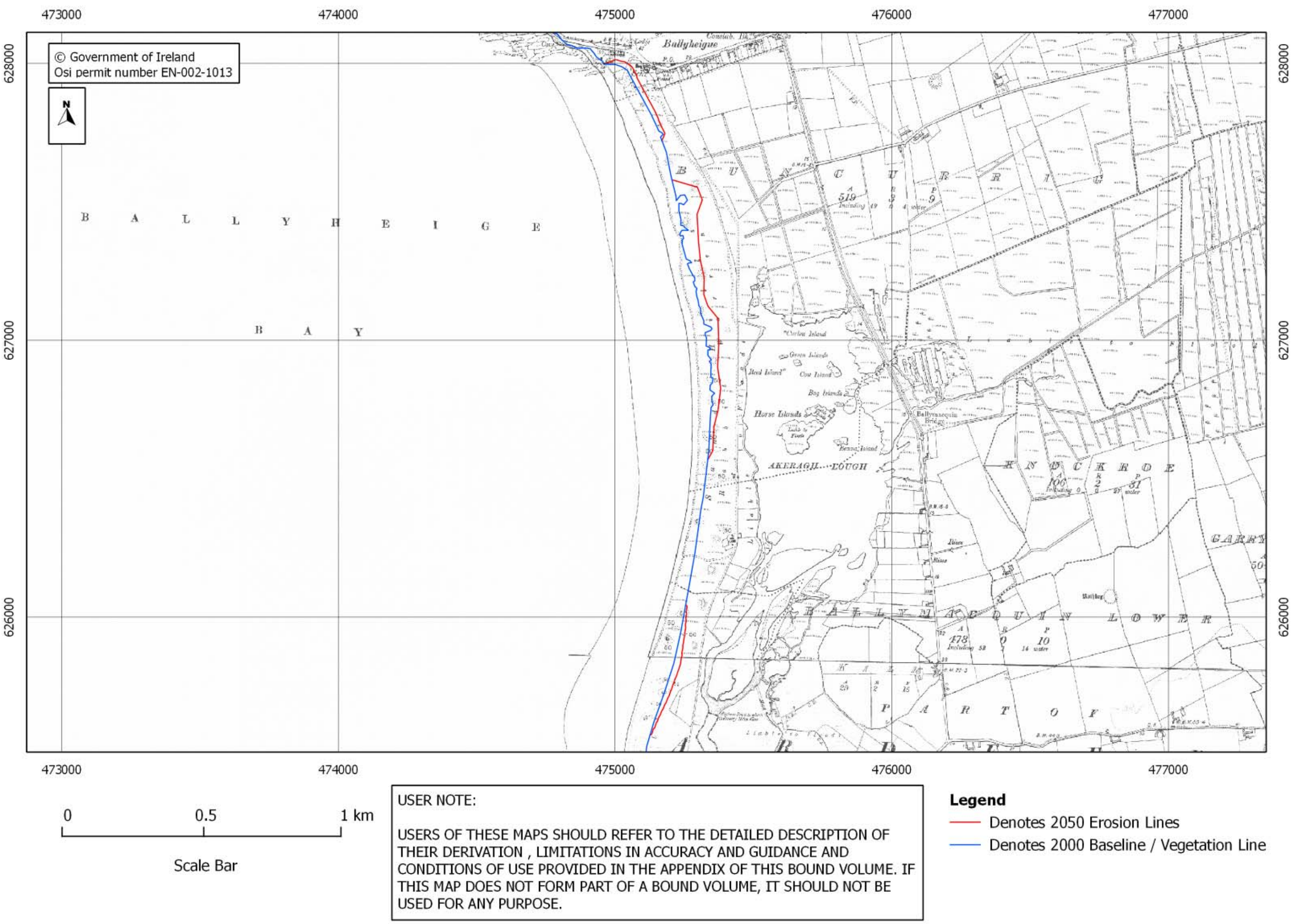


Figure 6.11: Ballyheige to Banna, 2050 Erosion Map

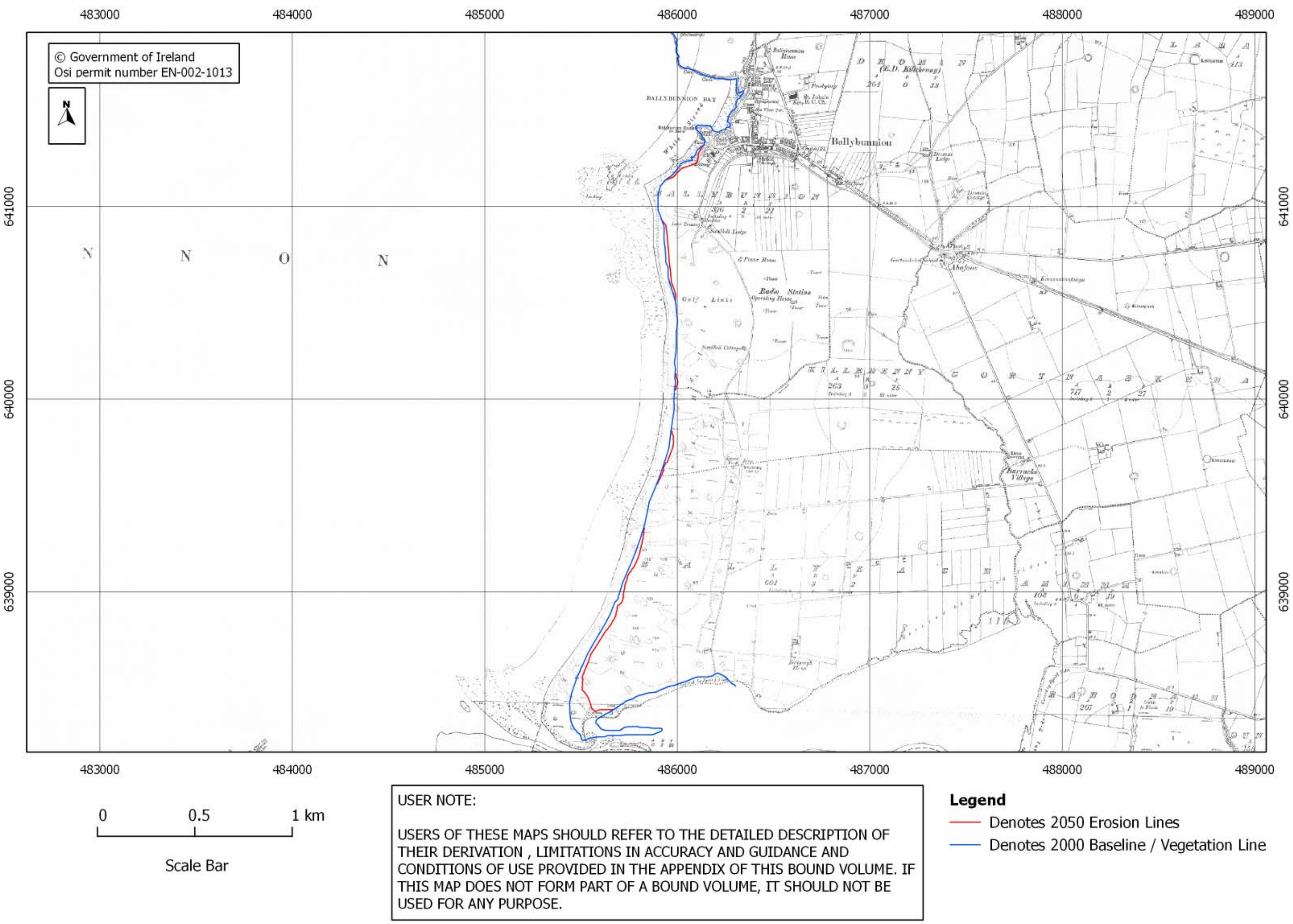


Figure 6.12: Ballybunnion, 2050 Erosion Map

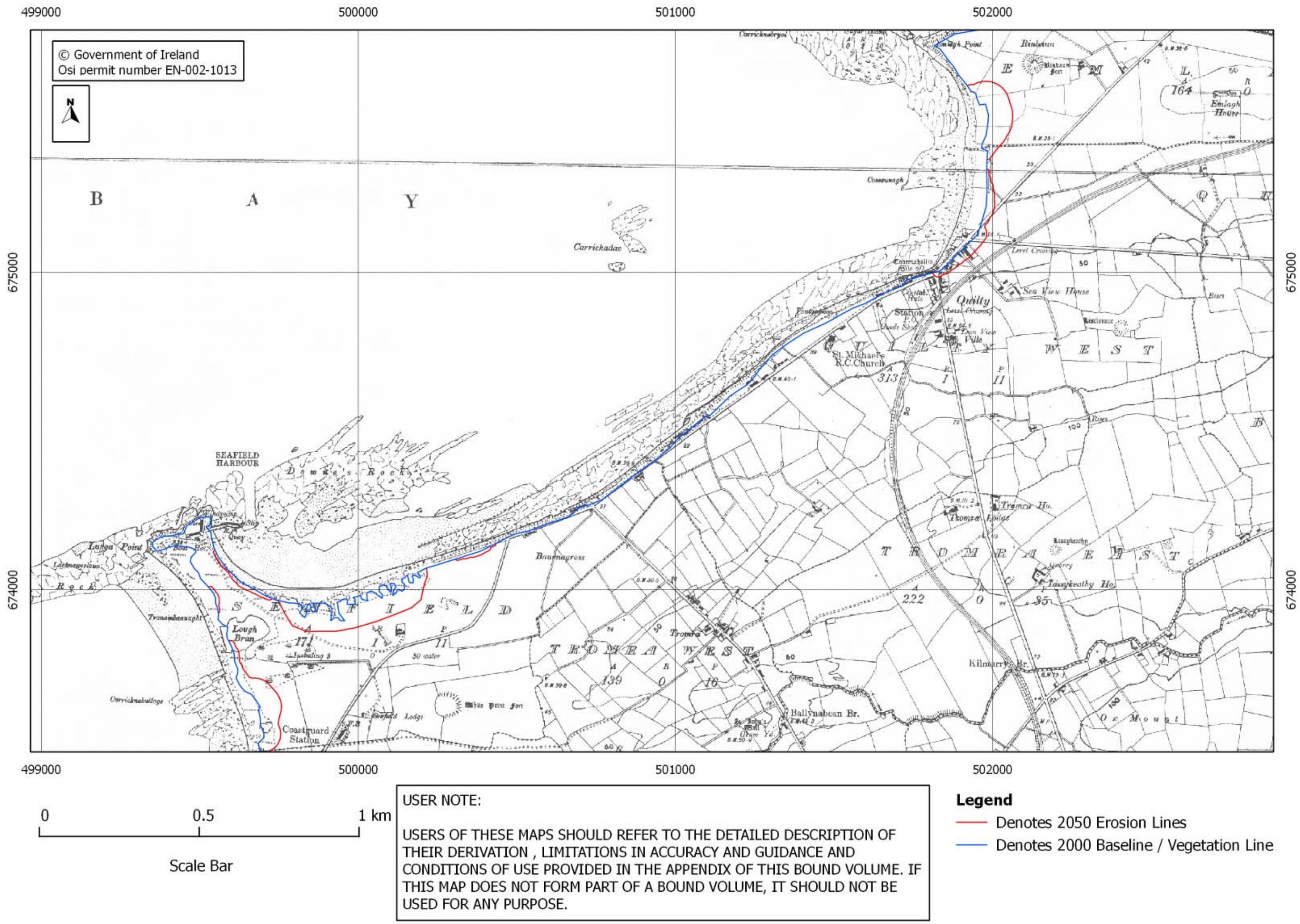


Figure 6.13: Seafield to Quilty, 2050 Erosion Map

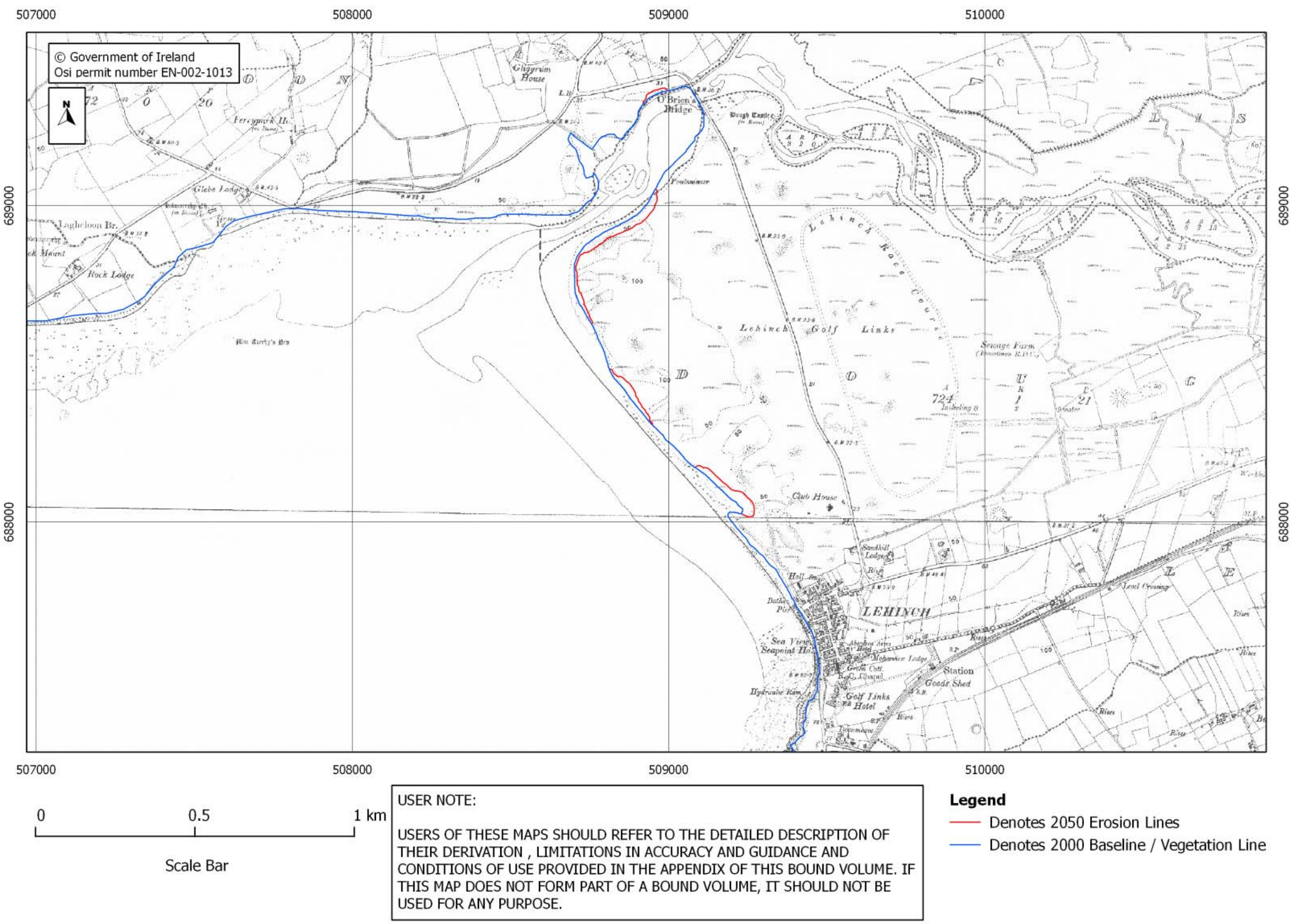


Figure 6.14: Lehinch, 2050 Erosion Map

7.0 Conclusions and Recommendations

7.1 Conclusions

The conclusions of Phase 4 of the Irish Coastal Protection Strategy Study are as follows:-

1. The approach of combining synthesised data from the Irish Seas Tidal Surge Model (ISTSM) with available tide gauge data and undertaking joint probability analysis to derive extreme water levels around the coastline as applied to the south east and north east coast was not appropriate to the south west coast due to a lack of reliable historic tide gauge data. Consequently an extreme value analysis of total water levels was carried out for the south west coast which has worked satisfactorily for this section of coastline.

2. The limited availability of historic and present tide gauge records was a significant problem with the flood hazard assessment aspects of the study as it made model calibration and validation difficult.

3. The extreme value analysis of total water levels undertaken in this study showed that relatively narrow confidence limits can be achieved using the applied methodology and thus the extreme water levels derived are considered to be of sufficient accuracy not only for this strategic level study but also for more detailed investigations. The estimated accuracy of the total water levels presented in this report at 95% confidence limits is ±180mm relative to OD Malin for both the 0.1% and 0.5% AEP events. It should be noted that not all areas within the Shannon Estuary model domain may have water levels predicted within this tolerance, as calibration data was only available in certain areas, and only limited bathymetry information was available for parts of the estuary. However, this was considered when choosing the prediction point locations within the Shannon Estuary. It should also be noted for this reason that all prediction points east of the Fergus Estuary hold less reliability than those to the west.

4. The accuracy of the floodplain analysis undertaken was found to be very reliant on the availability of accurate Digital Terrain Models. Notwithstanding this and given the limited accuracy of the NDHM data, flood extents of sufficient accuracy can still be derived for strategic purposes, albeit at lower levels of confidence compared to those derived using LiDAR based Digital Terrain Models. For the purposes of the flood extents shown in Appendices 3A and 3B a very low confidence (less than 40%) may be assumed, at least for those flood extents not derived from LiDAR DTM data.

5. A strategic level flood hazard and potential risk assessment for the study coastline has been completed and predictive coastal floodplain maps prepared showing both the extreme flood extent representing the 0.1% AEP and the indicative flood extent representing the 0.5% AEP. These maps,

together with flood depth maps for the 0.5% AEP, are presented at a scale of 1:25,000 in Appendices 3A and 3B of this report.

6. A review of the predictive floodplain mapping showed potential coastal flood risk, to predominantly occur in or near coastal settlements with four primary areas of potential coastal flood hazard identified for the south west coast as follows: Castlemaine Harbour, Tralee to Derrymore, Ballyheige to Barrow and Moneycashen to Finuge. A further five areas were identified for the Shannon estuary, Foynes to Aughinish, Newtown to Adare, Limerick City, Shannon to Portdrine and Ennis to Newmarket on Fergus.

7. Previous phases of this study have demonstrated that comparison of historical and current aerial photography can be used to determine historic coastline changes and annualised rates of erosion to a level of accuracy sufficient for strategic assessment purposes. The principal source of inaccuracy in the resulting analysis is the geo-referencing and rectification of the historic aerial photography.

8. A strategic level erosion hazard assessment for the study coastline has been completed and predictive erosion maps prepared for the years 2030 and 2050. These maps are presented at a scale of 1:25,000 in Appendix 4 of this report.

9. A review of these erosion extent maps showed that there were seven primary areas of potential significant coastal erosion hazard identified as follows: Waterville to Ballinskelligs, Rossbehy to Cromane, Fermoyle to Tonakilly, Ballyheige to Banna, Ballybunnion, Seafield to Quilty and Lehinch.

10. In contrast to the assessment of coastal flood hazard and potential risk, the coastal erosion assessment along the south west coast has indicated that there is generally little threat from erosion in the urbanised areas. This is primarily due to the fact that the urbanised coastline is mostly either naturally resilient or protected by man-made defences and hence analysis of the aerial photography did not detect any coastline change in the assessment period.

11. The mean annualised erosion rate of all areas along the study coastline where an erosion hazard was identified was approximately 0.5 metres. The maximum annualized erosion rate identified throughout the study coastline occurred at Ventry Strand, County Kerry and equated to a rate of 3.12 metres. However the mean annualised erosion rate at Ventry Strand was 0.71 metres. The highest mean annualised erosion rate of 1.03 metres occurred at Beale, County Kerry. The maximum annualized erosion rate in County Clare was 3.11 metres and occurred at Kilcredaun. The highest mean annualised erosion rate in County Clare was 0.57 metres at Seafield.

12. It is anticipated that the strategic coastal flood and erosion extent maps produced in this study will be of particular interest to local authority planners in considering such potential threats to future proposed development at the planning stage. This information has been referenced in the publication

"The Planning System and Flood Risk Management, Guidelines for Planning Authorities, Nov 2009".

13. It is anticipated that these strategic flood and erosion maps will also be of assistance to local authorities and emergency services generally in respect of the management of potential risk and its likely social, economic and environmental impacts.

14. These flood and erosion maps may also be used to undertake strategic assessment of the economic value of assets at risk from both coastal flooding and erosion.

15. Whilst every effort has been taken throughout this study to optimise the accuracy of the flood and erosion maps produced, there are unavoidable inaccuracies and uncertainties associated with these maps. These uncertainties are discussed and highlighted throughout the report and in the disclaimer and guidance notes appended to this report.

7.2 Recommendations

The recommendations of this study are as follows:-

1. In view of the limited availability of historic and present tide gauge records encountered during this study, it is recommended that OPW improve and expand the tide gauge network in Ireland since high quality observational data is essential and cannot be completely replaced by numerical simulations. The scarcity of good quality historical records is particularly relevant in establishing joint probability relationships between extreme wave and water levels.

2. OPW and coastal Local Authorities should engage with each other in relation to the findings of this report with a view to developing appropriate strategies for the management of the identified coastal flood and erosion hazards and associated risks.

3. It is recommended that the potential impacts of climate change be incorporated into the findings of these coastal flood and erosion assessments as soon as possible.

Glossary of terms

Admiralty Tide Tables	Daily predictions, times and heights of the high and low waters for UK and Ireland ports produced by the United Kingdom Hydrographic Office
AEP	AEP denotes Annual Exceedance Probability. This is the probability of an event occurring or being exceeded in any one year. For example a 0.5% AEP event has a 0.5% probability (or 1 in 200 chance) of occurring or being exceeded in any one year. Similarly, a 0.1% AEP event has a 0.1% probability (or 1 in 1000 chance) of occurring or being exceeded in any one year.
ArcGIS software	A collection of Geographical Information Systems software used for authoring, serving, analysing and publishing geographic information.
Astronomic tides	Daily change in sea water levels due to the rotation of the earth and the gravitational forces of the sun and moon along with the hydrodynamic response to the bathymetry.
Bathymetry	Data giving the depth of a large water body to provide the underwater topography.
Charnock Parameter	The wave age dependency of the non-dimensional sea surface roughness
Chi-Square	A statistical calculation that tests the goodness of fit of observed values compared to theoretical probability, and determines whether it is likely to occur by chance or is atypical. i.e the greater difference between observed and expected frequencies, the more likely it is statistically significant.
C-Map	Part of the Mike Suite of Software, enabling bathymetry data to be extracted for modelling purposes.
Confidence Limits	Two statistics that form the upper and lower bounds of a confidence interval and predict the range of values within which a particular parameter lies. For example, the 95% confidence limits would encase 95% of the data between two boundaries, with 2.5% of the overall data removed at either end.
Coriolis Acceleration	The acceleration experienced by a mass moving in a north south direction due to the Earth's rotation.
Correlation Coefficients	The measure of interdependence of two or more variables that range in value from a positive or negative number. A correlation coefficient of 0 indicates no relationship whereby +/-1 indicates a perfect positive/negative relationship.
Datum (geographic)	An imaginary surface or set of points used to define the size and shape of a geoid on the earths surface and the base point from which heights and depths of all other points on the earth's surface are measured.
Dfs2 Files	Marine GIS two dimensional grids used as part of the Mike Suite of Software, often used to display hydrodynamic data, for example model results or input climatic conditions or bathymetry.

DGPS	Differential Global Positioning System: improves the accuracy and reduces the errors in the position measured by a GPS receiver.
DTM	A Digital Terrain Model is a digital representation of a ground surface topography or terrain. It is often represented as a grid of squares or raster image and is generated from the interpolation of ground point data e.g. LiDAR ground point data.
Ebb tide /flow	The period / flow between high water slack and low water slack.
ECMWF	European Centre for Medium Range Weather Forecasts: International meteorological organisation funded by large number of European national meteorological services.
Ekman Layer	Boundary layer in a rotating system and refers to the area to which a force applied to a horizontal boundary is transmitted, e.g. the depth to which wind induces a current over a deep volume of water
ERA 40 Data Set	Created by ECMWF, the ERA 40 dataset contains a large amount of reanalysis climate data for years 1957-2002.
EVA	Extreme Value Analysis: A statistical analysis of stochastic processes to estimate the probabilities of rare or extreme events.
Friction Coefficient	The value assigned to represent the surface stress due to the wind and is a function of wind speed.
Gamma distribution	A two parameter family of continuous probability distribution.
Generalised Pareto distribution	A right-skewed probability distribution law that can model tails of a wide variety of distributions.
Geocentric Datum	A datum which has its origins at the earth's centre and best approximates the earths surface, used in WGS84 and ETRS89 datum.
Geocentric Orthometric Height	The height of a given point relative to the geocentric datum and measured orthogonal to the surface described by this datum.
GIS	Geographical Information System: A computer system capable of storing information and linking that information to specific locations on a geographical map.

GFS	Global Forecast System: A numerical forecast prediction model run by 'National Oceanic and Atmospheric Administration' NOAA.
GLOSS	Global Sea Level Observing System: An international programme which monitors sea levels globally for long-term climate change studies.
Gravimetric Measurements	Measurements of gravity, both in terms of its direction and magnitude
GRIB Files	Gridded Binary File is a mathematical data format used to store and exchange meteorological charts and other patterns of historical and forecast weather data.
GSI	Geological Survey of Ireland: provide information and data on aspects of Irish geology.
GSI Quaternary Geological Mapping	Mapping of the geological formations formed in the most recent geological period (Quaternary) produced by GSI
GTM	Global Tidal Model
Histogram Analysis	Analysis of the frequency distributions of a data set.
Instationary	Wave events are dependent on the preceding timestep.
INSS	Irish National Seabed Survey, surveying programme managed by GSI with the aim of surveying and mapping most of the offshore Irish seabed.
Inverse Distance Weighted Method	The most commonly used techniques for interpolation of scatter points. It estimates values for intermediate unknown points by averaging the values of sample data points of neighbouring data, taking account of the distance. Scatter data close to the estimated value are given a higher weighting than more remote points.
Iso-gravity Surface	Surface of constant gravity, identical to a surface derived through conventional levelling techniques
ISTSM	Irish Seas Tidal Surge Model

Jack-knife Resampling Technique	A method for establishing the uncertainty of a particular probability distribution in relation to a data set. In the jackknife resampling method the bias and the standard deviation of the quantile estimate is calculated by sampling n data sets of (n−1) elements from the original data set.
Joint Probability Analysis	Analysis to derive the probability of occurrence of events in which two or more specific outcomes will simultaneously occur.
KMS	Kort and Matrikelstyrelsen: A Danish government organisation responsible for national mapping, e.g. ordnance survey.
Kolmogorov-Smirnov Test	Often referred to as the K-S test, it tests the goodness of fit between the expected distribution and the observed distribution.
LiDAR data	Light Detection and Ranging: Uses light signals through lasers and optical detectors to measure land elevation.
Log-Normal distribution	A probability distribution whereby the log of the random variable is normally distributed
Log-Pearson Type3 distribution	A probability distribution whereby the log of the random variable follows the Pearson distribution. A statistical technique that typically predicts the flood of a river and calculates the distribution frequency, so floods of various sizes can be predicted.
MIKE 21 FM model	Two dimensional flexible mesh coastal modelling package produced by DHI (The Danish Hydraulic Institute)
Maximum Likelihood Method	A technique in statistics in which the parameters are determined that maximise the fit between the probability distribution and the sample data
Mean Flow Values	The average flow data calculated over a number of years often referred to as Q_{mean}.
Method of L-moments	Linear combinations of probability weighted moments that provide measures of location, dispersion, skewness, and shape of the data sample.
Method of Moments	A technique for constructing estimated parameters that are based on matching the sample moments with the corresponding distribution moments.
Metocean Hindcast Model	A model which uses historical meteorological input data to produce long time series of wind and sea parameters over large areas.

MRF	Medium Range Forecast: Also known as the extended-range forecast because it forecasts weather one to two weeks in the future.
MSL	Mean Sea Level: the average sea surface level of all tides over a long period of time.
NAO	North Atlantic Oscillation: A large-scale fluctuation in the difference of sea level pressure between Iceland and the Azores. The surface pressure drives surface winds and winter storms from west to east across the North Atlantic affecting temperature and precipitation thus impacting on marine and terrestrial ecosystems.
NOAA	The National Oceanic and Atmospheric Administration (NOAA) is a federal agency focused on the condition of the oceans and the atmosphere under the United States Department of Commerce which presents information on the ocean, weather, and climate change.
NSW	Nearshore Spectral Wind-wave Model: A two-dimensional model that describes the propagation, growth and decay of short-period waves in near-shore areas.
NTSLF	National Tidal and Sea Level Facility, the UK National Tide Gauge Network, run by the Tide Gauge Inspectorate, records tidal elevations at 44 locations around the UK coast, checks and publishes its readings.
O.D. Malin	Ordnance Datum Malin: A vertical land levelling datum currently used in the Republic of Ireland based on the mean sea level recorded between January 1960 and December 1969 measured at Malin Head tide gauge
Operational Surface Model	An atmospheric model used for operational forecasting of the weather on the earths surface.
Orthometric Height	The distance of a point in relation to a vertical datum measured along a line normal to the geoid.
Ortho-photography	An aerial photography that has been geo-referenced so it has geometric accuracy and represents the earth's surface with precise details so true distances can be measured.
OSI	Ordnance Survey Ireland is the National Mapping Agency for Republic of Ireland.
Partial Duration Series (PDS)	PDS is also known as peak over threshold (POT) series and analyses extreme events whereby data above a threshold is used independently of its occurrence in the record (in contrast to an Annual Maximum Series).
Photogrammetric Data	Precise measurements of distances or dimensions based on the use of photographic records, e.g. aerial photographs used in surveying and map-making. Stereo photogrammetry uses two photos taken at the same time with a known distance and orientation to each other to define topography (3D data)

O.D. Poolbeg	The now superseded Irish land levelling Datum used up to 1970 also known as Dublin Datum, based on the low water of spring tide at Poolbeg lighthouse, Dublin, observed on 8 April 1837
PSMSL	Permanent Service for Mean Sea Level: organisation collecting, analysing, and publishing sea level data from a global network of tide gauges.
Quasi-Stationary	Wave events are independent of the preceding timestep.
Refracted	The change in direction of a wave when influenced by a change in bathymetry.
RTK-GPS	Real Time Kinematic - GPS is a process where GPS signal corrections are transmitted in real time from a reference receiver at a known location to one or more remote rover receivers. The use of an RTK capable GPS system can compensate for atmospheric delay, orbital errors and other variables in GPS geometry, increasing positioning accuracy to within a centimetre.
Seiches and Seiching Effect	Abrupt changes in meteorological conditions, such as the passage of an intense depression, may cause oscillations in sea level (or Seiches). The period between these successive waves may vary between a few minutes and around two hours. Small seiches are not uncommon around the coast of Ireland.
Shoaling	The transformation of waves due to shallowing water depths as they propagate inshore.
Standard Deviation	A statistical measure of the spread of data from the mean.
Standardised Least Squares Criterion	A method of fitting a distribution to a fixed collection of points using the square of the difference between the observed data and the calculated data point.
Surge	A sudden increase (or decrease if negative) in tidal flow or elevation compared to the expected flow or elevation due to astronomic tides. Surge can be caused by high winds (storm surge) and / or atmospheric pressure.
Surge Residual	The change in sea level caused by the effect of pressure variations and persistently strong winds.
Theoretical Probability Distributions	A statistical function that describes all possible values and likelihoods that a random variable can take within a given range.
Threshold/Fixed Location Parameter Method	Method of fixing the "origin" of a probability distribution by using the threshold from the POT analysis

Tidal Harmonics / Constituents	Sets of amplitudes and phases describing the changes in tidal elevation based on sinusoidal curves with different periods.
Tidal Regime	The typical tidal pattern at a specific location.
Topographical Data	Data describing the changes in surface elevation in relation to a fixed datum.
Truncated Gumbel distribution	A probability distribution whereby the random variable follows the Gumbel distribution truncated at the threshold value from the Peak Over Threshold (POT) analysis.
Weibull distribution	A probability distribution whereby the random variable follows the Weibull distribution.

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