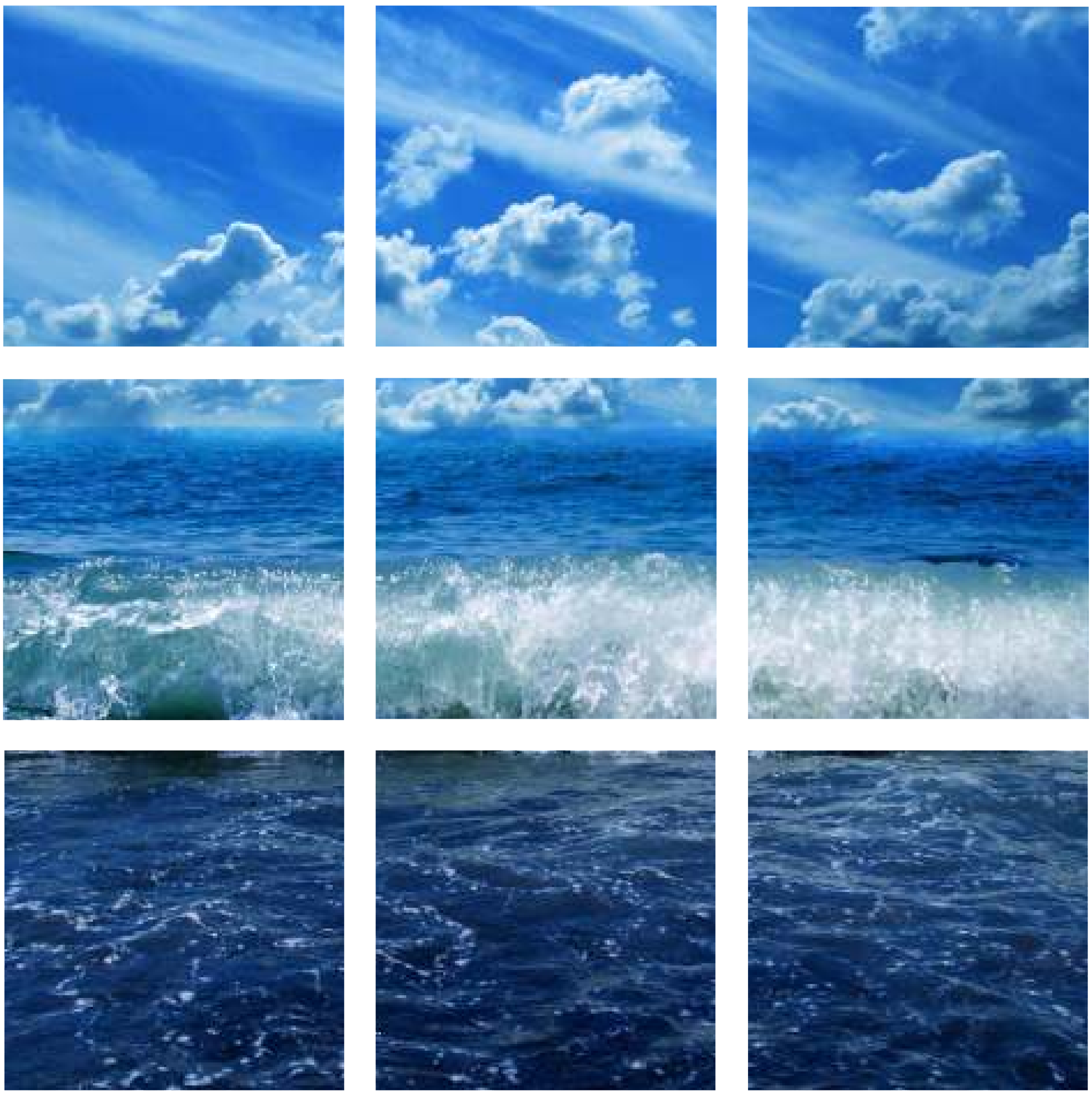
Irish Coastal Protection Strategy Study
Phase 2 - South East Coast

Work Packages 2, 3 & 4A - Technical Report

IBE0104/June 2010



Office of Public Works

Irish Coastal Protection Strategy Study - Phase II

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Strategic Assessment of Coastal Flooding and Erosion Extents

South East Coast - Dalkey Island to Carnsore Point Pilot Area

Final Technical Report - June 2010

RPS

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Schedule of Included Digital Data (Refer Appendix 10)

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	
0.1% AEP Confidence	ESRI Shapefile	
0.5% AEP Confidence	ESRI Shapefile	

Erosion Related

Erosion 2030	ESRI Shapefile
Erosion 2050	ESRI Shapefile
Erosion Confidence	ESRI Shapefile

1.0 Executive Summary

This report presents the work undertaken and the findings of Phase 2 of the Irish Coastal Protection Strategy Study (ICPSS), Work Packages 2, 3 and 4A for the south east 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. Work Package 4B refers to an economic risk assessment prepared for the same phase of work, which is the subject of a separate report entitled 'Work Package 4B Strategic Assessment of Economic Risk from Coastal Flooding and Erosion'.

The knowledge of extreme water levels along the coast is a key element in the development of coastal protection strategy. Consequently work packages 2 and 3 were commissioned to establish an extreme flood extent for a pilot section of coastline between Dalkey Island and Carnsore Point and to derive predictive coastal flood extent maps for a range of probabilities, particularly for the 0.1 % and 0.5 % annual exceedance probabilities (AEP's). In addition, predictive coastal flood depth maps were derived for the 0.5% AEP. For the purposes of this study, these flood extent and flood depth maps are broadly classified as flood hazard maps.

This study used numerical modelling of combined storm surges and tide levels to obtain extreme water levels along the pilot coastline. The application of extreme value analysis and joint probability analysis to both historic recorded tide gauge data and data generated by the numerical model allowed an estimation of the extreme water levels of defined exceedance probability to be established along the pilot section of coastline.

A Digital Terrain Model (DTM) of the south east coast derived primarily from airborne LiDAR data was used in the study to define the extent of the predictive floodplain. The predictive flood extents were calculated by combining the results of the surge and tide level modelling, the statistical analysis, and the DTM using GIS technology. In the course of the study, this DTM was further developed and quality controlled and in particular survey coverage was extended to include areas further inland to ensure the full extent of the floodplain was covered.

The resulting predictive coastal flood extent and flood depth maps are presented in the report (Refer Appendix 7 and Section 6). A review of these predictive floodplain maps generated throughout the study area showed that coastal flood hazard existed predominantly in or near coastal settlements with seven primary areas of potential coastal flood risk identified as follows : Bray, Ballygannon to Five Mile Point, Five Mile Point to Wicklow, Arklow, Cahore Point to Morriscastle, Wexford to Curracloe and Rosslare. The extent of the predictive floodplain for each of these primary areas of potential coastal flood risk is shown in detail in Section 6 from Figure 22 to Figure 35.

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 national coastal protection strategy. A strategic level erosion assessment was therefore undertaken along the study coastline 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 the 1970's, 2000 and 2004 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 8 and Section 7). A review of the erosion maps generated throughout the study area showed that there were ten primary areas of potential coastal erosion risk identified as follows: Shanganagh to Bray, Greystones, Ballygannon to Five Mile Point, Five Mile Point to Wicklow, Kilpatrick, Ardamine, Glascarrig, Killincooly to Blackwater, Blackwater to Ballinesker and Rosslare. The extent of the predicted erosion for each of these primary areas of potential coastal erosion risk is shown in detail in Section 7, from Figure 36 to Figure 55.

The analysis of coastal erosion along the pilot coastline indicated that there was generally little potential risk associated with coastal erosion in the larger urban areas, primarily due to the fact that these areas are protected by man-made defences and hence the analysis of the aerial photography did not detect any significant change. In more rural areas there were instances where annualised erosion rates in excess of 3 metres per year were observed, however generally the rates were less than 0.5 metres per year.

It was concluded, that the adopted approach of combining synthesised data from the tidal and storm surge model, including joint probability analysis with the available recorded tide gauge data, worked well in the pilot 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 was therefore considered that these methodologies could be extended to other coastal areas around Ireland, in order to more fully inform OPW of the extent of the coastal flood and erosion hazard and potential risk in Ireland.

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 risks to 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 potential risk 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 the appended disclaimers and guidance notes.

2.0 Introduction

This report presents the work undertaken and the findings of Phase 2 of the Irish Coastal Protection Strategy Study (ICPSS), Work Packages 2, 3 and 4A for the south east coast of Ireland. It follows on from an earlier Phase 1 study involving a general overview of coastal protection in Ireland which was concluded in October 2004. 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 together with the proximity of the UK coastline, both the tidal regime and the effects of wind on south east coastal water levels are complex. As such the 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 a combination of analytical and numerical modelling techniques was developed for this study. The applicability of this methodology to the pilot coastline and other vulnerable areas was also assessed to inform future role out of the study.

The objective of Work Package 2 was to establish an extreme coastal flood extent for the pilot area from Dalkey Island to Carnsore Point. 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 1). As such, 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 in areas defined to lie within this flood extent would at least require further investigation of the coastal flood hazard at planning stage. Predictive 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 in 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 or since the assessment period (1973-2005).

This report outlines how the extreme water levels for a range of locations over the pilot 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 strategic 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, a storm surge model was used to simulate historic water levels for a range of extreme conditions. To simulate the development of storm surges around Ireland a dedicated model was developed using some of the latest technology in tidal modelling. The storm surge model, referred to as the Irish Sea Tidal Surge Model (ISTSM) covers the whole of Ireland and has a more detailed mesh in the pilot area, as outlined in the calibration report (Reference 3). This model was extensively tested and calibrated prior to the simulation of storm surges and proven to obtain a good correlation with tidal water levels along the coast. For this study the ISTSM was used to simulate storm surge events relevant to the pilot area, which had occurred in the past 50 years.

3.1.1 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 1). The tidal surge model used in this study covers an area of 18° longitude and 13.5° latitude as shown in Figure 1. Overall the model covers the Northern Atlantic Ocean up to a distance of 600km from the Irish Coast.

Table 1: List of locations used in tidal model for calibration

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

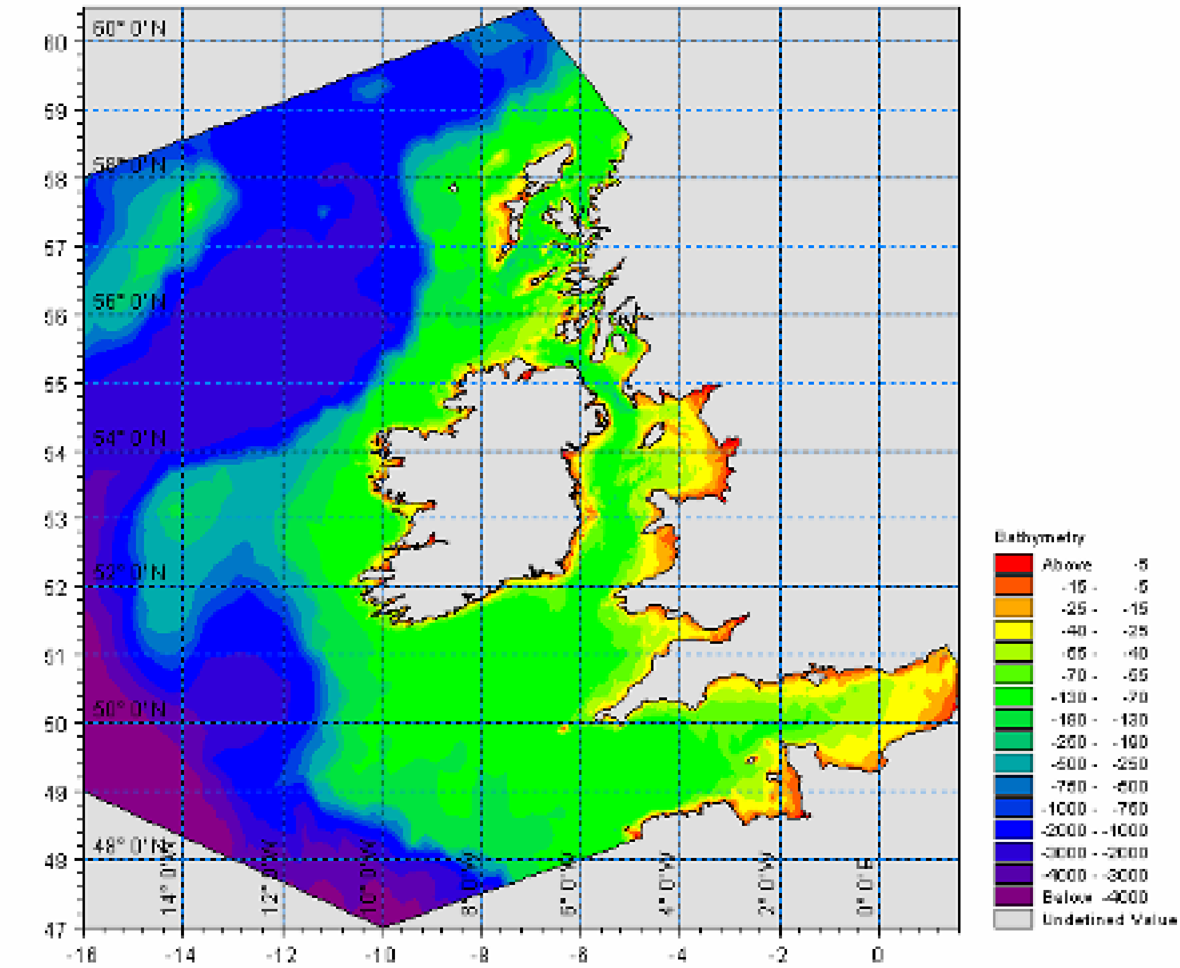


Figure 1: Extent of Irish Sea Tidal Surge Model (ISTSM)

The Irish Sea 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 the pilot area and other regions of importance to satisfactory model performance. Thus the model provides greater detail along the shoreline and over banks in the pilot area when compared to other parts of similar model domain. Along the Atlantic boundary, the model features a mesh size of 13.125' (24km) while the Irish Atlantic coast has been depicted using cells of on average 3km in size. In the Irish Sea, which is of primary interest at this stage, the maximum cell size is limited to 3.5 km decreasing to 200m along most of the Irish coastline.

The bathymetry for the model was generated using a number of different sources. Large parts 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) under the Irish National Seabed Survey (INSS) have been included in the bathymetry of the model. This includes the Zone 3 data West of Ireland, Dublin Bay and adjacent areas and Zone 2 survey of the Malin Sea area.

Both survey data commissioned 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 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).

3.1.2 Historic Storm Surge Selection

In order to simulate historic storm surges (hindcasting) which are relevant to the pilot area, the water level records from gauges at Dublin and Fishguard were reviewed and all storm surge events with surge residual in excess of 0.5 metres were selected.

For Fishguard, the recorded water level data originated from the National Tidal and Sea Level Facility (NTSLF) maintained by the British Oceanographic Data Centre was analysed. In this database, records are available on an hourly basis for the periods 1963-1971, 1973-1992 and 15 minute interval data from 1993-2000 and 2001 to present. The surge residual is also available in this data set for the same periods. From this record, all periods with a surge residual larger than 0.5m for a duration of more than 1 hour were identified.

At Dublin, all historic water levels from 1980-2000 were analysed by RPS staff and all water levels above 4m were extracted. To supplement this data set, digital data from 2000-2005 was obtained, additionally extreme tidal level analysis data generated for Dublin City Council was incorporated. However, there were a number of issues associated with the 1980-2000 dataset as the data was recorded on paper via a tracing device until the end of 1999 and only then was the gauge converted to digital recording. Frequently, one entire week was recorded on one sheet which covered a drum turning once in 24 hours. Thus there were usually 13 flood and ebb tides on one sheet. An example of such a sheet is shown in Figure 2.

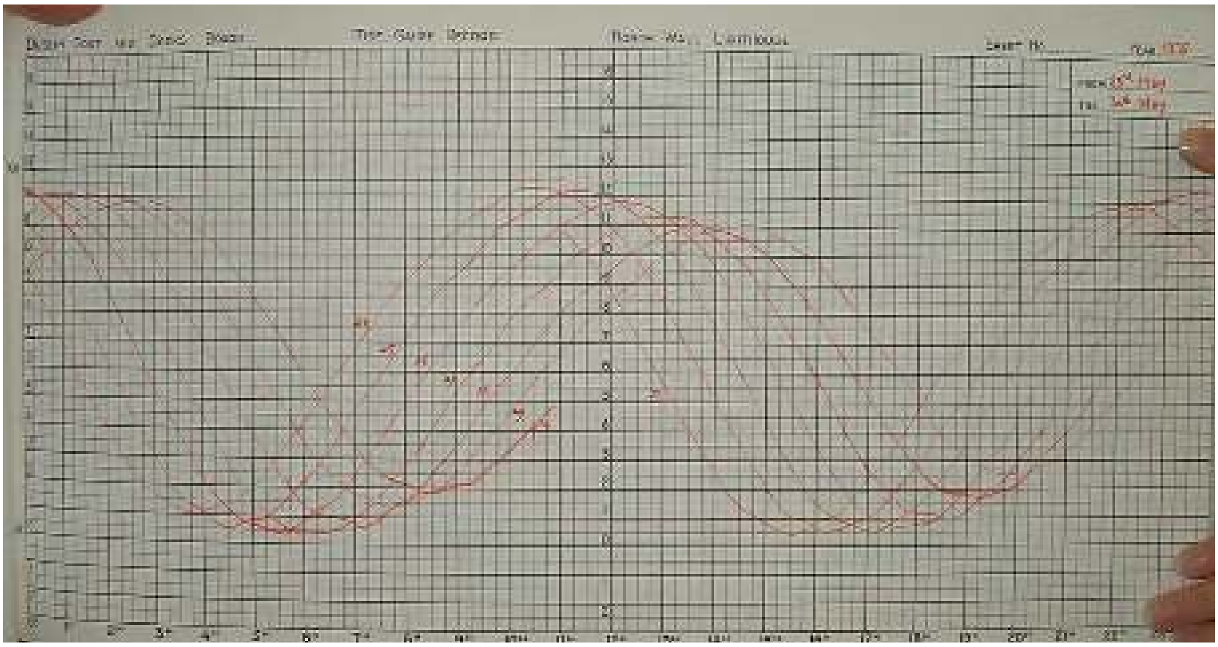


Figure 2: Tide gauge record from Dublin North Wall

On a number of occasions, in particular under storm surge conditions, the recording was less clear and it was very difficult to distinguish the separate curves. This made the analysis of different high water levels difficult also occasionally high water levels were associated with the wrong date. To further complicate matters the location and datum of the gauge was altered during this period and the recording also changed from imperial to metric units.

In addition, the trace recorded by the gauge often showed a significantly shorter period of oscillation (less than 3 hours). This was in part attributed to poor damping of the gauge chamber and also to seiching effects observed in Dublin Bay. Figure 3 shows the recorded water level and the predicted tidal elevation, together with the derived surge residual (red line on different scale) to illustrate this point. The surge residual clearly shows the higher harmonics due to seiching.

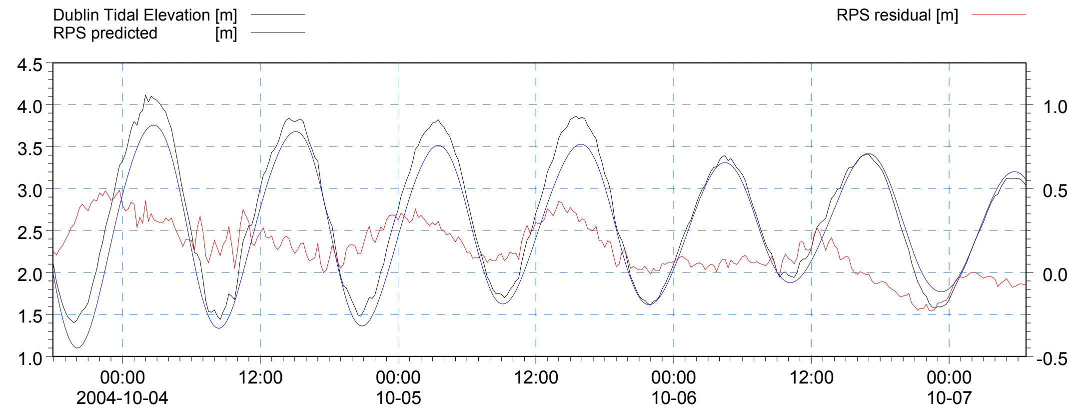


Figure 3: Digital recorded surface elevation at Dublin with predicted water level and surge residual (different scale)

Based on data from these two tide gauge locations, a number of surge events were selected. 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 duration. A list of all storm surge runs used in this study is given in Table 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 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	Peak value (m)
1	25/11/1959 00:00	02/12/1959 18:00	7.75	1.125	4.94
2	18/10/1961 00:00	25/10/1961 18:00	7.75	1.125	4.89
3	05/01/1962 00:00	12/01/1962 18:00	7.75	1.125	4.87
4	01/03/1962 00:00	09/03/1962 18:00	8.75	1.125	4.94
5	06/01/1974 00:00	13/01/1974 18:00	7.75	1.125	5.04
6	04/02/1974 00:00	11/02/1974 18:00	7.75	1.125	4.88
7	24/01/1975 00:00	31/01/1975 18:00	7.75	1.125	4.88
8	07/12/1981 00:00	14/12/1981 18:00	7.75	1.125	5.05
9	25/02/1982 00:00	04/03/1982 18:00	7.75	1.125	4.45
10	10/10/1982 00:00	19/10/1982 18:00	9.75	1.125	5.00
11	27/12/1983 00:00	03/01/1984 18:00	7.75	1.125	4.68
12	21/11/1984 00:00	28/11/1984 18:00	7.75	1.125	4.56
13	09/12/1986 00:00	16/12/1986 18:00	7.75	1.125	4.54
14	26/01/1988 00:00	02/02/1988 18:00	7.75	1.125	4.72
15	03/02/1989 00:00	10/02/1989 18:00	7.75	1.125	4.92
16	05/04/1989 00:00	12/04/1989 18:00	7.75	1.125	4.40
17	08/12/1989 00:00	25/12/1989 18:00	17.75	1.125	4.92
18	19/01/1990 00:00	08/02/1990 18:00	20.75	1.125	4.96
20	19/02/1990 00:00	26/02/1990 18:00	7.75	1.125	4.92
21	30/12/1990 00:00	06/01/1991 18:00	7.75	1.125	4.56
22	06/11/1991 00:00	13/11/1991 18:00	7.75	0.500	4.52
23	30/07/1992 00:00	06/08/1992 18:00	7.75	0.500	4.88
25	04/01/1993 00:00	19/01/1993 18:00	15.75	0.500	4.92
26	01/11/1994 00:00	08/11/1994 18:00	7.75	0.500	4.36
27	19/10/1995 00:00	26/10/1995 18:00	7.75	0.500	5.02
28	02/01/1996 00:00	13/01/1996 18:00	11.75	0.500	4.56
29	18/12/1999 00:00	26/12/1999 18:00	8.75	0.500	5.06

Run No.	Start date and time	End date and time	Duration (Days)	Met grid resolution	Peak value (m)
30	14/01/2002 00:00	05/02/2002 18:00	22.75	0.500	5.46
31	04/11/1963 00:00	20/11/1963 18:00	16.75	1.125	0.79*
32	14/02/1966 00:00	27/02/1966 18:00	13.75	1.125	0.74*
33	25/11/1966 00:00	02/12/1966 18:00	7.75	1.125	0.78*
34	07/01/1969 00:00	19/01/1969 18:00	12.75	1.125	0.89*
35	01/09/1974 00:00	08/09/1974 18:00	7.75	1.125	0.82*
36	27/12/1975 00:00	04/01/1976 18:00	8.75	1.125	0.79*
37	13/09/1981 00:00	21/09/1981 18:00	8.75	1.125	0.79*
38	18/03/1986 00:00	25/03/1986 18:00	7.75	1.125	0.80*
39	21/03/1987 00:00	28/03/1987 18:00	7.75	1.125	0.92*
40	25/12/1987 00:00	01/01/1988 18:00	7.75	1.125	0.86*
41	02/12/1994 00:00	09/12/1994 18:00	7.75	0.500	0.98*
42	11/01/1995 00:00	22/01/1995 18:00	11.75	0.500	0.75*
43	05/02/1995 00:00	18/02/1995 18:00	13.75	0.500	0.85*
44	22/10/1996 00:00	30/10/1996 18:00	8.75	0.500	0.86*
45	12/02/1997 00:00	21/02/1997 18:00	9.75	0.500	0.93*
46	18/12/1997 00:00	05/01/1998 18:00	18.75	0.500	0.84*
47	15/10/1998 00:00	26/10/1998 18:00	11.75	0.500	0.76*
48	20/12/1998 00:00	04/01/1999 18:00	15.75	0.500	0.83*
49	24/10/2000 00:00	31/10/2000 18:00	7.75	0.500	0.86*
50	24/11/2000 00:00	14/12/2000 18:00	20.75	0.500	0.85*
51	26/12/2000 00:00	05/01/2001 18:00	10.75	0.500	0.81*
52	19/10/2002 00:00	28/10/2002 18:00	9.75	0.500	0.88*
53	15/11/2002 00:00	25/11/2002 18:00	10.75	0.500	0.75*
54	07/01/2004 00:00	14/01/2004 18:00	7.75	0.500	0.82*
55	17/10/2004 00:00	31/10/2004 18:00	14.75	0.500	0.88*
56	05/01/2005 00:00	15/01/2005 18:00	10.75	0.500	4.83
57	07/12/2000 00:00	15/12/2000 18:00	8.75	0.500	4.95

It may be noted that both event No. 19 and 24 are omitted from the list, as they were not considered to be of significance due to low surge levels. This was due to some error in the original tidal record, which was only discovered once the meteorological conditions of this period had been simulated. Furthermore events in the above list ranging from No. 1 to 30 and 56 & 57 were selected based on tidal records from Dublin, whereas events No. 31 to 55 were based on analysis of records from Fishguard. The peak value provided in the last column is the observed value of the total water level to gauge datum in Dublin or the peak surge residual obtained from Fishguard (denoted by *).

The track of a number of the storm surge events is shown in Appendix 1. It should be noted that the storm during mid December 1989 caused the biggest observed surge of 0.937m in the modelling results. This however coincided with a rather low tide, whereas the January 2002 surge of 0.912m occurred at the same time as a spring tide. Interestingly, the 1989 storm tracked across Ireland, whereas all others tracked significantly further north of the country. In contrast, the lowest pressure resulting from these offshore storms was below 940kPa, a value rarely observed overland. The depression associated with the storm surge in 2002 tracked almost 12° away from Ireland with the lowest pressure at 929kPa. However a front associated with this depression resulted in extreme winds in the coastal waters, which essentially resulted in the extreme surge levels in Dublin.

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 0.50° which RPS further supplemented with additional data from GLOSS and PSMSL from the British Oceanographic Data Centre. For the simulation of the actual storm surges, seasonal components were 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. As an example the seasonal component at Dublin and Fishguard is shown in Figure 4.

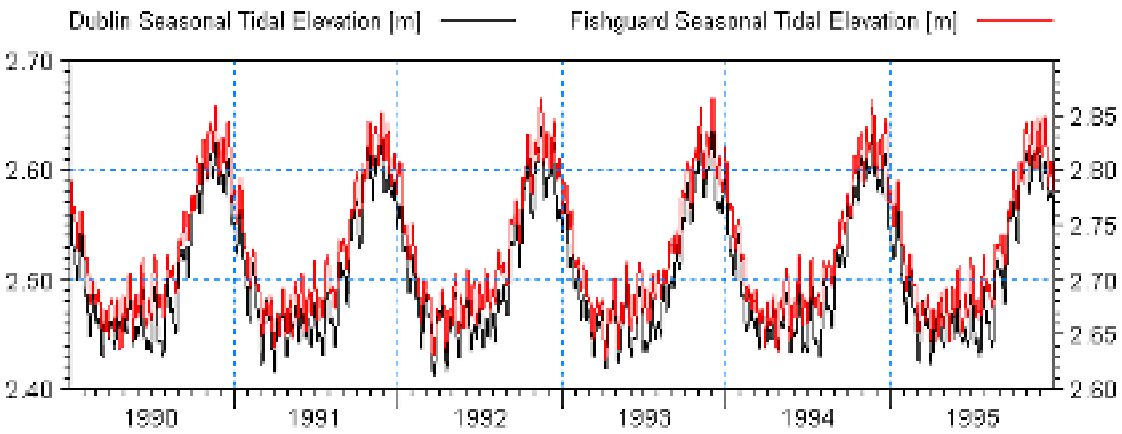


Figure 4: Seasonal Variation Water Level

In general, the seasonal water levels vary by only small amounts across a large area, for example the seasonal components observed at Dublin should be similar to those observed at Fishguard. Indeed this was used to test the quality of the data analysis for the digital records from the Dublin tide gauge and a good correlation was found.

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 Sea 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 temporal resolution. One of these organisations is the European Centre of Medium Range Weather Forecasts (ECMWF). The ECMWF is an international organisation supported by 26 European states. ECMWF data is used by a large number of the European meteorological services 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 both the ERA 40 data set and the operational surface model. 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 reproduce sufficient information to simulate the water level variation in the surge model on 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 Storm Surge Model

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 value to an upper wind speed limit above which a second constant value was used. This is illustrated in Figure 5, where the friction coefficient is shown in blue and the corresponding wind friction is shown by the red trace.

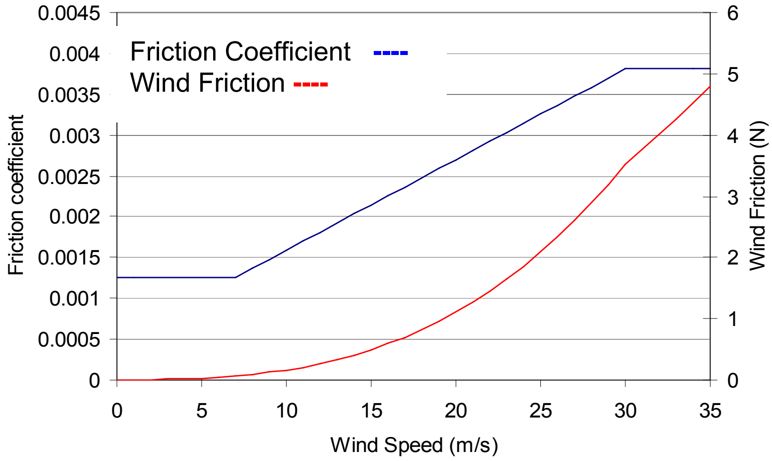


Figure 5: Friction coefficient used in the surge model

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. This was considered of particular importance in respect of the pilot area, 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 6. Such deviation would invariably result in a significant change in the surge, since the wind speed is squared in the friction term.

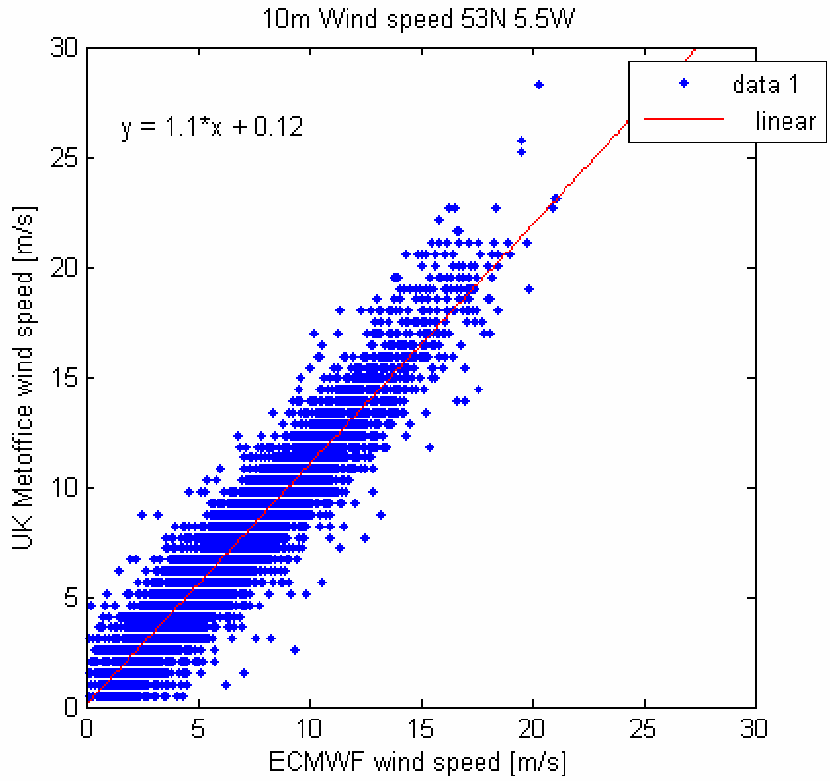


Figure 6: Correlation between wind velocities from the UK Met Office wave data set and ECMWF operational atmospheric analysis model for a location in the Irish Sea

This is further illustrated by Figure 7, 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 the wind 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 discussion 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 8.

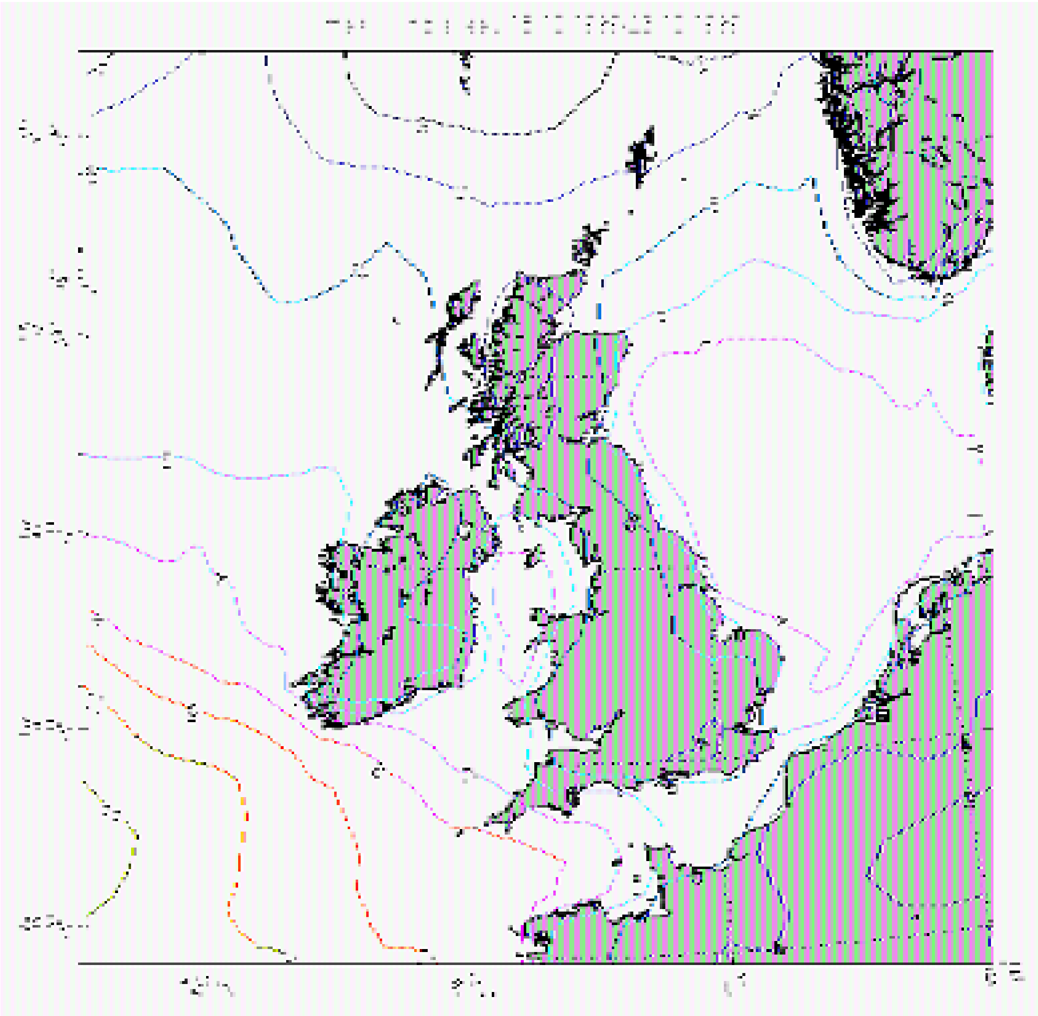


Figure 7: Mean wind speeds from operational surface analysis, wind speeds in m/s

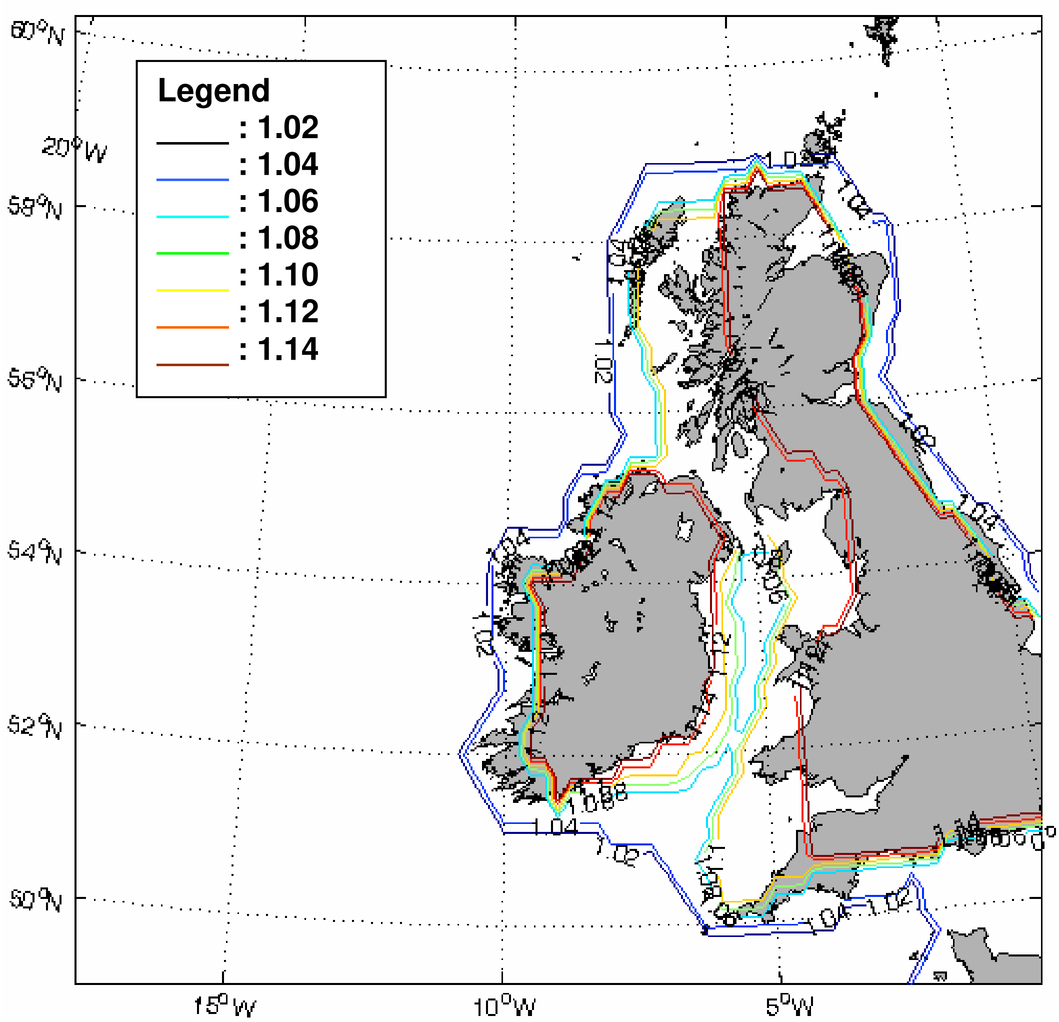


Figure 8: Factor map used for adjusting wind speeds to "over sea" velocities

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 tide gauges. In general the comparison between the subsequent model runs and measured values had greatly improved compared to the initial simulations. Model simulations undertaken with the modifications detailed above showed that the simulations were on average within +/- 50mm for the measured surge components at Dublin, Holyhead and Fishguard. A number of examples of the comparison of surge model simulations with measured surge residuals are shown in Appendix 2. It should be noted that all surges were simulated using the same basic set of parameters and modifications to these were not required on an event by event basis.

3.3.3 Effects from Seiching/Local Wind Set-up and Gusts in Dublin Bay and Wexford Bay

During the analysis of the Dublin North Wall tide gauge data it became apparent that the still water levels at the site were affected by some form of seiching, either in the harbour basin or in Dublin Bay, as discussed in Section 3.1.2. This had been observed quite regularly, however the exact cause had not been established. From the data analysis it was concluded, that the period of the seiching was in the order of 1-1.5 hours. This would indicate that the seiching is generated in the bay rather than the harbour since the resonant frequency of the various harbour basins would be in the order of 5-30 minutes rather than hours.

The results of the basic surge modelling did not show any seiching effects or local wind set-up in the Bay, however it was concluded that this was principally due to the meteorological conditions only being defined at 3 hourly intervals. This was 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 test if fluctuations in wind speed and direction would cause seiching/local wind set-up in Dublin Bay, a set of meteorological conditions was altered in the following manner: The average wind speed was interpolated to 30 minute intervals and a spatial resolution of 1/4°. This average wind speed was overlaid with a gamma distributed variation in wind speed, related to the magnitude of the average wind. As a result, a pseudo random wind field for the model was generated, which had the same average characteristics as the original 3 hourly dataset.

Some results of the simulation are shown in Figure 9, which shows predicted tidal elevations and combined tide and surge levels at Dublin North Wall, both with and without gusts, taken from the numerical model. Only small variations are visible from the average field simulation as the storm surge is dominated by the prevailing wind.

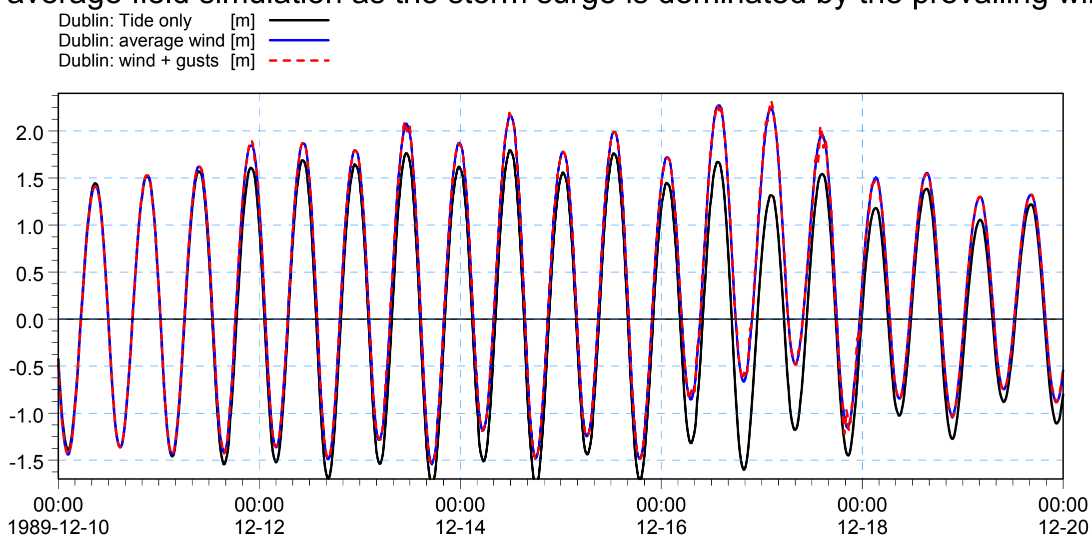


Figure 9: Seiching in Dublin Bay, tidal elevations and combined tidal and surge elevations with average wind and with gusts

Figure 10 shows the extracted surge residuals for the same time period as Figure 9. The surge residual using the 3 hourly wind data resulted in a maximum elevation of 0.94, whereas with the 30 minute wind data a maximum elevation of 1.04 was simulated.

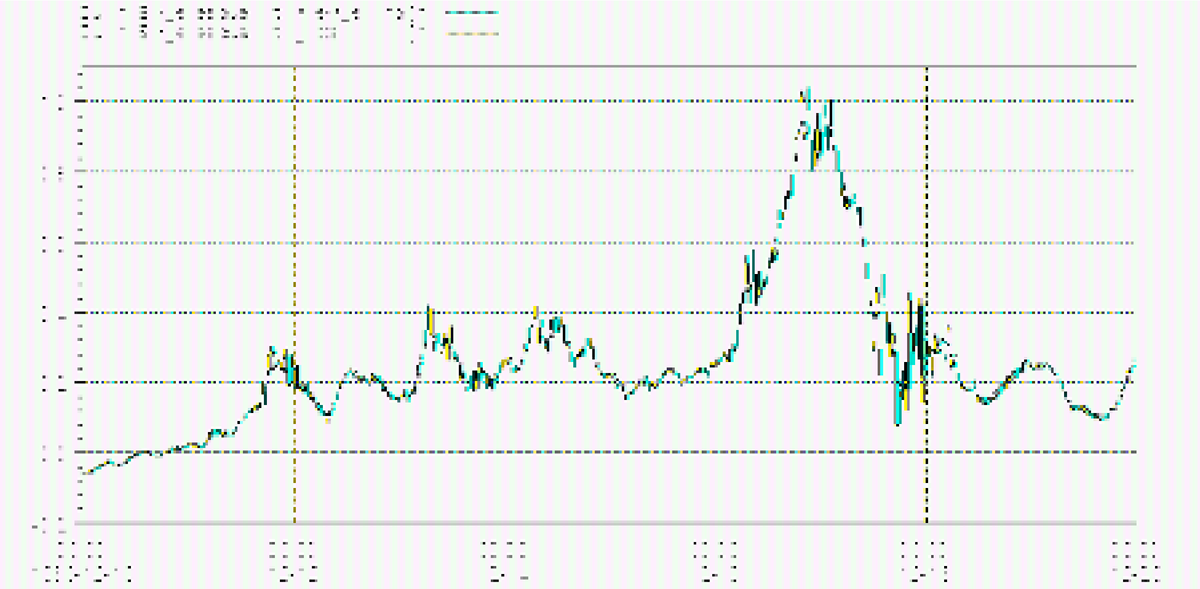


Figure 10: Seiching in Dublin Bay, surge residual with and without the influence of gusts

To investigate the significance of the seiching around the Bay, surge residuals for the same event at different locations are shown in Figure 11: which in addition to the surge residual at the Dublin Harbour gauge shows corresponding information for a point in the centre of Dublin Bay (Point 1) and a location south of Greystones (Point 10). This diagram illustrates that the seiching effect is far more pronounced in the harbour when compared to a location outside in the open Bay. This is a typical characteristic of seiching, since the nodes are often found in the centre of the affected area. The diagram also confirms that this effect is most dominant in Dublin Bay and of less significance along the remainder of the pilot area coastline.

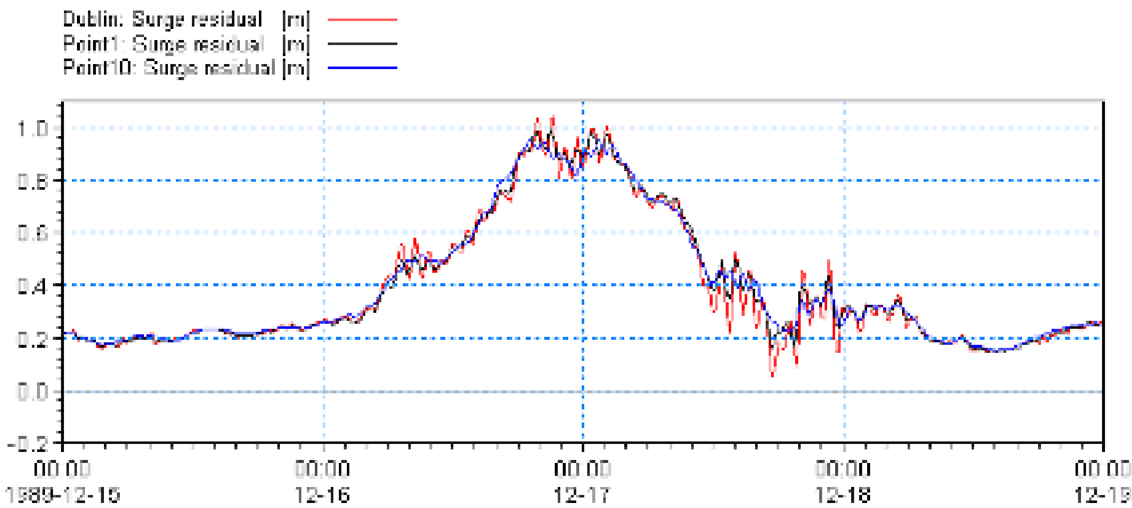


Figure 11: Comparison of seiching and surge in Dublin North Wall, Dublin Bay and Greystones

Since the simulation covered the entire pilot area it was also possible to compare the differences in surge water level caused by varying the wind speeds on a sub-hourly basis over the entire model domain. From this simulation, it was concluded that in addition to the effect on the extreme water levels simulated by the model at the Dublin gauge, seiching can raise water levels by up to 200mm above typical storm surge levels under conditions coincident with large storm surges. The effect of seiching varies around the coast of Dublin Bay, with higher amplitudes towards the southern and northern shores.

With regard to the Wexford Harbour area, a similar analysis indicated that 50-100mm were required on top of the modelled extreme levels, with 50mm added along all other parts of the coastline for local wind set up effects.

The modelling has confirmed that the seiching in Dublin Bay is caused by the fluctuation of wind speed and direction. It is primarily caused by the movement of water in the north/south direction in the bay and has a period of around 1 ½ hours.

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, two simulations were carried out for each storm surge period. The first simulation included tidal components only and the second incorporated both tidal and storm surge components. In this way the surge component for all relevant points can be directly derived and separated from the tidal elevations (surge residual). As a result the extreme water levels can be derived as a combined probability of extreme tidal elevation and surge component.

The storm surge models were started using an initial condition (total water depth and u/v velocity) from the tidal simulation of the same surge period. Therefore at the start of the combined tide-surge model run (with initial forcing using the atmospheric pressure and wind) the correct tidal flow regime is already established in the model.

From the various storm simulations, time series of the surface elevations were extracted at 42 points as shown in Figure 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 conjunction with the extraction of the tidal levels, the surge residual was calculated for each point and from the resulting time series the total maximum water level per storm and the maximum surge level in each storm was derived. In this context, it was assumed that any depression combined with strong winds can be considered independent for the statistical analysis, if at least 4 days had passed between surge events and if the surge residual had fallen close to or below zero.

Figure 12: Location of extraction points along the pilot area

This approach led to the identification of 76 storm events, of which a number of events were considered to be too small to be of importance. After histogram analysis, the top 56 events were selected at each point leading to more than one event per year, since these covered a time span of 41 years.

4.0 Wave Climate Modelling

4.1 Introduction

Wave overtopping of existing coastal defences or coastal structures will often cause or add to flooding in the low lying areas located behind these defences. Areas where there was considered to be significant potential for wave over-topping were defined from an initial assessment using the OPW's south east coast LIDAR data, the coast of Ireland oblique imagery survey (Ref 8) and local knowledge of the area.

The following locations were initially identified as being potentially vulnerable to wave overtopping during storms.

- Bray promenade
- Greystones
- Wicklow
- Courtown promenade
- Rosslare Strand

Wave modelling was undertaken to establish the wave climate conditions at a number of locations in the pilot area. The offshore wave data for the study was taken from the UK Met Office's, European and UK Waters Wave Model for the period from 1990 to 2000. The location for the actual offshore wave points used in the study is shown in Figure 13. The UK Met Office model provides wind and wave data on a 3 hourly basis and the offshore wave roses derived from this data are also shown in Figure 13.

It may be seen from Figure 13 that the offshore wave climate is influenced by the shape of the Irish Sea and the exposure of the offshore area to swell from the Atlantic. Thus the offshore wave roses at the northern end of the pilot area are dominated by southerly waves while the waves offshore of Carnsore Point are predominantly from the south west direction.

The waves were transformed from offshore to the inshore area using the Mike21 Nearshore Spectral Wind-wave model (NSW). The NSW model is a stationary, directionally decoupled parametric wind-wave model that describes the propagation, growth and decay of waves in nearshore areas. The model takes into account the effects of refraction and shoaling due to varying depth, local wind generation and energy dissipation due to bottom friction and wave breaking.

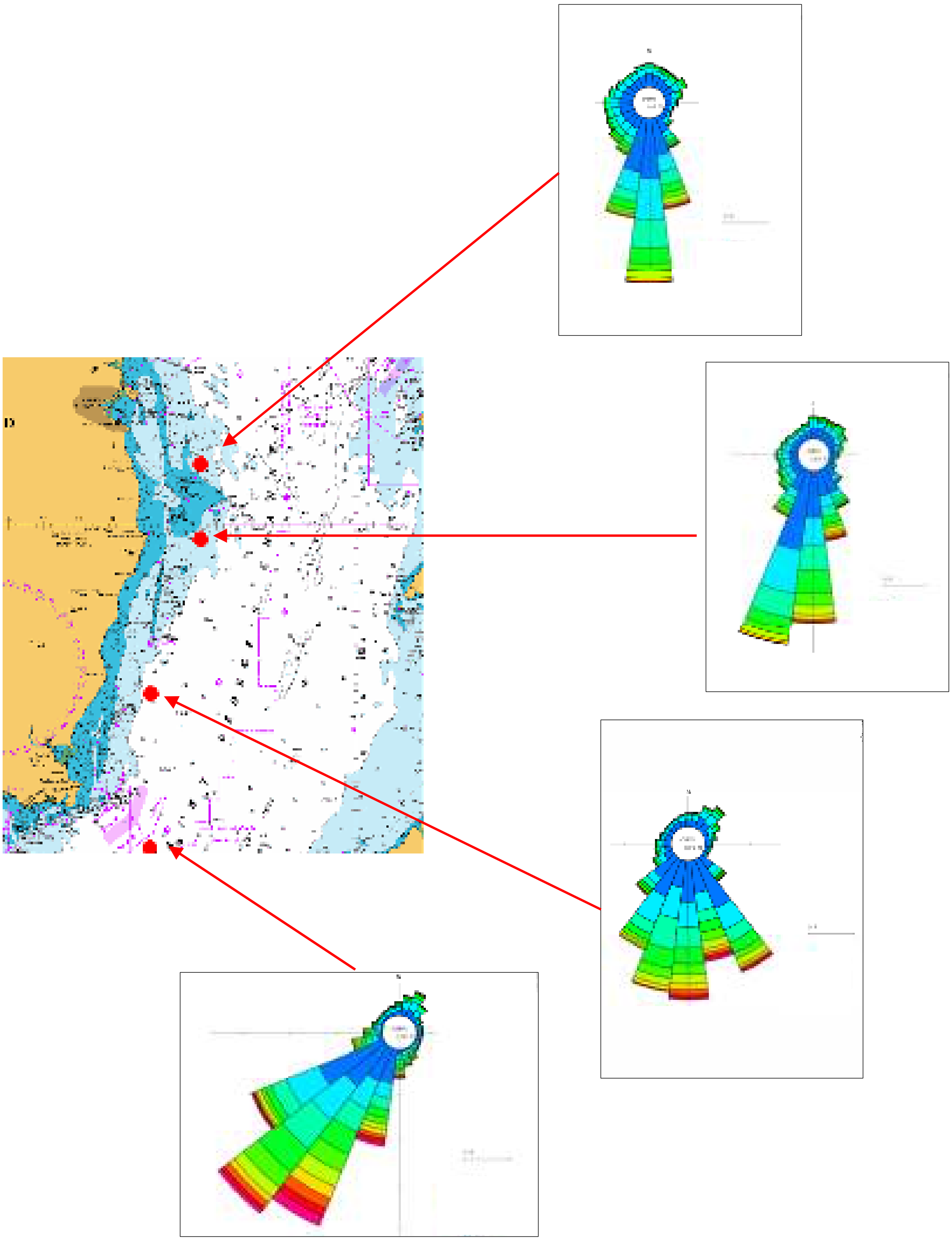


Figure 13: Offshore Data Point Wave Roses along the Pilot Study Area

For the majority of the study area the offshore waves were transformed inshore using two separate bathymetries. The offshore events were divided into a north east sector and a south east sector based on the offshore wave direction. Waves approaching from 350° to 90° were included in the north east sector while waves which approach from 90° to 210° were included in the south east sector. Around Rosslare and the Wexford estuary waves can also approach from the Atlantic in the form of swell as well as directly from the Irish Sea. Thus four bathymetries with directions 025°, 075°, 125° and 175° were used in the wave transformation.

The banks that lie off the east coast of Ireland have a significant effect on the inshore wave climate at the shoreline of the study area. As can be seen from Figure 14, even at high tide the banks reduce the height of the higher waves passing over and thus protect the shoreline. In areas where there are gaps in the banks, e.g. at Courtown, the storm waves can be refracted through these gaps into the nearshore area.

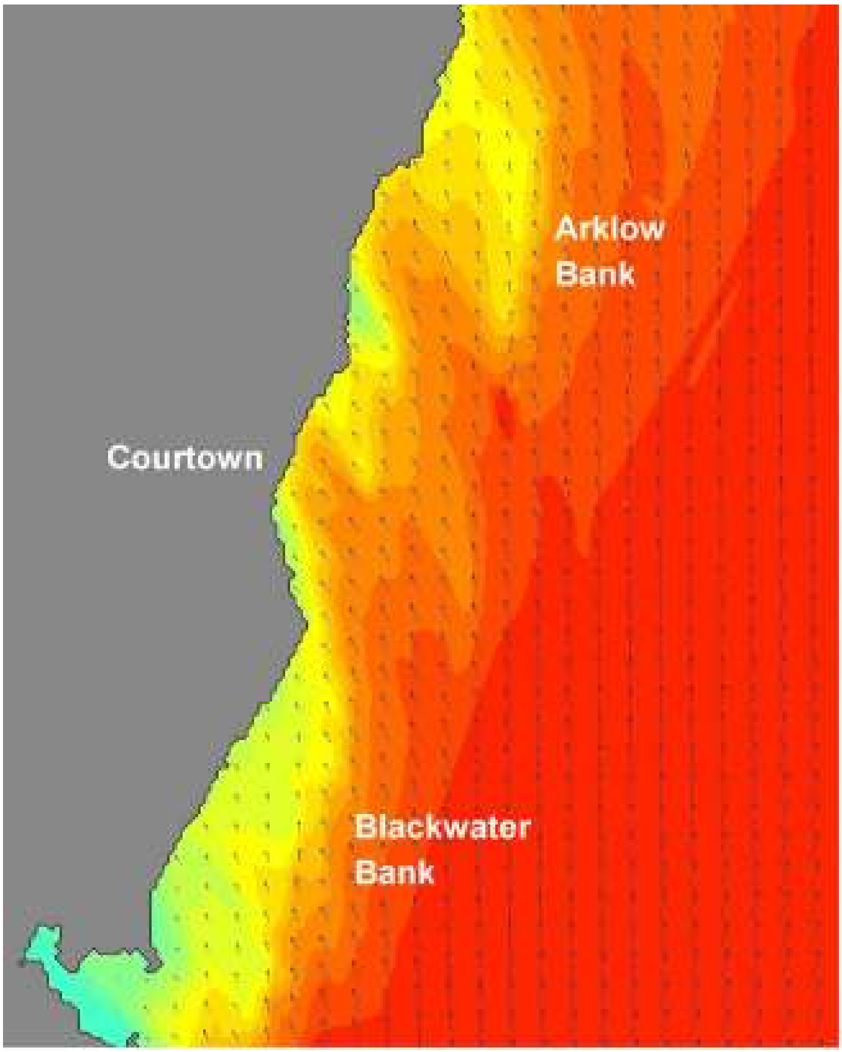
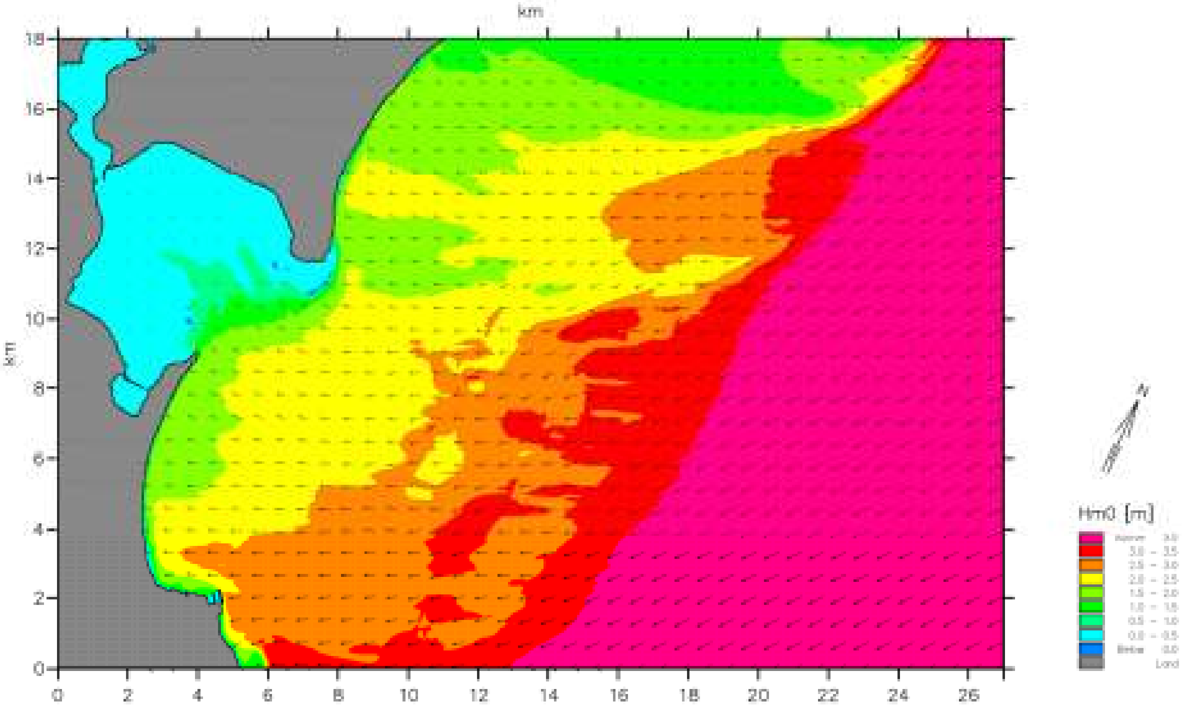
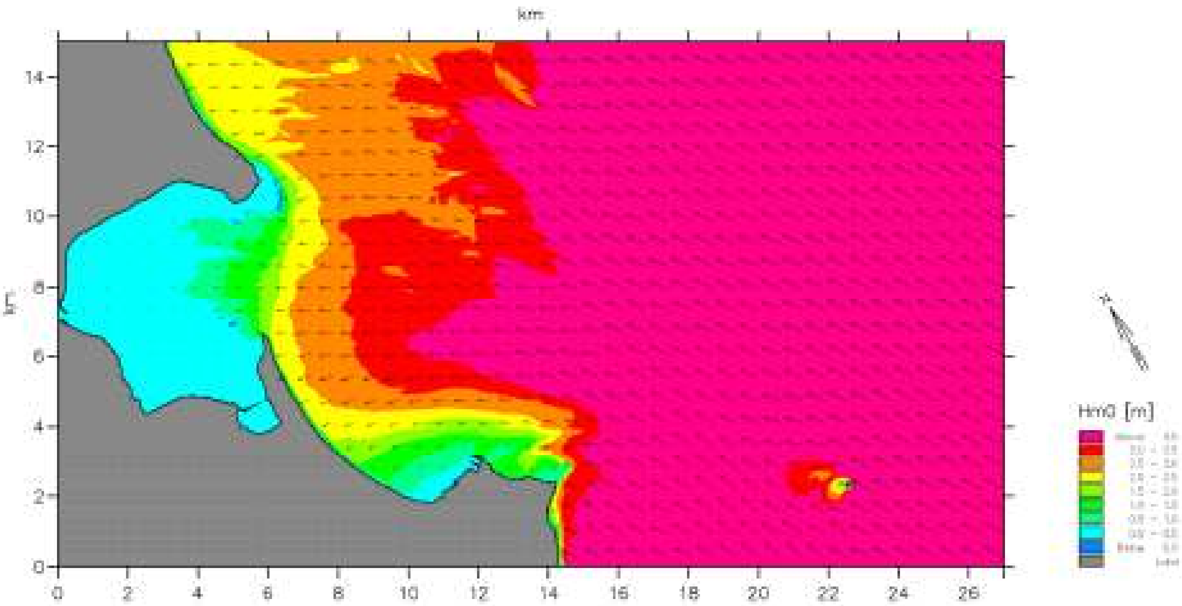


Figure 14: Significant wave heights and mean wave direction for a southerly storm at high water

The effect of the banks on the inshore wave climate can also be seen in Figure 15 which shows the wave heights and mean wave directions approaching Rosslare during both north east and south east gales at high tide. It can be seen that the presence of the banks significantly reduces the wave heights at Rosslare during north east gales compared to those encountered during south east gales which can approach Rosslare from south of the Long Bank.



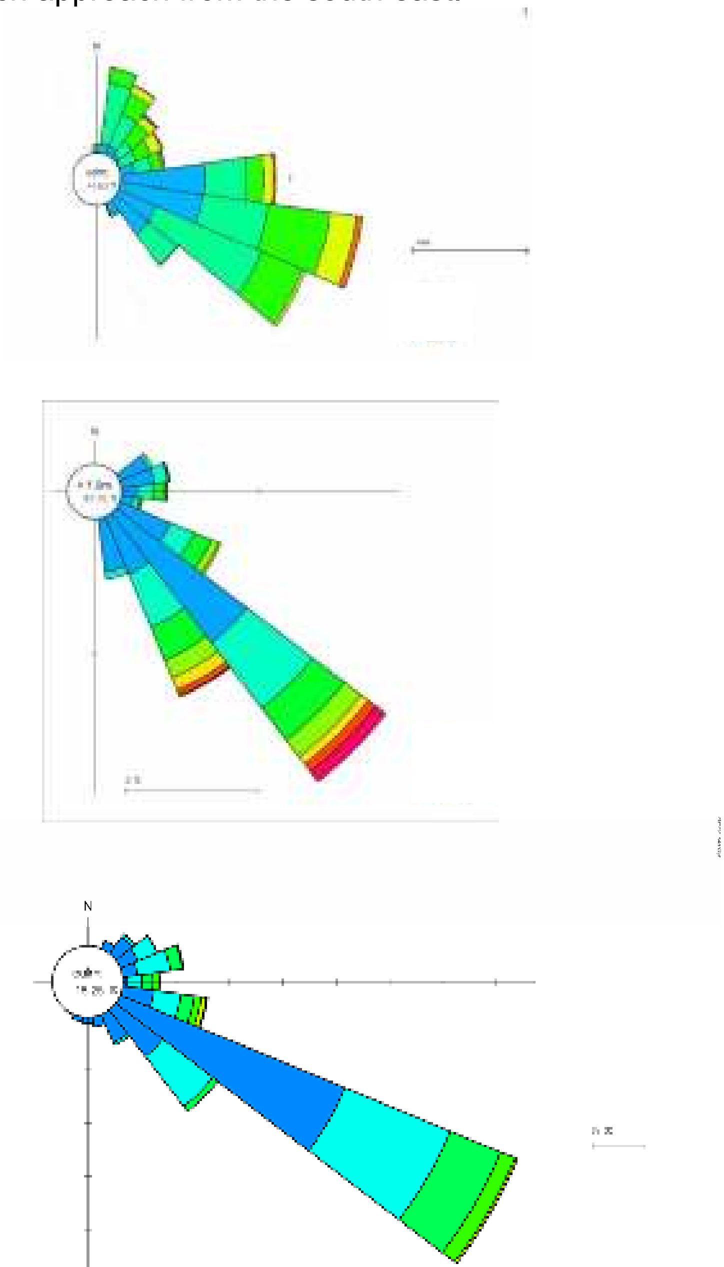
Wave Height and Direction – NE Gale at High Tide



Wave Height and Direction – SE Gale at High Tide

Figure 15: Wave height and direction inshore at Rosslare

Typical annual inshore wave roses from the period 1992-2000 are shown in Figure 16 for Greystones, Courtown and Rosslare. It is clear from these inshore wave roses that large waves can approach the inshore area at locations such as Courtown where the gaps in the offshore banks allow the dominant wave direction a clear approach to the site. In areas such as Greystones the offshore banks protect the coast from waves approaching from most of the predominant wave directions, as a result a more even spread of the prevailing wave directions is found inshore in this area. As noted above, the offshore banks at Rosslare protect the beach from the largest waves from the north east so the inshore wave climate is dominated by waves which approach from the south east.



Greystones

Courtown

Rosslare

Figure 16: Inshore Wave Roses

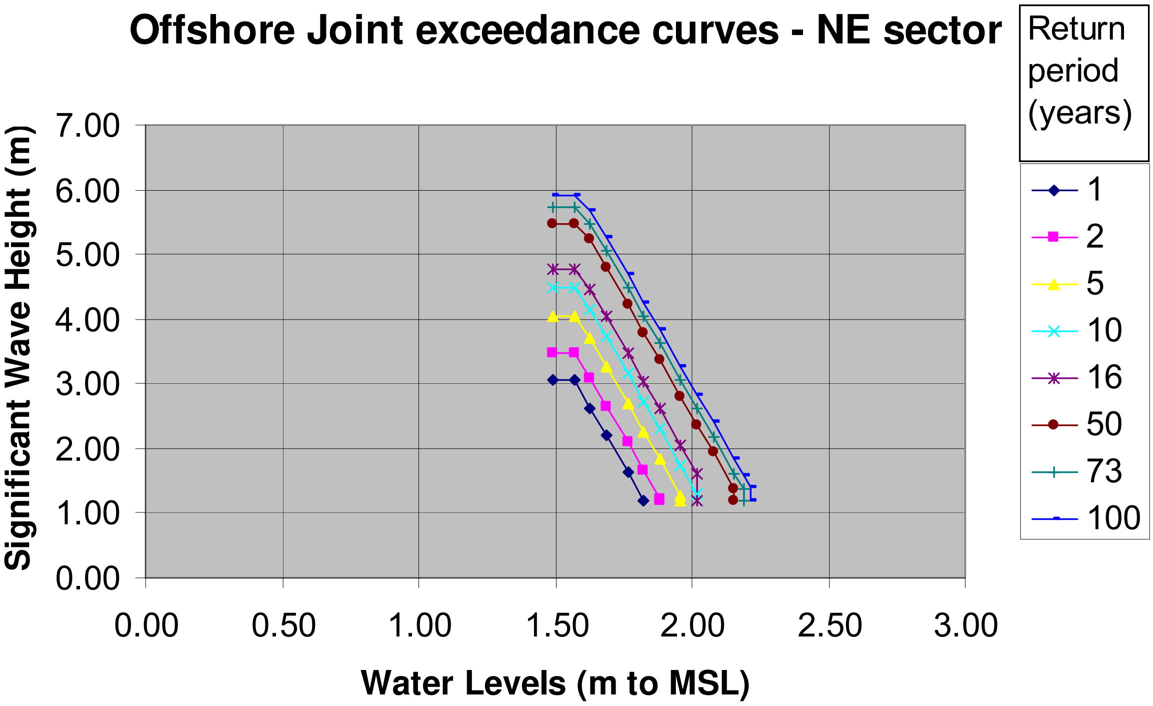
4.2 Joint Probability of Waves and Water Levels

Since the height of the waves approaching the shoreline over much of the study area is affected by the depth of water over the offshore banks, the joint probability analysis was based on the inshore wave heights derived from the results of the wave transformation modelling and the appropriate water levels for the area as derived from the Dublin tide gauge records. Consequently the joint probability analysis could only be undertaken for the section of the study area from Dalkey to Wicklow as the water levels for the section of coast south of Wicklow were too remote from Dublin to give a meaningful result. There were no other reliable sources of tidal data that could be related to the available three hourly wave records and so the northern section of the coast was used to derive correlation coefficients which were applied to the entire study area.

The joint probability analysis was undertaken for wave heights and water levels for each of the north east and south east offshore wave direction sectors by producing a joint event matrix for each sector from the 16 years of wave and water level data. This analysis was undertaken using the software tools and methodology as described in section 5.7 of the DEFRA / Environment Agency RSD Guidance on Joint Probability Analysis (Reference 2). This method involves selecting a correlation coefficient between the two variables and is normally based on established relationships (e.g. wave height and sea level) for an adjacent area. Although correlation coefficients are published in the DEFRA / Environmental Agency Guidance, none of these relate to areas on the western side of the Irish Sea.

For this study, the joint event matrices relating wave heights and water levels were used to define the correlation coefficient for each of the north east and south east wave sectors. For the offshore waves, the analysis indicated that there was a strong correlation (0.6) between the wave height and water levels for events from the south east sector while there was less correlation (0.15) for events from the north east sector. Inshore, the effect of the water depth over the banks resulted in there being a strong correlation between the wave height and water levels for both sectors with correlation coefficients of 0.6.

Some examples of the joint probability plots are shown in Figure 17 and Figure 18 for the north east and south east offshore and inshore wave directions, respectively. The inshore joint probability curves show that a 1 in 100 year event may be composed of a 1 in 10 year return period water level with a 1 in 5 year wave event or alternatively a 1 in 1 year water level with a 1 in 40 year wave event. These probability curves apply to both the north east and south east sectors. Plots are to referenced to mean sea level, but can be converted to OD Malin by subtracting circa 0.2m from the water levels.



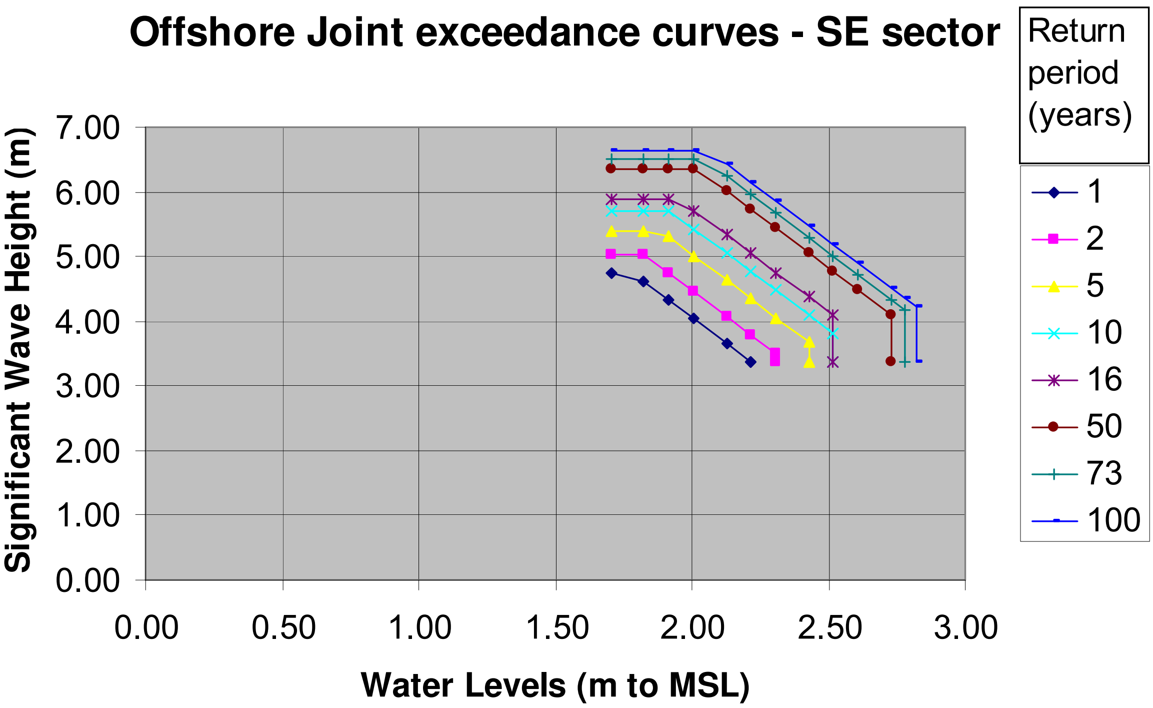
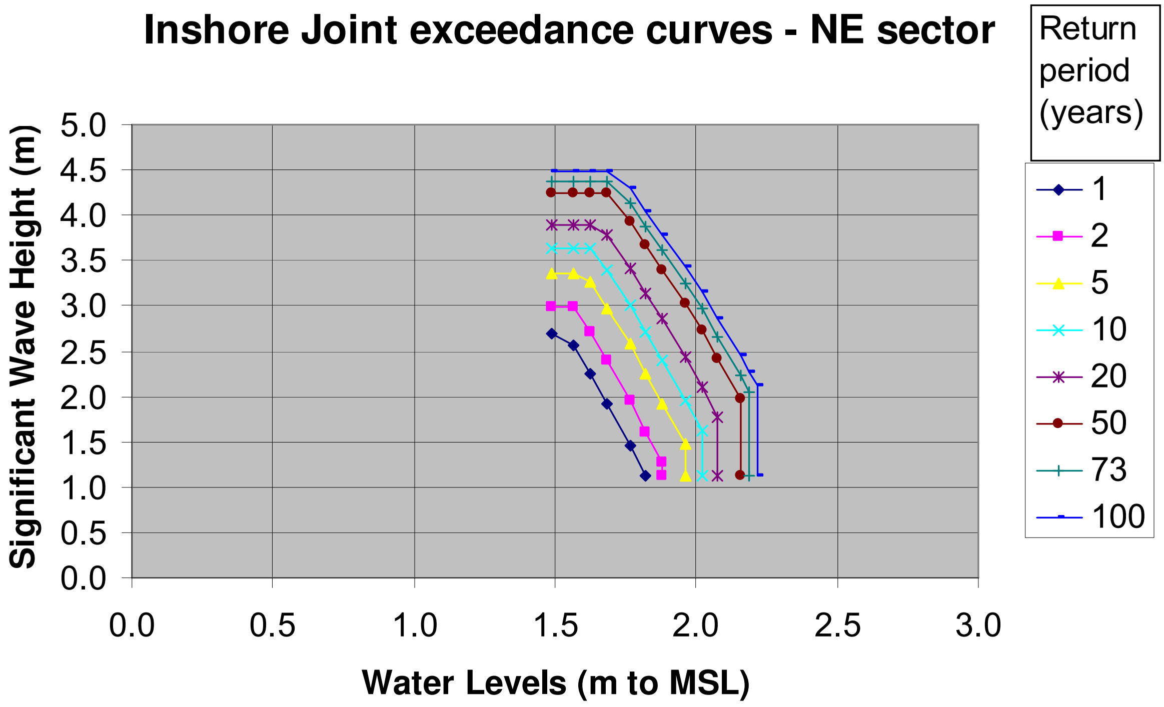


Figure 17: Offshore joint wave and water level exceedance curves



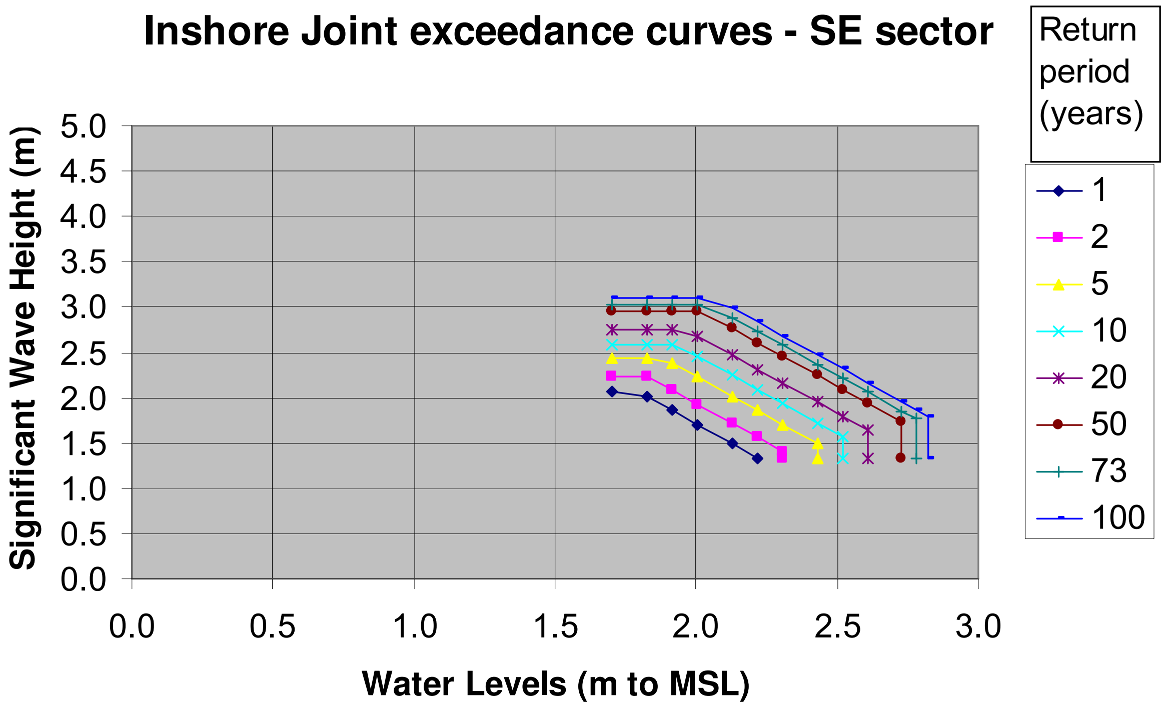


Figure 18: Inshore joint wave and water level exceedance curves

5.0 Extreme Value Analysis of Water Levels

5.1 Introduction

Extreme value analysis (EVA) was undertaken by fitting theoretical probability distributions to the observed water level values. 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. Seven distributions were 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. Using these methods the parameter of the statistical distributions are determined.

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 the extreme coastal water levels or the combination of waves and 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.

The extreme value analysis and subsequent probability analysis were applied in two ways depending on the relationship between surge and tidal conditions at each of the 42 data points. In areas of low currents the extreme surge levels can be considered independent in terms of current-surge interaction. The extreme value analysis could therefore be applied to the surge and tidal conditions separately and a joint probability analysis carried out.

In shallow water regions, where the tidal currents are much stronger, the current and surge conditions are strongly dependent and the combined i.e. total water levels had to be evaluated and probability distributions applied directly.

The joint probability analysis was undertaken using the method outlined in section 4.2 and as per Reference 2. The correlation coefficients relevant to the study were chosen from review of comparable data sets from Holyhead and Fishguard. The output was validated against an analysis of water levels at Dublin by undertaking the joint probability analysis for a point close to the entrance of Dublin Port and comparing the resulting values against the results of an extreme value analysis of the total water levels recorded at Dublin North Quay.

5.2 EVA for Areas with Low Current-Surge Interaction: Points P1-30 & 35-40

Extreme value analysis of surge

The extreme value analysis of surge 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 methods used to evaluate the parameters are given below.

- Truncated Gumbel method - maximum likelihood
- Two parameter Weibull - method of moments
- 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 19, with the parameters of the distribution 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 events and the relevant surge residual values are shown for 0.1% and 0.5% annual exceedance probability in Table 3. 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 10mm difference) and the standard deviation is in the order of 80 to 95mm. All results are given in Appendix 3.

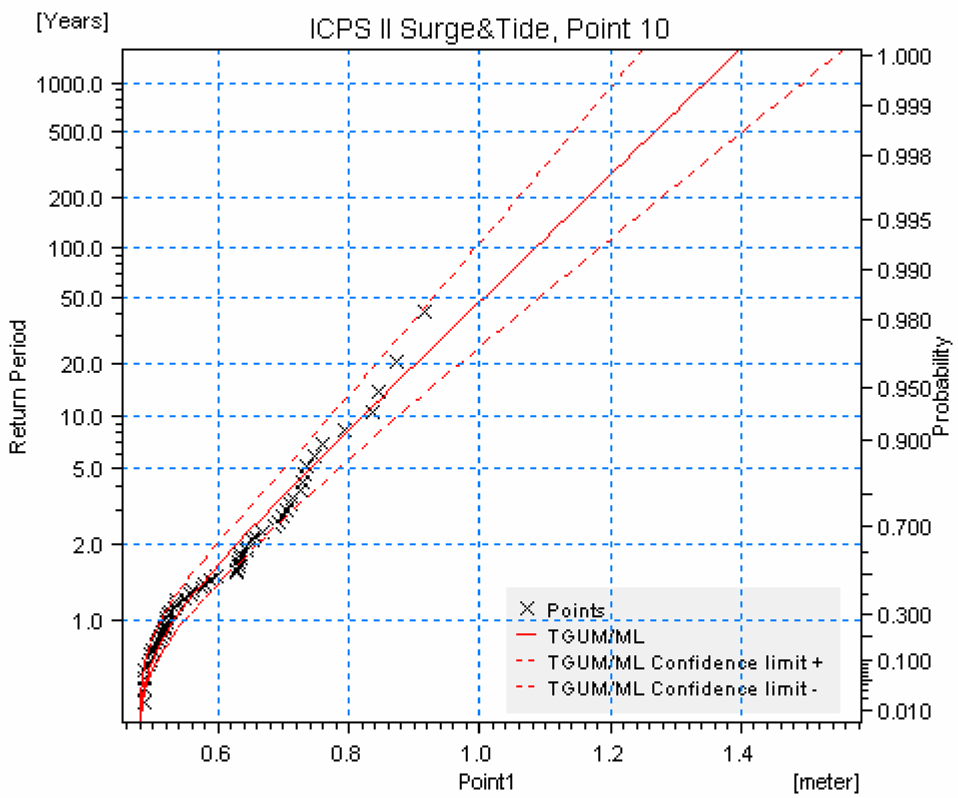


Figure 19: Simulated surge residuals and fitted truncated Gumbel distribution with confidence limits

Table 3: Extreme surge residual values for 0.1% & 0.5% AEP events

	Coordinate		0.1% exceedance value			0.5% exceedance value		
	Longitude	Latitude	estimated value [m]	averaged value [m]	st.dev [m]	estimated value [m]	averaged value [m]	st.dev [m]
Point 1	-6.13472	53.3397	1.395	1.402	0.089	1.210	1.216	0.070
Point 2	-6.11926	53.2901	1.411	1.418	0.088	1.218	1.224	0.067
Point 3	-6.09151	53.2679	1.434	1.441	0.090	1.235	1.241	0.068
Point 4	-6.10708	53.2459	1.413	1.420	0.088	1.217	1.223	0.066
Point 5	-6.0635	53.1529	1.410	1.418	0.088	1.212	1.218	0.066
Point 6	-6.09377	53.2103	1.426	1.435	0.088	1.225	1.232	0.066
Point 7	-6.07062	53.1797	1.408	1.415	0.089	1.213	1.218	0.067
Point 8	-6.05036	53.1393	1.411	1.419	0.088	1.212	1.218	0.066
Point 9	-6.03331	53.1000	1.408	1.416	0.088	1.207	1.214	0.066
Point10	-6.03367	53.0595	1.374	1.381	0.089	1.182	1.188	0.066
Point11	-6.04403	53.0199	1.342	1.349	0.089	1.157	1.162	0.066
Point12	-6.03656	52.9839	1.326	1.332	0.088	1.142	1.148	0.066

	Coordinate		0.1% exceedance value			0.5% exceedance value		
	Longitude	Latitude	estimated value [m]	averaged value [m]	st.dev [m]	estimated value [m]	averaged value [m]	st.dev [m]
Point13	-6.00899	52.9518	1.307	1.312	0.093	1.136	1.140	0.071
Point14	-6.03538	52.9053	1.251	1.255	0.089	1.093	1.096	0.068
Point15	-6.05261	52.8603	1.252	1.256	0.089	1.093	1.096	0.069
Point16	-6.09507	52.8395	1.253	1.256	0.091	1.093	1.095	0.069
Point 17	-6.129	52.8054	1.234	1.237	0.090	1.076	1.078	0.069
Point 18	-6.13945	52.7797	1.223	1.226	0.090	1.065	1.068	0.069
Point 19	-6.14061	52.7393	1.176	1.179	0.084	1.030	1.032	0.065
Point 20	-6.16476	52.7095	1.202	1.204	0.087	1.048	1.051	0.066
Point 21	-6.19942	52.6756	1.175	1.177	0.086	1.025	1.027	0.065
Point 22	-6.2104	52.6603	1.160	1.161	0.084	1.013	1.014	0.064
Point 23	-6.22133	52.6194	1.111	1.113	0.080	0.974	0.976	0.062
Point 24	-6.20786	52.5935	1.118	1.120	0.081	0.979	0.981	0.062
Point 25	-6.19608	52.5526	1.138	1.140	0.079	0.996	0.998	0.061
Point 26	-6.21915	52.5233	1.191	1.194	0.086	1.037	1.039	0.065
Point 27	-6.24346	52.5002	1.170	1.172	0.084	1.021	1.022	0.064
Point 28	-6.28149	52.4696	1.151	1.152	0.084	1.005	1.006	0.064
Point 29	-6.31889	52.4313	1.127	1.129	0.084	0.984	0.986	0.064
Point 30	-6.35501	52.3943	1.101	1.103	0.083	0.961	0.963	0.063
Point 35	-6.3841	52.3110	1.105	1.108	0.081	0.961	0.963	0.063
Point 36	-6.38256	52.2804	1.036	1.038	0.077	0.903	0.905	0.060
Point 37	-6.33707	52.2592	0.987	0.984	0.089	0.871	0.869	0.068
Point 38	-6.31681	52.2333	1.172	1.173	0.097	1.015	1.016	0.074
Point 39	-6.34165	52.2002	1.114	1.114	0.092	0.968	0.968	0.070
Point 40	-6.36556	52.1685	1.167	1.168	0.096	1.013	1.014	0.074

Extreme value analysis of tides

Even though the occurrence of certain tidal levels is not a random process but determined by the reoccurring constellation of sun and moon in relation to the earth, the joint occurrence of a certain tidal level and a specific surge level can be considered semi-random. To estimate their joint probability the extreme tidal levels were also analysed using an extreme value analysis. In this analysis it was found that a fixed threshold level provided the best results, with a level of just above mean high water springs generating the best dataset. As with the surge analysis, the full range of distributions was evaluated. The three parametric Weibull distributions were found to give the best fitting results. Although extreme tides occur approximately every 18 years they are not all the same and there are even higher water levels at higher return periods. Thus using a probability distribution with monotonic increasing values for higher return period is valid, though it might over predict higher return period events slightly as can be seen in Figure 20.

The analysis of tides was undertaken for Dublin, Wicklow, Arklow, Courtown and Rosslare using 50 years of predicted tidal data. This data was derived using tidal harmonics from the analysed time series of recorded water levels supplemented with additional seasonal values from a harmonics library held in-house by RPS.

The probability distribution for extreme astronomic tidal levels at Wicklow is shown in Figure 20. Water levels were evaluated for the 1 in 0.01 to 1 in 100 year events (i.e. 100 occurrences per year to 0.5% exceedance probability) for all five locations mentioned above. These astronomic water levels were interpolated to the points P1-30 and P35-40 proportionally to the change in mean sea level using the tidal and surge model. It is important to note that the steepest gradient in the water level / occurrence distribution is found with frequent occurrences.

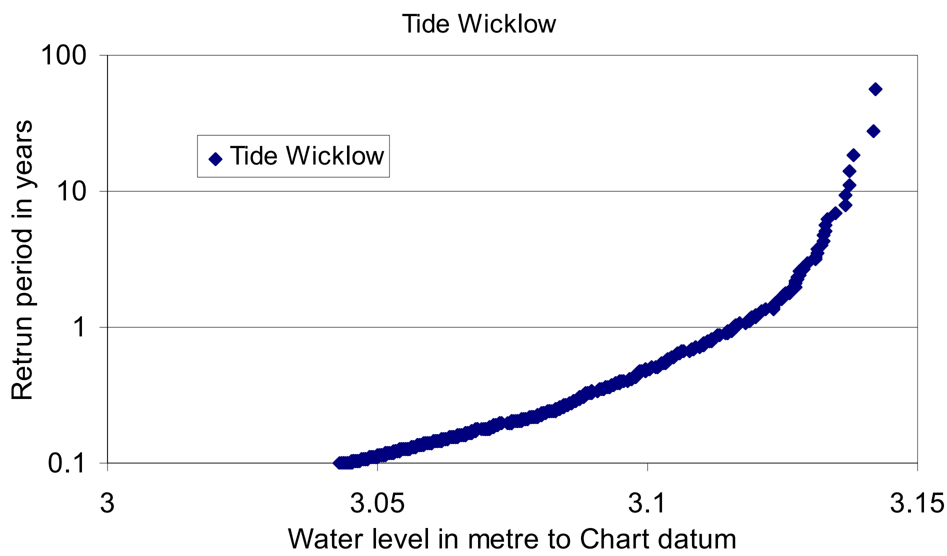


Figure 20: Probability distribution of astronomic high water levels at Wicklow

5.3 Joint Probability of Tidal & Storm Surge Water Levels: Points P1-30 & P35-40

The joint probability analysis undertaken based on Holyhead data showed, as expected, a weak relationship exists between high astronomic tides and extreme surge events. This relationship is related to the highest tides occurring during autumn and spring months, which also tends to coincide with the stormiest weather conditions in the northern hemisphere. As discussed in Section 5.1, the joint probability analysis was undertaken using the software tools and methodology as described in Reference 2. A bi-variant distribution was applied with ρ = 0.025 which was tested using Holyhead data and validated using Dublin water levels.

Table 4 presents the results of the joint probability analysis in terms of return period of tidal component against return period of surge component. The return period of the surge component is given in the centre of the table. From these return periods the surge water levels were calculated and added to the tidal water levels given by the return period of the tidal component on the left hand side. The result is shown in Table 5.

		Joint exceedence return period (years)							
		2	5	10	20	50	100	200	1000
		Marginal return period (years) for surge component							
Marginal return period for tidal component	0.01	1.454152	4.147674	9.165291	20	50	100	200	1000
	0.02	0.727076	2.073837	4.582646	10.12647	28.8837	63.82553	141.038	888.9402
	0.05	0.29083	0.829535	1.833058	4.050586	11.55348	25.53021	56.41519	355.5761
	0.1	0.145415	0.414767	0.916529	2.025293	5.776739	12.76511	28.20759	177.788
	0.2	0.072708	0.207384	0.458265	1.012647	2.88837	6.382553	14.1038	88.89402
	0.5	0.029083	0.082953	0.183306	0.405059	1.155348	2.553021	5.641519	35.55761
	1	0.014542	0.041477	0.091653	0.202529	0.577674	1.276511	2.820759	17.7788
	2	0.007271	0.020738	0.045826	0.101265	0.288837	0.638255	1.41038	8.889402
	5	#N/A	0.008295	0.018331	0.040506	0.115535	0.255302	0.564152	3.555761
	10	#N/A	#N/A	0.009165	0.020253	0.057767	0.127651	0.282076	1.77788
	20	#N/A	#N/A	#N/A	0.010126	0.028884	0.063826	0.141038	0.88894
	50	#N/A	#N/A	#N/A	#N/A	0.011553	0.02553	0.056415	0.355576
	100	#N/A	#N/A	#N/A	#N/A	#N/A	0.012765	0.028208	0.177788

Table 4: Joint probability table showing probability of surge component associated with tidal component

As can be seen in Table 5 up to thirteen water levels were calculated as a result of the joint probability analysis. The highest water level was then used as the extreme water level for this given point and return period (circled in red in Table 5). In general the extreme water levels were found to be associated with higher return period surges and relatively low return period tidal levels, though this varied throughout the pilot area.

		Joint exceedence return period (years)							
		2	5	10	20	50	100	200	1000
Marginal return period for tidal component	0.01	1.0368464	1.1421481	1.2218058	1.3002009	1.3922577	1.461896	1.5315342	1.6932293
	0.02	1.0201735	1.1254752	1.2051329	1.2847906	1.3900924	1.4697501	1.5494078	1.7343672
	0.05	0.9852112	1.090513	1.1701707	1.2498284	1.3551301	1.4347878	1.5144455	1.699405
	0.1	0.9503251	1.0556268	1.1352845	1.2149422	1.320244	1.3999017	1.4795594	1.6645188
	0.2	0.9092293	1.0145311	1.0941888	1.1738465	1.2791482	1.3588059	1.4384636	1.6234231
	0.5	0.8468455	0.9521473	1.031805	1.1114627	1.2167644	1.2964221	1.3760798	1.5610392
	1	0.7945638	0.8998655	0.9795232	1.0591809	1.1644826	1.2441403	1.323798	1.5087575
	2	0.7386709	0.8439726	0.9236303	1.003288	1.1085898	1.1882475	1.2679052	1.4528646
	5	0	0.7655781	0.8452358	0.9248935	1.0301952	1.1098529	1.1895106	1.3744701
	10	0	0	0.7831965	0.8628542	0.968156	1.0478137	1.1274714	1.3124308
	20	0	0	0	0.7989464	0.9042481	0.9839058	1.0635635	1.2485229
	50	0	0	0	0	0.8174945	0.8971522	0.9768099	1.1617693
	100	0	0	0	0	0	0.83015	0.9098077	1.0947671

Table 5: Joint probability table showing total water level associated with tidal return periods (MSL)

5.4 Coastal Areas with High Current-Surge Interaction: Points P31-34

In Wexford Harbour, it was considered that there is no significant interaction of surges and tidal current. Indeed, anecdotal evidence suggests that during frequent easterly wind conditions, the tidal levels in the Harbour do not drop during ebb flow. Therefore an analysis using joint probability was not considered possible, since there were not enough events to obtain an analysis with sufficiently narrow confidence intervals. This area was assessed using the total water level from the numerical model. Probability distributions were fitted to all data sets and the best fitting distribution selected for deriving the return period water levels. It is interesting to note that at the points close to the entrance the truncated Gumbel distribution provided the best fit, whereas the two parametric Weibull and the Gamma distribution provided a better fit to the data inside the Harbour. The extreme water levels are given in Table 6.

Table 6: Extreme Total Water Levels in Wexford Harbour

			Return Period Water Levels to MSL							
	latitude	longitude	2	5	10	20	50	100	200	1000
Point 30	52.3944	-6.35501	1.094	1.195	1.274	1.34	1.438	1.507	1.574	1.731
Point 31	52.3456	-6.35488	1.1	1.199	1.279	1.351	1.446	1.516	1.584	1.743
Point31b	52.3546	-6.41088	1.184	1.315	1.419	1.517	1.634	1.722	1.808	2.005
Point 32	52.3624	-6.47787	1.19	1.34	1.456	1.549	1.684	1.774	1.861	2.052
Point 33	52.335	-6.4476	1.142	1.29	1.403	1.51	1.643	1.741	1.839	2.063
Point33b	52.3127	-6.44507	1.117	1.246	1.359	1.465	1.599	1.699	1.798	2.026
Point 34	52.3006	-6.40914	1.096	1.218	1.311	1.394	1.505	1.586	1.667	1.853
Point 35	52.311	-6.3841	1.147	1.251	1.337	1.41	1.517	1.592	1.666	1.838

6.0 Floodplain Mapping

6.1 Creating Flood Heights for the Floodplain Mapping

The surge modelling and the 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. 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 we 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 through the study this method 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. This is based on the results of a joint project with Ordnance Survey UK and Ordnance Survey Northern Ireland, whereby Ordnance Survey Ireland 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 21. 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 pilot 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 Dublin North Quay, which resulted in a difference of 0.031metres between observed MSL and the secondary corrective surface. At Rosslare a MSL was derived from gauged records from a temporary tide gauge installed by the Client. This produced a difference of 0.053metres between observed MSL and the secondary corrective surface. Given the limited length of record this was considered to be acceptable. It should be noted, that the above differences are within the stated accuracy of the OSGM02 conversion.

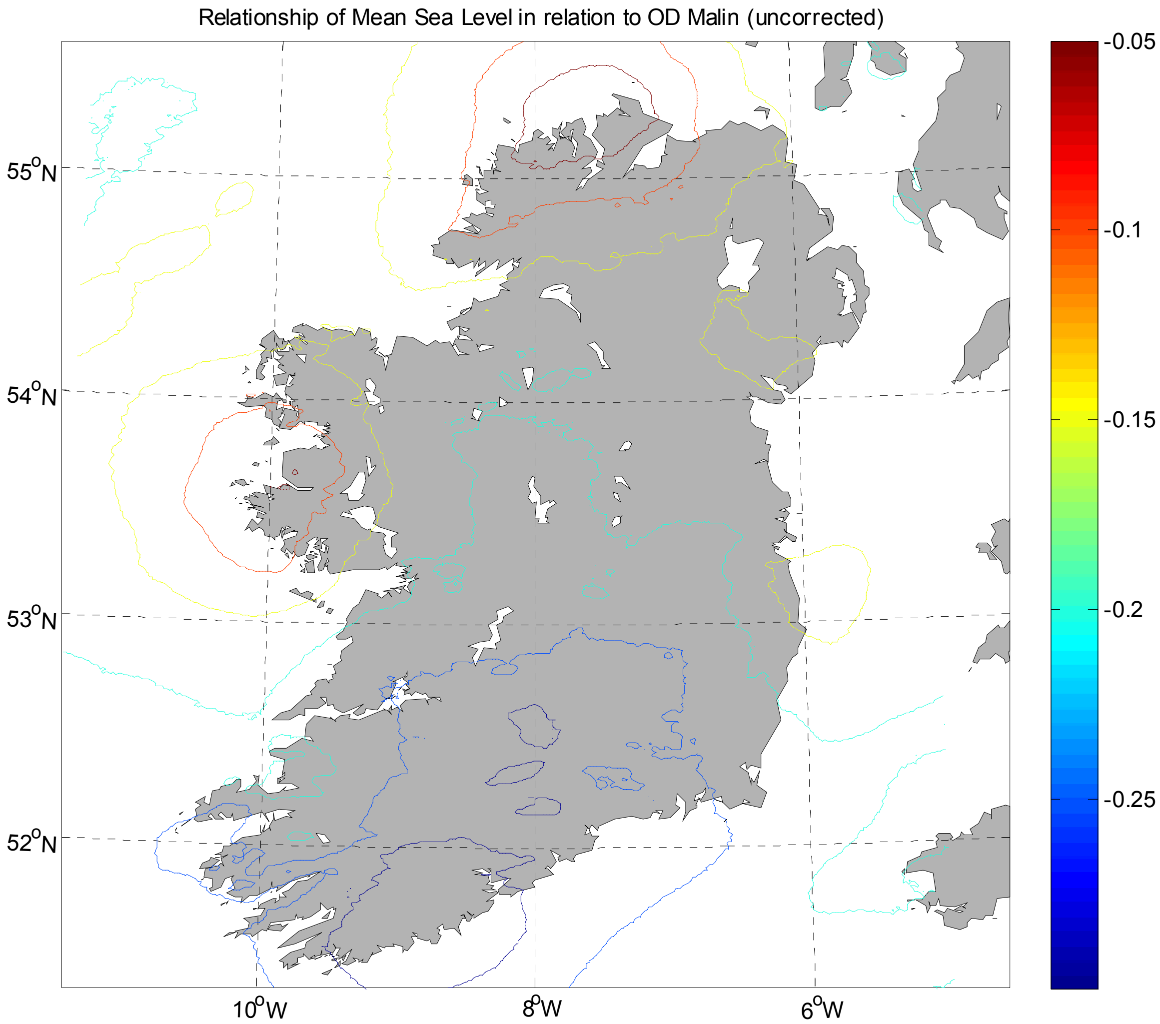


Figure 21: Secondary corrective surface between OSGM02 gravity and OSGM02 OD Malin

The detailed conversions for each of the extreme value analysis points are shown in the following tables. Table 7 gives the results of the joint probability analysis of combined tide and surge events for all locations excluding Wexford Harbour (points 1-30 and 35-40) whilst Table 8 gives the same information for Wexford Harbour (points 31-34). In Table 7 and Table 8 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 12.

Table 7: Joint Probability Table showing Combined Tide and Surge Levels in Pilot Area for Points 1-30 and 35-40 (all heights in metres)

		Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Point 7	Point 8	Point 9
Coord-inate	**Longitude**	**-6.13472**	**-6.11926**	**-6.09151**	**-6.10708**	**-6.0635**	**-6.09377**	**-6.07062**	**-6.05036**	**-6.03331**
	Latitude	**53.33977**	**53.29011**	**53.26793**	**53.24596**	**53.15293**	**53.2103**	**53.1797**	**53.13938**	**53.10006**
Height to mean sea level for different AEP	50%	2.43	2.38	2.31	2.29	2.15	2.24	2.19	2.12	1.95
	20%	2.55	2.51	2.44	2.42	2.29	2.37	2.32	2.25	2.08
	10%	2.64	2.61	2.54	2.52	2.38	2.47	2.42	2.35	2.18
	5%	2.74	2.70	2.64	2.62	2.48	2.57	2.52	2.45	2.29
	2%	2.86	2.83	2.77	2.75	2.62	2.71	2.65	2.58	2.42
	1.0%	2.95	2.93	2.87	2.85	2.72	2.81	2.75	2.68	2.52
	0.5%	3.05	3.03	2.97	2.94	2.82	2.91	2.85	2.78	2.62
	0.1%	3.26	3.25	3.21	3.17	3.05	3.14	3.07	3.02	2.85
MSL to OD Malin		-0.144	-0.126	-0.119	-0.114	-0.103	-0.106	-0.100	-0.104	-0.106
Seich/set-up allowance		0.050	0.100	0.050	0.050	0.050	0.050	0.050	0.050	0.050
Height to OD Malin for different AEP	**50%**	**2.33**	**2.36**	**2.24**	**2.23**	**2.10**	**2.18**	**2.14**	**2.07**	**1.89**
	20%	**2.46**	**2.48**	**2.37**	**2.36**	**2.23**	**2.32**	**2.27**	**2.20**	**2.03**
	10%	**2.55**	**2.58**	**2.47**	**2.45**	**2.33**	**2.42**	**2.37**	**2.30**	**2.13**
	5%	**2.64**	**2.68**	**2.57**	**2.55**	**2.43**	**2.52**	**2.47**	**2.40**	**2.23**
	2%	**2.76**	**2.81**	**2.70**	**2.68**	**2.56**	**2.65**	**2.60**	**2.53**	**2.36**
	1.0%	**2.86**	**2.90**	**2.80**	**2.78**	**2.66**	**2.75**	**2.70**	**2.63**	**2.46**
	0.5%	**2.95**	**2.30**	**2.90**	**2.88**	**2.76**	**2.85**	**2.80**	**2.73**	**2.56**
	0.1%	**3.17**	**3.22**	**3.14**	**3.11**	**2.99**	**3.09**	**3.02**	**2.96**	**2.80**

Table 7 continued (all heights in metres)

		Point 10	Point 11	Point 12	Point 13	Point 14	Point 15	Point 16	Point 17	Point 18
Coord-inate	**Longitude**	**-6.03367**	**-6.04403**	**-6.03656**	**-6.00899**	**-6.03538**	**-6.05261**	**-6.09507**	**-6.129**	**-6.13945**
	Latitude	**53.05957**	**53.01992**	**52.98392**	**52.95186**	**52.90536**	**52.86034**	**52.83956**	**52.80548**	**52.77978**
Height to mean sea level for different AEP	50%	1.85	1.76	1.72	1.43	1.29	1.14	1.09	1.06	1.04
	20%	1.98	1.89	1.84	1.54	1.39	1.25	1.19	1.16	1.14
	10%	2.07	1.98	1.93	1.63	1.47	1.33	1.27	1.24	1.22
	5%	2.17	2.07	2.02	1.71	1.55	1.41	1.35	1.32	1.30
	2%	2.30	2.20	2.14	1.82	1.65	1.50	1.45	1.41	1.39
	1.0%	2.39	2.29	2.24	1.91	1.73	1.58	1.53	1.49	1.47
	0.5%	2.49	2.38	2.33	1.99	1.81	1.66	1.61	1.57	1.55
	0.1%	2.71	2.60	2.54	2.19	1.99	1.85	1.80	1.76	1.73
MSL to OD Malin		-0.109	-0.115	-0.117	-0.122	-0.131	-0.136	-0.141	-0.151	-0.153
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%**	**1.79**	**1.70**	**1.65**	**1.36**	**1.20**	**1.06**	**1.00**	**0.96**	**0.93**
	20%	**1.92**	**1.82**	**1.77**	**1.47**	**1.31**	**1.16**	**1.10**	**1.06**	**1.04**
	10%	**2.01**	**1.91**	**1.86**	**1.56**	**1.39**	**1.24**	**1.18**	**1.14**	**1.12**
	5%	**2.11**	**2.01**	**1.96**	**1.64**	**1.47**	**1.32**	**1.26**	**1.22**	**1.20**
	2%	**2.24**	**2.13**	**2.08**	**1.75**	**1.57**	**1.42**	**1.36**	**1.31**	**1.29**
	1.0%	**2.33**	**2.22**	**2.17**	**1.84**	**1.65**	**1.50**	**1.44**	**1.39**	**1.37**
	0.5%	**2.43**	**2.32**	**2.26**	**1.92**	**1.73**	**1.58**	**1.52**	**1.47**	**1.45**
	0.1%	**2.65**	**2.53**	**2.48**	**2.12**	**1.91**	**1.76**	**1.70**	**1.66**	**1.63**

Table 7 continued (all heights in metres)

		Point 19	Point 20	Point 21	Point 22	Point 23	Point 24	Point 25	Point 26	Point 27
Coord-inate	**Longitude**	**-6.14061**	**-6.16476**	**-6.19942**	**-6.2104**	**-6.22133**	**-6.20786**	**-6.19608**	**-6.21915**	**-6.24346**
	Latitude	**52.73938**	**52.70954**	**52.67562**	**52.66032**	**52.61946**	**52.59355**	**52.55262**	**52.52339**	**52.50022**
Height to mean sea level for different AEP	50%	1.11	1.09	1.07	1.06	1.06	1.06	1.07	1.16	1.21
	20%	1.21	1.20	1.17	1.16	1.15	1.15	1.16	1.26	1.31
	10%	1.28	1.27	1.24	1.23	1.22	1.22	1.23	1.34	1.39
	5%	1.36	1.35	1.32	1.31	1.29	1.29	1.30	1.41	1.46
	2%	1.45	1.44	1.41	1.40	1.38	1.38	1.39	1.51	1.55
	1.0%	1.52	1.52	1.49	1.47	1.45	1.45	1.46	1.58	1.63
	0.5%	1.60	1.60	1.56	1.55	1.52	1.52	1.54	1.66	1.70
	0.1%	1.77	1.78	1.74	1.72	1.68	1.69	1.70	1.84	1.88
MSL to OD Malin		-0.158	-0.165	-0.170	-0.172	-0.174	-0.176	-0.180	-0.185	-0.188
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%**	**1.00**	**0.98**	**0.95**	**0.94**	**0.93**	**0.93**	**0.94**	**1.02**	**1.07**
	20%	**1.10**	**1.08**	**1.05**	**1.04**	**1.03**	**1.03**	**1.03**	**1.12**	**1.17**
	10%	**1.17**	**1.16**	**1.12**	**1.11**	**1.10**	**1.10**	**1.10**	**1.20**	**1.25**
	5%	**1.25**	**1.23**	**1.20**	**1.18**	**1.16**	**1.17**	**1.17**	**1.28**	**1.32**
	2%	**1.34**	**1.33**	**1.29**	**1.27**	**1.25**	**1.26**	**1.26**	**1.37**	**1.42**
	1.0%	**1.41**	**1.41**	**1.37**	**1.35**	**1.32**	**1.33**	**1.33**	**1.45**	**1.49**
	0.5%	**1.49**	**1.48**	**1.44**	**1.42**	**1.39**	**1.40**	**1.41**	**1.53**	**1.57**
	0.1%	**1.66**	**1.66**	**1.62**	**1.60**	**1.55**	**1.56**	**1.57**	**1.71**	**1.74**

Table 7 continued (all heights in metres)

		Point 28	Point 29	Point 30	Point 35	Point 36	Point 37	Point 38	Point 39	Point 40
Coord-inate	**Longitude**	**-6.28149**	**-6.31889**	**-6.35501**	**-6.3841**	**-6.38256**	**-6.33707**	**-6.31681**	**-6.34165**	**-6.36556**
	Latitude	**52.46963**	**52.43138**	**52.39436**	**52.31103**	**52.28048**	**52.25926**	**52.23334**	**52.20024**	**52.16859**
Height to mean sea level for different AEP	50%	1.26	1.28	1.29	1.35	1.35	1.35	1.53	1.60	1.77
	20%	1.36	1.38	1.38	1.45	1.44	1.43	1.64	1.70	1.87
	10%	1.43	1.45	1.45	1.52	1.50	1.49	1.72	1.77	1.95
	5%	1.50	1.52	1.52	1.60	1.57	1.55	1.80	1.85	2.03
	2%	1.59	1.61	1.61	1.69	1.66	1.63	1.90	1.95	2.13
	1.0%	1.67	1.69	1.68	1.76	1.72	1.69	1.98	2.02	2.21
	0.5%	1.74	1.76	1.76	1.83	1.79	1.75	2.06	2.09	2.28
	0.1%	1.91	1.92	1.92	2.00	1.95	1.89	2.24	2.26	2.46
MSL to OD Malin		-0.190	-0.195	-0.198	-0.197	-0.196	-0.196	-0.200	-0.205	-0.205
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%**	**1.12**	**1.14**	**1.14**	**1.21**	**1.20**	**1.20**	**1.38**	**1.45**	**1.61**
	20%	**1.22**	**1.23**	**1.24**	**1.30**	**1.29**	**1.28**	**1.49**	**1.54**	**1.71**
	10%	**1.29**	**1.31**	**1.31**	**1.38**	**1.36**	**1.34**	**1.57**	**1.62**	**1.79**
	5%	**1.36**	**1.38**	**1.38**	**1.45**	**1.42**	**1.40**	**1.64**	**1.69**	**1.87**
	2%	**1.45**	**1.47**	**1.47**	**1.54**	**1.51**	**1.48**	**1.75**	**1.79**	**1.97**
	1.0%	**1.53**	**1.54**	**1.54**	**1.61**	**1.58**	**1.54**	**1.83**	**1.86**	**2.05**
	0.5%	**1.60**	**1.61**	**1.61**	**1.69**	**1.64**	**1.60**	**1.91**	**1.94**	**2.13**
	0.1%	**1.77**	**1.78**	**1.77**	**1.85**	**1.80**	**1.74**	**2.09**	**2.11**	**2.31**

Table 8: Joint Probability Table showing Combined Tide and Surge Levels in Wexford Harbour for Points 31-34 (all heights in metres)

Return Period		Point 31	Point 31b	Point 32	Point 33	Point 33b	Point 34
	latitude	**52.3456**	**52.3546**	**52.3624**	**52.3350**	**52.3127**	**52.3006**
	longitude	**-6.3549**	**-6.4109**	**-6.4779**	**-6.4476**	**-6.4451**	**-6.4091**
Height to mean sea level for different AEP	50%	1.10	1.18	1.19	1.14	1.12	1.10
	20%	1.20	1.32	1.34	1.29	1.25	1.22
	10%	1.28	1.42	1.46	1.40	1.36	1.31
	5.0%	1.35	1.52	1.55	1.51	1.47	1.39
	4.0%	1.38	1.54	1.59	1.54	1.50	1.42
	2.0%	1.45	1.63	1.68	1.64	1.60	1.51
	1.0%	1.52	1.72	1.77	1.74	1.70	1.59
	0.5%	1.58	1.81	1.86	1.84	1.80	1.67
	0.1%	1.74	2.01	2.05	2.06	2.03	1.85
MSL to OD Malin		-0.195	-0.198	-0.201	-0.198	-0.201	-0.199
Seich/set-up allowance		0.050	0.100	0.100	0.100	0.100	0.100
Height to OD Malin for different AEP	**50%**	**0.96**	**1.09**	**1.09**	**1.04**	**1.02**	**1.00**
	20%	**1.05**	**1.22**	**1.24**	**1.19**	**1.15**	**1.12**
	10%	**1.13**	**1.32**	**1.36**	**1.31**	**1.26**	**1.21**
	5.0%	**1.21**	**1.42**	**1.45**	**1.41**	**1.36**	**1.30**
	4.0%	**1.23**	**1.45**	**1.49**	**1.44**	**1.40**	**1.32**
	2.0%	**1.30**	**1.54**	**1.58**	**1.55**	**1.50**	**1.41**
	1.0%	**1.37**	**1.62**	**1.67**	**1.64**	**1.60**	**1.49**
	0.5%	**1.44**	**1.71**	**1.76**	**1.74**	**1.70**	**1.57**
	0.1%	**1.60**	**1.91**	**1.95**	**1.97**	**1.93**	**1.75**

6.2 Accuracy of Predicted Combined Tide and Surge Levels

The accuracy of the predicted annual exceedance probability (AEP) of combined tide and surge levels is dependent on the accuracy of the various components used in deriving these levels i.e. 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.

6.3 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; 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 generally prepared by combining the extreme tide and surge water levels outlined in Tables 7 and 8 with OPW's south east coast digital terrain model (DTM). 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 are expected to follow this report.

The data for analysis initially comprised two layers, a point layer containing spot heights for extreme water levels in a north-south orientation 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 LiDAR elevation data for the Irish coastline at a 2m resolution (DTM). 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 the same extent as the LiDAR 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 LiDAR layer. The output from this 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.

6.4 Accuracy of the Digital Terrain Model

The accuracy of the available topographical data was initially assessed by ERA-Maptec (See Reference 4 and Reference 5) who reported that 50% of the data points had a vertical accuracy of better than ±0.2m, and approximately 5% of the points had a vertical error of greater than ±1.0m. ERA-Maptec was subsequently commissioned to produce a single Digital Terrain Model (DTM) out of the various topographical data sources as reported in Reference 6 and Reference 7. As there was a large amount of ground elevation data from four different surveys, ERA Maptec created a merged dataset, using the Infoterra 2005 LiDAR data, BKS 2004 LiDAR data and BKS 2005 photogrammetric data together with Blom 2007 LiDAR data. As the Blom data proved most accurate, it was used where possible in the final merged dataset, superseding the less accurate data.

ERA-Maptec undertook an analysis of the vertical accuracy of the final combined DTM using RTK-GPS ground survey points supplied by the Client as a frame of reference. The height differences in metres between the DTM model heights and each of the ground survey heights were calculated. In addition to assessing the accuracy by data input source, ERA-Maptec also undertook a further accuracy analysis for the different geographical/spatial regions of the DTM models. This was performed by selecting ground survey data points which fell only within homogeneous parts of the DTM models constructed from a single input data source (Infoterra 2005, BKS 2004, BKS 2005 or Blom 2007).

A further independent quality control assessment on DTM vertical accuracy was then undertaken by RPS, focussing on the main urban centres considered to be at risk from coastal flooding. To facilitate the assessment, RDS Ltd. were commissioned to carry out a Quality Control (QC) survey of five sample areas on the south east coast; namely Bray, Wicklow, Arklow, Wexford and Rosslare. The subsequent data was processed by RPS to compare the accuracy of the DTM with the survey points. The details and results of the survey are presented and discussed in Appendix 6: Quality Control Survey Report.

Taking into consideration the Quality Control surveys and assessments carried out by ERA Maptec and also by RPS/RDS, the overall vertical accuracy of the DTM was established, with the results of these surveys having been combined to produce one single dataset for the purpose of calculating overall accuracy statistics presented in Table 9.

For all twelve locations mean height difference and standard deviation values ranged between -0.225m to 0.180m and 0.112m to 0.429m respectively. Maximum height differences ranged between 0.078m to 1.828m and minimum height differences ranged between -2.494m to -0.565m. The RMSE of height difference values was in general quite high, ranging from 0.121m at Castlebridge to 0.473m at Wexford Harbour. Appendix 6 details the analysis and results of the combined QC exercise.

The results also indicated that at the 95% confidence limit, the accuracy of the DTM varied from between:

- -0.276m to 0.504m at Bray
- -0.891m to 0.296m at the Breaches
- -0.488m to 0.228m at Wicklow
- -0.266m to 0.743m at Brittas Bay
- -0.214m to 0.582m at Arklow
- -0.235 to 0.356 at Courtown
- -0.280m to 0.278m at Curracloe
- -0.264m to 0.144m at Castlebridge
- -1.074m to 0.703m at Wexford Harbour
- -0.728m to 0.241m at Wexford
- -0.882m to 0.210m at Rosslare

At the 99% confidence limit the accuracy of the DTM varied from between:

- -0.752m to 0.714m at Bray
- -1.691m to 0.712m at the Breaches
- -0.820m to 0.656m at Wicklow
- -0.470m to 1.251m at Brittas Bay
- -0.561m to 0.895m at Arklow
- -0.427m to 0.534m at Courtown
- -0.768m to 0.497m at Curracloe
- -0.544m to 0.297m at Castlebridge
- -1.647m to 1.451m at Wexford Harbour
- -1.161m to 0.719m at Wexford
- -1.344m to 0.495m at Rosslare

Combining all locations, at the 95% confidence limit the accuracy of the DTM varied between -0.609m to 0.446m and between -1.142m to 0.756m at the 99% confidence limit. The overall RMSE is 0.274m.

Clearly the principal source of potential inaccuracy in the derivation of the extreme tidal flood outlines relates to inaccuracy within the DTM data as even in the most accurate area the range of potential error in the DTM data is greater than that associated with the extreme water level predictions, and for most surveys is approximately twice the error.

Table 9: Overall vertical accuracy statistics for combined ERA Maptec and RDS results

	Max	Min	Mean	St.Dev.	95% Percentile	Upper 95% Confidence Limit	Lower 95% Confidence Limit	Upper 99% Confidence Limit	Lower 99% Confidence Limit	RMSE	Count
Bray	1.039	-1.359	0.167	0.230	0.441	0.504	-0.276	0.714	-0.752	0.284	1416
Greystones	0.078	-0.704	-0.225	0.207	-	-	-	-	-	0.305	13
Breaches	0.744	-1.862	-0.027	0.279	0.247	0.296	-0.891	0.712	-1.691	0.280	308
Wicklow	0.959	-1.185	-0.058	0.180	0.166	0.228	-0.488	0.656	-0.820	0.189	893
Brittas Bray	1.417	-1.577	0.058	0.281	0.630	0.743	-0.266	1.251	-0.470	0.287	219
Arklow	1.209	-1.391	0.180	0.204	0.459	0.582	-0.214	0.895	-0.561	0.272	2251
Courtown	0.664	-0.621	0.060	0.151	0.309	0.356	-0.235	0.534	-0.427	0.163	284
Curracloe	0.651	-1.106	-0.073	0.185	0.203	0.278	-0.280	0.497	-0.768	0.198	88
Castlebridge	0.356	-0.565	-0.048	0.112	0.115	0.144	-0.264	0.297	-0.544	0.121	317
Wexford Harbour	1.828	-1.852	-0.197	0.429	0.404	0.703	-1.074	1.451	-1.647	0.473	283
Wexford	1.549	-2.494	-0.090	0.246	0.159	0.241	-0.728	0.719	-1.161	0.262	3287
Rosslare	1.073	-2.331	-0.173	0.258	0.101	0.210	-0.882	0.495	-1.344	0.311	1998
Total	1.828	-2.494	-0.010	0.274	0.360	0.446	-0.609	0.756	-1.142	0.274	11357

6.5 Accuracy of the Digital Terrain Model and Flood Extents

Further quality control assessments were undertaken by RPS to verify the horizontal accuracy of the flood extents generated from the combination of the predicted extreme water levels with the DTM. A level comparison was undertaken between the 0.5% and 0.1% flood extents and survey points for five locations. Table 10 shows the horizontal accuracy derived at these five locations for the 0.5% and 0.1% AEP flood extents. Further information can be found in Appendix 6 of this report.

Table 10: Horizontal Accuracy of Flood Extents

LOCATION	0.5% AEP	0.1% AEP
Bray	75m	85m
Wicklow	2m	2m
Arklow	32m	45m
Wexford	19m	25m
Rosslare	2m	2m

Horizontal accuracy of the flood extents for 0.5% AEP ranged from as accurate as 2 metres at Wicklow and Rosslare to 75 metres at Bray, showing the vast extents to which horizontal accuracy can differ. For 0.1% AEP, horizontal accuracy ranged from 2 metres at Wicklow and Rosslare to 85 metres at Bray. For both 0.5% and 0.1% AEP's, Wexford and Arklow were found in the middle of the range, with Wexford having higher accuracy than Arklow. The large variation in extrapolated horizontal accuracy in the flood extents limits the confidence that can be assigned to the results of this study, however for most urban areas the difference found between the survey and the DTM generated flood extent was in the order of 2m, which is the cell size of the DTM.

6.6 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.

Overall it has to be stressed, that the accuracy of the flood maps depends largely on the accuracy of the Digital Terrain Model. Thus while the water levels are produced to high accuracy (+/- 180mm, 95% confidence interval), the resulting maps have lower accuracy due to the accuracy of the Digital Terrain Model. Based on the various quality control survey work carried out as part of this study, the standard deviation of the DTM was estimated in the order of 250mm. Recent LiDAR data acquisition, also used in the study, has shown significantly improved accuracy levels. Thus re-flying the relevant area and obtaining equivalent data sets would considerably improve confidence in the flood outlines. In general higher confidence in the resulting flooded areas 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 the failure of defences or valves on sewers.

In order to more accurately assess the confidence in the flood extents, a confidence analysis procedure was developed and applied on the south east coast. 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. Further information on the methodology and results can be viewed in Appendix 9.

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 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%. For example, flood extents in the Bray area can be considered as having high or medium confidence (39% to 45%), with both Rosslare (45% to 54%) and Wexford (44% to 53%) having low and medium confidence. The final flood extents with associated confidence levels for the entire south east coast are shown in Appendix 7 of this report. Most of the flood extents were classified as having high or medium confidence, with a number of areas showing low confidence. Very few areas were assigned very low confidence, with the majority of these located around Wexford Harbour.

6.7 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 east coast study area, being the primary outputs of the tidal flood hazard assessment, are presented in Appendix 7. There are 22 plans illustrating the flood extent for the two events and these are displayed at a scale of approximately 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 extent of the DTM used in this flood assessment, where there was no DTM available no flood assessment has been undertaken.

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

A review of the floodplain maps, including flood depth maps, in Appendix 7, 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 of potential coastal flood risk are presented in Figures 22 to 28 in respect of the 0.1% AEP event and in Figures 29 to 35 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 are as follows:- :

- Bray, Co Wicklow
- Ballygannon to Five Mile Point, Co Wicklow
- Five Mile Point to Wicklow, Co Wicklow
- Arklow, Co Wicklow
- Cahore Point to Morriscastle, Co Wexford
- Wexford, Castlebridge and Curracloe, Co Wexford
- Rosslare, Co Wexford

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 section of the 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 Appendix 7)

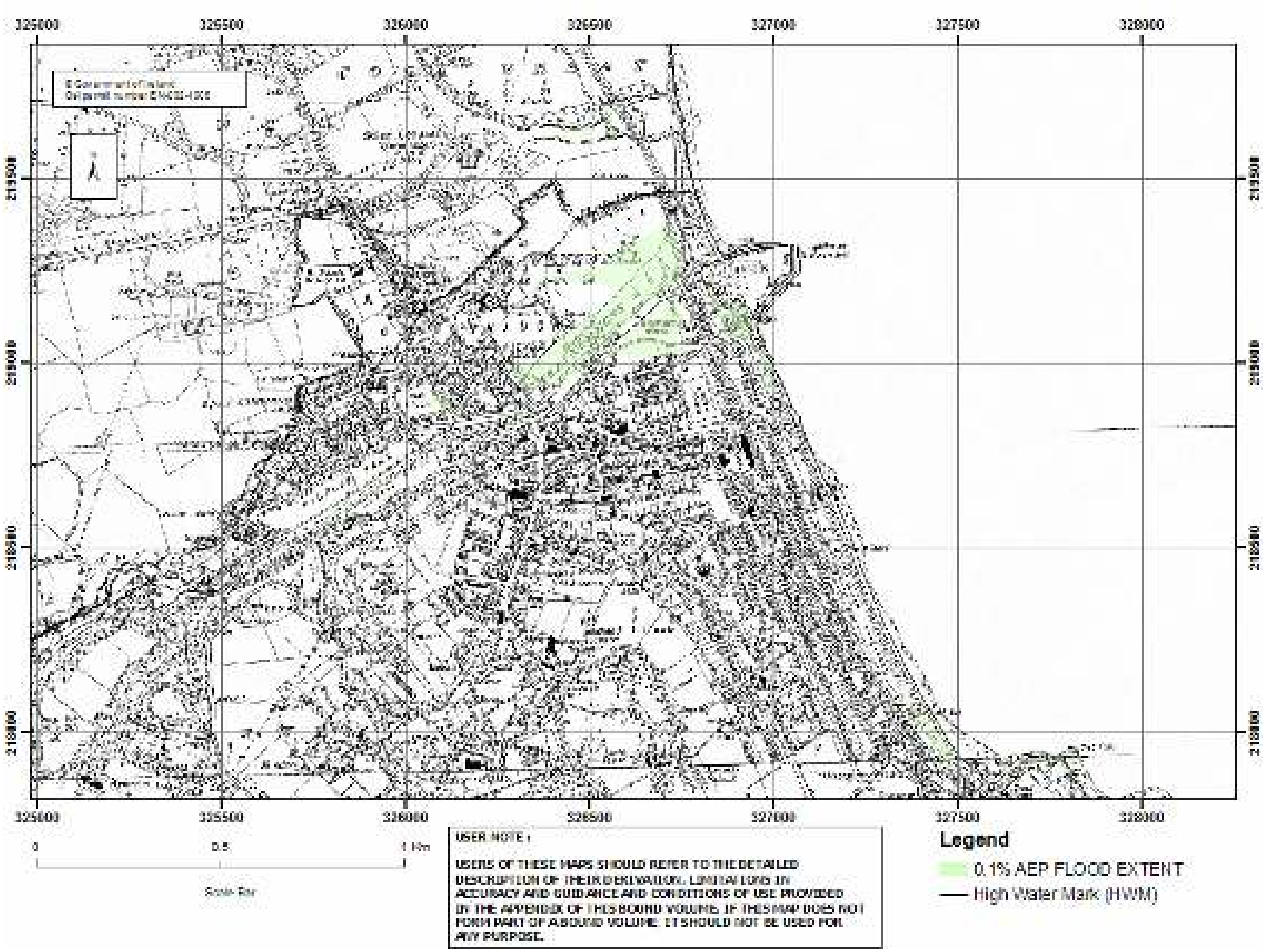


Figure 22: Bray Predictive Flood Extent Map, 0.1% AEP

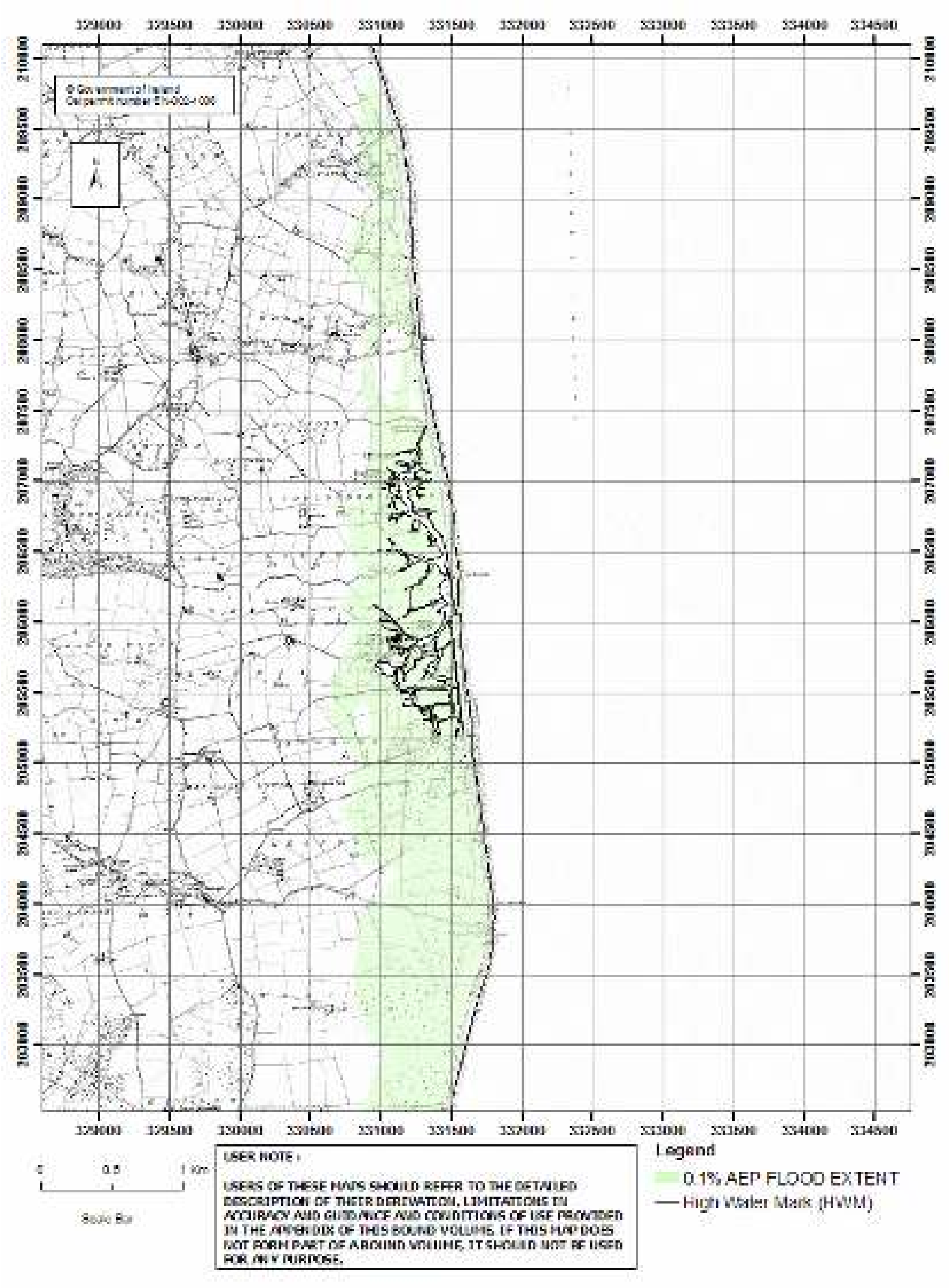


Figure 23: Ballygannon to Five Mile Point Predictive Flood Extent Map, 0.1% AEP

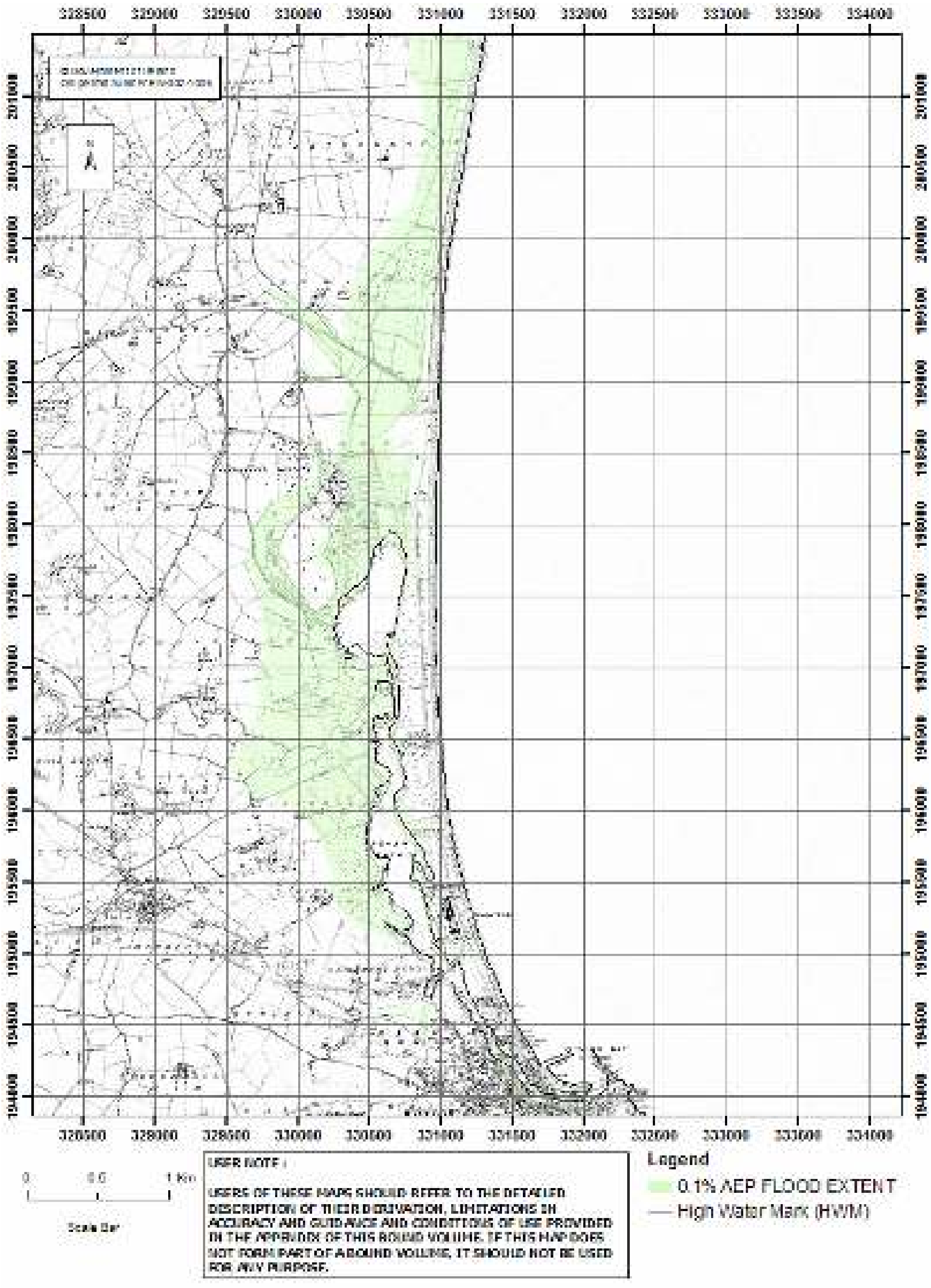


Figure 24: Five Mile Point to Wicklow Predictive Flood Extent Map, 0.1% AEP

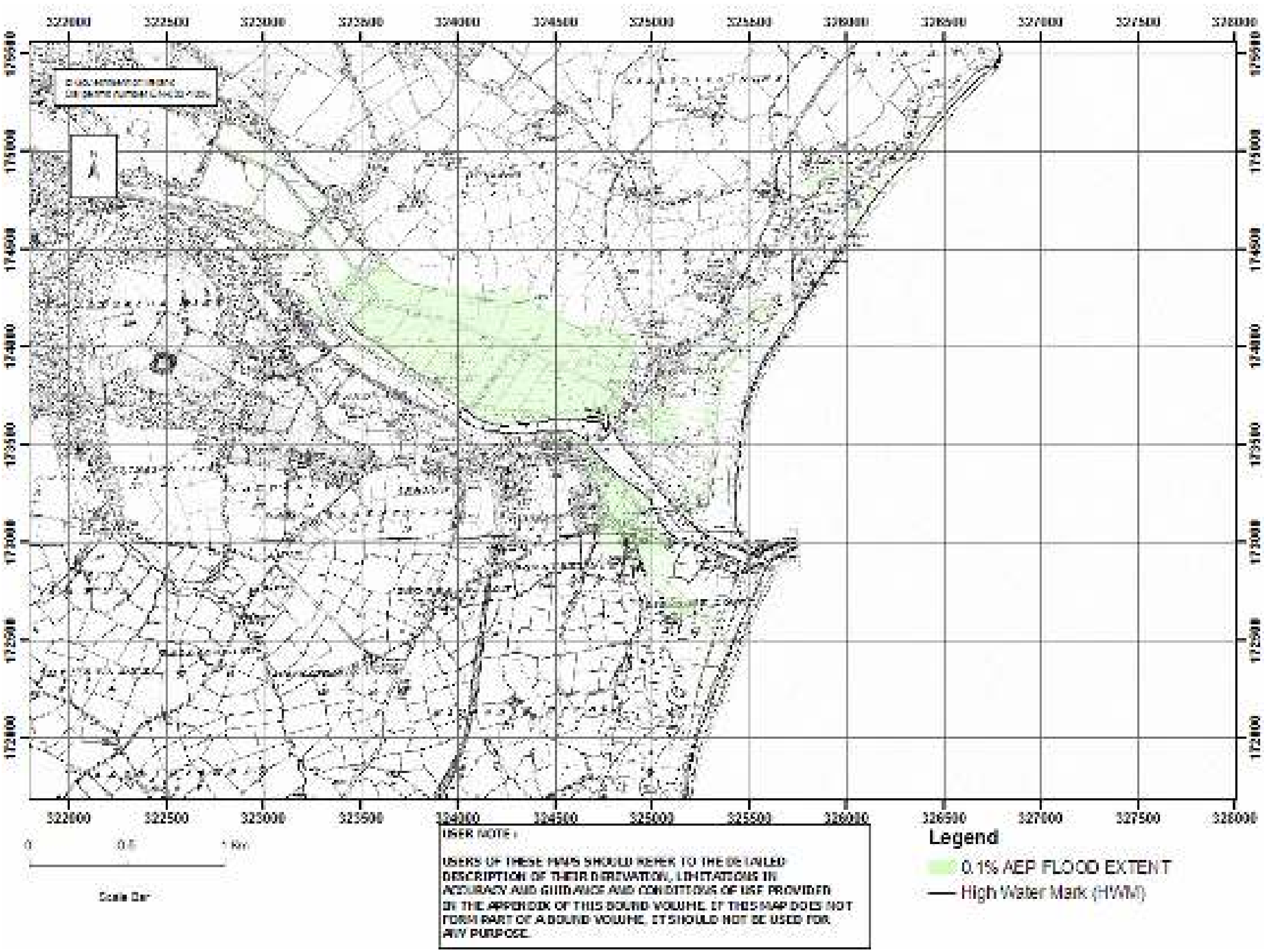


Figure 25: Arklow Predictive Flood Extent Map, 0.1% AEP

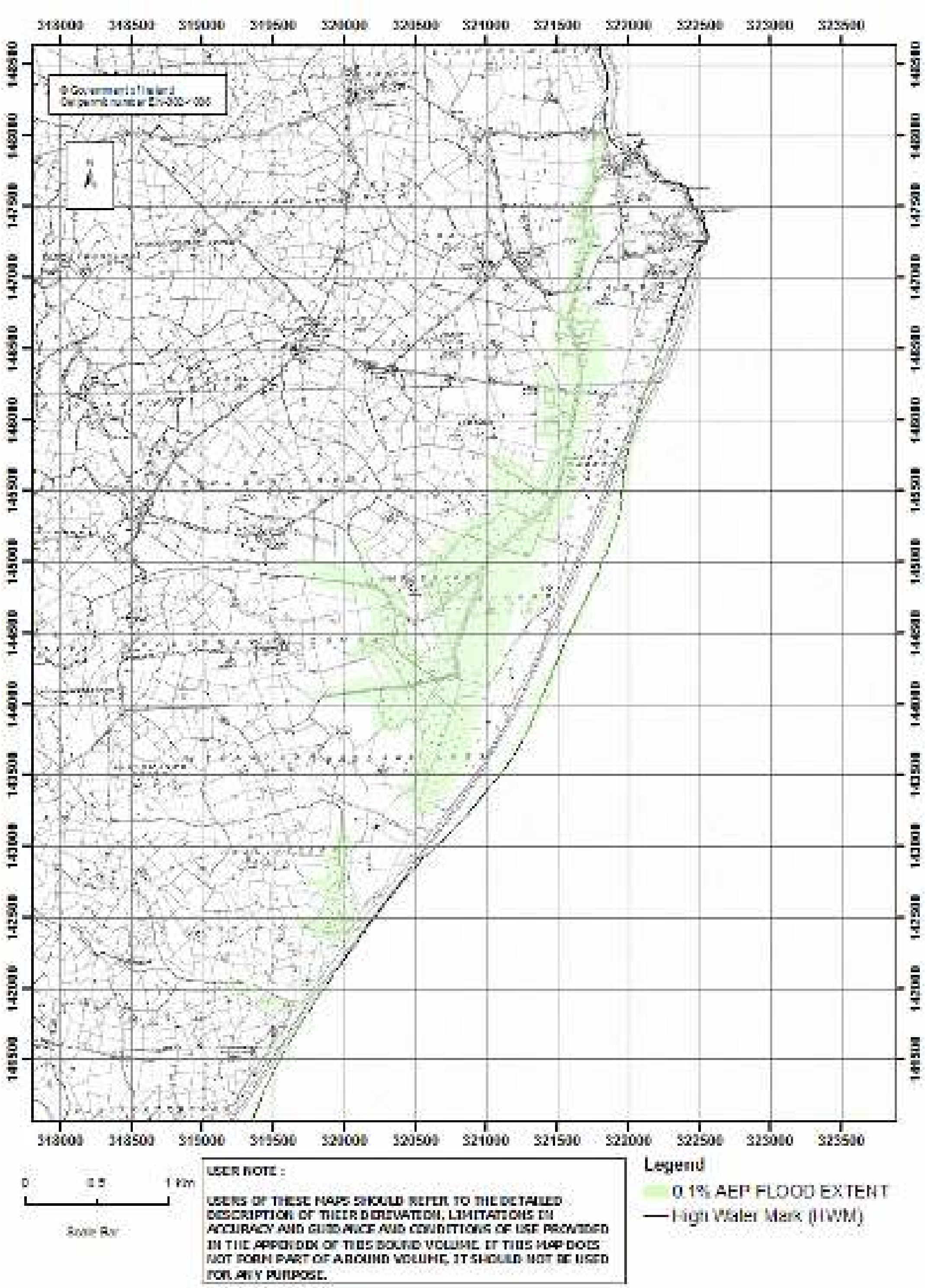


Figure 26: Cahore Point to Morriscastle Predictive Flood Extent Map, 0.1% AEP

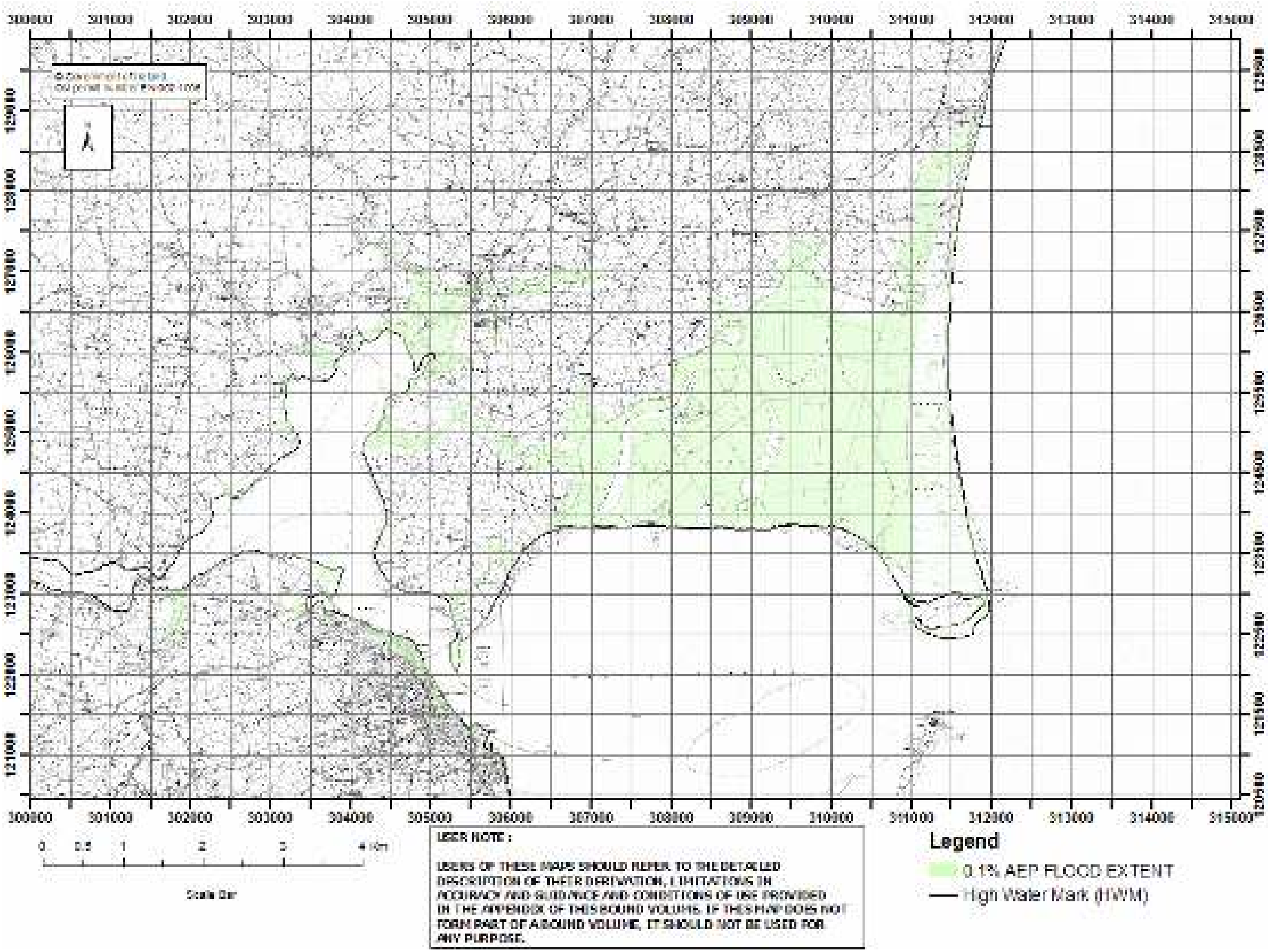


Figure 27: Wexford, Castlebridge and Curracloe Predictive Flood Extent Map, 0.1% AEP

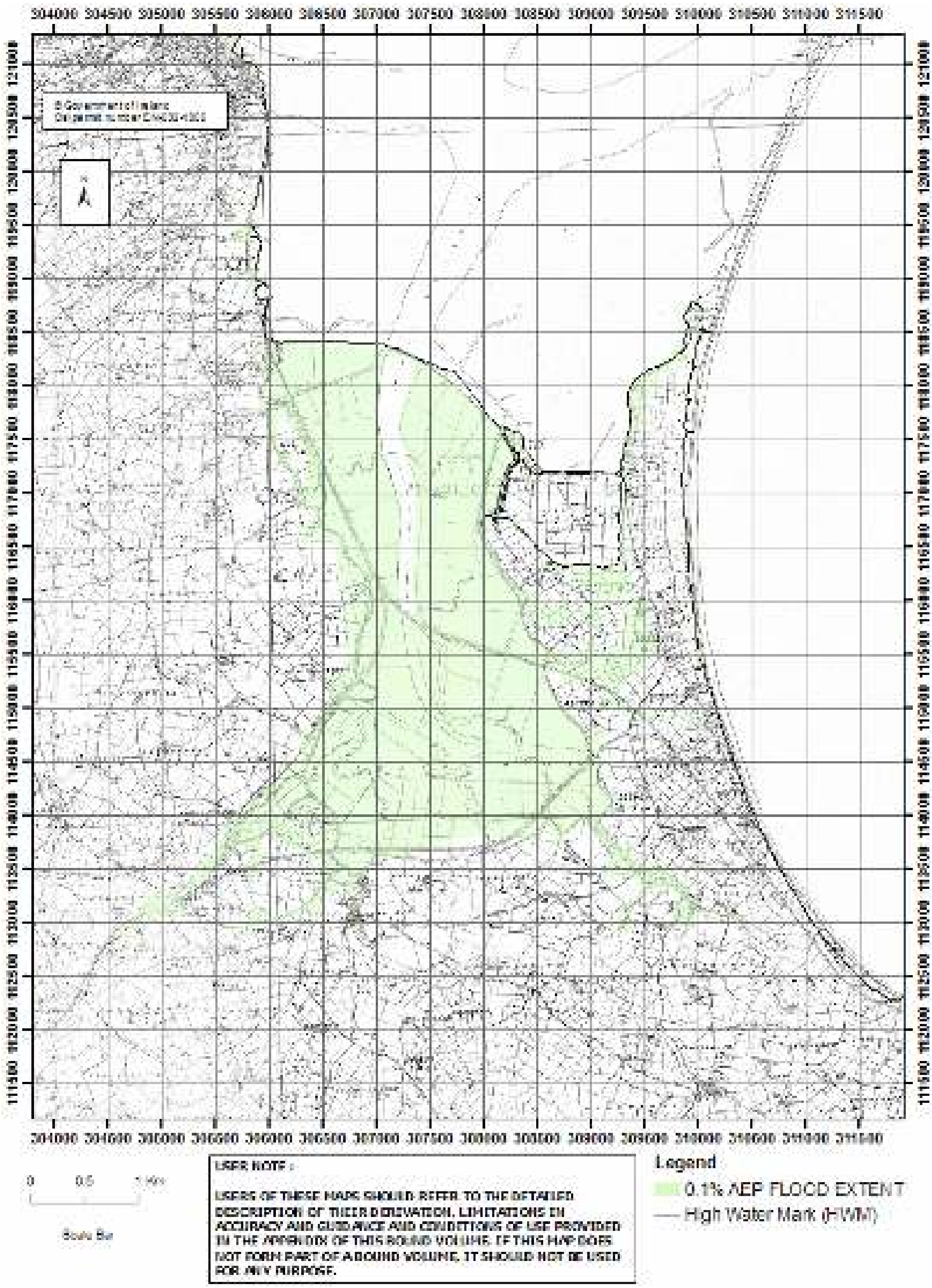


Figure 28: Rosslare Predictive Flood Extent Map, 0.1% AEP

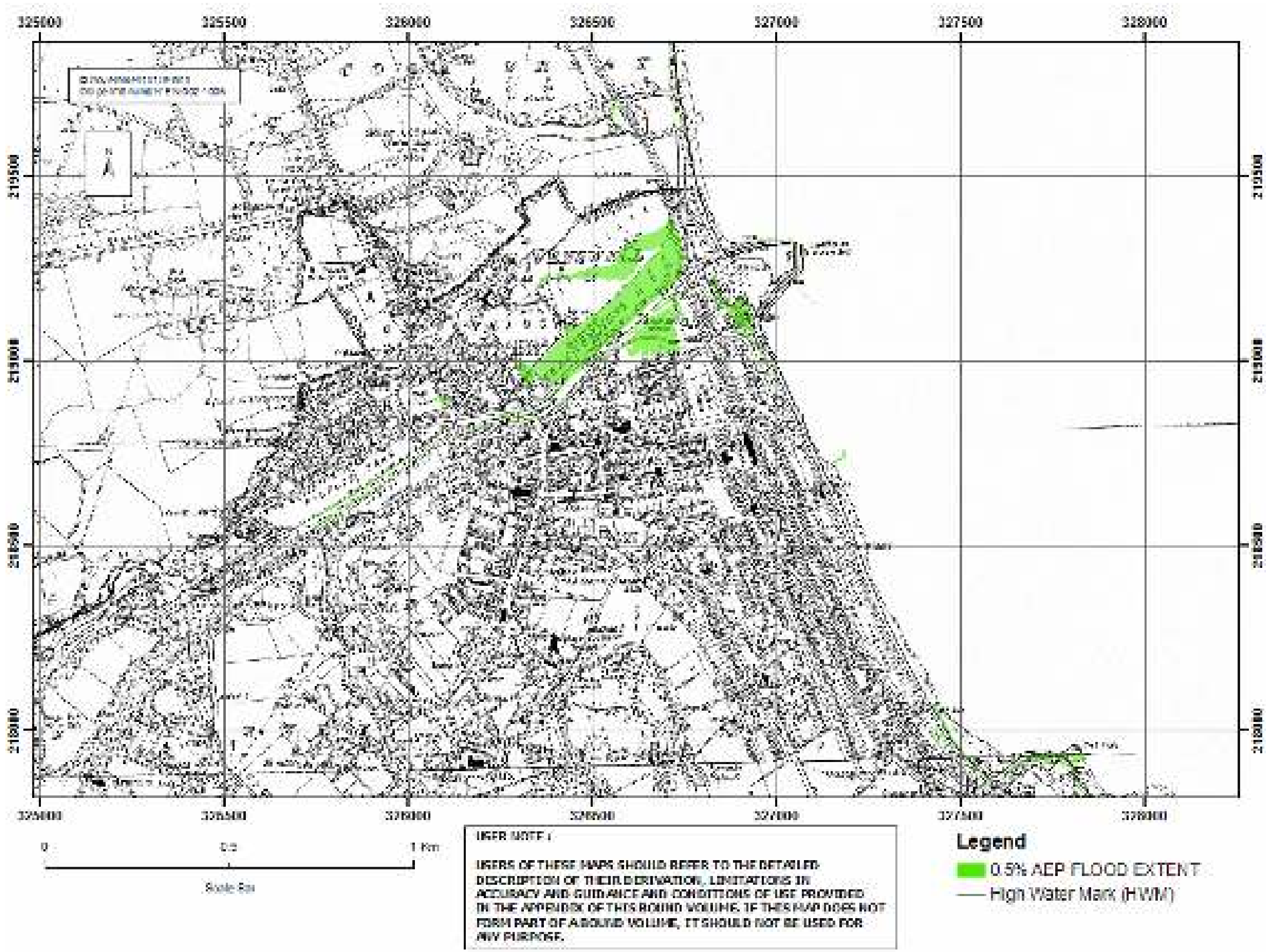


Figure 29: Bray Predictive Flood Extent Map, 0.5% AEP

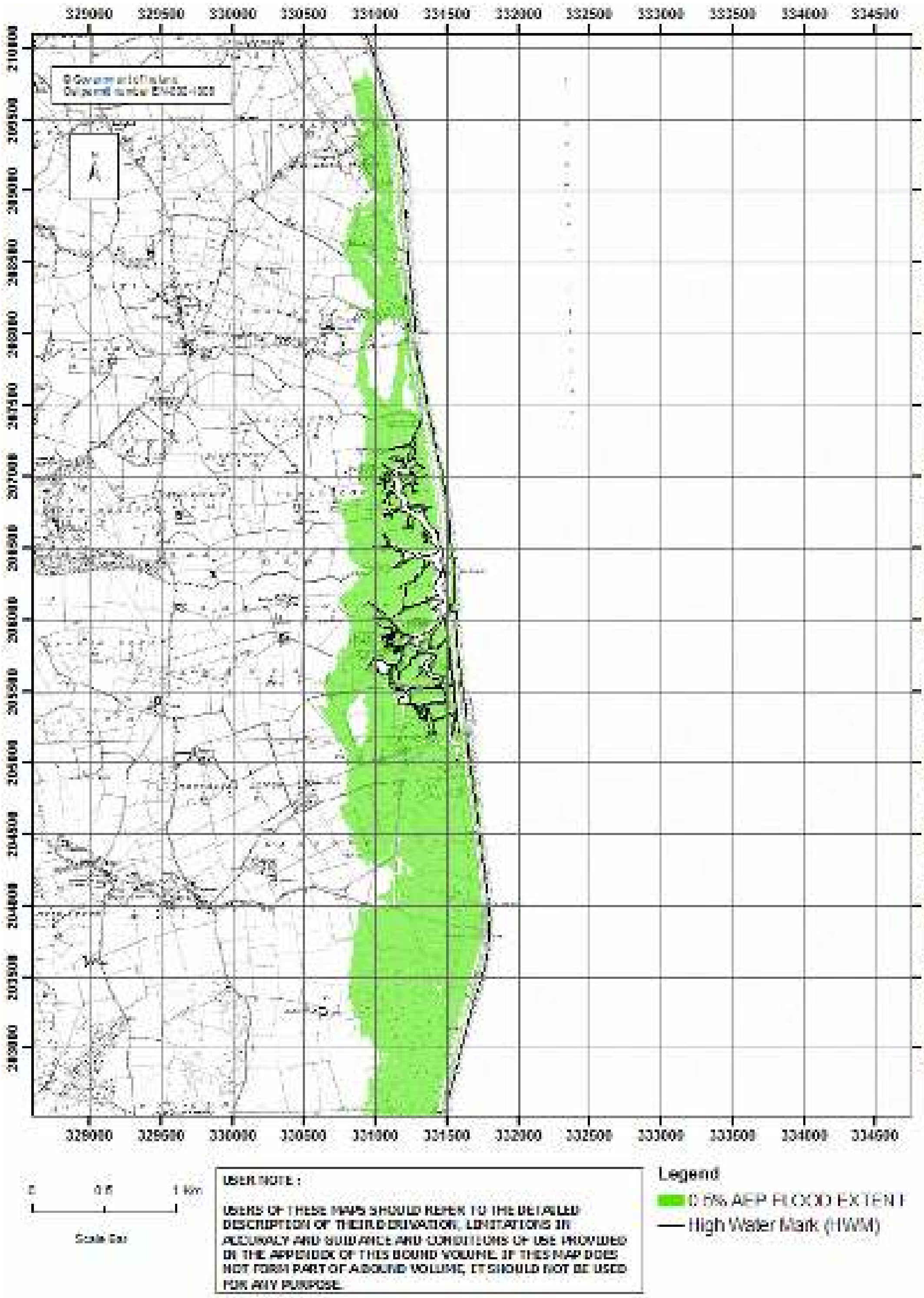


Figure 30: Ballygannon to Five Mile Point Predictive Flood Extent Map, 0.5% AEP

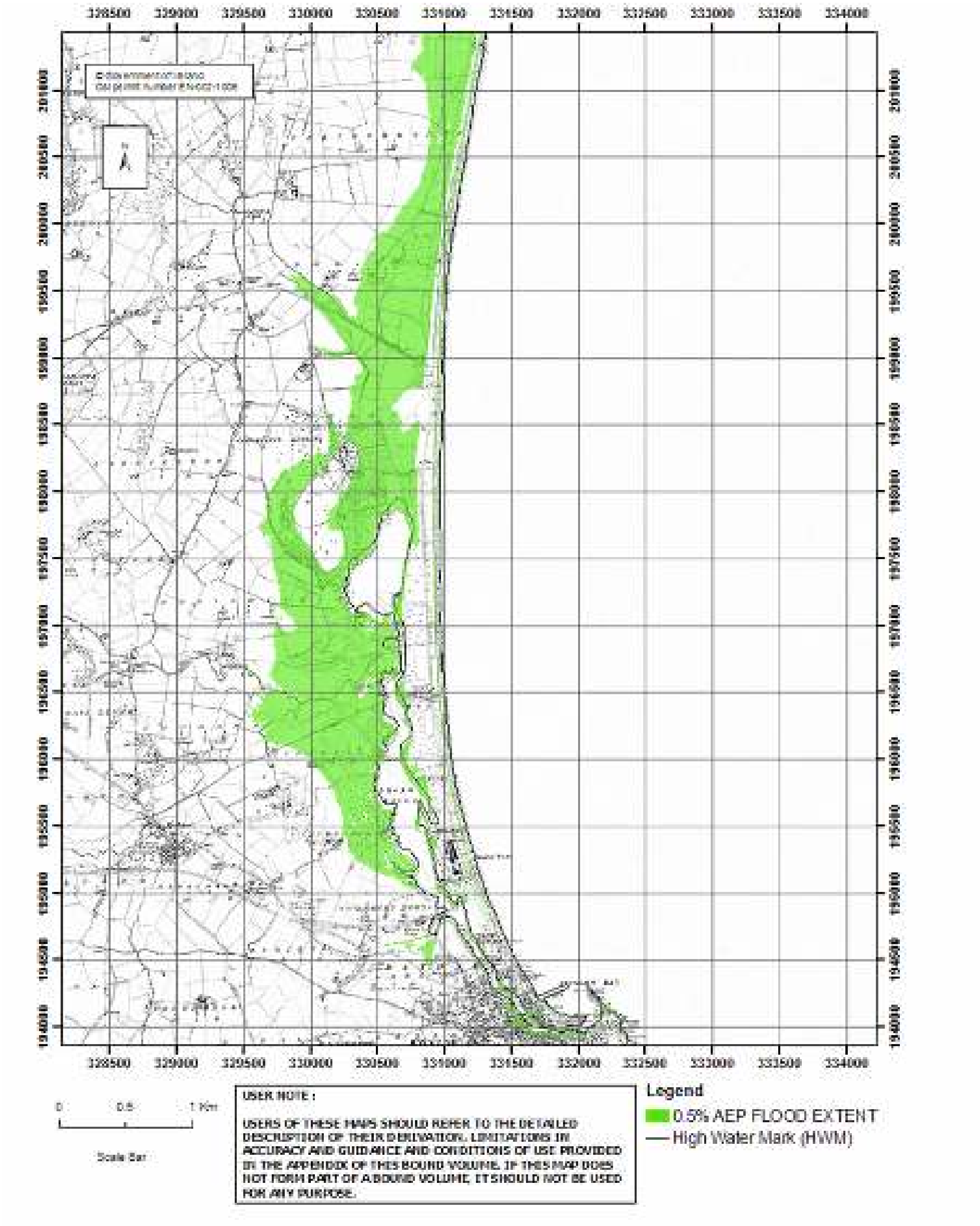


Figure 31: Five Mile Point to Wicklow Predictive Flood Extent Map, 0.5% AEP

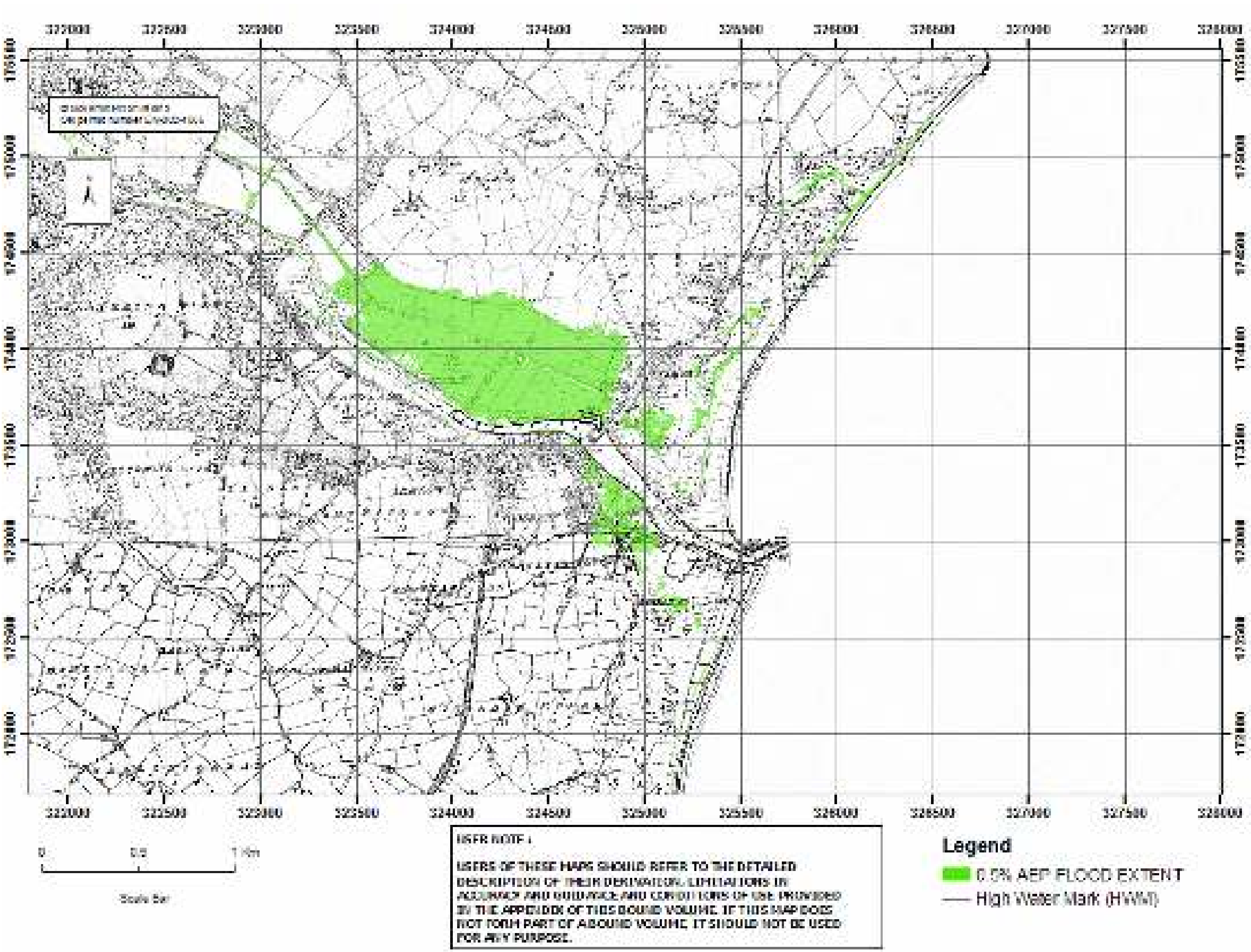


Figure 32: Arklow Predictive Flood Extent Map, 0.5% AEP

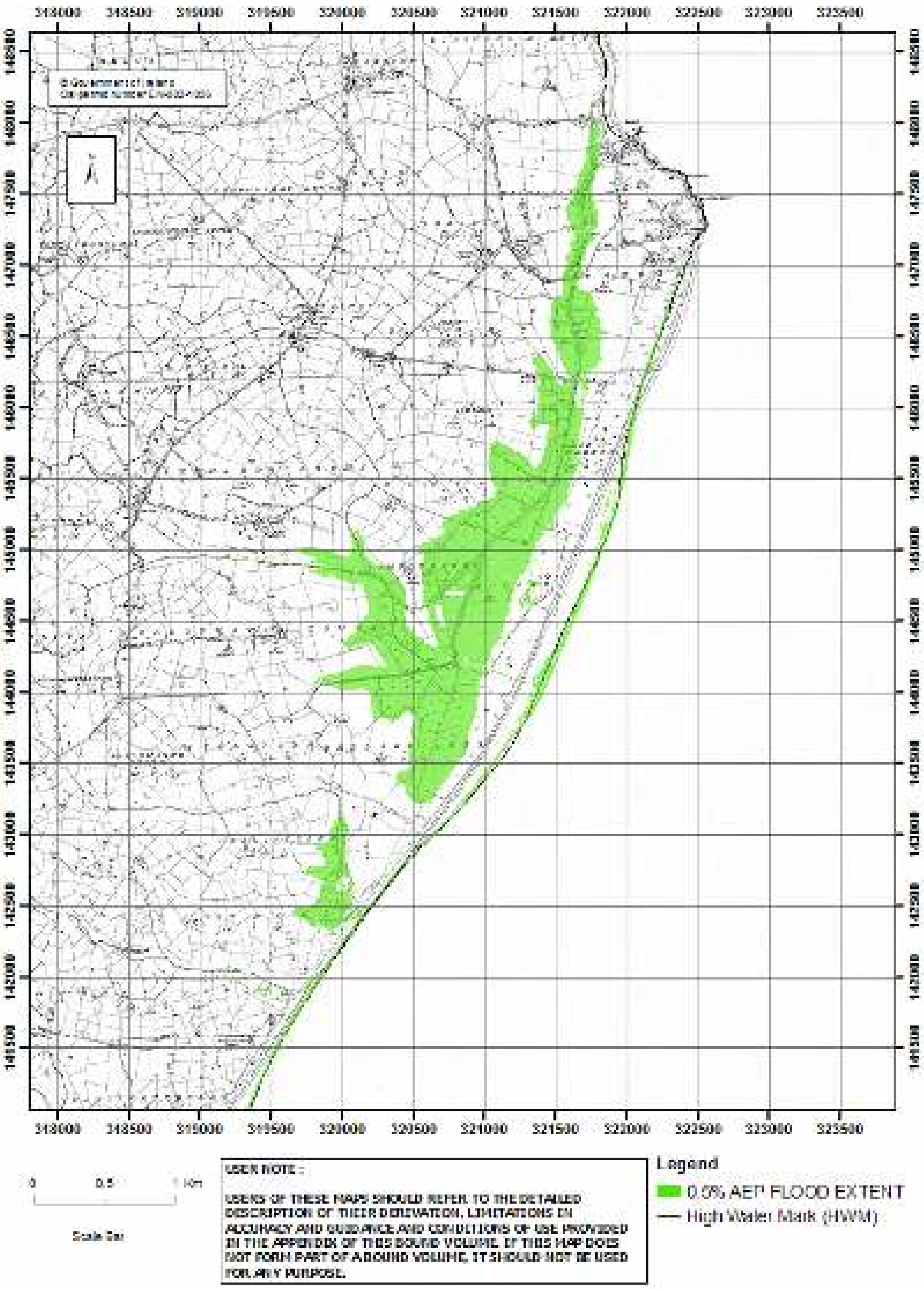


Figure 33: Cahore Point to Morriscastle Predictive Flood Extent Map, 0.5% AEP

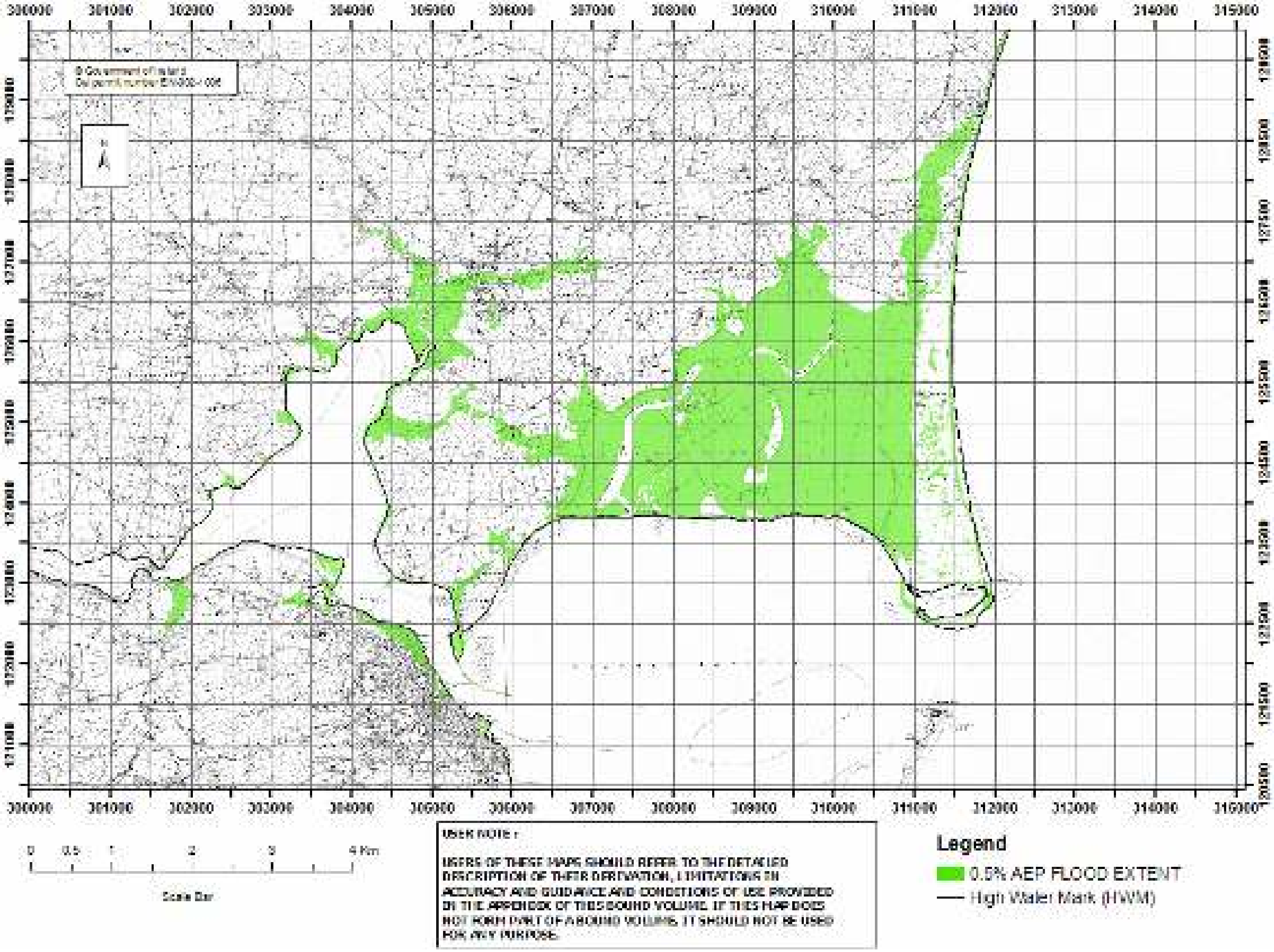


Figure 34: Wexford, Castlebridge and Curracloe Predictive Flood Extent Map, 0.5% AEP

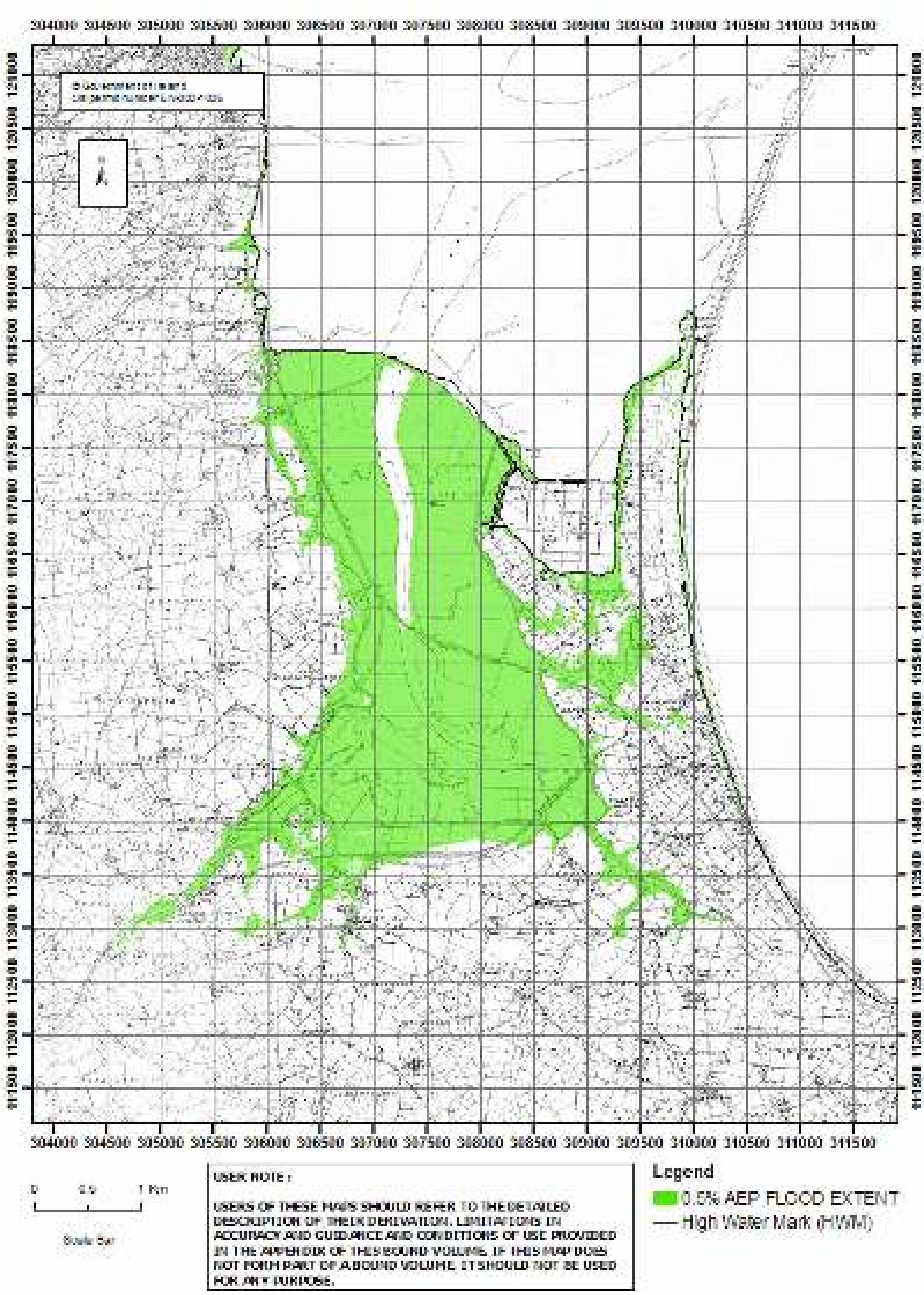


Figure 35: Rosslare Predictive Flood Extent Map, 0.5% AEP

7.0 Erosion Assessment

7.1 Introduction

The work undertaken in Work Package 4A comprising a strategic level erosion hazard and potential risk assessment, is outlined in this section. 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 to facilitate consideration by planners of the hazard and potential risks to future proposed development near the coastline (both strategic and non-strategic) at planning stage.

It is also expected that the erosion maps will be of assistance to local authorities in respect of the management of the hazard, 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.

7.2 Data Collection & Processing

The first stage of the assessment involved estimating the historic rate of erosion or retreat along the pilot coastline and converting this to an annualised erosion rate. The coastline was then assumed to continue to be eroded in the future at the same rate, thus enabling an estimate to be made of the position of the coastline in the years 2030 and 2050. Initially seven different datasets were used in this assessment which included;

- The OSI historical 6 Inch (1;10560) series mapping from around 1890 to 1900 (scanned, rectified and geo-referenced)
- The OSI most recent 6 Inch series mapping
- The OSI monochromatic aerial photography from 1973 to 1975 (digitised geo-referenced vegetation line)
- The OSI colour aerial ortho-photography from 2000 and 2004 (digital and geo-referenced)
- The Coast of Ireland Aerial Oblique Imagery Survey, 2003.
- The GSI Quaternary (Subsoil) Geological Mapping
- The OSI 2005 series, large scale digital vector mapping (comprising scales from 1:1000 to 1: 5,000)

Initially the coastlines as shown on the two OSI 6 Inch mapping series were digitised and compared to establish how their positions had changed in the past 100 years. However it was found that either there was an error in the geo-referencing of one or other of the mapping series or the depiction of the coastline, particularly on the older mapping, was inaccurate. This became apparent when comparison of the two mapping series indicated significant differences in locations where the coastline was rocky or consisted of man-made structures that were known not to have changed significantly in the past 100-150 years. Consequently this method of determining the rate of coastal change proved unreliable and was not considered further in the study.

The 1970's OSI aerial photography series was supplied as a collection of A1 sized prints at an approximate scale of 1:7000. To facilitate comparison with the more recent OSI 2000 and 2004 aerial photography, key features (high water mark and visible vegetation line) were digitised by RPS using ArcGIS software. Reference co-ordinates for the photographs were established using identifiable features and buildings shown on both the aerial photography and the OSI 2005 series digital large scale vector mapping.

In general where there was good overlap between images and a good coverage of identifiable features for geo-referencing, horizontal position errors (RMS) of less than 2m were achieved in the digitisation process. However in some areas, particularly those close to the edge of the individual photographs where there was little or no overlap between adjoining images the distortion at the edges of the photographs reduced the level of accuracy that could be achieved to as much as 10 m.

7.3 Identification of Coastal Change

The visible vegetation lines (top of cliff line adopted in steeper areas) digitised from each of the three OSI aerial photographic surveys, 1970's, 2000 and 2004 were compared to determine the degree of coastal change over the intervening period. The 1970's imagery series did not provide complete coverage of the pilot coastline, however it did extend to approximately 95% of the coastline, with the missing section located south of Rosslare Europort.

The change in position of the coastline between the 1970's and later aerial photography was measured at intervals of approximately 1km along the coast and annualised erosion rates over the intervening period derived. This method provided a measure of the rate of coastal change or erosion on un-protected areas of the coast. Significant portions of the pilot coastline, however, are presently protected and indeed many were protected even in the 1970's. For these areas it was often not possible to detect any measurable change in the position of the coastline and consequently there are areas where there is no predicted erosion rate shown or where the predicted erosion rate may be underestimated due to the presence of coastal protection works.

To provide an indication of the areas where it was either not possible to quantify the erosion rate or where the erosion rates derived may be affected by the presence of coastal protection works, a coastline classification was undertaken. This involved sub-dividing the pilot coastline according to the class types listed below:-

- Rocky, where bedrock with little or no overburden forms the coastline,
- Sedimentary, where soft sediments are the predominant coastal form,
- Non coastal defence structure, where a man made structure, harbour, quay, promenade etc forms the coastline i.e. a structure other than a purely coastal defence structure,
- Sedimentary with coastal defence structure, where a naturally soft coastline has been defended using revetments, wave walls or other similar structures, irrespective of the size or effectiveness of the structures.

This classification was based on a detailed review of the Coast of Ireland Aerial Oblique Imagery Survey of 2003 (Reference 8). An erosion classification line was developed by assigning attributes to the high water line extracted from the large scale OSI vector mapping or where this data was not available, a digitised line taken from the 2000 aerial photography.

7.4 Discussion of Results

An erosion "baseline" derived from the visible vegetation line or where appropriate cliff top line as shown on the OSI 2000 ortho-photography was used to generate the 2030 and 2050 erosion maps, included as Erosion_2030 and Erosion_2050 in the digital Appendix 10. In deriving these lines it was assumed that coastal erosion would continue for the next 50 years at a similar rate to that observed over the past 25-30 years.

The erosion maps were developed primarily as a tool to identify any assets which were likely to be affected by coastal erosion over the intervening periods, for inclusion in a subsequent strategic economic evaluation of coastal flood and erosion risk as reported in Reference 9. In developing the erosion maps the coast was divided into nominal lengths, typically 1km, and an annualised average rate of coastal retreat applicable to each sector established by visual reference. The resulting preliminary erosion lines contained a number of steps where the annualised rate of erosion derived from the comparison of aerial photographic series changed between adjacent sectors. These preliminary lines were then 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 non-erodible areas were included with the area vulnerable to erosion.

The mean annualised erosion rate of all areas along the pilot coastline where an erosion hazard was identified was approximately 0.6 meters. The maximum erosion rate identified occurred at Kilpatrick in County Wexford and equated to an annualised erosion rate of 3.75 metres.

7.5 Uncertainty and Limitations of Erosion Maps

Where the coastline was defended at the time of the original aerial survey and is still protected today, no erosion maps have been 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, 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 full confidence analysis of the erosion lines was undertaken and as detailed in Appendix 9. RPS developed a quantitative methodology for determining the level of confidence using GIS techniques, based on a similar scoring and weighting system, to that used for the flooding confidence, whereby the effect of individual parameters was accounted for in the analysis.

All sectors of the erosion confidence lines were assigned a confidence rating i.e. even where no erosion is indicated by the analysis a confidence score was assigned during this assessment. Very high confidence was represented by a score of over 85%, with high confidence between 70-85%, medium confidence between 55-70%, low confidence between 40-55% and very low confidence being represented by a result of less than 40%. Overall the analysis indicated that there was generally a medium level of confidence in the position of the erosion lines identified for the south east coast. There were however some localised areas where the analysis had identified a very low confidence generally as a result of the presence of coastal protection works. The principal areas of very low confidence in the erosion assessment were; Killiney, Bray, Newcastle, Jacks Hole, Glennaglogh, Courtown, Pollshone, Cahore, Blackwater, and Rosslare.

7.6 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 8. These datasets are also presented on CD in digital form (ArcGIS shape files) in the report (Refer Appendix 10).

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

- Shanganagh to Bray,
- Greystones,

- Ballygannon to Five Mile Point,
- Five Mile Point to Wicklow,
- Kilpatrick,
- Ardamine,
- Glascarrig,
- Killincooly to Blackwater,
- Blackwater to Ballinesker
- Rosslare.

Erosion maps for each of these ten primary areas of potential coastal erosion hazard were prepared and are shown on Figures 36 to 45 for the year 2050 and on Figures 46 to 55 for the year 2030.

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 these erosion hazard maps, there are unavoidable inaccuracies and uncertainties associated with these maps. These uncertainties are discussed in this section of the 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 8).

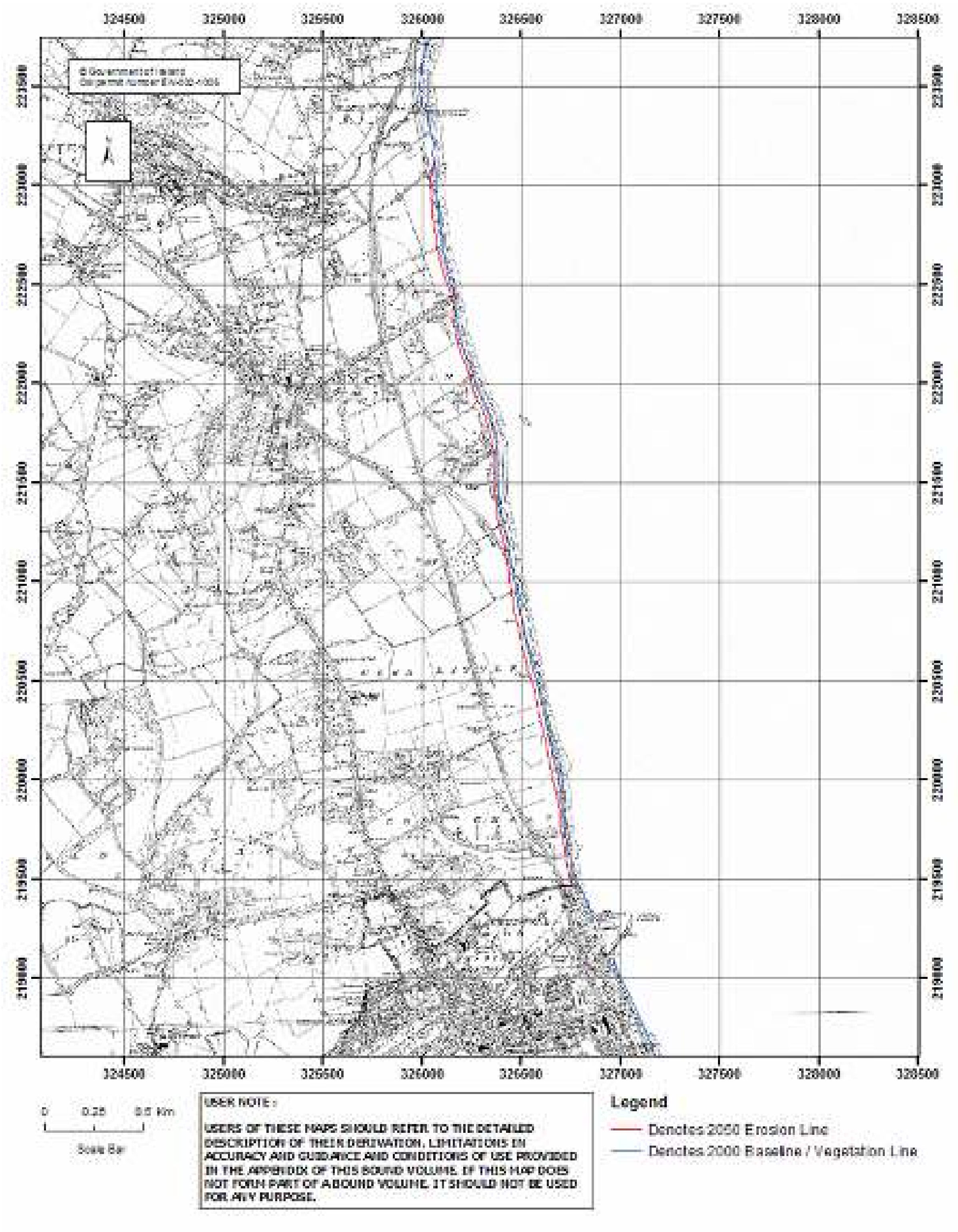


Figure 36: Shanganagh to Bray, 2050 Erosion Map

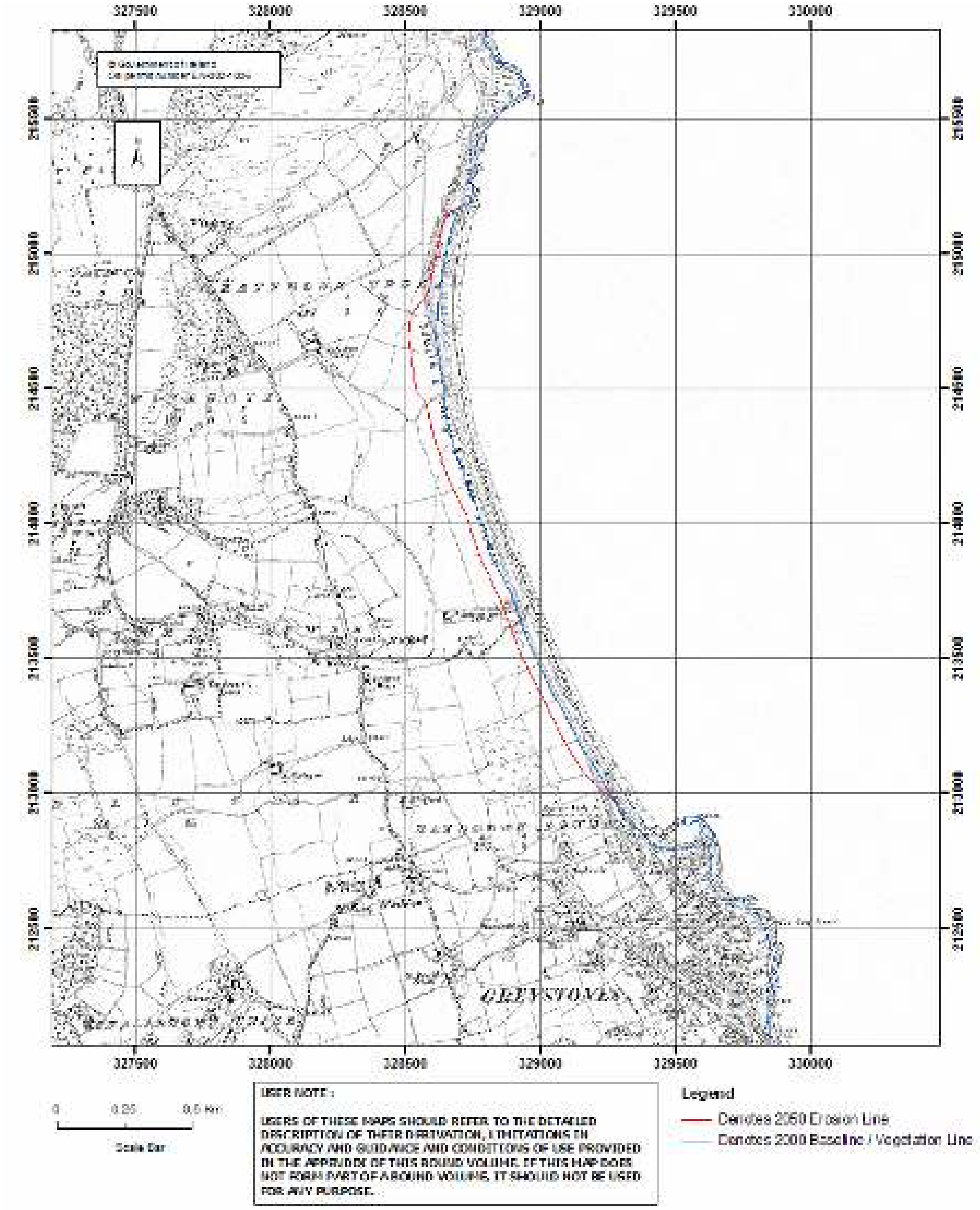


Figure 37: Greystones, 2050 Erosion Map

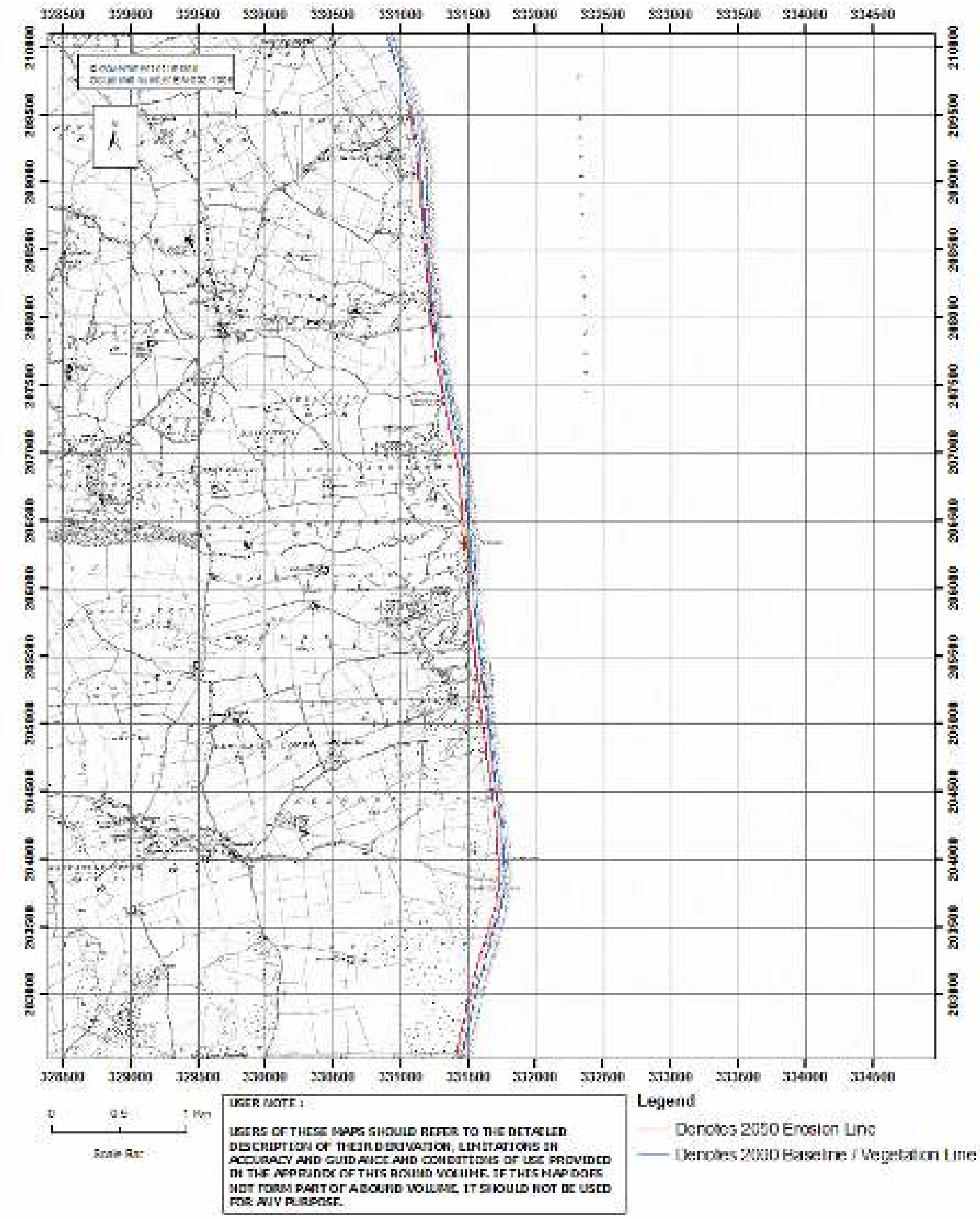


Figure 38: Ballygannon to Five Mile Point, 2050 Erosion Map

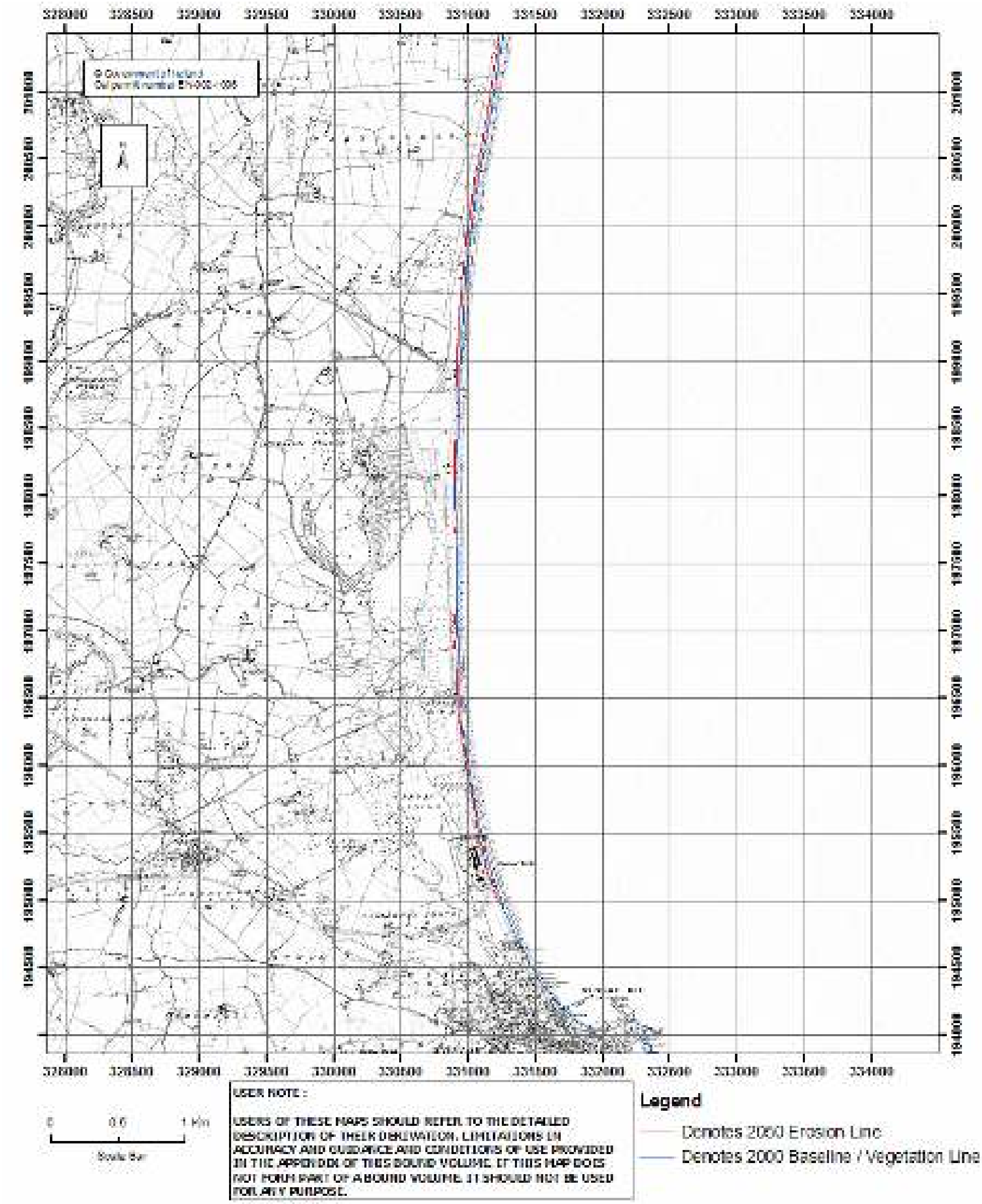


Figure 39: Five Mile Point to Wicklow, 2050 Erosion Map

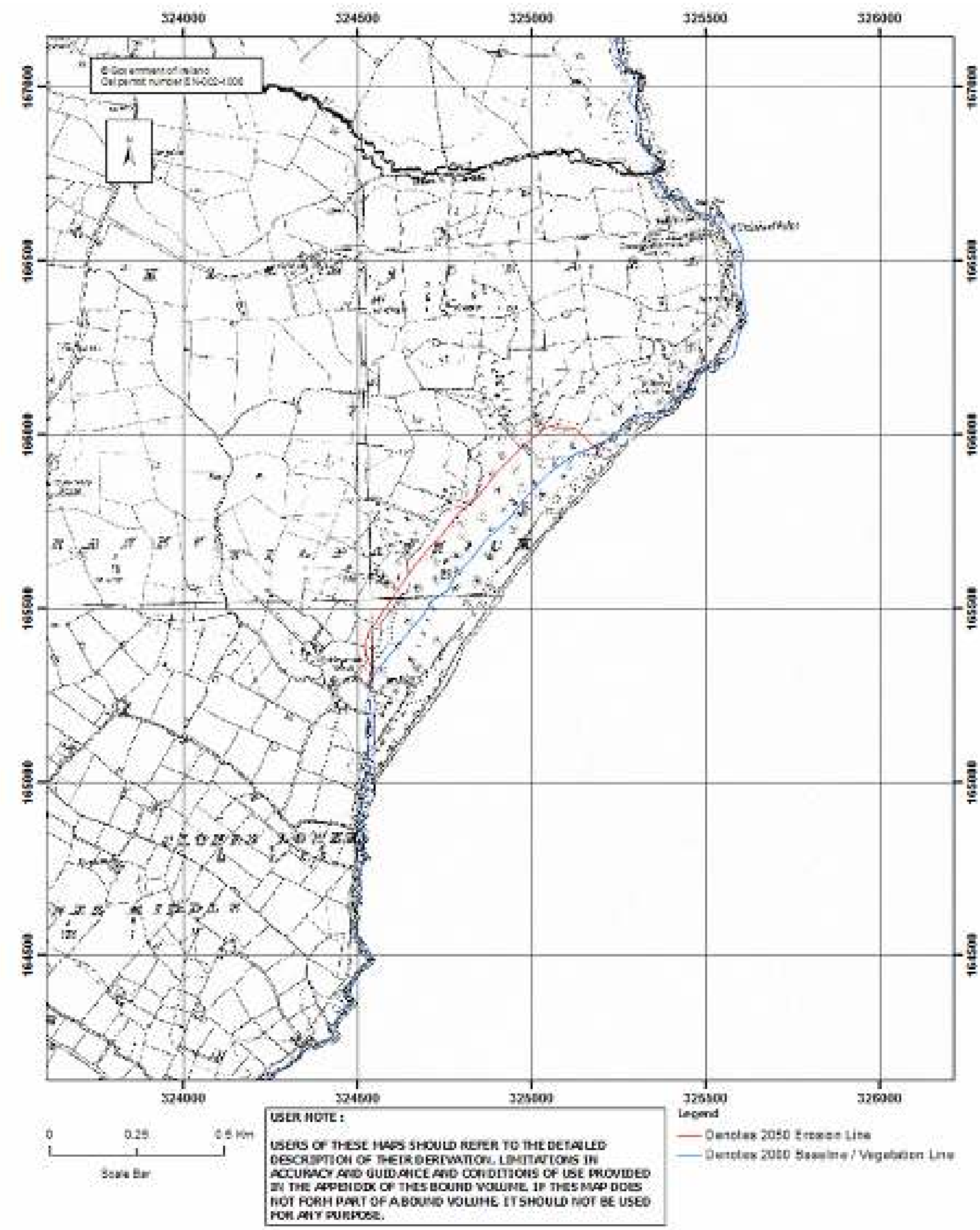


Figure 40: Kilpatrick, 2050 Erosion Map

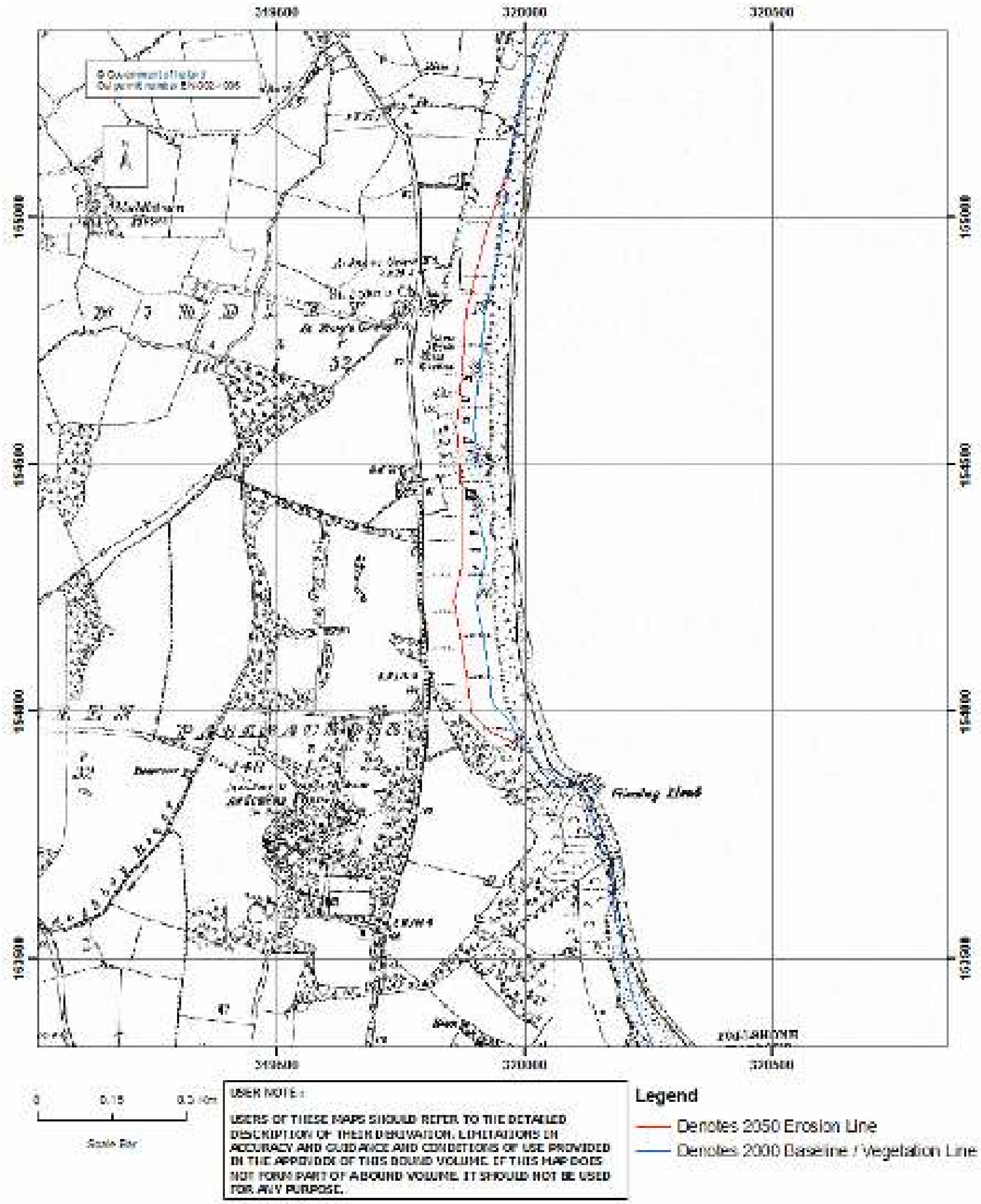


Figure 41: Ardamine, 2050 Erosion Map

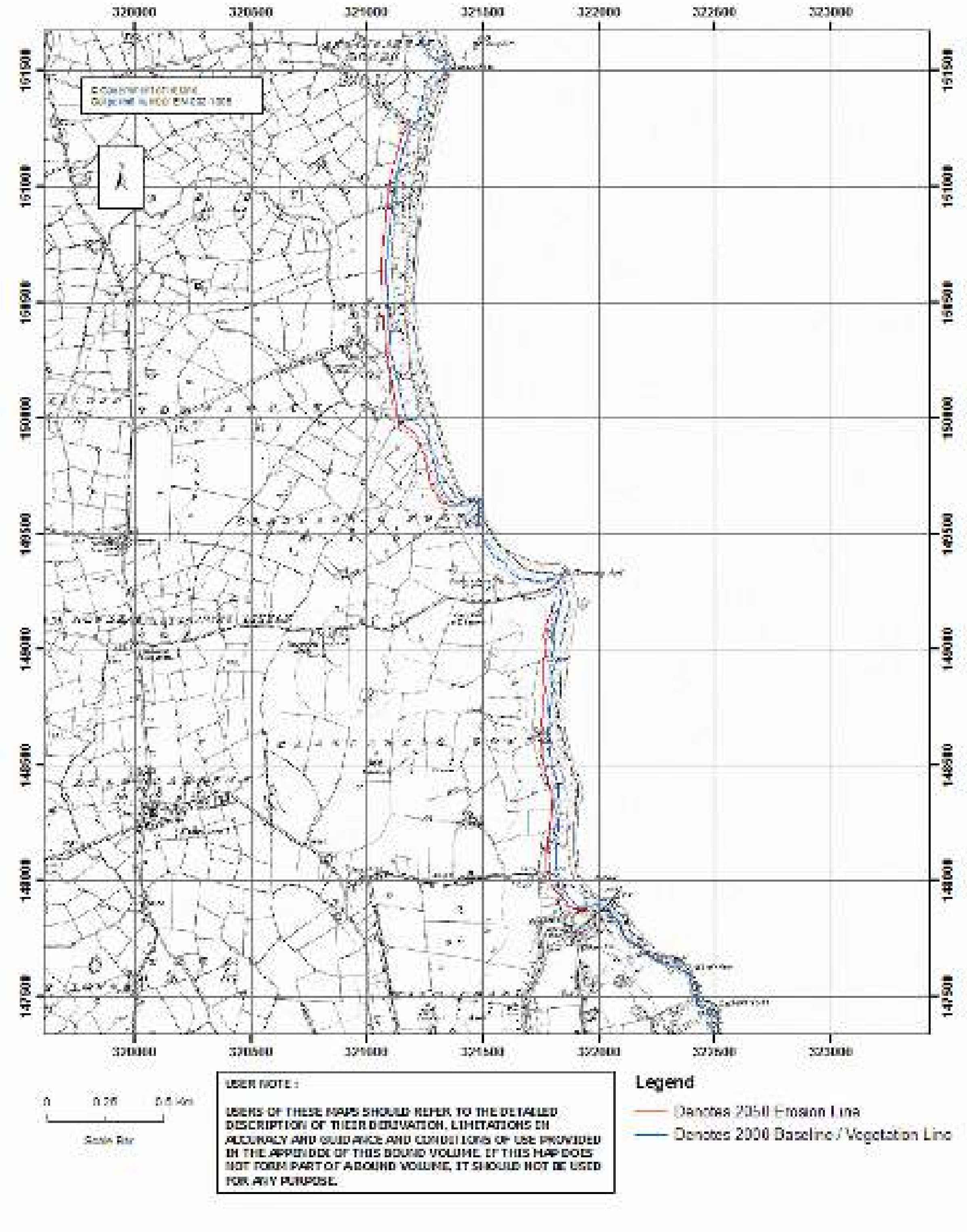


Figure 42: Glascarrig, 2050 Erosion Map

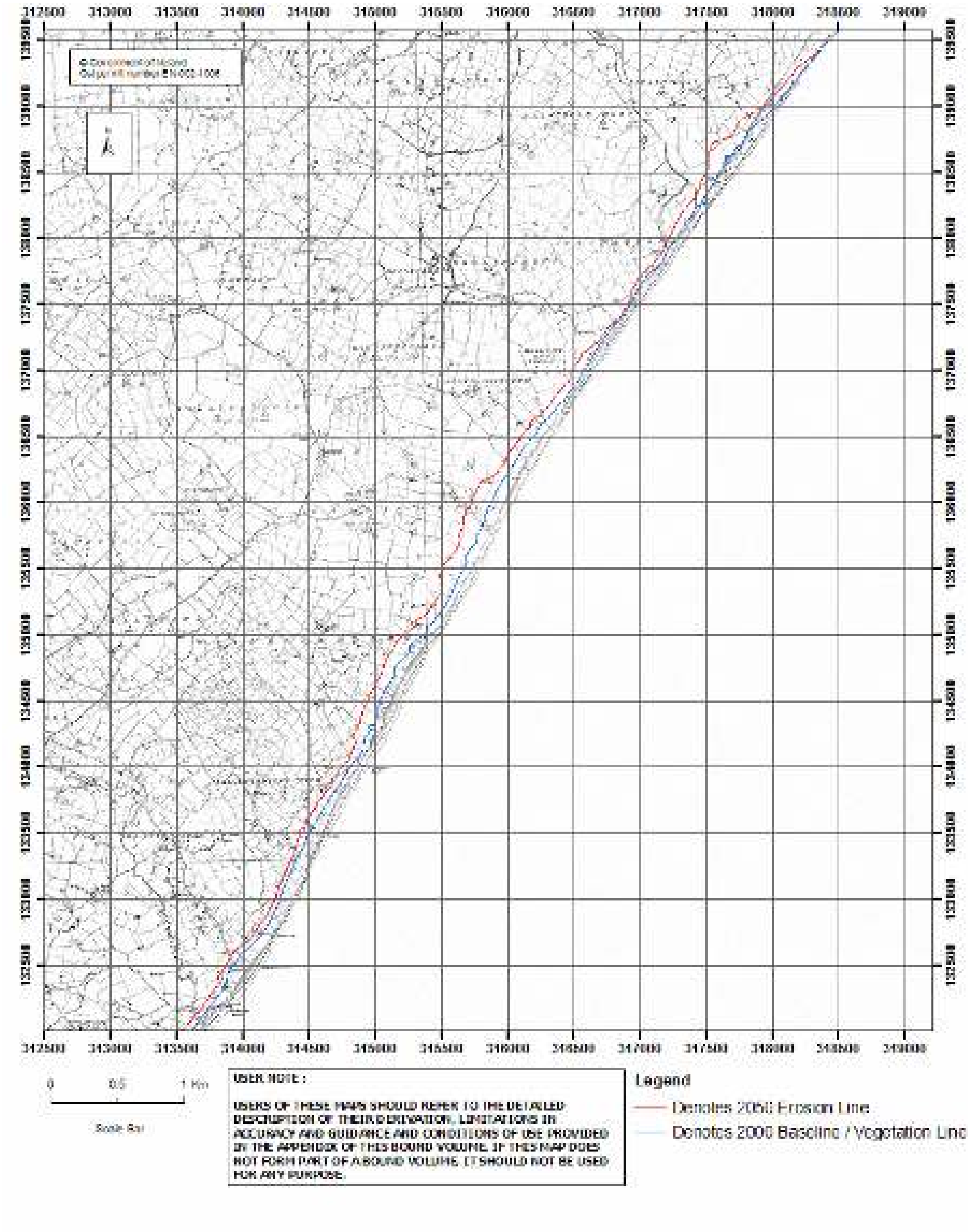


Figure 43: Killincooly to Blackwater, 2050 Erosion Map

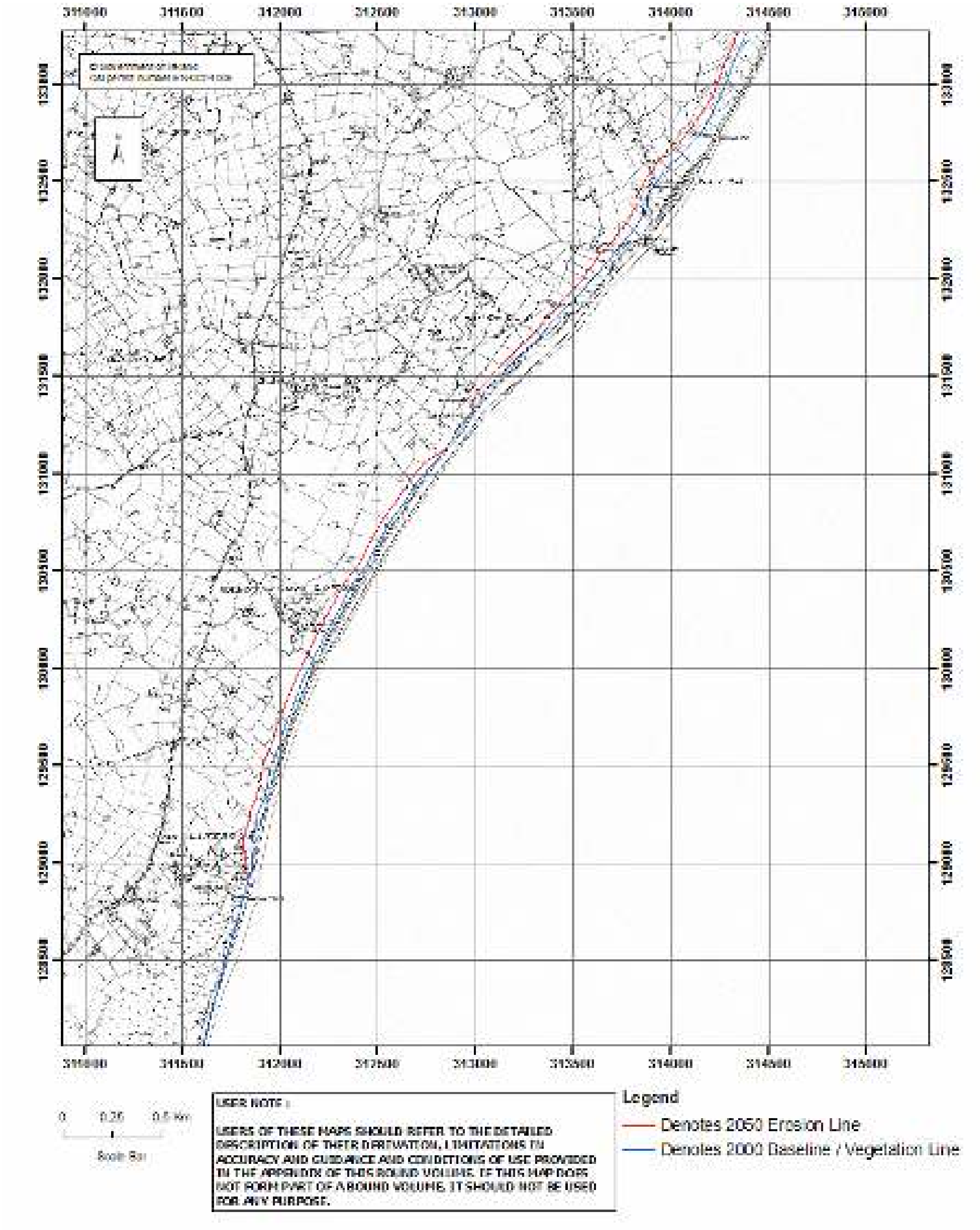


Figure 44: Blackwater to Ballinesker, 2050 Erosion Map

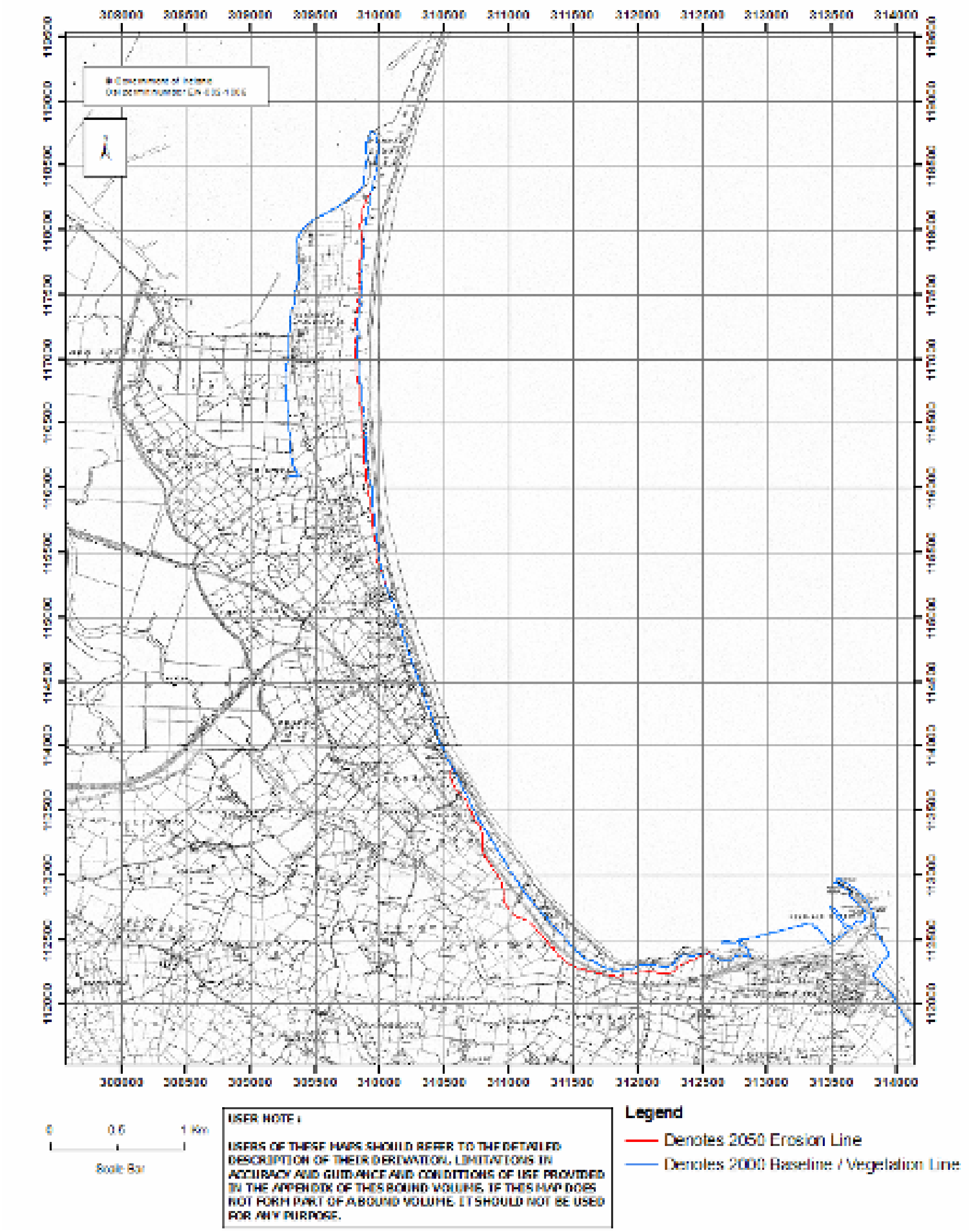


Figure 45: Rosslare, 2050 Erosion Map

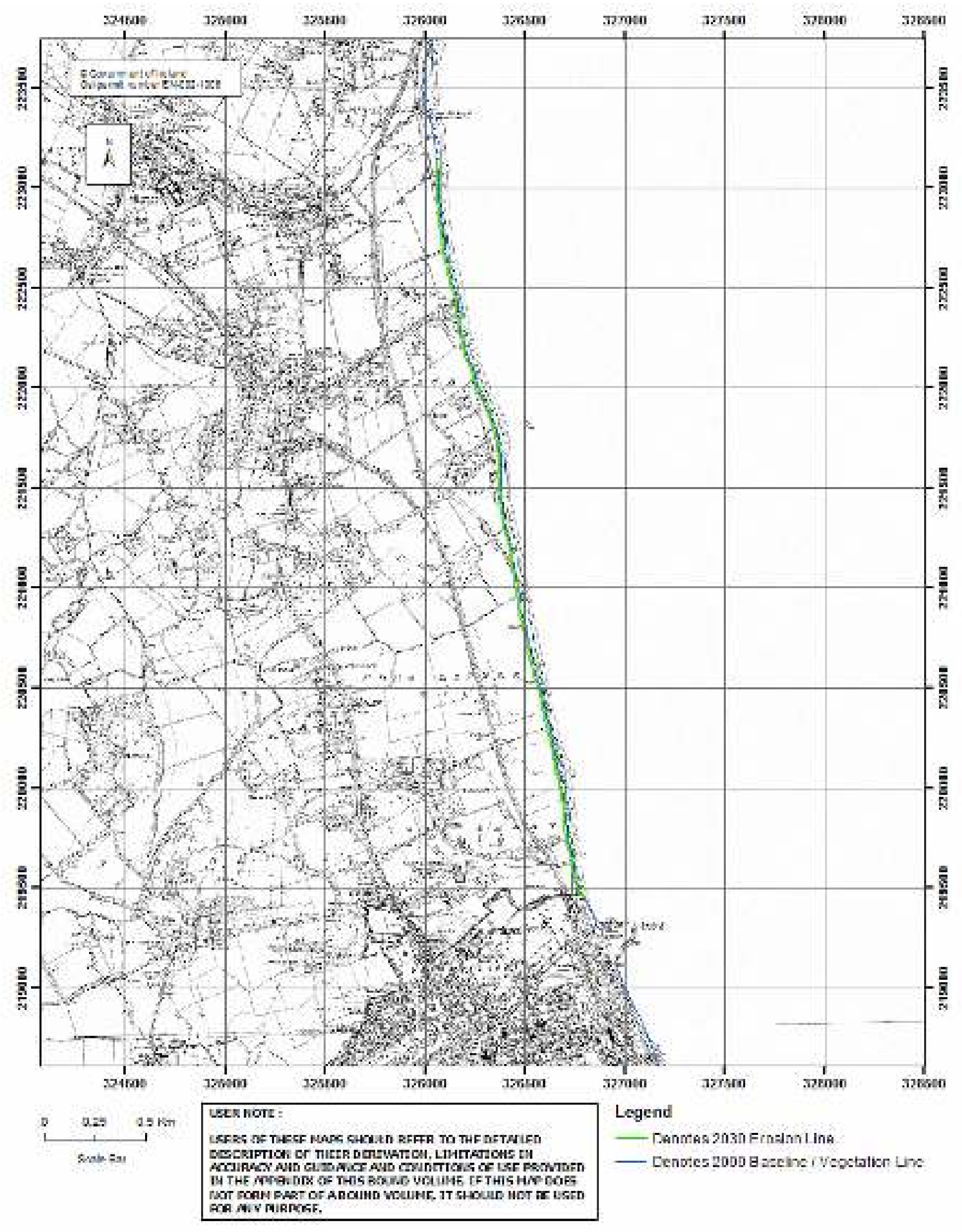


Figure 46: Shanganagh to Bray, 2030 Erosion Map

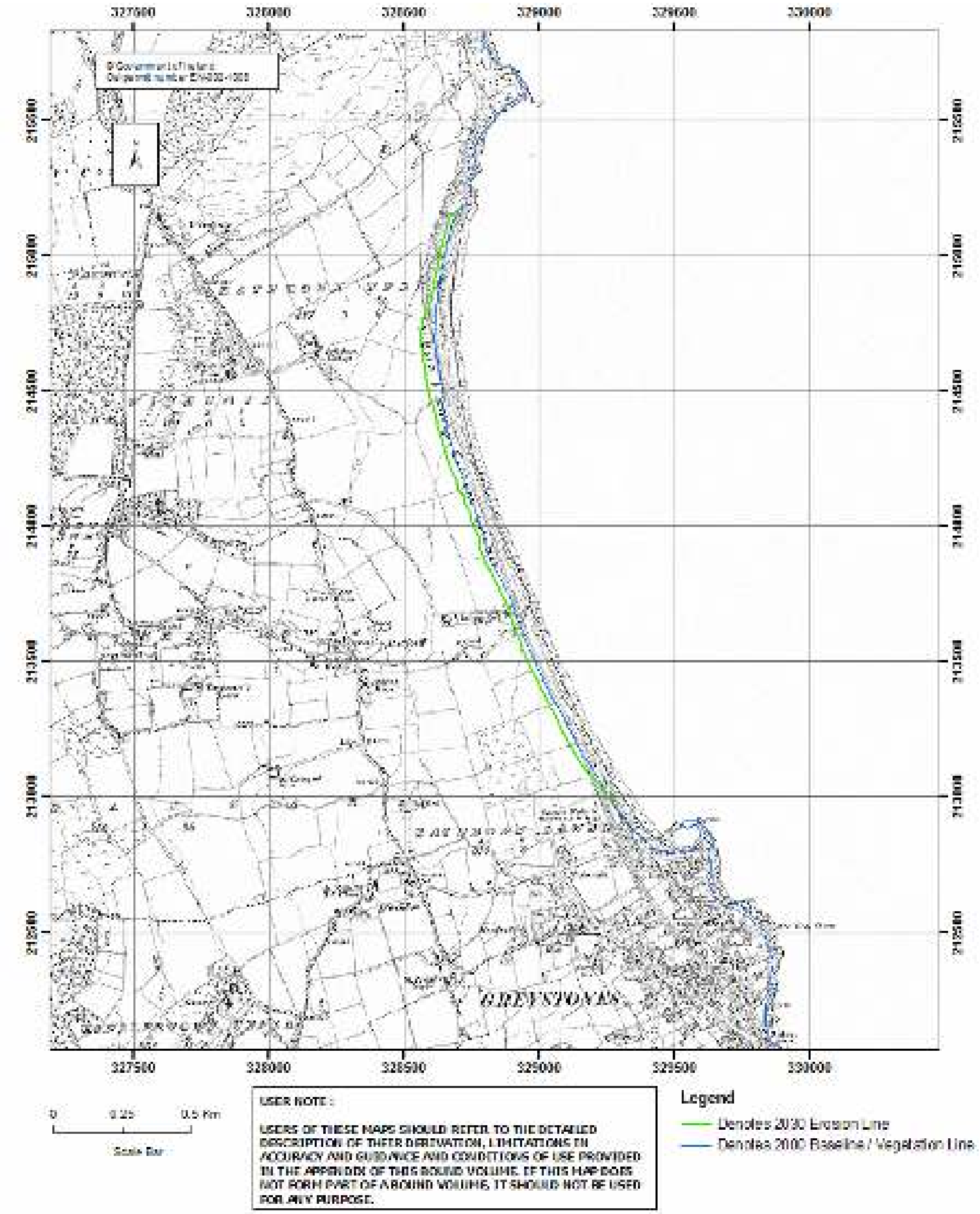


Figure 47: Greystones, 2030 Erosion Map

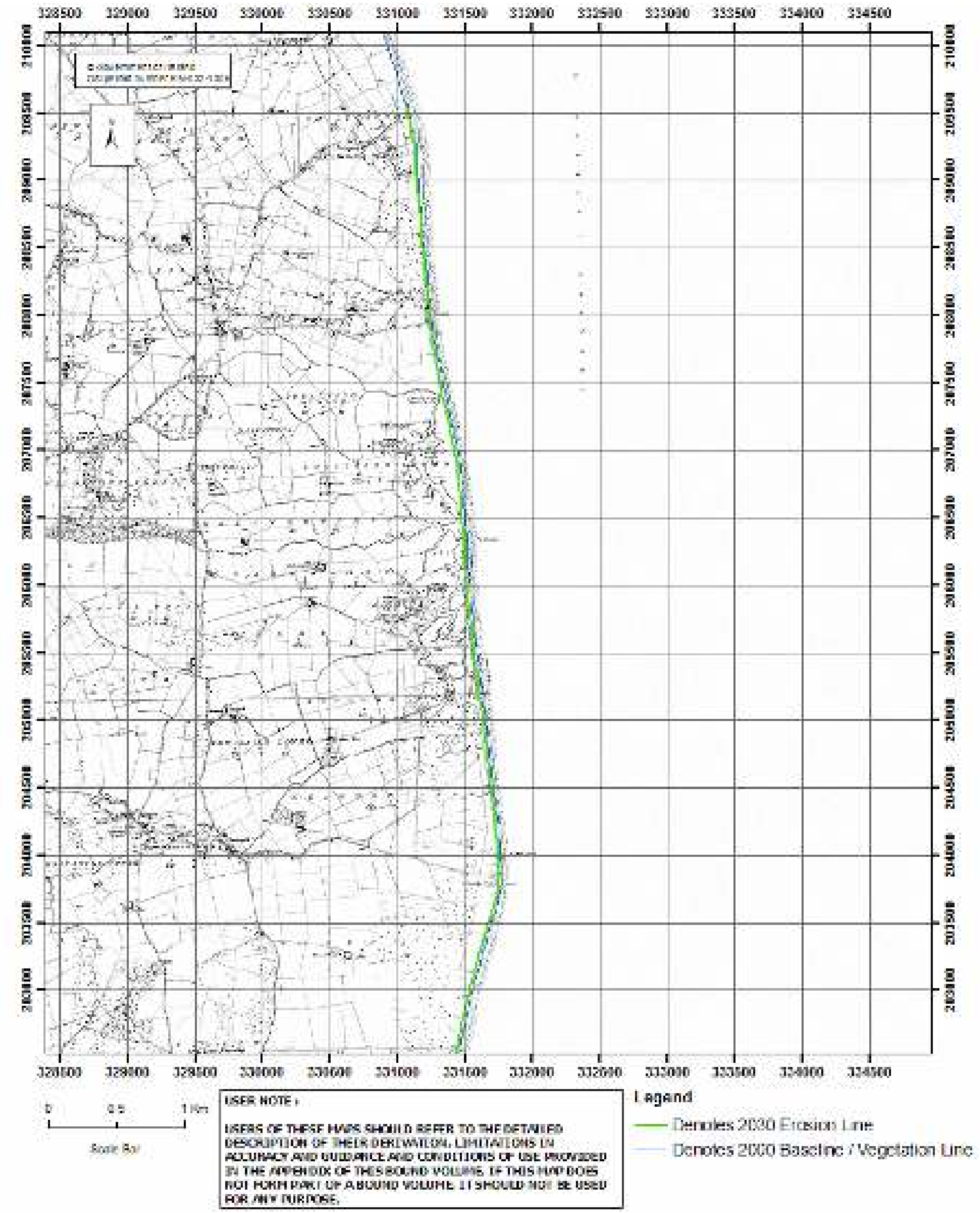


Figure 48: Ballygannon to Five Mile Point, 2030 Erosion Map

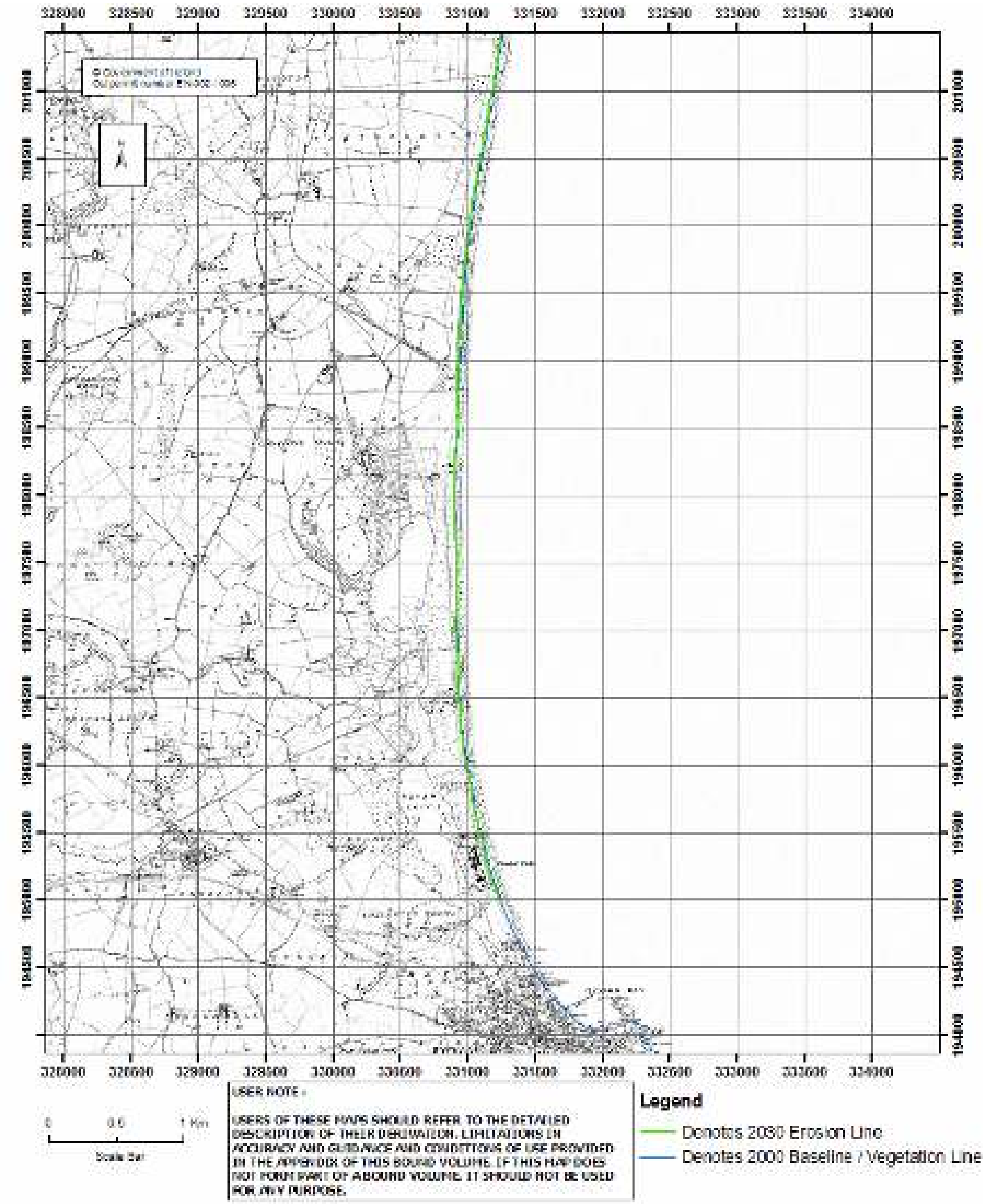


Figure 49: Five Mile Point to Wicklow, 2030 Erosion Map

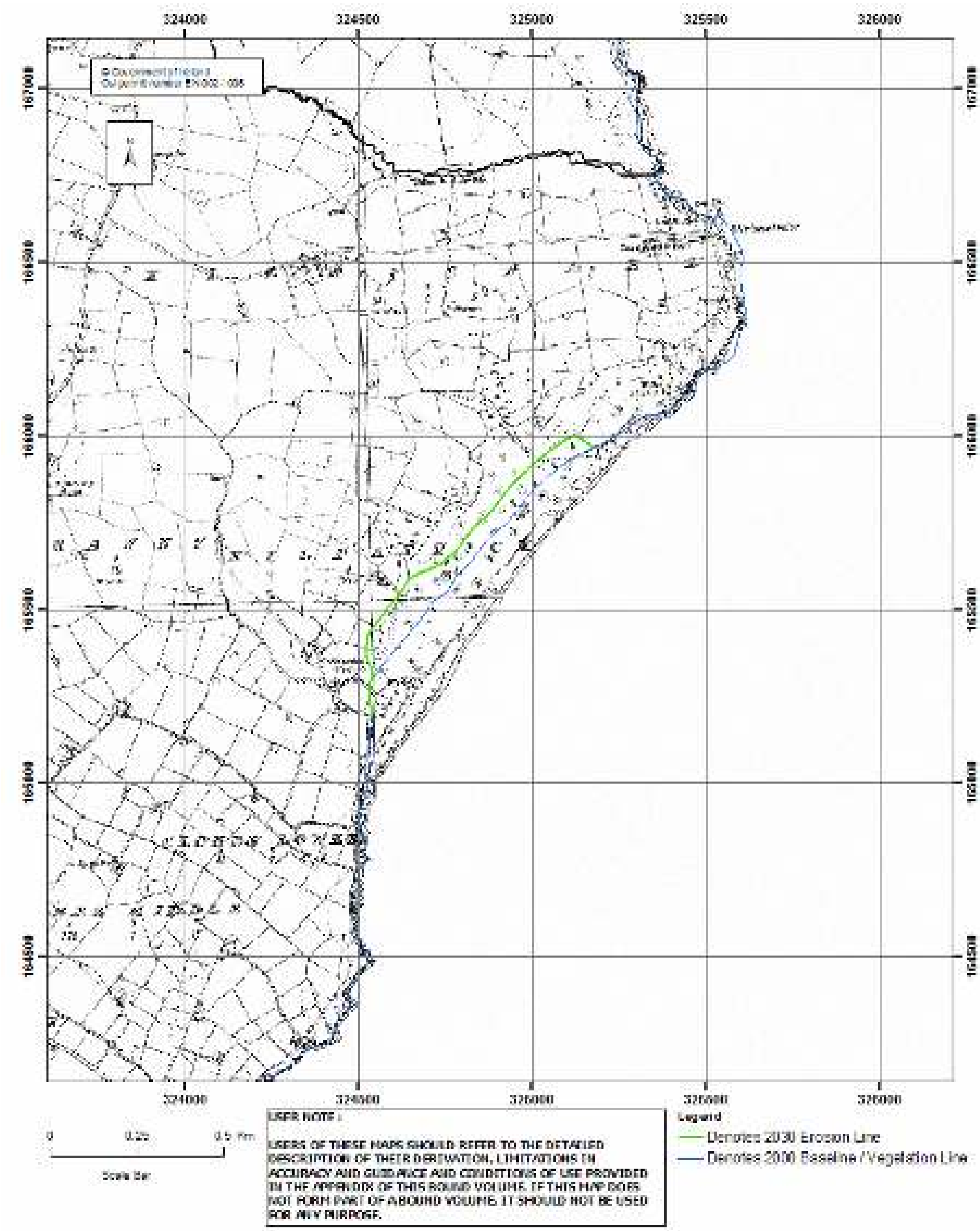


Figure 50: Kilpatrick, 2030 Erosion Map

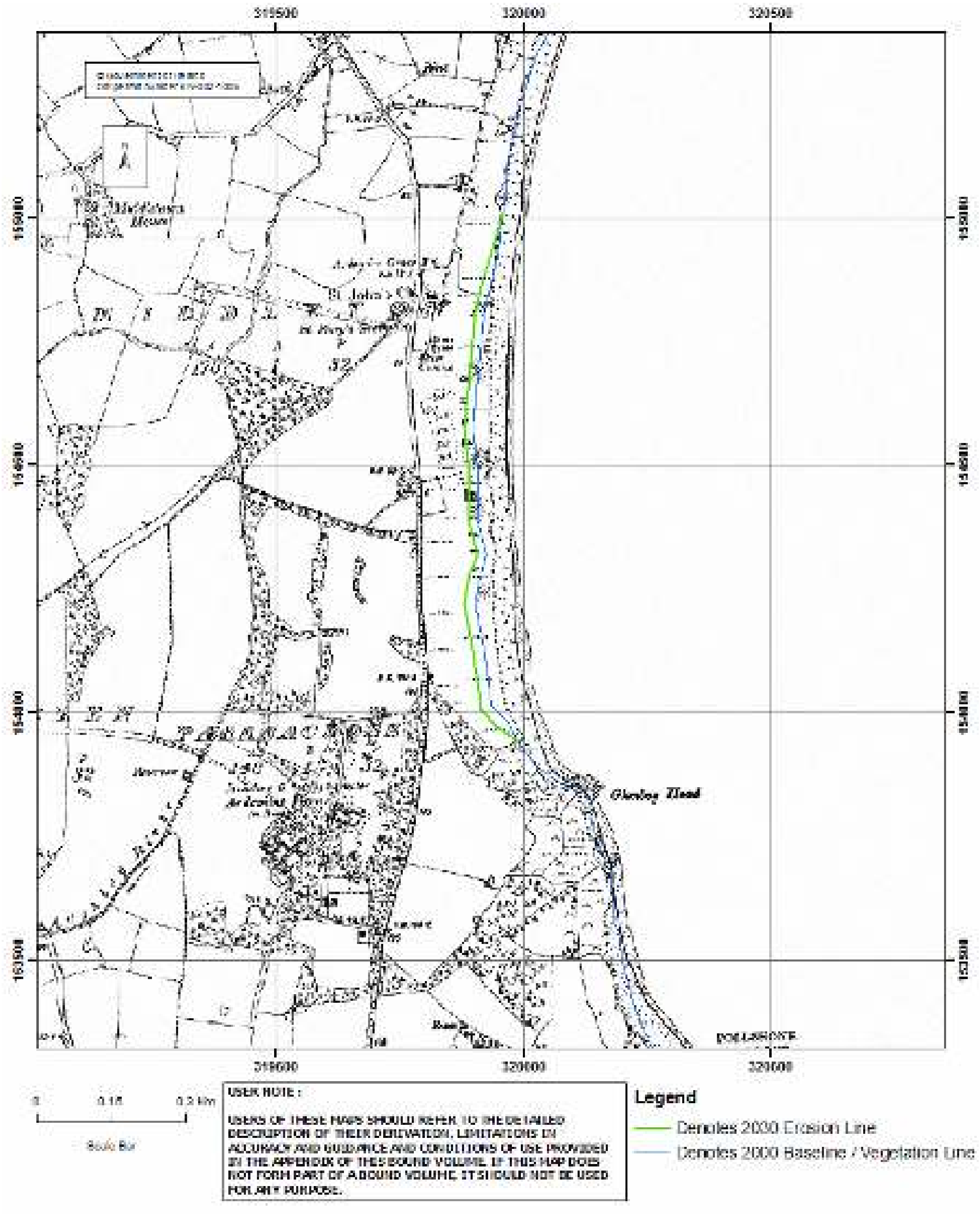


Figure 51: Ardamine, 2030 Erosion Map

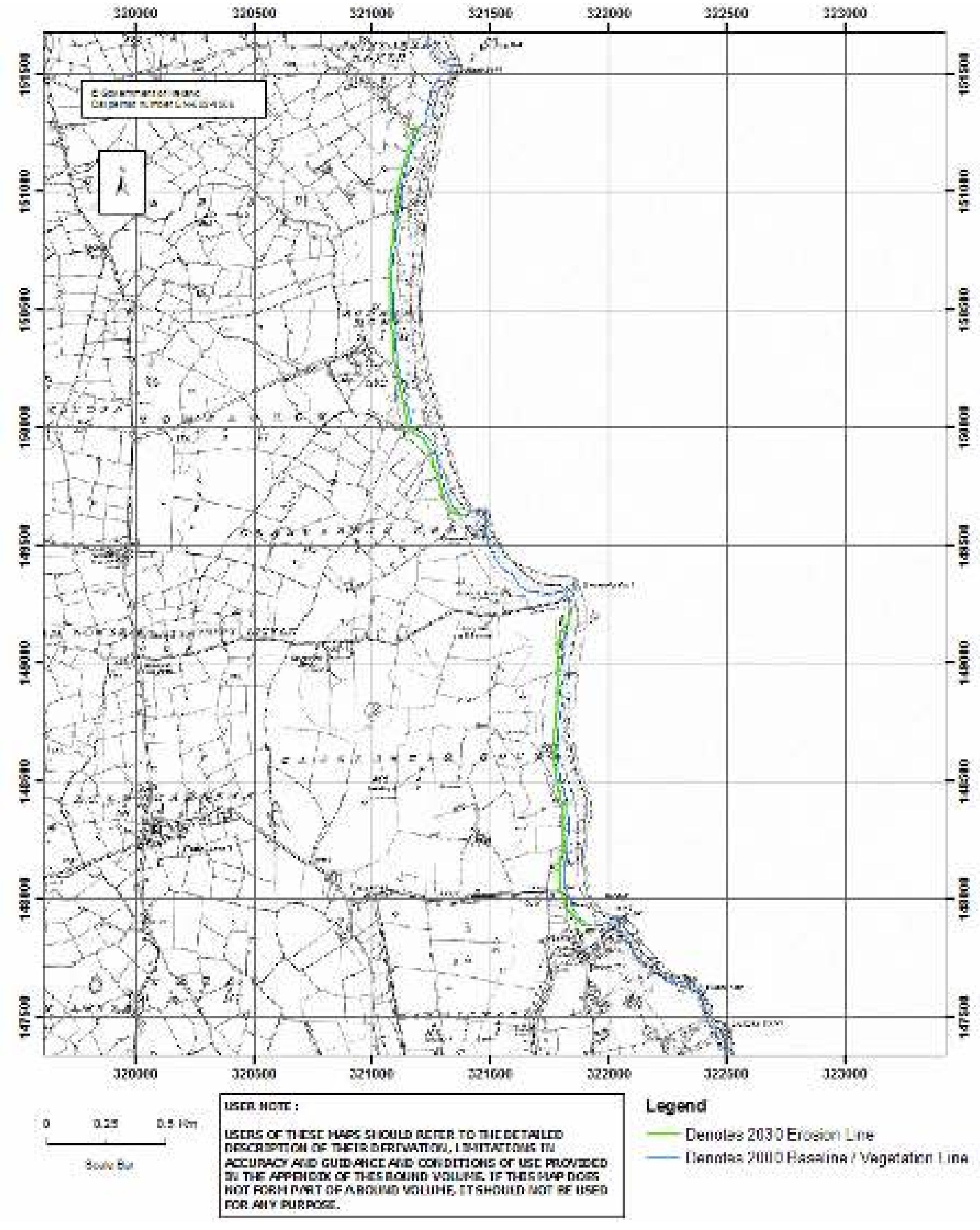


Figure 52: Glascarrig, 2030 Erosion Map

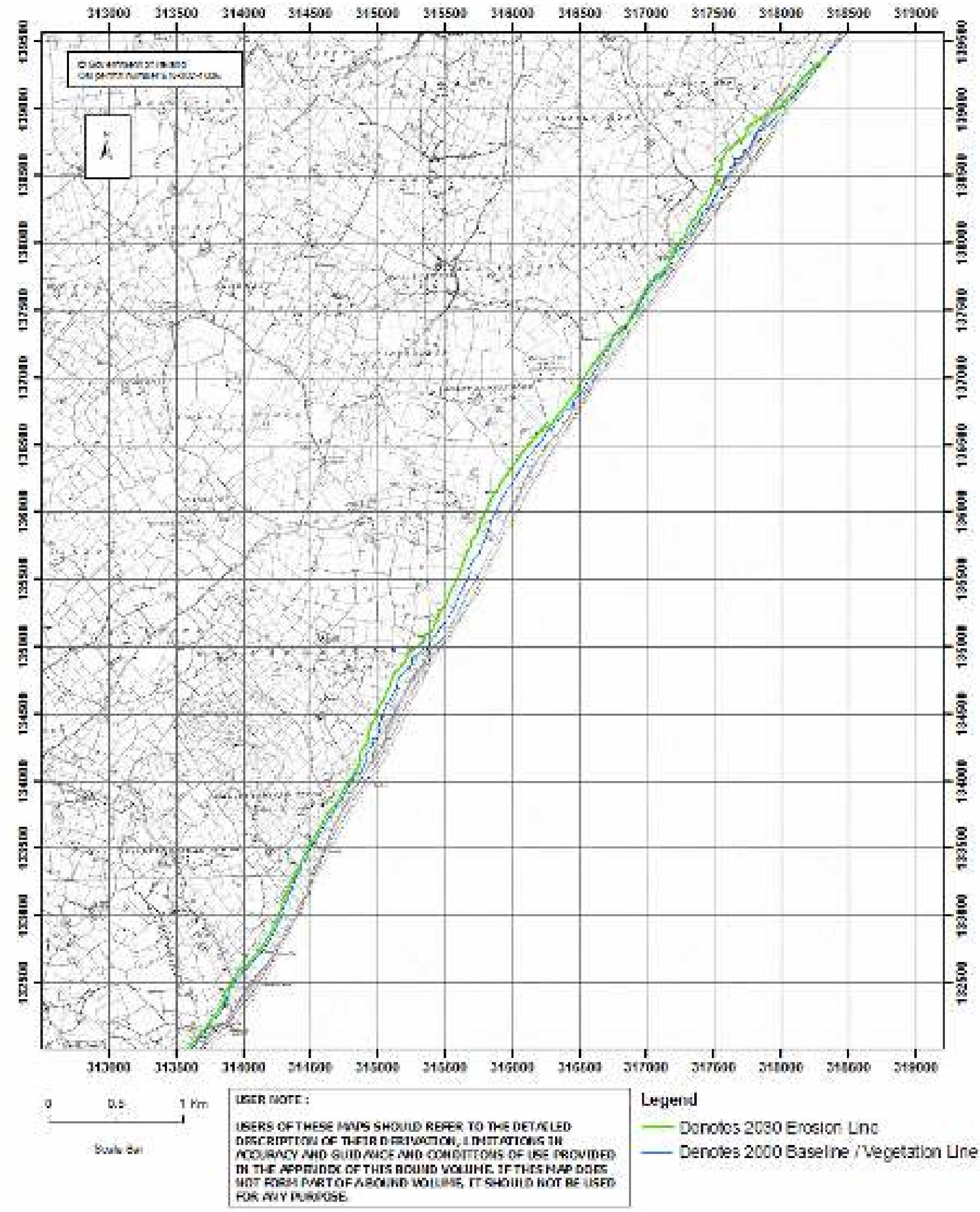


Figure 53: Killincooly to Blackwater, 2030 Erosion Map

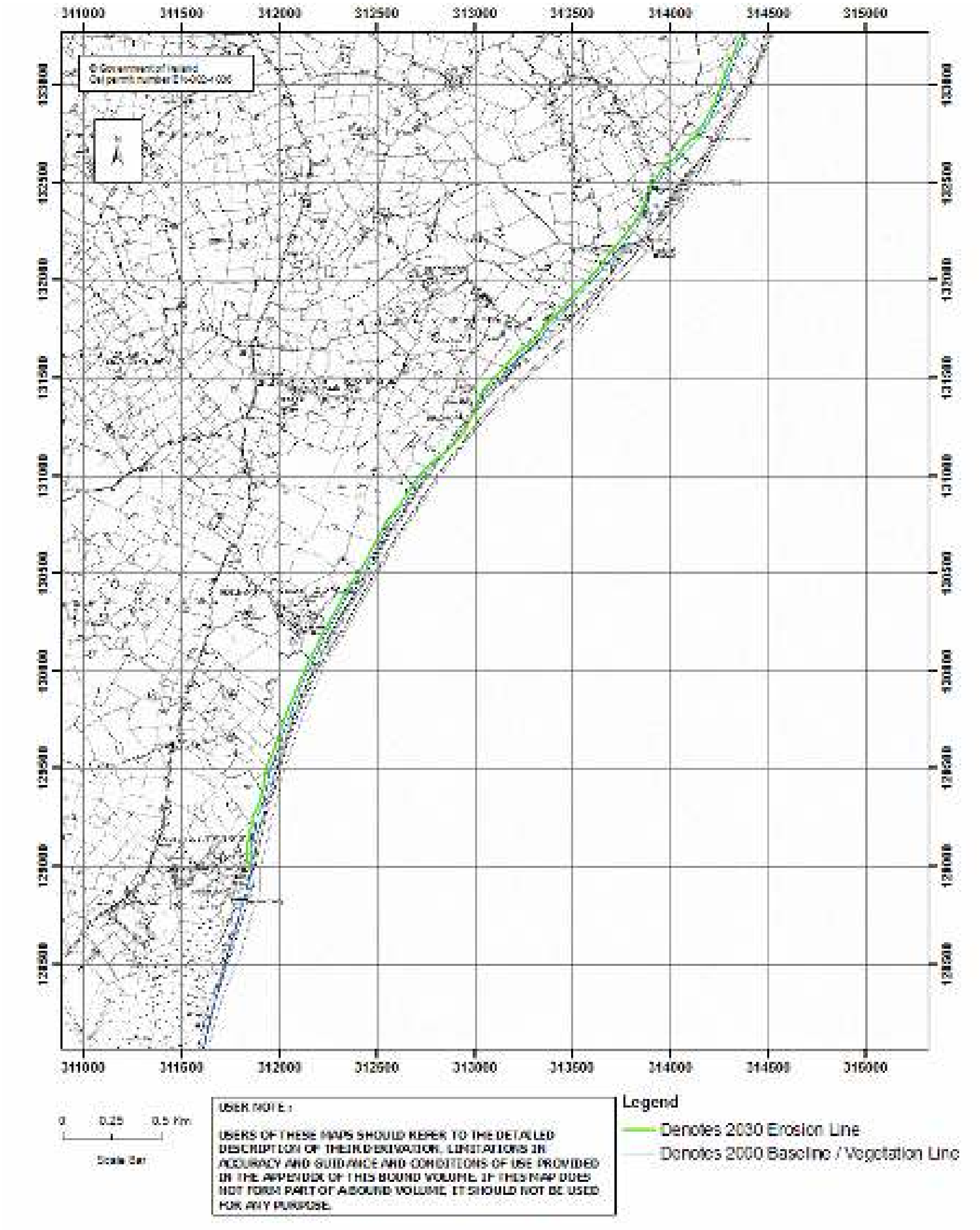


Figure 54: Blackwater to Ballinesker, 2030 Erosion Map

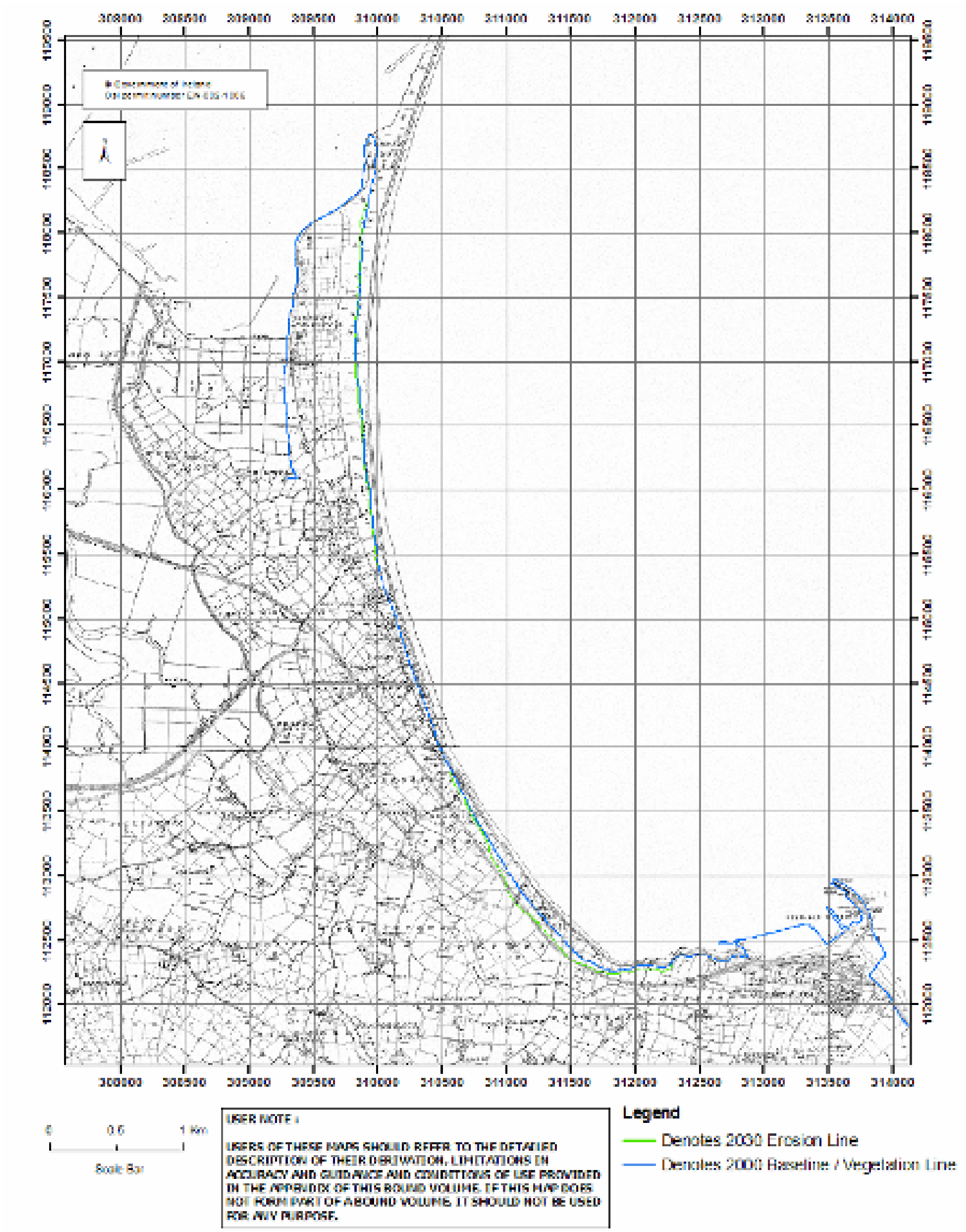


Figure 55: Rosslare, 2030 Erosion Map

8.0 Conclusions and Recommendations

8.1 Conclusions

The conclusions of Phase 2 of the Irish Coastal Protection Strategy Study are as follows:-

1. The approach of combining synthesised data from the Irish Sea Tidal Surge Model (ISTSM) with available tide gauge data and undertaking joint probability analysis to derive extreme water levels around the coastline worked well in the pilot area.

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

3. The extreme value analysis of 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 combined tide and surge levels presented in this report at 95% confidence limits is ±180mm relative to OD Malin for the 0.1% AEP event and ±130mm relative to OD Malin for the 0.5% AEP event.

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 large scale LiDAR surveys available for this pilot study area, flood extents of sufficient accuracy can still be derived for strategic purposes, albeit at different levels of confidence.

5. This study identified a number of issues associated with the conversion between the marine levelling system commonly used for coastal models and the terrestrial survey datum, OD Malin. After detailed discussions with OSI a conversion routine capable of accurately translating levels from the marine survey data to ordnance datum for comparison with the DTM was developed.

6. 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 Appendix 7 of this report.

7. A review of these predictive floodplain maps showed potential coastal flood risk, predominantly in or near coastal settlements with seven primary areas of potential coastal flood risk identified as follows : Bray, Ballygannon to Five Mile Point, Five Mile Point to Wicklow, Arklow, Cahore Point to Morriscastle, Wexford to Curracloe and Rosslare.

8. This study has demonstrated that comparison of historical and current aerial photography can be used to determine historic coastline changes and annualised rates of erosion to a reasonable level of accuracy for strategic assessment purposes. The principal source of inaccuracy in the resulting analysis was the geo-referencing and rectification of the historic aerial photography.

9. 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 8 of this report.

10. A review of these erosion maps showed that there were ten primary areas of potential coastal erosion risk identified as follows: Shanganagh to Bray, Greystones, Ballygannon to Five Mile Point, Five Mile Point to Wicklow, Kilpatrick, Ardamine, Glascarrig, Killincooly to Blackwater, Blackwater to Ballinesker and Rosslare.

11. In contrast to the assessment of coastal flood hazard and potential risk, the coastal erosion assessment along the pilot coastline indicated that there is generally little threat from erosion in the larger urbanised areas. This is primarily due to the fact that the urbanised coastline is mostly protected by man-made defences and hence analysis of the aerial photography did not detect any coastline change in the intervening period.

12. The mean annualised erosion rate of all areas along the pilot coastline where an erosion hazard was identified was approximately 0.6 metres. The maximum erosion rate identified occurred at Kilpatrick in County Wexford and equated to an annualised erosion rate of 3.75 metres.

13. It is anticipated that the strategic coastal flood and erosion maps produced in this study will be of particular interest to local authority planners in considering such potential threats to future proposed development at planning stage. This information has been referenced in the recent publication "The Planning System and Flood Risk Management, Guidelines for Planning Authorities, Nov 2009".

14. It is anticipated that these strategic flood and erosion maps will 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.

15. 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.

16. 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.

8.2 Recommendations

The recommendations of this study are as follows:-

1. It is recommended that the methodology of combining synthesised data from the Irish Sea Tidal Surge Model (ISTSM) with available tide gauge data and undertaking joint probability analysis to derive extreme water levels, developed as part of this pilot study, should be applied in other coastal areas around Ireland, since recorded tidal data is known to be equally scarce for all other parts of the Irish coastline.

2. 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 required 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.

3. It is suggested that the methodology applied to the production of strategic floodplain maps in this study should be extended to other parts of the Irish coastline to provide a consistent nationwide assessment of the extent of coastal flood hazard in Ireland.

4. It is suggested that the methodology applied to the production of strategic erosion maps in this study should be extended to other parts of the Irish coastline to provide a consistent nationwide assessment of the extent of the coastal erosion hazard in Ireland.

5. It is recommended that all mapping presented in this report should be read in conjunction with the appended disclaimers and guidance notes.

6. It is recommended that OPW and coastal Local Authorities 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 hazards and potential risks.

7. It is recommended that the potential impacts of climate change be incorporated into 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.
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 Sea Tidal Surge Model
Jack-knife Re-sampling Technique	A method for establishing the uncertainty of a particular probability distribution in relation to a data set. In the jackknife re-sampling 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.
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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