EFFECTS OF SEA LEVEL RISE ON HABITATS AROUND CLEW BAY

Susan Iremonger, PhD

Faculty of Life and Health Sciences

University of Ulster

Coleraine

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SUMMARY

The Earth's climate is changing; the average air temperature is rising. Temperature increase is causing the oceans to expand, which leads to sea level rise. Politically accepted forecasts of sea levels indicate rises of up to 1m or more by 2100, which may be increased due to recent findings on ice sheet melts. Even small increases in sea level can inundate huge areas of land. Natural habitats near sea level will be affected by these rises, with habitats migrating to adjacent lands if possible. Many habitats will simply be lost. Current EU law demands the protection of biodiversity through monitoring extent and condition of habitats.

An examination of the elevation of land near the sea and the habitats it supports can be used to investigate the effect of sea level rise on biodiversity. Ireland is an island nation and has a high coastline to land area ratio. Clew Bay has been called Ireland's archipelago because of the many islands in the bay. The topography around the bay is an intricate mosaic of hills and valleys which will be impacted by any rise in sea level. A digital elevation model (DEM) at a suitable resolution was available for the Bay and could be used for an analysis of the effects of sea level rise on habitats. It was not ideal as its coverage of the land surrounding the Bay was not complete, but other DEMs available were too coarse. Three land cover/habitats datasets were available that could be used for an analysis.

The datasets were not ideal, the CORINE dataset being very coarse, the Teagasc Habitats Indicator dataset being better resolution but still not ideal in the classification used and the Commonage Habitats dataset, while of good resolution was of limited extent and had many compound habitat classes. An analysis was performed with each of these to model how much of each habitat class was lost on inundation to 1m, 2m, 3m…to 20m. As none of these datasets were ideal for this analysis a supervised classification was run on a Landsat ETM image, with training provided by the other datasets, aerial orthophotos and ground-truthing. The resulting classified image was analysed for the same statistics as the other datasets.

Low-lying habitats would be most affected by sea level rise, particularly wide areas of mud/sand flats that support important bird populations. Saltmarshes, rocky shores, beaches and dunes would also be diminished, with the effects of "coastal squeeze".

Some grasslands and heaths would also be affected. Important wetlands (bog, fen and swamp) would largely be protected by existing sea barriers from currently forecasted sea level rises, but may be adversely affected by flooding from inland sources due to increased rainfall.

The creation of better spatial data for habitats in Ireland is strongly recommended. The use of newly available high-resolution DEMs along with better habitat maps would produce excellent information about the areas most likely to be impacted by sea level rise. New visualisation tools would strengthen these analyses and help to pinpoint areas most in need of management resources.

ABBREVIATIONS

AOI	Area of Interest
CBD	Convention on Biological Diversity
DEM	Digital Elevation Model
ERDAS	A program for image analysis
ESRI	Environmental Systems Research Institute
ETM+	Enhanced Thematic Mapper Plus
IPCC	Intergovernmental Panel on Climate Change
GCP	Ground Control Point
GIS	Geographic Information System
NASA	National Aeronautics and Space Administration
NPBR	National Platform for Biodiversity Research
OS	Ordnance Survey (Ireland)
SAR	Synthetic Aperture Radar
SPOT	Systeme Pour l'Observation de la Terre
TM	Thematic Mapper
UNEP	United Nations Environment Programme
USGS	United States Geological Survey
WCSD	World Commission on Sustainable Development
WSSD	World Summit on Sustainable Development

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This work was carried out to investigate possible effects of sea level rise on habitats of Clew Bay and the author disclaims responsibility for its impacts on any persons or property.

1 INTRODUCTION

1.1 CLIMATE CHANGE AND BIODIVERSITY.

Scientists overwhelmingly agree now that the atmosphere is warming up, largely due to increases in the proportion of "greenhouse gases" (UNEP & GRID-Arendal, 2009). Scenarios of the effects of climate change show that the temperature of the Earth will increase by up to 5 degrees by 2100 (IPCC, 2007c). The world is already committed for the next 40 years to a particular level of climate change because of the historic complement of emissions: beyond this the magnitude of climate change will be determined by current and future emissions (Hulme *et al.*, 2002). United Nations (UN) Secretary Ban Ki Moon stated on 3rd Sep 2009 that according to scientists the arctic could be ice-free in 2030 (in summer), which is decades earlier than scientists had agreed in the IPCC, in 2007. It is no longer relevant to discuss whether the climate is changing but rather how much change we are committed to and how fast this will occur (UNEP, 2009).

This is affecting the ecology of the globe, leading to changes in land cover, habitats and biodiversity (IPCC, 2007b). We are creating the greatest extinction crisis since the natural disaster that wiped out the dinosaurs 65 million years ago (CBD, 2000). Natural communities and the biodiversity they support will be affected by the change in climate: communities will change in composition as some species will compete better with the changed climate and others will be out-competed (Mitchell *et al.*, 2007). One of the effects of the rising temperatures is a rise in sea level, which is affecting coastal natural communities (Nicholls *et al.*, 2007b). The warming of the sea leads to an increase in sea volume (Nicholls *et al.*, 2007a). This in turn means a rise in sea levels along the coastal areas of land masses. The rise in level is exacerbated by melting of glaciers and ice sheets. Although there will be local differences, there was a rise of 17cm in the 20th century (UNEP & GRID-Arendal, 2009), and the official forecasts from modelling of up to 88cm by 2100 (IPCC, 2007c). These forecasts are due to be revised upwards with the most recent observations of ice melt (Dahl Jensen & Steffen, 2009; Richardson *et al.*, 2009) (Figure 1). For coastal areas, sea level rise is the most important effect of climate change (Tsyban *et al.*, 1990). The following were identified as the main areas of impact:

1) Lowland inundation and wetland displacement
2) Shoreline erosion
3) More severe storm-surge flooding
4) Saltwater intrusion into estuaries and freshwater aquifers
5) Altered tidal range in rivers and bays
6) Changes in sedimentation patterns
7) Decreased light penetration to benthic organisms.

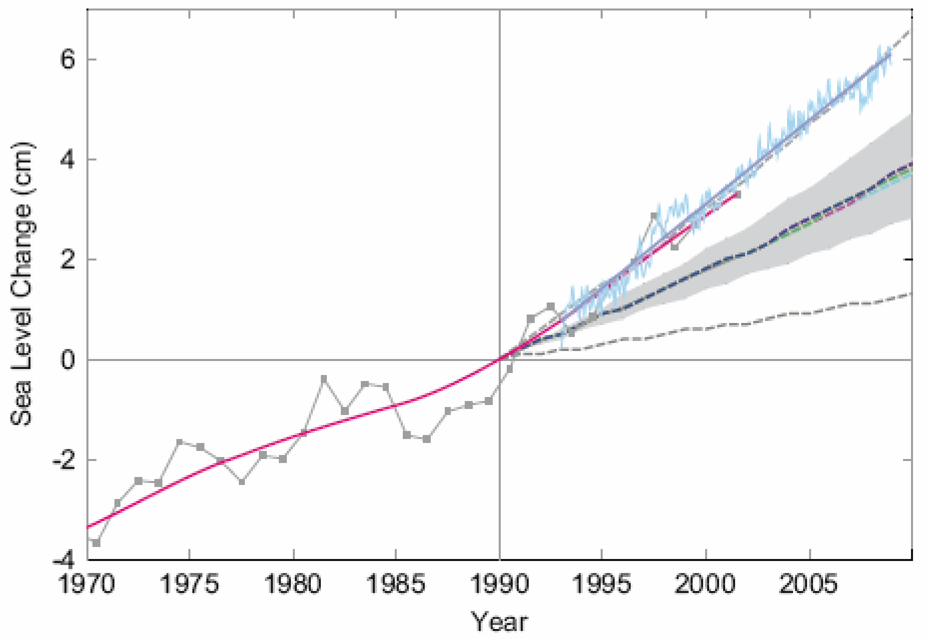


Figure 1. Change in sea level from 1970 to 2008, relative to sea level at 1990. The solid lines are based on observations smoothed to remove the effects of interannual variability (light lines connect data points). The envelope of IPCC projections is shown for comparison; this includes the broken lines as individual projections and the shading as the uncertainty around the projections. From: Dahl Jensen, D. & Steffen, K. (2009). Changes in the Greenland Ice Sheet. In: Synthesis Report. Climate Change. Global Risks, Challenges & Decisions. Proceedings of conference, Copenhagen, 10-12 March 2009. 2nd Ed. (eds K. Richardson, W. Steffen, H.J. Schellnhuber, J. Alcamo, T. Barker, R. Leemans, D. Liverman, M. Munasinghe, B. Osman-Elasha & N. Stern), pp. 9-10. University of Copenhagen, Copenhagen. Reproduced with permission.

Where possible, coastal habitats may migrate inland with the rise in sea level, but many of these are currently restricted in the distance they can move because of barriers caused by human buildings and infrastructure (Bijlsma *et al.*, 1995) ("coastal squeeze" (Radley & Dargie, 1995)). As coasts are dynamic systems the effect of sea level rise is not only a horizontal shift in coastline, but also estuaries and lagoons can become sinks for sediment, implying the potential for major coastal instability due to sea level rise in the vicinity of tidal inlets (Nicholls *et al.*, 2007b).

Spatial studies aiming to quantify the effects of sea level rise on coastal habitats generally depend on the presence of datasets with terrain information or Digital Elevation Models (DEMs) and habitat or other mapped biodiversity information

(BRANCH Partnership, 2007; Liu & de Smedt, 2005). The DEM is used to model flooding levels over the habitats, and information is extracted indicating habitats most affected, their location and extent (BRANCH Partnership, 2007). This can aid in the planning of measures to mitigate the effects of sea level rise. Some countries have concentrated on planning for a rise in sea level, such as the UK (see UK Climate Impacts Programme (CIP, 2009)), others are not so far ahead. The UK has significant data on risk of flooding under current conditions, by postal code, and proposes plans for mitigation (Environment Agency, 2009), as 2.4 million properties are at risk of flooding from rivers or sea in England alone. Shoreline management plans were made by each local authority and the next generation of these is expected in 2010 (Environment Agency, 2009). Regional forecast reports have been published, which among other items outline the risks of climate change to biodiversity (e.g. (Entec UK Ltd, 2000)), in particular stating that (a) the region's biodiversity is under tremendous pressure from climate change and (b) the pattern of species and habitats in the region will change.

1.2 IRELAND.

1.2.1 Ireland's coasts.

Ireland is an island nation with a land surface of 81,500km^2 and has a coastline of some 7,400km, (Marine Institute, 1996). The coastline is irregular and crenellate in form and is characterised by a bay-headline type configuration and conditioned by a high wave energy regime. The sea is an important resource for fisheries and the shipping trade, and the coast attracts tourism in large numbers. These activities create employment and give rise to a considerable amount of infrastructure development. Much of the economic activity along Atlantic coasts is related to fisheries and tourism, and depends on the health of the natural environment. The importance of the coastal zone in Ireland was recognised in the establishment of the Department of the Marine and Natural Resources (1988) and the Marine Institute (1991).

About 10% of Ireland is considered to be of prime importance for nature conservation and is included in a system of protected areas (DAHGI, 2002). Habitats commonly associated with Irish coasts include those of cliffs, beaches and barriers (sand and gravel types), lagoons, dunes, machair (sand "plains"), saltmarshes, mudflats and other wetlands (Devoy, 2008). Ireland is obliged to report on its natural communities to the European Commission using the CORINE classification scheme (EC DG

Environment, 2007). This monitoring is part of an effort to halt biodiversity loss by 2010 (EEA, 2007).

1.2.2 Impacts of climate change

Ireland's biodiversity would be susceptible to impact from various climate change effects (Donnelly *et al.*, 2004). Threats to the coast from climate change include an increase in flooding due to more severe rain events and a rise in sea level (Berry *et al.*, 2007; McGrath *et al.*, 2005) . Land retreat of 1m per 1cm rise on sandy coastlines may be expected, and combining this with more severe storm surge events and with reduced return periods (Lowe & Gregory, 2005), an area of approximately 300km^2 is at risk of inundation (Sweeney *et al.*, 2003). Possibly 30% of coastal wetlands could be lost with a rise in sea level of 1m (Devoy, 2008).

Making well-founded forecasts of future scenarios are not simple. Increased temperature (air and seawater) and rainfall under climate warming may add to the productivity of biotic systems (vascular and algal plants and carbonates). Rises in biological productivity from eutrophication and sedimentary changes have already been noted from many coastal sites in Ireland. For coastal sediment accumulation these may be seen as positive trends. The growth of coastal plant communities and also the productivity of marine carbonates provide positive feedbacks to sedimentary accumulation at the coast. The supply of carbonates is an important component of beach sands (Guilcher *et al.*, 1961).

Ireland's position, in the centre of Northwest Europe's coastal margin (between Lat 52-55° N) means that its tidal range is relatively high, up to 5m spring tidal range, which affects the development of its littoral vegetation. This is further influenced, particularly on the Atlantic coast, by storm surges and swells (Cooper *et al.*, 2004; Lozano *et al.*, 2004). Waves are the most powerful forcing factor in morphodynamic change along coasts (MacClenahan *et al.*, 2001). Ireland's Atlantic coast is therefore very vulnerable to the predicted effects of sea level and storm intensity increase, although in 2000 Devoy reported no apparent effects of climate change on sea level rise and coastal changes (Devoy, 2000). About 4% of the Irish coast is protected by shoreline defences that were originally built as property or agricultural boundaries. Many of these are old and in need of repair or restructuring: unlikely to serve as adequate defences in the face of sea level rise (Carter, 1991). As an example of contrast, in the UK preparations for adaptation to sea level rise are more advanced than in most European coastal countries. In England and Wales, it is recommended that new coastal defences consider an allowance for accelerated sea level rise. Strategic shoreline management plans have also been prepared, which include proposals for managed retreat (termed managed realignment) in flood-prone areas with low levels of development, and allowing continued erosion of retreating cliffs (de la Vega-Leinert & Nicholls, 2008).

1.2.3 The importance of high-resolution DEMs

One obstacle to carrying out detailed studies of the effect of flooding and future trends is the lack of high resolution DEMs that can model flooding at a local scale. A study of potential flooding of Cork was carried out recently, in which a DEM was built from specially-commissioned airborne LiDAR data (McGrath *et al.*, 2003). The expense of acquiring these data is generally prohibitive for any studies that are not Government-sponsored. Satellite data available are lower resolution both horizontally and vertically and not ideal for local studies, although these can be interpolated to produce possible higher resolution datasets. The interpolation process risks incurring errors of the Modifiable Areal Unit Problem (MAUP, (Openshaw, 1984)).

1.3 A PROJECT OPPORTUNITY USING LIDAR DATA

An opportunity to carry out a study of the risks to coastal natural communities from flooding has arisen through the recent acquisition of airborne LiDAR data for an area around Clew Bay, Co. Mayo. The data are from 2002, for use in the management of marine resources under the auspices of the INFOMAR project, a joint venture of the Marine Institute and the Geological Survey of Ireland (INFOMAR, 2009). The LiDAR image mainly covers the waters of the bay, but the islands and a coastal fringe of the mainland are also included (Figure 2).

The Clew Bay area is a natural archipelago, with a large number of small islands giving way to a mainland that includes gently undulating topography and relatively rugged hills. Because of all the inlets and islands this Bay area contains a massive length of shoreline for its area, supporting a correspondingly large amount of coastal habitat that will be affected by sea level rise. It is thus a very good location for a study of this nature. The drumlin landscape was formed during the last glacial period when sediments were laid down and smoothed over by advancing ice - the sea subsequently inundated the area, creating the multitude of islands (NPWS, 2001). Much of the area is dominated by farmland but there are pockets of natural vegetation as well as more extensive natural areas mainly in elevated locations, with blanket bog (Figure 3). The juxtaposition within Clew Bay of a wide variety of habitats, including seven listed on Annex I of the EU Habitats Directive, and the combination of important flora and fauna, including one Red Data Book plant and two mammals listed on Annex II of the EU Habitats Directive, make this a site of considerable national and international importance (NPWS, 2001). The entire Bay has been designated a Special Area of Conservation under EU law.

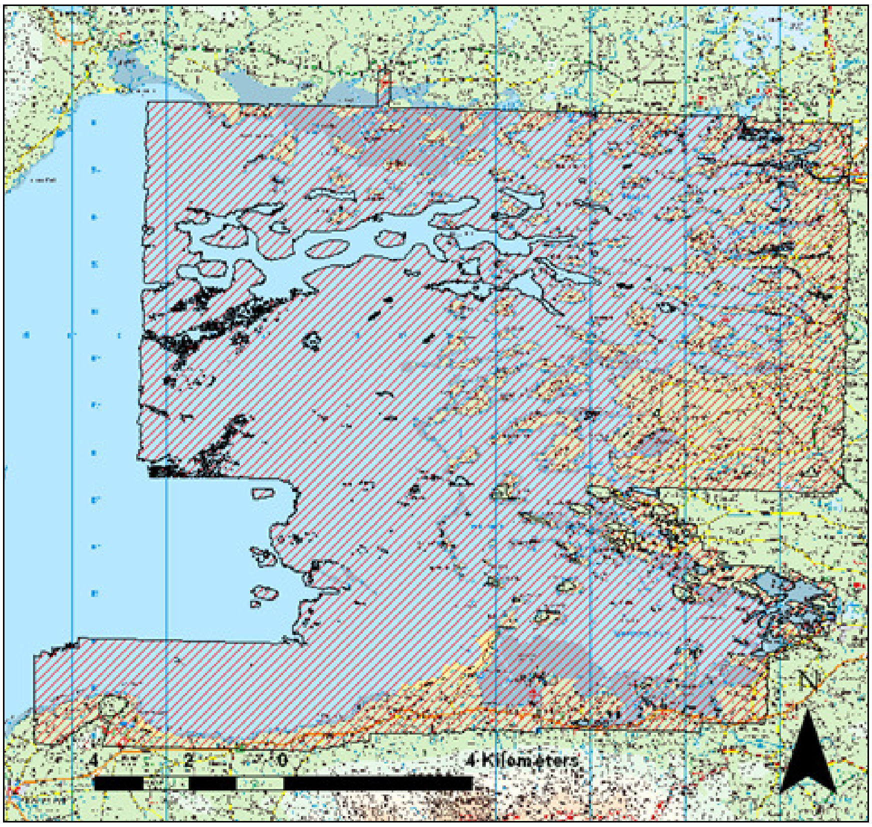


Figure 2. Extent of the LiDAR data over Clew Bay (red hatched area) over the OS Discovery Series map for geolocation. The data covers mainly the Bay but also a fringe of land around the bay, and numerous islands.

Figure 3.View over Carrowcally area of Clew Bay showing drumlin landscape including small islands. This image was taken from the Coast of Ireland Oblique Imagery Survey, 2003 and is copyright of the Government of Ireland. It is used here with the permission of OPW.

Parts of this coastal area flood frequently when spring tide conditions are accompanied by low-pressure weather systems, a southwesterly wind (which prevails) and heavy rainfall. The same was found in the study of the Cork area by McGrath *et al.* (2003). Some minor roads are not passable even at present during high tides. Flooding even in more inland areas during very wet periods has been extreme, as in interior Mayo in December 2006 (McNulty, 2006; Siggins, 2006)(Figure 4). Fears about storm damage to coastal areas are causing grave concern (O'Neill, 2008). Historical storms have been catalogued by (MacClenahan *et al.*, 2001) for the West of Ireland, and Cooper *et al.*(2004) noted that the direction as well as the timing and force of the storm affected the impact on the coastal systems. Extensive areas of flat land exist in the Clew bay coastal area, supporting communities such as reedbeds and machair. With a rise in sea level as forecasted by scientists (MacDonald, 2009; Nicholls *et al.*, 2007b), the flooding of natural communities and infrastructure around the coast will increase, potentially causing massive changes to the biodiversity of the area.

Figure 4. Flooded road at The Neale, Co. Mayo, 3rd December 2006. Courtesy of Michael Donnelly.

The availability of the LiDAR-derived DEM has afforded a rare opportunity to make a study of the effects of sea level rise on the habitats around Clew Bay. This DEM will be overlaid on the Ordnance Survey maps of the area and the available datasets for land cover and habitats. An analysis should indicate the amount of habitat that would be inundated under different sea level rise scenarios.

Aim

To determine impacts of flooding from future sea level rise on habitats and biodiversity in the Clew Bay area.

Objectives

- To examine the coastal natural communities of Clew Bay as shown in CORINE data and other sources, using classification of imagery if necessary.
- To create visual potential flood maps using a Geographic Information System (GIS).
- To pinpoint areas most likely to be influenced by sea level rise around Clew Bay and highlight the natural communities that would be affected.
- To assess the human infrastructure in these areas in terms of barriers to sea encroachment and to biodiversity movement.
- To indicate possible changes to biodiversity and land cover brought about by more frequent and severe flooding.

2 LITERATURE REVIEW

2.1 CLIMATE CHANGE

The IPCC was established in 1988 due to concern about the changing temperature of the atmosphere (IPCC, 2009). The Panel is composed of top climate change scientists, who review findings of the international scientific community and draft major reports on the processes and effects of climate change into the future. As the Panel is intergovernmental, governments throughout the world must agree on the wording of the contents of the reports, along with the scientists. In 1990 the IPCC published its first Assessment Report, which provided much baseline information (IPCC, 1990). This was followed by three more reports, the most recent of which was published in 2007 (IPCC, 1995, 2001b, 2007a).

Predictions of climate change were devised using modelling scenarios, taking into account many factors including population growth and movements, economics and environmental matters. For assessing climatic factors, both atmospheric and ocean General Circulation Models (GCM) were used, and global emissions scenarios were generated ("SRES") ((IPCC, 2001c), Appendix 2). Predictions of global mean temperature rise from 2000 to 2090 ranged from more than 1 to 5°C (IPCC, 2001c), depending on levels of emissions, alternative energy use, technological advances and other factors.

2.2 SEA LEVELS

Although these temperature rises can seem low, they will have a profound effect on other physical and biological aspects of the Earth, in particular the distribution of water. Global warming heats up the oceans, which causes them to expand and the sea level to rise (Nicholls *et al.*, 2007a). Currently much water is stored as ice in polar regions and on high mountains, and climate warming is already causing massive changes (Holland *et al.*, 2008; Lowe *et al.*, 2006; Pfeffer *et al.*, 2008). The melting ice eventually ends up in the oceans, which causes the level to rise (Meier *et al.*, 2007). For the past 3000 years, mean sea level rose by between 0.1 and 0.2mm per year. Since 1990, the rise has been 1-2mm per year, and scientists predict that this will accelerate during the next few decades and into the 22nd century (McLean & Tsyban, 2001; Solomon *et al.*, 2009). Sea level will rise by 0.09–0.88m between 1990 and

2100 according to the full range of six illustrative scenarios derived for the IPCC (Church & Gregory, 2001; Tsyban *et al.*, 1990). Since that publication scientists have increased their predictions to more than 1m (Figure 1, Section 1.1)(Dahl Jensen & Steffen, 2009; IOP Conference Series, 2009; MacDonald, 2009; Solomon *et al.*, 2009).

Recently (Pritchard *et al.*, 2009) have documented changes in the Greenland and Antarctic ice sheets that show these melting faster than was accepted by the IPCC, and recommended that estimates of global sea level rise should be revised upwards. Other authors have documented the melting of ice at accelerated rates (Joughin, 2008; Scott, 2009; Sole *et al.*, 2008). The only certainty at this point is that ocean levels will rise, but by how much remains a question (Pritchard *et al.*, 2009).

Estimates of storm surges show that high winds and low atmospheric pressure combine to create surges of more than 1m (Lowe & Gregory, 2005), causing local coastal flooding. A far more massive type of surge can be caused by a tsunami. Tsunamis represent one of the most potentially serious forms of coastal flood risk, although the flooding is not permanent it can have devastating and long-lasting effects. Some European tsunamis recent history were 1755 Lisbon, 1693 Sicily and 1783 Calabria. Tsunami hazard in Europe is real (Dawson *et al.*, 2004). The Lisbon tsunami is reconstructed as having a wave amplitude of 5-15m (Thiebot & Gutscher, 2006). This deposited large boulders in West Portugal, and evidence of its effects reach as far as the Scilly Isles (UK) (Banerjee *et al.*, 2001). The calculation of risk from Tsunami in Europe is subject to accurate probability forecasts of earthquake, volcanic activity or asteroid strike. Historical data can contribute significantly to these calculations and are as yet inadequate (Dawson *et al.*, 2004). In any case, the probability of a tsunami striking a coastline during both a high tide and a storm surge should be included in risk analyses (Dawson *et al.*, 2004).

2.3 COASTAL SYSTEMS.

Coastal ecosystems provide a wide range of goods and services to humans, including the filtering of water, food, shoreline stabilisation, tourism and biodiversity (Burke *et al.*, 2000). Coastal ecosystems are among the most productive of the world. They encompass a broad range of habitat types and harbour a wealth of species and genetic diversity, including priority habitats that require protection under EU law (Council of the European Communities, 1992). They store and cycle nutrients, filter pollutants from inland freshwater systems, and help to protect shorelines from erosion and storms (Burke *et al.*, 2000). The beauty of coastal ecosystems makes them a magnet for the world's population. People gravitate to coastal regions to earn a living from fishing and agriculture, as well as for leisure, recreational activities and tourism (Burke *et al.*, 2000). Approx 20% of the world's human population live within 30km of the sea, and nearly double that live within 100km of the coast (Cohen *et al.*, 1997; Gommes *et al.*, 1998). The intensity of human activity puts pressure on these coastal systems, causing reductions in their extent or integrity (Burke *et al.*, 2000). This degradation in turn makes these more vulnerable to damage (Danielsen *et al.*, 2005). A change in the natural environment such as shoreline inundation regime or prevalence of salt causes alteration in the species composition of the communities (Cooper, 1982; Lammerts *et al.*, 2001), leading to biodiversity loss. Currently the sensitivity of plant communities to change is being used in devising tools for coastal vulnerability assessment (García-Mora *et al.*, 2000; Grunewald & Schubert, 2007).

2.4 BIODIVERSITY MAPPING

Biodiversity, the variety of life, includes diversity at genetic, species and ecosystem levels. It forms the web of life of which humans are an integral part and upon which we so fully depend (CBD, 2000). The recognition of the importance of biodiversity is shown by international instruments such as the Convention on Biological Diversity (CBD), which Ireland ratified in 1996 (CBD, 2009). This convention is part of the international effort towards sustainable development, which is development that meets the needs of the present without compromising the ability of future generations to meet their own needs (WCSD, 1987). Ecosystems are being fragmented or eliminated, and innumerable species are in decline or already extinct (CBD, 2000). The World Commission on Sustainable Development (WCSD) continues to find pathways for mitigating the destruction of the world's resources, including biodiversity (Spangenberg, 2007; WSSD, 2002). These internationally-recognised problems for biodiversity have given rise to efforts to halt loss by 2010 in the EU (EEA, 2007), and to at least halve the rate globally (WSSD, 2002).

EU member states are obliged to protect their biodiversity through compliance with two European legal instruments, the Habitats Directive (Council of the Euopean Communities, 1992) which has been updated to include accession countries (European Commission, 2008) and the Birds Directive (Council of the European

Communities, 1979) (similarly updated), in addition to national nature protection laws. A network of protected areas (Natura 2000, (European Commission, 2009)) extends across Europe, including sites with special importance for habitats, endangered species and birds (Special Areas of Conservation, SACs, and Special Protection Areas, SPAs). The EU is refining a process of tracking biodiversity in each member state using a set of 26 indicators such as ecosystem coverage and the abundance and distribution of selected species (EEA, 2007). The extent of activity to protect biodiversity at the highest political levels, demonstrated above, attests to its importance to humans.

Many nations have their own classification schemes for habitats and vegetation that are used in ecological surveys and as a basis for conservation management plans (e.g. National Vegetation Classification System of the U.S. (TNC & ESRI, 1994), and of the UK (Rodwell, 2000). A Europe-wide classification system for habitats was established and used in the listing of habitats of conservation concern in the EU Habitats Directive (Council of the European Communities, 1992). The CORINE (Coordination of Information on the Environment) land cover project of the European Commission was started in 1985 with the aim of producing a map with a uniform standardised classification system for all nations in the European Community (EEA, 2000). Both the classification and the map are updated periodically to keep current with advances in science and also with the enlargement of the EU (Romao, 1996). The habitats classification is, however, a far more detailed account of natural communities than that used in the map, which only records broad land-cover classes.

The original maps were based on Landsat MSS imagery, but also other sources such as national maps and databases. The scale of the national maps was set at 1:100,000, with a minimum mapping unit of 25 ha. These contributed to the composition of European maps at scales of 1:250,000 and 1:1,000,000. These scales and resolutions were set with consideration of the interpretation possibilities of the imagery, the level of information required in the finished product and budgetary constraints (EEA, 1994). One of the main purposes of the project was to contribute to sound management of the natural resources of the EU by showing the locations and amounts of different natural communities (EEA, 1994).

The project is one of many using remotely sensed imagery and GIS to contribute to natural resource management, biodiversity conservation planning and monitoring change, e.g. around Natura 2000 sites (Thomson *et al.*, 2007). Sound environmental management, particularly where biodiversity loss is a focus, requires frequent and spatially detailed assessments of species numbers and distributions (Turner *et al.*, 2003). The direct collection of such information is costly, but the use of remote sensing to monitor habitat extent and quality can contribute directly to conservation planning (Amarnath *et al.*, 2003; Foody, 2005; Griffiths *et al.*, 2000; Kerr & Ostrovsky, 2003; Skole & Tucker, 1993). The habitats in which vulnerable species are found can be used as a proxy for the occurrence of those species, although this approach should be applied with caution; the use of ancillary data can reduce errors (Foody, 2008; Rogers & et al., 2002; Scott & Csuti, 1997; Turner et al., 2003). The technical specification of imagery used for habitat mapping has improved in recent years, rendering any resulting maps more reliable.

More detailed and cover/habitat maps are available for some countries, but an issue remains about the classification of the land cover units for use in biodiversity monitoring. For national maps the classification units need to be fairly broad, such as “wetland”, “heath” or “broadleaf forest”, but these categories are not as useful for biodiversity estimation and monitoring as finer classes, such as “raised bog”, “blanket bog”, “fen” and “ash-oak forest”. In Ireland Habitat Indicator maps were produced on a county by county basis by Teagasc, which had a higher resolution than the CORINE land cover maps and also had a more detailed classification system (Loftus *et al.*, 2002). Another classification scheme that is widely used by local authorities and the National Parks and Wildlife Service (NPWS) in Ireland is that produced by the Heritage Council (Fossitt, 2000). This scheme, however, has not been not used in a map at the national scale but in more local ecological studies (e.g. Galway habitats survey (Natura, 2005)). The mapping of natural communities can be problematic as in nature many habitats occur in an intimate mosaic and do not have defined boundaries (Cross, 2006). This is one reason why habitat maps produced recently for NPWS have not used the habitat or land cover classifications defined above, but show areas assigned to other names, and in many cases using two names for the same defined polygon (Bleasdale, 2007). Vegetation classification is generally more detailed than habitat or land cover classification (see for example Rodwell (2000) and White and Doyle (1982)), and similar problems are encountered in mapping as with habitats. Although Ireland’s plant communities have been well researched and documented, they have not been mapped as an entity. A potential vegetation map of Ireland was produced but does not show the extent of each vegetation type as it is today (Cross, 1998, 2006). It indicates what the vegetation would be without the vast impact brought to bear by humans.

2.5 SATELLITE IMAGERY FOR LAND COVER MAPPING

A wide range of Earth observation satellites now exist (Figure 5). A number of these are useful for land cover mapping and can contribute to the determination of habitat structure and species composition. An international body has been set up to coordinate remote sensing enterprises into one system, the GEOSS (Global Earth Observation System of Systems), and GEO-BON (Group for Earth Observations Biodiversity Observation Network, 2009) focuses on biodiversity information within this system (Muchoney *et al.*, 1994; Scholes *et al.*, 2008). The processes used for deriving land cover information usually involve the application of statistical clustering methods to multispectral remote sensing data (Kerr & Ostrovsky, 2003). Land cover maps are used at scales from local (e.g. Muchoney *et al.*, 1994) to regional and global (e.g. (EC JRC, 2003)). Sensors with a 1km resolution such as AVHRR and SPOT VEGETATION cover the earth once a day and so are useful for global monitoring (USGS, 2009a; Vegetation Programme, 2009). A sensor on the MODIS satellite was designed to do a similar job but at a higher resolution of 250m. Besides pixel size, another important technical capability of the sensor is its spectral range. For simple impressions of the Earth’s cover, detection of reflected light in the visible spectrum may suffice, but for other applications a wider spectral capability is required (Lambin & Geist, 2006; Townshend *et al.*, 1994). For vegetation detection the infra red wavelengths are of particular importance as they differentiate between a green inanimate object and a photosynthetically active green leaf (Sellers, 1985).

For land cover mapping a useful tool is the NDVI (Normalized Difference Vegetation Index (Tucker, 1979), which uses the difference between electomagnetic reflection in the visible red (VR) and near infra red (NIR) wavelength bands to detect presence of photosynthetically active vegetation (NDVI=(NIR-VR)/(NIR+VR)). In general, if there is much more reflected radiation in near-infrared wavelengths than in visible wavelengths, then the vegetation in that pixel is likely to be dense and may contain some type of forest. If there is very little difference in the intensity of visible and near-infrared wavelengths reflected, then the vegetation is probably sparse and may consist of grassland, tundra, or desert (Figure 6). The index can be used to show areas of landscape heterogeneity and biological diversity, contributing to efforts to delineate conservation areas (Gould, 2000). NDVI results can be marred by a number of phenomena including cloud and cloud shadow effects, so for best results the use of composite images is recommended. This is possible when using the low resolution satellites with daily coverage but not generally practical with higher resolution satellites, so more care must be taken with the interpretation of the results (Holben, 1986). Multitemporal medium-resolution imagery (Landsat) was, however, used recently in a study of the habitats of an area in North Wales, during which it was determined that early spring and early autumn were the optimum dates to use in combination for discerning different land cover types with NDVI (Lucas *et al.*, 2007).

Figure 5. Array of satellites currently deployed for observing the Earth.

Figure 6. Very low values of NDVI (0.1 and below) correspond to barren areas of rock, sand, or snow. Moderate values represent shrub and grassland (0.2 to 0.3), while high values indicate temperate and tropical rainforests (0.6 to 0.8). To see how the picture of vegetation of the Earth changes over time, click the following link: http://earthobservatory.nasa.gov/GlobalMaps/data/mov/MOD13A2_M_NDVI.mov
Copied from NASA Web pages (public domain).

2.6 Effects of climate change on biodiversity

Species are generally found within certain environmental ranges, being adapted for life under prevailing conditions (Hannah *et al.*, 2005). Climate change is affecting the physiology, phenology distribution of European plant and animal species (Alcamo *et al.*, 2007). Knowledge of the physiology and biogeography of various species leads to expectations of how they would react to climate change, for example, species ranges have been found to have shifted poleward or upslope (Hannah *et al.*, 2005). In Ireland the native flora contains both arctic-alpine elements and species of the Mediterranean (Webb *et al.*, 1996). As the changed conditions will have important implications for animals and plants, particularly those at the limits of their ranges, the complement of these in the natural communities will change (Donnelly *et al.*, 2004). Climatic pressures are in addition to those of land use change, habitat space availability and fragmentation that already threaten biodiversity locally and globally (Sala *et al.*, 2000). Predictions of species distribution should take into account not only the "Climate envelope" (Hijmans & Graham, 2006; Thomas *et al.*, 2004) but also interactions with other organisms (Davis *et al.*, 1998).

Thomas *et al.* (2004) argued that climate change will have a greater effect on biodiversity than other pressures. Their modelling assessed extinction risks for sample regions that covered 20% of the Earth's surface, and forecasted that 15-37% of species would be "committed to extinction" by 2050. Modelling reactions of species associated with particular habitats, Berry *et al*. (2003) ranked a number of habitats according to their resilience to climate change in Britain and Ireland. Important factors affecting adaptive capacity were the availability of suitable space for the species to move into and the ability of species to migrate.

A Europe-wide assessment of the future distribution of 1,350 plant species (nearly 10% of the European flora) under various SRES scenarios indicated that more than half of the modelled species could become vulnerable, endangered, critically endangered or committed to extinction by 2080 if unable to disperse (Thuiller *et al.*, 2004). Under the most severe climate scenario (A1, see IPCC (2000)), and assuming that species could adapt through dispersal, 22% of the species considered would become critically endangered, and 2% committed to extinction. Certain habitats were found to be particularly vulnerable to climate change in Ireland (Byrne *et al.*, 2003).

Areas designated for conservation may need to be re-designed as habitats and species for which they were created move out (Kirby, 2003). In coastal systems planning adaptation can be approached in three ways: (a) protection, (b) accommodation and (c) retreat (Berry *et al.*, 2007; Nicholls & Klein, 2005). However, planning for the impacts of sea level rise was not found to be at an advanced level in many European countries, and there is a need for more impact vulnerability studies relevant to coastal management.

2.7 FLOOD MAPPING

Flooding associated with sea level rise and storm surge can be mapped and modelled using DEMs (Islam & Sado, 2000; Schmitz *et al.*, 2007; Townsend, 2001). DEMs used to be made mainly from the interpolation of contour maps (Leenaers & Okx, 1989), but the advances in radar observation technology generated techniques for deriving elevation data from satellite and air-borne sensors. Two methods are interferometric synthetic aperture radar and digital image correlation. Digital elevation data are usually organised into one of three data structures—(1) regular grids, (2) triangulated irregular networks (TIN), and (3) contours—depending on the source and/or preferred method of analysis (Wilson & Gallant, 2000).

Global DEMs are generally available now with a cell resolution of 1km and a vertical accuracy averaging 60m (e.g. GTOPO30, from the EROS Data Centre of USGS). These are too general for most work at the national level, but other DEMs are available for certain parts of the world at higher resolutions (e.g. Landmap has DEMs derived from ERS SAR (Synthetic Aperture Radar) imagery with 25m cells and a 10m vertical accuracy for the UK and parts of the Republic of Ireland). Airborne sensors such as LiDAR facilitate very high resolution imaging, to 1m vertical accuracy and 5m cell resolution, which is used to make even more detailed DEMs. These are generally required for making detailed studies of flood hazard mapping (Paul Bates, pers. comm. re: Lismap FP).

Flood extent during flooding events in Bangladesh (Islam & Sado, 2000) and West Bengal (Sanyal & Lu, 2004) was delineated by directly mapping the reach of water using 1km resolution satellite imagery. The drawback of mapping at this resolution is that part of each cell may be flooded but other parts may not, so it can just give a general impression of areas flooded. However, it can be used to guide higher-resolution studies, which can focus on areas most at risk (Schmitz *et al.*, 2007).

Figure 7. Flooding on 19th November 2009 near Knockaniska bridge, due to high rainfall (top left) and without flooding (1st December, top right). Orthophoto (bottom) shows location of camera (red dot), looking towards sea barrier (yellow star). Sea barrier usually holds back sea water at high tide from encroaching on land, but during flooding of land slows flood waters exiting to sea.

Mapping areas at risk of flooding is the first basic step to looking at how flooding will affect the environment in the future (Liu & de Smedt, 2005). Flood hazard mapping using a DEM has been carried out for at least 20 years (Leenaers & Okx, 1989). In terms of land cover, natural communities and biodiversity, an increase in flooding can mean a change in the composition and extent of different habitats (McElwain & Sweeney, 2006; Walmsley *et al.*, 2007). Flood maps can be overlaid on other maps to show the different types of land, land cover and natural communities at risk of flooding, using a GIS such as ArcGIS (ESRI, 2008; Gibson & Power, 2000; McGrath *et al.*, 2003).

In the Clew Bay area flooding caused by heavy rainfall occurs (Office of Public Works, 2009), as was experienced during November 2009 (Met Eireann, 2009). Indeed, barriers to sea encroachment can cause flooding on the landward side of the barrier as river water builds up after heavy rainfall (Figure 7). The Office of Public Works has put many areas at risk of flooding on maps: Figure 8 shows flood hazard points in the vicinity of the study area for this project. This type of flooding is distinct from that of sea level rise in that it is temporary, but it can combine with rises in sea level to exacerbate damage (Leatherman, 2001; McGrath *et al.*, 2003; Nicholls *et al.*, 2007b).

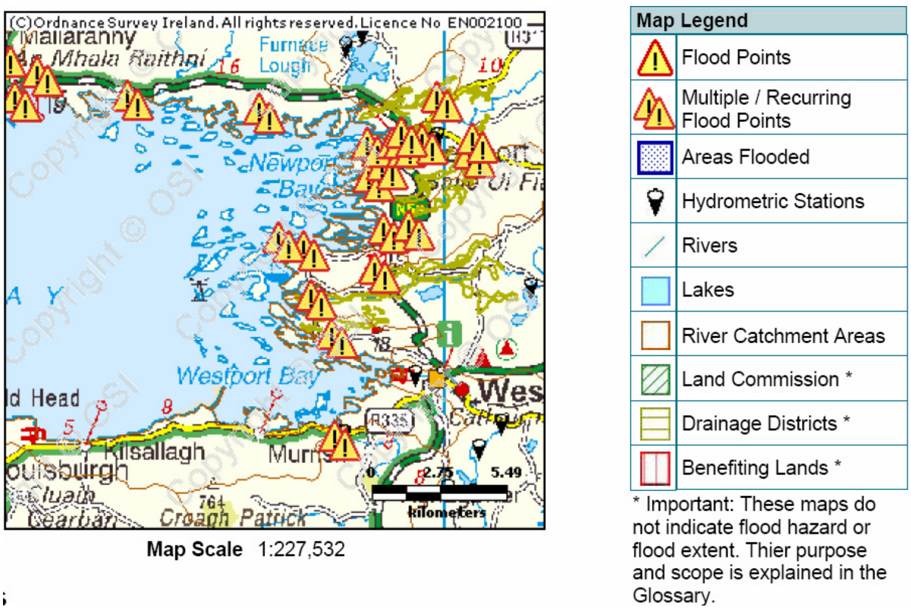


Figure 8. Flood hazard map for the Clew Bay area as presented on www.floodmaps.ie (Office of Public Works).

3 METHODS

The outline methodology for this project was to use elevation data in conjunction with mapped habitat or land cover information to show the extent of natural communities that would be affected by a rise in sea level. This would give indications of any biodiversity loss that may be expected, and may give pointers as to what mitigating measures could be undertaken to minimise losses. Programs used throughout were ERDAS Imagine 9.0 from Leica Geosystems, and ArcMap 9.1 (ArcView and ArcCatalog) from ESRI. The methodology descriptions that follow address:

1. the acquisition and preparation of :
    - aerial photos and Ordnance Survey (OS) maps
    - suitable DEMs
    - suitable habitat/land cover maps
    - satellite imagery for a habitat/land cover map
2. the overlay of these datasets under different flooding scenarios for modelling:
    - a visual assessment of flooding
    - a statistical analysis to determine the amounts of habitat/land cover potentially lost.

The biggest issue with the OS, orthophoto and Irish habitat dataset resources was to get permission to use them from Republic of Ireland agencies. Applications were made to the National Parks and Wildlife Service and to the Mayo County Council, stressing the information that would be forthcoming for the national information database from this project. Permission was gratefully received from these two bodies.

Figure 9 shows the study area with some place names used in the following sections.

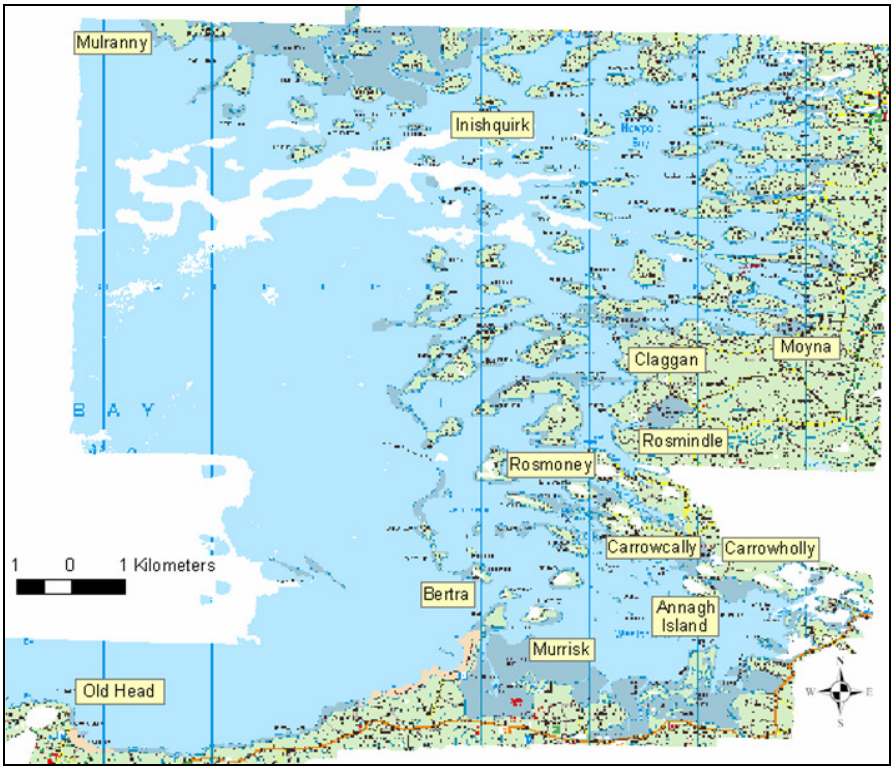


Figure 9. Study area extent around Clew Bay depicted on OS Disclovery Series map with some place names relevant to the study. Areas of NoData from the LiDAR DEM are excluded from the study and are in white.

3.1 ACQUISITION AND PREPARATION OF DATA.

3.1.1 Ordnance Survey maps and aerial orthophotos.

These datasets were provided by Mayo County Council. Maps in the Discovery Series (version 2007), the 6" maps and digital orthophotos of the study area were obtained. No further preparation was necessary on these datasets, which were all compatible with the Irish National Grid (ING). Orthophotos were taken July/August 2006 at a height of 6,706m (22,000ft): scale 1:44,000 and resolution 3m/pixel or 300dpi.

3.1.2 DEM

The main DEM that was of interest in this project was that from the LiDAR data, available through Geological Survey of Ireland (Geological Survey of Ireland, 2009) (see Section 1.3). Although covering a reasonable area of the coast, this dataset contained significant areas of NoData. While it could be used in this state to perform analyses, it was planned to attempt to patch the holes in the dataset (the NoData areas) with data from another source, even if this would be of a coarser resolution.

The Ordnance Survey contour data were investigated to assess the possibility of interpolating a DEM from the contours, but this was not possible as the contour lines were only available as a Lines feature file without elevation attribute: not as a contour file (Mayo County Council, 2009, pers. comm.). Additionally the caveats from the Ordnance Survey about the accuracy of the positioning of the lines were discouraging. The other main DEM that was available to the project was one through the Landmap project, built from SAR data. The SAR DEM was of lower resolution than that of the LiDAR, but the cover was more complete. The possibility of filling the holes in the LiDAR data with the SAR data was explored.

3.1.2.1 LiDAR DEM

This was the highest resolution DEM available for the area, having cells of 5m x 5m and a vertical resolution of 1m. The DEM included much of the marine area of Clew Bay, but the inclusion of land was restricted, with patches of NoData (Figure 10). However, sizeable swathes of the southern and eastern coastal area were covered which would provide adequate basis for the overlay studies. Using the Fledermaus viewer it was possible to exaggerate the vertical axis of the data so that the topography patterns were more apparent to the naked eye (Figure 10). In Figure 10 areas of No Data are shown in black, showing some of the smaller islands in the south of the bay with their tops having NoData, in addition to a large part of the land mass to the east. Depth/elevation ranges were from -30m to +53m. All data in the project were referenced to the ING.

The data were collected on 22 and 23 June 2002 using a LADS Mk11 Aircraft, with GPS base stations set up in the centre of Dublin and at Dublin airport (approximately 280km distant). Mainline sounding was conducted using 5m x 5m laser spot spacing which has a swath width of 240m. In general lines were flown at a line spacing of 100m which provided a planned 200% coverage of the survey area. The exceptions to this were the three southern-most lines, which were flown at the end of the survey to extend the survey area to the south. These lines were flown at 200m line spacing, thus providing only 100% coverage in this area. Due to cloud and rainy weather the survey was conducted at the lowest flight height possible for the aircraft, 366m, and was interrupted whenever the cloud dropped below this height. The survey revealed a possible error of 18m in the supplied coordinates for the position of Slyne Head lighthouse. On analysis, the data were shown to have an accuracy rating of 4.1m horizontally and 0.53m vertically, which are both IHO-Order 1 accuracies. For more technical information see (Tenix -LADS Corporation, 2002).

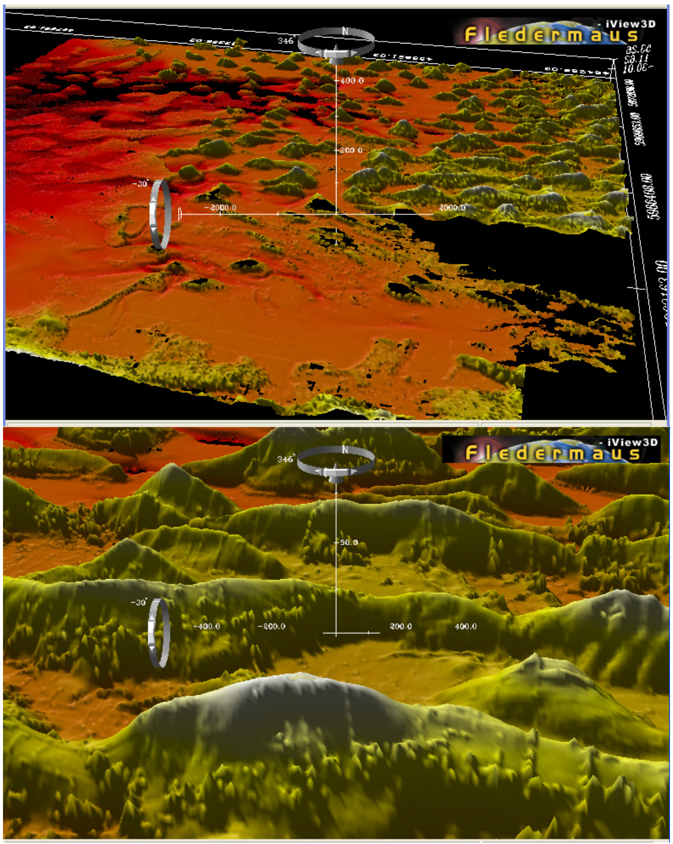


Figure 10. Image of Clew Bay area from airborne LiDAR data viewed through Fledermaus (above) and (below) a close-up of part of the image, in which lines of bumps representing field boundaries are visible.

An issue with using a DEM that has not been corrected to take into account surface features is that the model records the heights of dense vegetation and buildings, not necessarily the ground surface in all areas (Wilson & Gallant, 2000). This is apparent in Figure 10, where field boundaries can be clearly seen. These represent dense hedgerows and in some cases, walls. In late June (when the data were gathered), most deciduous trees would have been in leaf and many herbs and grasses at maturity. Ideally, a digital *surface* model would have been better for the purposes of this project, but that was not available. In this case, interpretation of results should take into account the nature of the DEM.

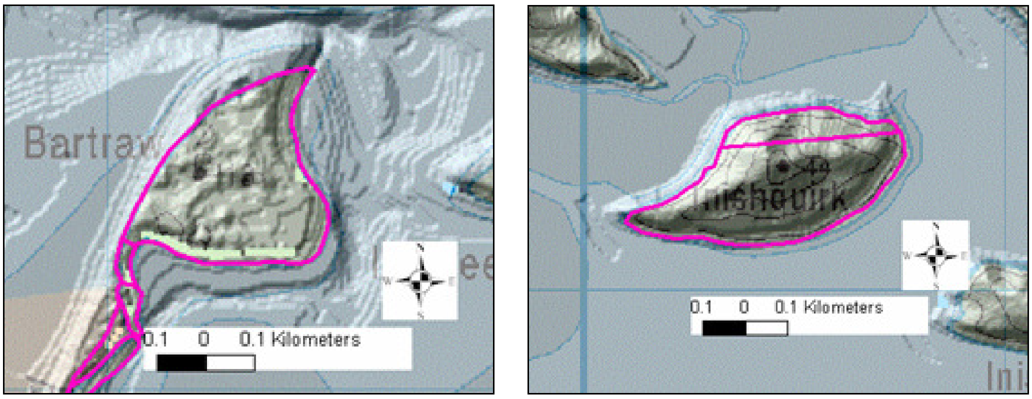


Figure 11. Hillshaded view of the DEM showing Bertra head (Bartraw, left) and Inishquirk (right), overlaid on OS Discovery Series map, with the Commonage Habitats (pink lines). The offset between the DEM and the other datasets is apparent.

Figure 12. Inconsistencies of OS Discovery Series with Orthophotos – see Murrisk pier, clearly visible on the orthophoto. The blue pier below it is the OS Discovery Series location for the pier. However, roads in the area line up well.

The DEM was overlaid on the OS Discovery Series maps and checked for georeference accuracy. It was found not to match the OS maps well, and similar results were found when comparing it to the Commonage Habitats data (Figure 11, an offset at Bertra Head and Inishquirk of about 60m to the north east). One of the reasons for the difficulties was inconsistencies between 6” maps, orthophotos and the OS Discovery Series (see Figure 12 and Figure 13). The OS Discovery Series, however, matched well with the Commonage Habitats dataset (see Figure 14), one of the datasets to be used for the overlay analyses (Section 3.1.3.3).

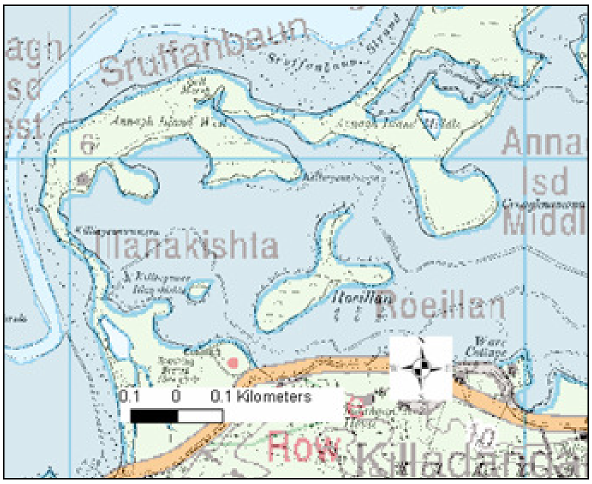


Figure 13. Area around Annagh Island showing small differences in coastal alignment of the 6inch maps (fine black lines) and the Discovery Series map (blue lines).

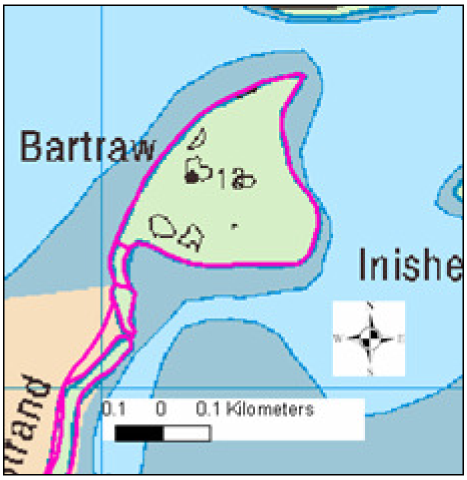


Figure 14. OS Discovery Series map of Bertra (Bartraw) area with the Commonage Habitats file overlaid (pink lines). This shows that the outlines of the habitats and the land forms in the OS map matched well.

ERDAS Imagine was used to rectify the DEM so that it was a better match to the OS Discovery Series maps. During this process different contrast stretches were applied to the DEM to get best locational accuracy for chosen reference points. A good agreement between the LiDAR DEM and the maps and photos was achieved (Figure 15 and Figure 16). Area statistics for the DEM were extracted by exporting the attribute file to a .dbf table. Areas were calculated from the “count” field using Excel.

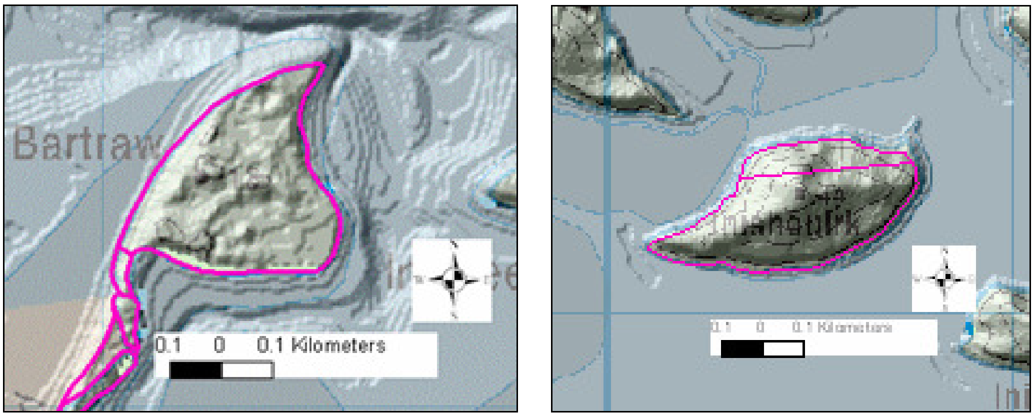


Figure 15. Detail of Bertra and Inishquirk as in Figure 11, but with the rectified DEM showing better agreement with the OS map and the Commonage Habitats file (pink lines).

Figure 16. Orhophoto of area near Old Head Pier (left) and the same photo draped over a hillshade of the rectified DEM (right), showing good agreement in geolocation between the datasets. The draped image appears with 3-D effects. NoData areas in the DEM appear white in both.

3.1.2.2 SAR DEM.

A DEM derived from SAR imagery was downloaded from Landmap. The DEM was produced by University College London and the Mimas data centre (University of Manchester) using interferometric techniques on the ERS 1 & ERS 2 data held in the Landmap Data Archive at a 25m resolution (Landmap, 2009). In general, SAR Interferometry processing requires an image registration step, interferogram formation, removal of systematic fringe trends, calculation of the interferometric coherence, adaptive filtering, phase unwrapping, generation of height model, and geocoding.

Serious anomalies were discovered in the dataset, concentrated around the borders of sea and land, and particularly affecting islands. These errors gave rise to coastal areas and islands being replicated and offset to the south west (Figure 17). In addition there was also an offset of the DEM from the OS Discovery Series map that would have to be geometrically corrected. Landmap indicated that there would not be a better DEM of this area available in time for use in the current project.

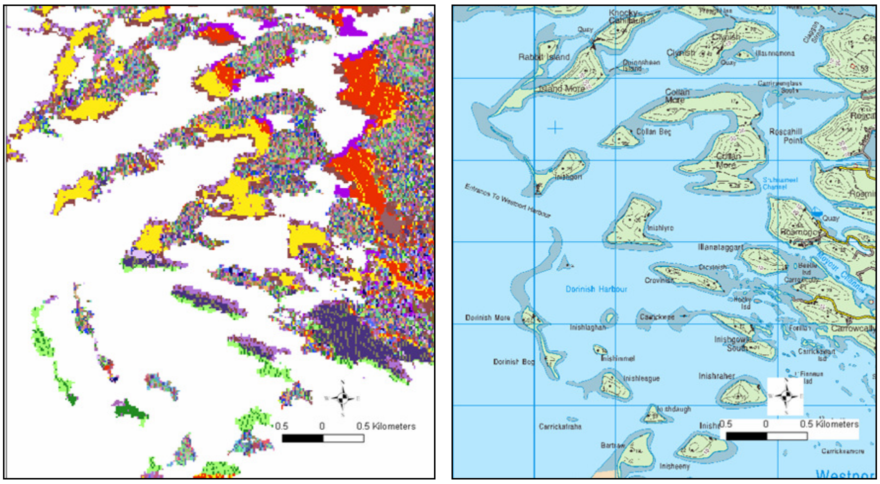


Figure 17. SAR DEM from Landmap (left) set to random colours, and the OS Discovery Series map of the same area (right). Problem with "shadows" of landforms at coast and the islands is apparent in the DEM. "Shadows" appear here as large areas of uniform colour, mainly yellow, red, two greens and very dark blue, to the south west of the landforms. White is NoData, mainly over sea.

The advantages of having the holes in the LiDAR data filled in by another DEM was considered to be important enough overlay the SAR DEM on the LiDAR to see how many of the holes would coincide with the erroneous SAR data. After rectifying the SAR DEM to the ING, the SAR and LiDAR data were merged to produce one DEM , and this was assessed for accuracy by comparing the patched section to OS map data. Too many inconsistencies were found and further use of the SAR DEM was abandoned. The use of SRTM (Shuttle Radar Topographic Mission) data was investigated also, but this was far too coarse and limited in extent for patching the LiDAR data (Figure 18) (Earth Resources Observation and Science Center, 2009). The maintenance of accuracy above providing a more complete cover of the Clew Bay area was prioritised in this study, so the LiDAR DEM was finally used on its own.

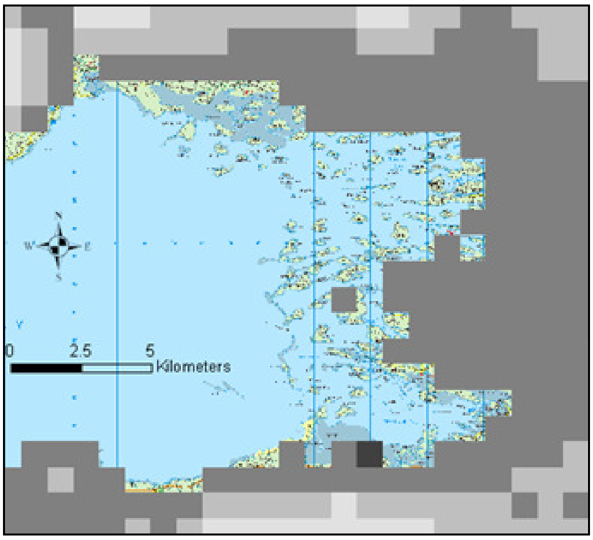


Figure 18. SRTM DEM extent (in greyscale) overlaid on the OS Discovery Series map of the Clew Bay area. The 75m cell resolution is very coarse, and many areas around the coast, including islands, are not covered.

3.1.3 Land cover and habitats datasets and ancillary information.

Available habitats or land cover datasets for the project were those that (a) provided unbroken spatial coverage of the study area or (b) only focused on specific community types or land categories. The CORINE 2000 dataset (3.1.3.1) and the Teagasc Habitat Indicator dataset (3.1.3.2) were the two available that had unbroken coverage of the area. Both had their roots in Landsat imagery, with information to aid the classifications coming from various sources, including aerial photography and (in the case of the Teagasc map) ground-truthing. The minimum mapping unit for the CORINE map was 25ha: coarse resolution in comparison to the Teagasc dataset, for which the resolution was 1ha. Datasets that gave habitat spatial extent for specific land categories or habitats were the Potential National Salt Marsh and the Commonage Habitats (3.1.3.3), and these were more detailed than the former two. Unfortunately a map showing habitats at the scale of the Commonage data was not available for the whole study area. After extracting the information from the existing datasets an attempt was made to make a more detailed habitat map that would encompass the study area (Section 3.1.4). Some datasets that did not show spatial extent of community but recorded point occurrences were also referred to (3.1.3.4). Names of habitats in the datsets are italicised and capitalised in this report to differentiate them from habitat names used more loosely (e.g. *Unimproved grassland* or grassland).

3.1.3.1 CORINE 2000

The CORINE 2000 land cover dataset was available through the Environmental Protection Agency (Ireland). It was made from an analysis using Landsat TM and ETM+. The minimum mapping unit was 25ha. There were 33 land cover classes mapped for Ireland at Level 3 of the CORINE land cover classes agreed for Europe (ERA-Maptec, 2004; EEA, 2000)(see Appendix 1), but only 13 were represented in the Clew bay study area (Figure 19).

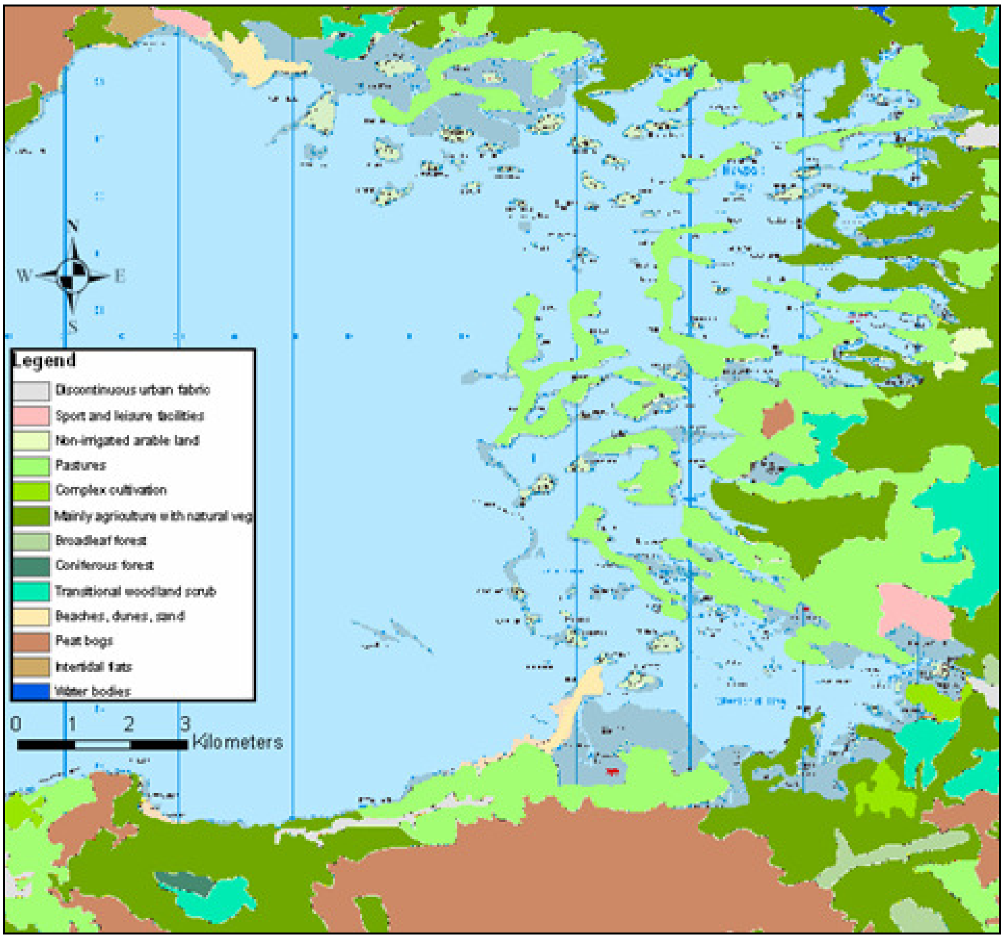


Figure 19. CORINE 2000 land cover data for the Clew Bay area.

The CORINE 2006 data were released in late August 2009, too late for inclusion in the analyses for this project, but an examination of the 2000-2006 change data showed no change in the land cover within the study area (Figure 20). The five change polygons closest to the study area were examined to see the nature of the changes in land cover. The areas were compared to the appearance of the land in the aerial orthophotos.

In order to make the 2000-2006 change dataset, the CORINE team had carried out some updating to the original 2000 data before making the comparisons. An examination of the 2006 data for the current project showed that the *Intertidal flats* category had been corrected to be more inclusive of the large expanse covered by these in the Clew Bay area. The differences in extent of these in the original 2000 data and the 2006 data are shown for the northern part of Clew Bay in Figure 21. A similar situation pertains in the southern part of the bay.

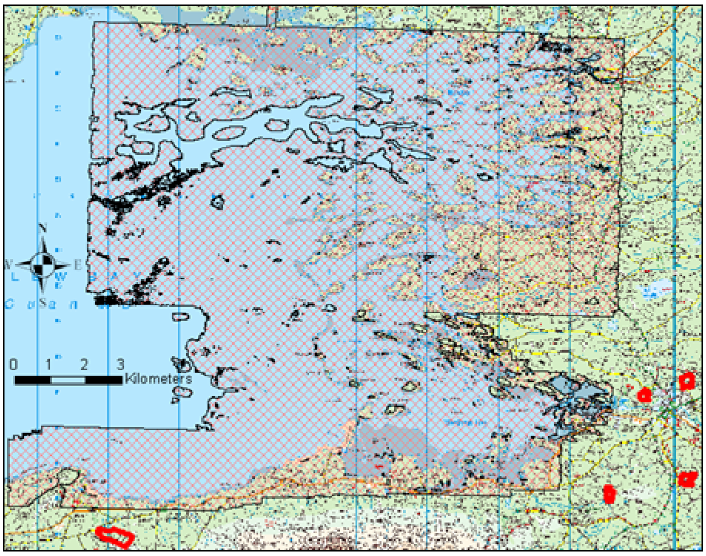
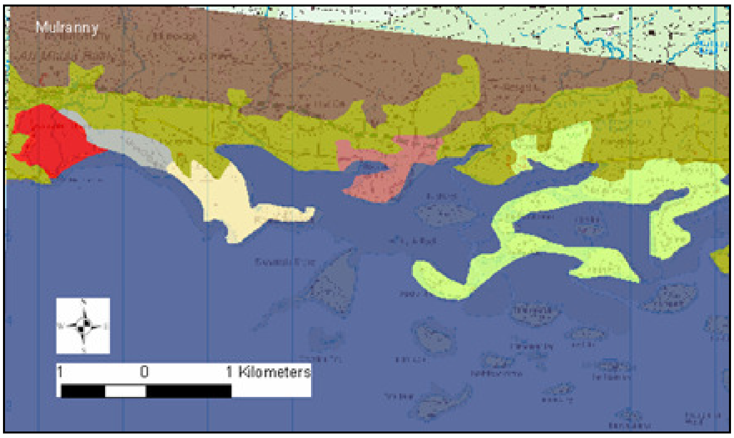


Figure 20. CORINE land cover change parcels (2000 – 2006) in red, overlaid on OS Discovery Series map showing study area (crosshatch). There were no red parcels overlapping the study area, but five nearby.

Further scrutiny of Figure 21 showed that the *Intertidal flats* class actually included a few islands (seen through the red in the Figure) that were not intertidal. A preliminary examination of the area figures (see Section 3.2.2) for *Intertidal flats* recorded significant cover of these above the intertidal range (Table 1). For this reason, the *Intertidal flats* figures were not pursued further in this analysis, however it is acknowledged that they do cover a very significant area of coastal Clew Bay: see analysis of Classified Image data (Section 4.3.4).



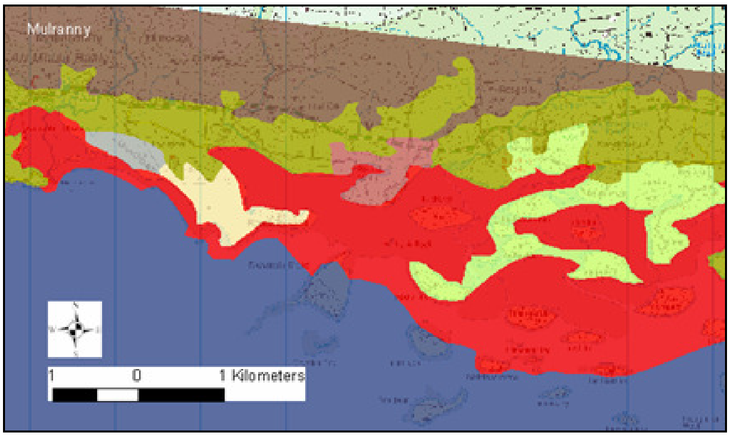


Figure 21. Northern shores of Clew Bay east of Mulranny, showing extent of *Intertidal flats* (423) class, in bright red, in the CORINE 2000 (above) and CORINE 2006 (below) datasets. The OS Discovery Series is in the background.

Table 1. Some area figures from Corine 2006 for *Intertidal flats* that were discarded after finding that they included areas of islands outside of intertidal elevation range.

Elevation (m)	Area (ha)
0	1664
1	746
2	253
3	130
4	102
5	78
6	64

3.1.3.2 Teagasc Habitat Indicator dataset

Teagasc made a land cover map from Landsat 5 TM imagery (1995) using supervised classification methodology (Fealy 2004). Training points were obtained from black and white 1:40,000 aerial orthophotos (also 1995) and some field exercises. The orthophotos were also used for pseudo-ground-truthing. Minimum mapping unit was 5ha. This resulted in a 13-class dataset (see Table 2).

Table 2. Thirteen land cover classes in the Teagasc land cover dataset.

LAND COVER CLASS
Bog & Heath
Cut & Eroding Bog
Cut Bog
Dry Grassland
Wet Grassland
Water
Mature Forest
Forest(U) & Scrub
Bare Rock
Rocky Complex
Built Land
Sand
Coastal Complex

This product was used in a project to produce a Habitat Indicator map, in which some of the broad categories were subdivided. The map was essentially an enhancement of the land cover map by increasing the classification and spatial resolution of many of the land cover thematic classes occurring over peat, namely; *Bog & Heath*, *Cut Bog*, *Cut & Eroding Bog*, *Wet Grassland* and *Dry Grassland*. These land cover classes were indicative of habitat type in a very broad sense only in that they represented combinations of more detailed habitat classes (Loftus *et al* 2000).

The core element of the habitat indicator mapping methodology was the design and execution of an expert rule base through a spatial modeller. This incorporated information from the Land Cover map, a Subsoil map, DEM derivatives and a peatland map (Fealy, 2004; Hammond, 1978). The expert rule base was a series of conditions which dictated the mapping of particular habitat indicator classes. For example in indicating the likely presence of lowland blanket bog as a thematic class the expert rule base demanded the following conditions; *Bog & Heath* as a thematic class from the land cover thematic map; *Peat* from the parent Subsoil thematic map; elevation less than 150m from the DEM; and location west of a line defined in the Ireland Peatland Map to mark the eastern limit of *Lowland blanket bog*. (Hammond 1978). There were over 160 conditions defined to model the Habitat Indicator map. Fourteen new habitat indicator classes were modelled from five land cover classes (see Table 3), and minimum mapping unit was 1ha. The map for the Clew Bay area is shown in Figure 22.

Table 3. Habitat indicator classes used in the Teagasc map, shown here with codes (left) and the corresponding habitat codes from Fossitt (2000).

CODE	HABITAT INDICATOR CLASS	CODE (Fossitt 2000)
GSW	*Wet Grassland*	GA1, GA2, GS4
GAGS	*Dry Grassland*	GA1, GA2, GS1-3, BC1-4
FM	*Water*	FL1-8, CW1-2
ER	*Bare Rock*	ER1-4, CS1-3
CR	*Rocky Complex*	ER1-4, HH1-HH4, HD1
WNWD	*Mature Forest*	WN1-7, WD1-4
WSWL	*Forest (unclosed canopy) & Scrub*	WS1-5
BL	*Built Land*	BL3, GA2
CD	*Sand*	CD1-3
C	*Coastal Complex*	CD1-3, L
F	*Fen*	PF1-3
FC	*Cutover Fen*	PB4
FR	*Reclaimed Fen*	PB4
RBF	*Raised Bog / Fen*	PB1 PF1-3
RBFC	*Cutover Raised Bog / Fen*	PB4
RBFR	*Reclaimed Raised Bog / Fen*	PB4
UBB	*Upland Blanket Bog*	PB2
UBBC	*Cutover Upland Blanket Bog*	PB4
UBBCE	*Cutover / Eroding Upland Blanket Bog*	PB4, PB5
UBBR	*Reclaimed Upland Blanket Bog*	PB4
LBB	*Lowland Blanket Bog*	PB3
LBBC	*Cutover Lowland Blanket Bog*	PB4
LBBCE	*Cutover / Eroding Lowland Blanket Bog*	PB4, PB5
LBBR	*Reclaimed Lowland Blanket Bog*	PB4
H	*Heath*	HH1-HH4, HD1
W	*Wetland*	GS4, GM1, PF1-3, FS1-FS2
CM	*Salt Marsh*	CM1-2

3.1.3.3 Commonage Habitats dataset.

Commonage areas were surveyed in 2007 under a scheme to assess the impact of grazing (Anon, 2001). Field surveys were carried out and the land cover classified according to a set scheme (Table 4). As many of the areas were a mosaic of two or more different defined habitat categories the map had polygons that were assigned mixed classes (e.g. IX/XI, II/VII). Figure 23 shows the cover of the polygons in this dataset within the frame of the study area of Clew Bay formed by the LiDAR DEM (Figure 2).

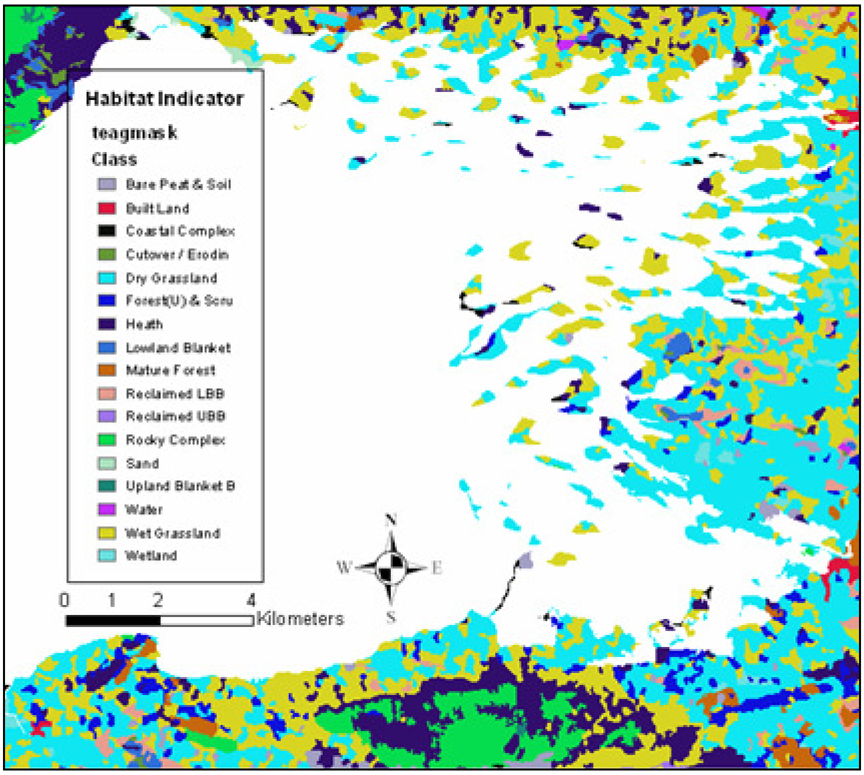


Figure 22. Teagasc Habitat Indicator dataset of the Clew Bay area.

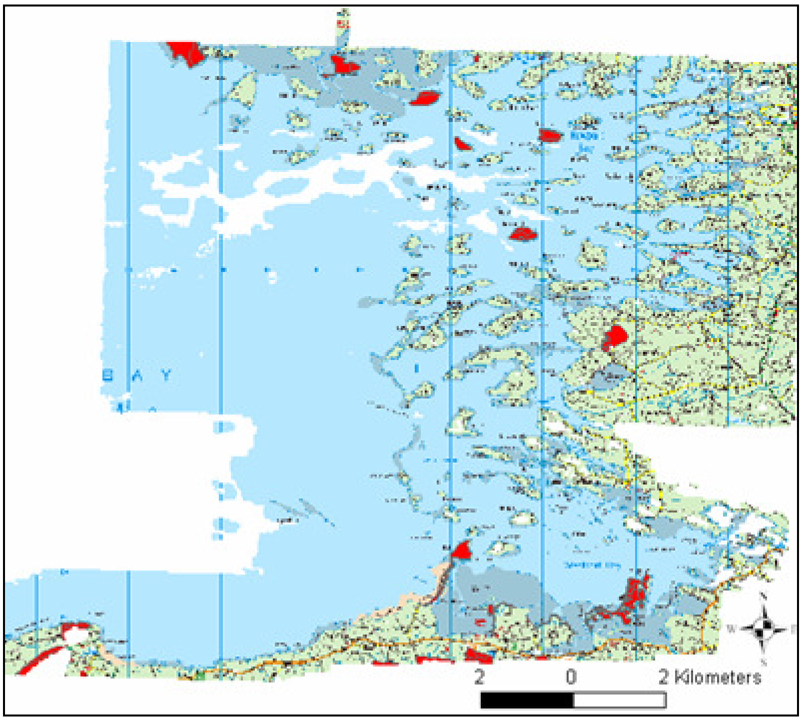


Figure 23. Commonage areas surveyed (in red) overlaid on the OS Discovery Series map, clipped to the extent of the LiDAR DEM (see text).

Table 4. Commonage Habitat classification and symbols used.

Blanket Bog	I
Wet Heath	II
Dry Heath (includes maritime)	III
Upland Grassland	IV
Other habitats	V
Improved Grassland	VI
Dune	VII
Unimproved wet grassland	VIII
Unimproved dry grassland	IX
Fen/Marsh/Swamp	X
Saltmarsh	XI
Beach/Shingle/Reef/Shore	XII
Limestone pavement/Grassland	XIII
Limestone pavement(>75% rock)	XIV
Scrub	XV
Permanent open water (turlough)	XVI

Using ArcMap, the Commonage Habitats dataset was converted to raster and masked to the extent of the study area. Original habitat codes were automatically changed through this process to a set of 20 numbers ranging from 1 to 67. Extra classes were formed from combinations of two or more of the original classes (see Section 4.3.3). These were related back to the original codes by using the identify tool and the original vector coverage to produce a relational table. The attribute table of the raster file was exported and a Habitat field inserted, and populated with the original habitat codes using the relational table. The resulting table was joined onto the raster to produce a masked raster file that had the original codes.

3.1.3.4 Ancillary information.

The land cover/habitats datasets described above were the main existing datasets used for the overlay analyses. Other spatial datasets supplied by NPWS and used during the project are listed in Table 5. Files were available as polygons or points. Files specifically targeting Habitats Directive habitats were all only available as point files except for those delineating water bodies.

3.1.4 Satellite imagery and land cover

The datasets described in previous sections were not ideal for this study either because of their limited spatial extent or the lack of detail in their habitat/land cover classification. A new habitat dataset was made for the project with a classification that was more detailed than the CORINE or Teagasc datasets, and that had a more complete coverage than the Commonage Habitats dataset (see Section 3.1.3).

Table 5. Shapefiles supplied by NPWS and/or Mayo County Council used as ancillary information for the project.

Filename	Point or polygon
1210_1220_Moore&Wilson1999_Bleasdale_etal_1996_SI.shp	Point
3110_3130_lwseg_0207_SI.shp	Polygon
3140_lwseg_0207_SI.Shp	Polygon
3180_records_2007_SI.shp	Point
Commonage subunits_Dec07_SI.shp	Polygon
Dunes_Tim_Ryle_SI.shp	Polygon
Native_woodland_releves_SI.shp	Point
Native_woodland_SI.shp	Polygon
Npws_7140_records_2006_SI.shp	Point
Npws_7210_records_2006_SI.shp	Point
Npws_7230_records_2006_SI.shp	Point
Potential_national_saltmarsh_2007_SI.shp	Polygon
Saltmarsh_quad_Wymer_1984_SI.shp	Point
Saltmarshes_Curtis_Sheehy_Skeffington_1998_SI.shp	Point
Smhab1.shp	Polygon

3.1.4.1 Satellite data

A search was carried out for satellite data that would be available for free to the project. Two recent Landsat ETM+ images were available for the area from the USGS through the Global Visualisation Viewer (USGS, 2009b). These had low cloud cover and were from late May 2008 and early June 2007, ideal for the project. Unfortunately these had bad striping that would have required patching from other images (ERDAS, pers. comm. 2009), and they were abandoned.

The next option was to use an image from GLCF, which was older (2002) and also not from the main growing season, being from April: a disadvantage for land cover/vegetation analysis. On the positive side, this image was cloud-free and had no issues with banding. Co-incidentally it was also from the same year as the LiDAR DEM used for this study. In the absence of any other option this was downloaded.

In order to focus on the study area, a subset of the Clew Bay area of the image was created using an AOI (Area Of Interest) in ERDAS Imagine, first for the Bands 1-7 which had a resolution of approximately 30m, and subsequently for Band 8 which had a resolution of 15m, using the same AOI. These two files, one containing the multispectral Bands 1-7 and the other Band 8 were then merged to provide a multispectral product with a 15m resolution. This was then clipped to the shape of the LiDAR DEM, which defined the study area.

The merged image was overlaid on the OS Discovery Series maps and commonage habitats data to check for geometric accuracy. A number of areas throughout the study area were checked, and difficulties with correlation were found (Figure 24). The image was rectified with ERDAS Imagine, as for the LiDAR DEM (Section 3.1.2.1), and Figure 24 shows the achievement of better agreement with the commonage habitats file.

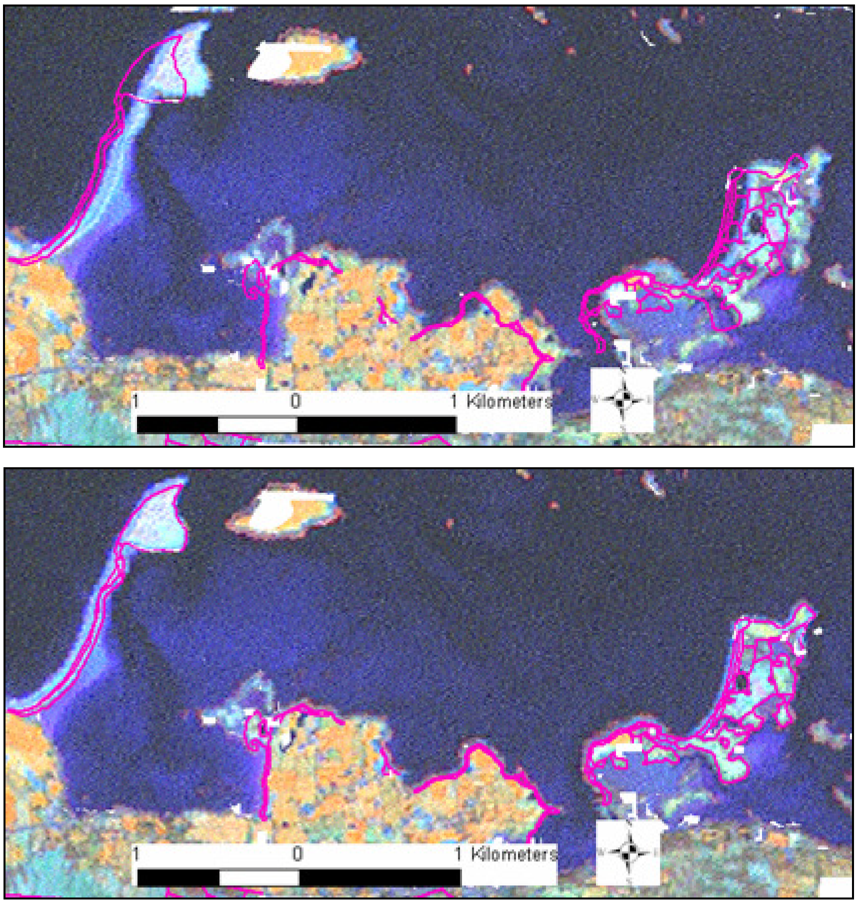


Figure 24. Landsat image and commonage habitats data for the area of Bertra and Annagh Island showing lack of agreement between the image and the habitats data in the unrectified image (above) and good agreement following rectification(below). The tip of Bertra head was showing displacement of about 180m to the northeast, in relation to the Commonage Habitats data, which had been previously found to have a very good match with the OS Discovery Series (Figure 14).

3.1.4.2 Image classification.

The image was classified using a supervised classification. Training areas for signatures were derived from orthophotos, the Teagasc Habitat Indicator dataset, the Commonage Habitats map and targeted fieldwork. Most interpretation work was carried out with the image displayed in 453 (RGB). ERDAS and ArcView were used together so that orthophotos could be displayed conveniently beside the ERDAS view of the Landsat image on which training polygons were being drawn (Figure 25). The classified image product was checked against the unclassified image using Viewer Swipe.

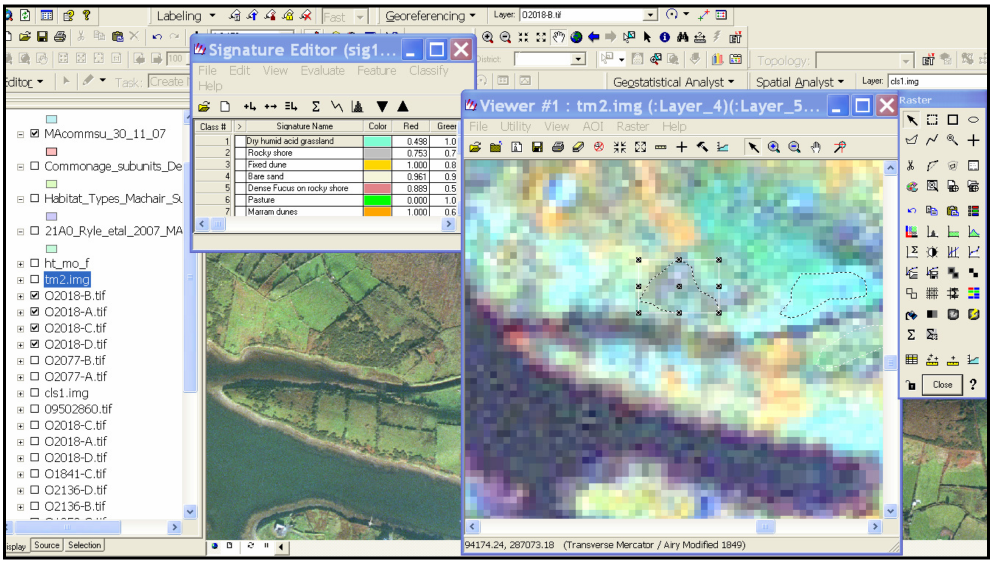


Figure 25. ArcView and ERDAS being used together to define the training polygons on the Landsat image while conveniently displaying the orthophotos.

Some targeted fieldwork was carried out to support the image classification work. Specifically, the areas of Bertra dunes (91,300, 284,400), Claggan swamp (94,600, 289,000) and Rosmindle wetlands (94,500, 287,600) were visited and an attempt was made to determine the habitats (Fossitt, 2000) in them by making some plant species lists and looking at the characteristics that would define the habitats. Photos were taken to illustrate areas determined to be of certain habitat types (see Appendix 3).

A number of attempts were made to classify the image. The signatures defined for the earlier attempts were too many, and were not specific enough for the narrow habitat defined, resulting in errors. In later attempts the land cover classes were broader but the signatures were found to be truer. However, it was very desirable to keep certain finer categories, particularly *Saltmarsh*, as it would be very much affected by sea level rise and was of particular conservation concern. *Saltmarsh* did not, however, have a specific enough signature to define it: pixels classified as *Saltmarsh* were found inland and at elevations higher than 6m. Saltmarsh is generally confined to elevations between approximately 3m and 5m (between mean high water neap tide and mean high water spring tide (Beeftink, 1977)). All saltmarshes in the Potential National Salt Marsh dataset for the Clew Bay area were found to be below 6m. Other classes that were specific to low coastal areas were *Sand/mud flats* and *Dense seaweed on rocks*.

One method of refining the classified image to reduce these errors was to carry out post-classification reclassifying exercises. These were attempted but abandoned as they were found to be inappropriate for the task. The image was subsequently divided into areas above 6m and areas between 0m and 6m, using the DEM and masking tools. Each part was then classified separately. After this the parts were mosaiced back together to make one image.

Subsequent refining of the image was carried out in three specific areas: Bertra head was converted to *Dune/dune grassland*, to agree with fieldwork ground-truthing and the Commonage Habitats map using the AOI method in ERDAS that converts all the pixels in a defined area to a particular class. The accuracy of classes at low elevations (between 1-6m) in the map was most important as these would be the first affected by sea level rise. On checking through the classified image using fieldwork, the Teagasc Habitats Indicator map, the Commonage Habitats map and orthophotos as references, good agreement was found in the Trawbaun low-lying area for *Dry and Wet grassland* and *Dense seaweed*, and in the Claggan swamp area for *Sand/mud*, *Water*, *Swamp*, *Heath*, *Broadleaf* and *Bog/fen/wet heath* classes. However, areas of *Saltmarsh* were found erroneously in the Claggan area. Similarly in the area from Rosmoney to Castleaffy there was good agreement with ground truthing, areas showing *Swamp* and *Bog/fen/wet heath* categories in the area of Rosmindle Bridge over Moyour river, *Dry heath* and *Bog/fen/wet heath* categories on Rosmoney and Rosmindle points, and *Sand/mud* and *Water* in Rosmoney lake and shore areas. *Wet* and *Dry grassland* and *Broadleaf* were also in appropriate places. However, some areas in Rosmindle were erroneously classified as *Saltmarsh*.

A method of reclassifying these to more appropriate classes guided by fieldwork, the aerial photos and the other datasets was devised that would be more appropriate than using the AOI in ERDAS which changes all pixels within the AOI to the new class, regardless of the original class. A polygon was drawn around the general area of Claggan that included the pixels classified as *Saltmarsh*. This was used to mask the area and clip it out. Using Reclass (ArcMap) the *Saltmarsh* pixels were converted to *Swamp* which was appropriate for that area (see Appendix 4 for model). The reclassified section of the image was then mosaiced back into the main image. A similar exercise was carried out for the Rosmindle area, but the pixels were reclassified to *Bog/fen/wet heath*, which was appropriate for that area.

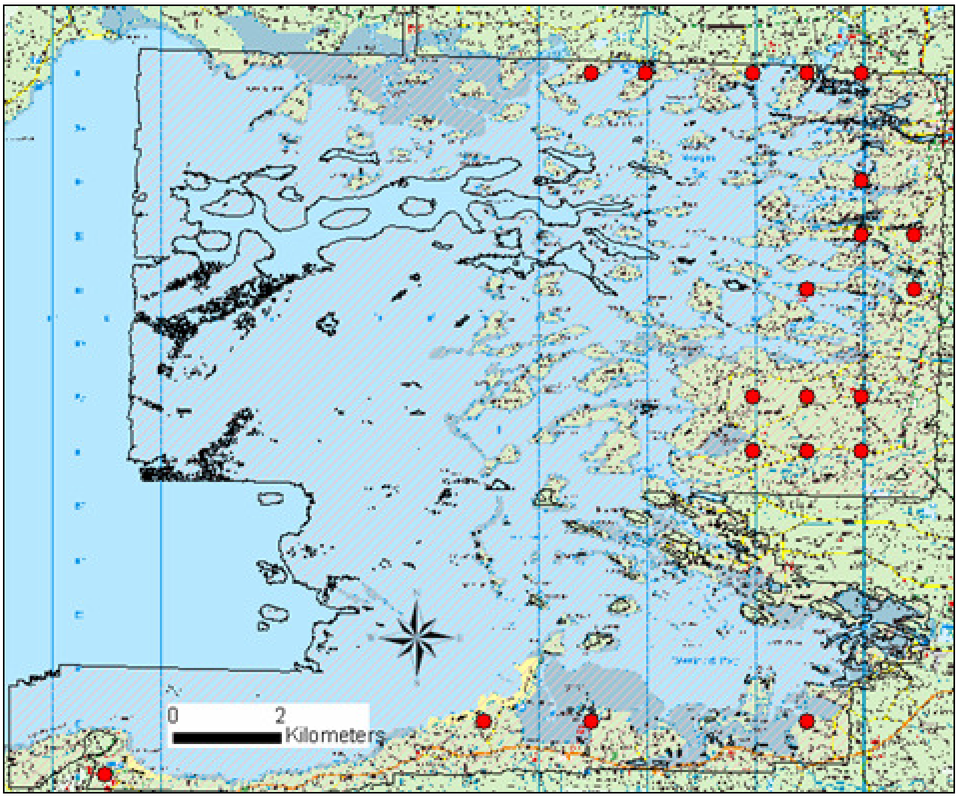


Figure 26. Map showing 20 accuracy assessment points (red) over OS Discovery Series with study area hatched.

A side-effect of using the DEM to cut out the study area from the main Landsat image was that the resulting files had smaller pixels than the original image: pixel size matched the DEM's 5m x 5m. Rather than try to automatically generalise these back to a 15m x 15m size, which could result in errors of MAUP (Openshaw, 1984), it was decided to leave these as they were. A visual assessment of the image showed up a lot of "salt and pepper" (Gibson & Power, 2000; Wheatley *et al.*, 2000). There are different filtering tools for reducing this: the one used here was Majority in ArcMap. The Majority filter was run first with number of neighbours set to 4; then the resulting file was again filtered with the setting at 8. Trial and error, and examination of the results, indicated that this combination produced the best results.

A comprehensive accuracy assessment of the classified image was beyond the scope of this project, but a basic objective assessment was carried out. Twenty points were chosen at OS Discovery Series grid-line junctions and checked for accuracy of classification with the Teagasc Habitat Inventory map, the Commonage Habitats map, the CORINE Land Cover map and orthophotos (Figure 26).

3.2 ANALYSES.

There were two parts to the modelling analyses. Firstly it was important to give a visual impression of the effect of sea level rise on the Clew Bay area, which involved creating overlays of the sea on the OS Discovery Series and some of the classified image. Secondly an extraction of statistics was necessary to show, for each land cover file, the amount of each land cover/habitat class that would be lost with rises in sea levels.

3.2.1 Visual impression of sea level rise.

DEM file was displayed over the OS Discovery Series map with the DEM's "NoData" set to display as white and progressively higher flooding levels showed by changing the symbology of the DEM layer.

3.2.2 Extraction of statistics.

Statistics of land cover loss to sea level rise were collected in a similar manner for the following datasets:

- CORINE 2000
- Teagasc Habitat Indicator
- Commonage habitats
- Classified image

Overlay files of a series of flood elevations were made from the LiDAR DEM by using ArcMap Extract by Attributes, and setting the Value to different elevations, e.g. Value >=0 produced a file with all elevations of zero and above, and all elevations less than zero converted to NoData. These files were made for elevations 0,1,2,3,4,5,6,7,8,9,10,15 and 20m (the "Extract files").

These files were to be used with the land cover datasets to extract habitat flooding information in the following way: The Extract by Mask tool of ArcMap was used with a land cover dataset and Extract file. The result was a dataset that included only the land covers that were above the elevation in the Extract file. The attribute table was exported to a .dbf file and used in Excel to create tables of the number of pixels of each land cover type still present under each flooding regime (Extract file). The number of pixels was processed to converted to hectares. Tables and graphs were produced to show how the amount of each land cover in the study area changed with level of flooding.

4 RESULTS

The results of the study are presented by firstly giving visual impression of the extent of flooding expected with incremental sea level rise, and then statistics indicating how much of the land, and each land cover type/habitat is lost by each water level increase.

4.1 TOPOGRAPHY AND TIDES IN THE STUDY AREA

Elevation ranged from -29 to +53m, distributed as shown in Figure 27. Sizeable areas of land below 5m were located inland. The low areas of Claggan, Rosmindle, Rossow River and Annagh Island areas were particularly sizeable, and much of the Carrowholly area was under 5 or 10m. The slope map shows a good proportion of the area below 5°, many low-lying areas being river valleys. The islands, particularly in the northern part of the bay, were hilly and did not have extensive areas of low-lying land.

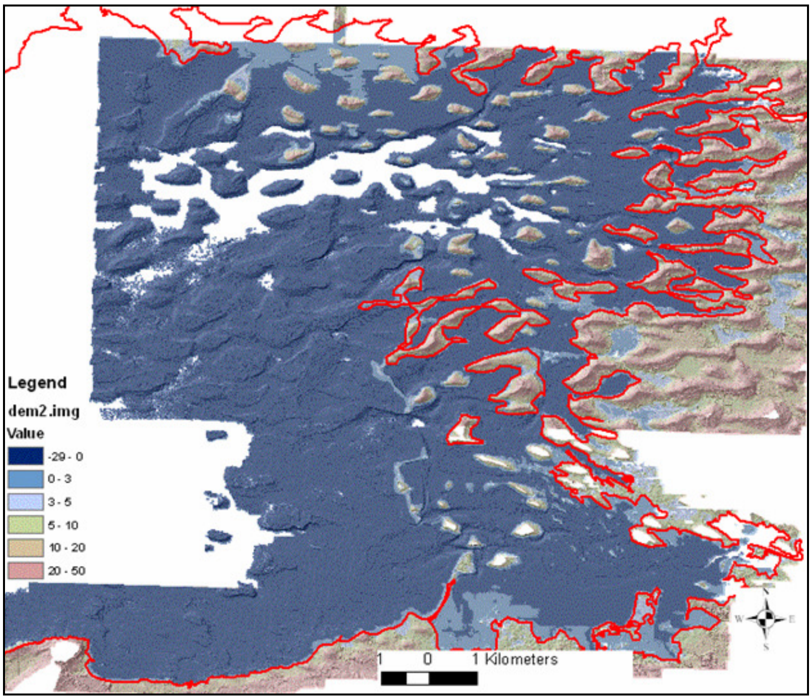


Figure 27. Elevation map of study area (m) draped over hillshade, with shoreline in red. Note that the shoreline file was very low resolution and omitted many areas.

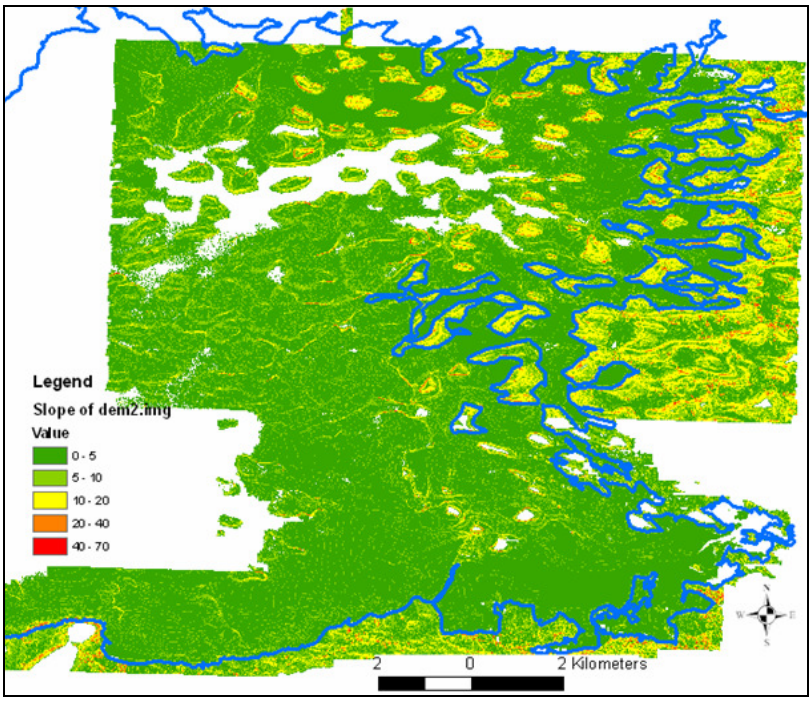


Figure 28. Slope (degrees) of land in the study area, shoreline file as in Figure 27, in blue.

Currently the greatest amplitude of tide levels is five metres, with 0m and 5m OD (Ordnance Datum) being the lowest and highest levels reached during a once-annually extreme "spring" tide. More frequent spring tides (twice per month) reach levels of 4.5-4.7m OD. The minimum amplitude at extreme neap tide is one metre, with 2 and 3m OD being the lowest and highest tide levels reached. OS maps generally show the coast as being at the average high tide: about 4m OD in the Clew Bay area (tide data from Proudman Oceanic Laboratory). The results presented below should be viewed bearing in mind that the current extreme high tide is 5m OD and that there are barriers to sea encroachment which prevent inundation by the sea in some low-lying areas (see Section 5).

4.2 VISUAL IMPRESSION OF FLOODING.

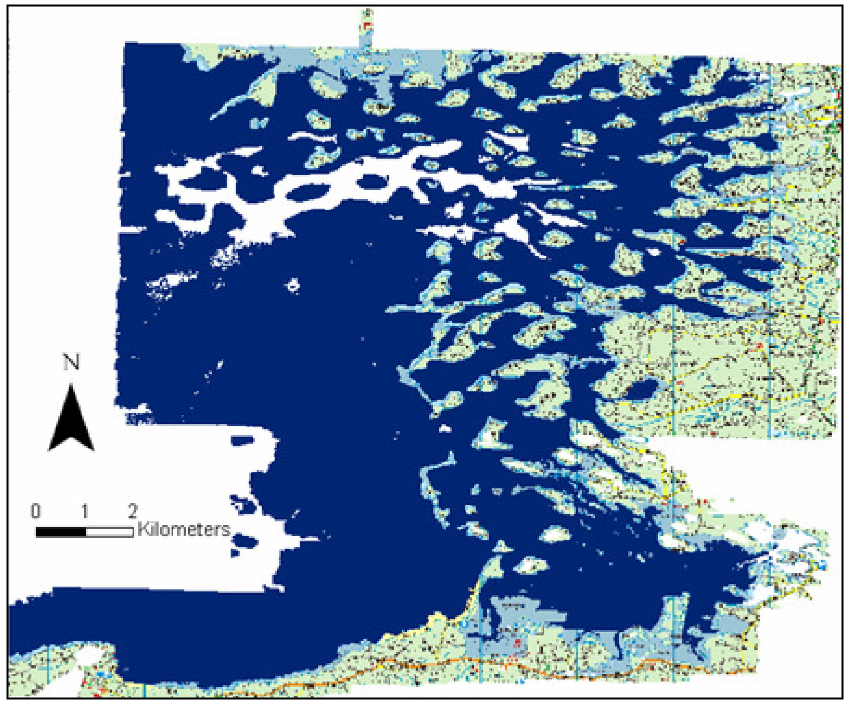
A comparison between DEM-based flood levels and the contour lines on the OS map indicated good agreement between these datasets. This was important for the credibility of the georectification and the accuracy of the DEM.

Loss of the land surface is shown in Figure 29 at incremental levels of sea rise, in 1m increments from 0-10m (0m being the level of extreme low tide). Flooding at 15m was also included. Increases by the year 2100 of over 1m are relatively unlikely but the forecasts are uncertain and levels will continue to rise after that (see Section 1.2.2). Additionally although the main sea level may not rise more than 1m, storm surge effects would raise sea levels locally for brief periods, enough to inundate larger areas. Another aspect to flooding by the sea is the possibility of tsunami (see Section 2.2). Referring to studies of past tsunamis, inundation of the land to 15m or more above the prevailing sea level should not be ruled out (although it is highly unlikely), and this would be exacerbated by higher sea levels due to climate change (Section 2.2). For this reason flooding levels of up to 20m were included in the analyses in Section 4.3.

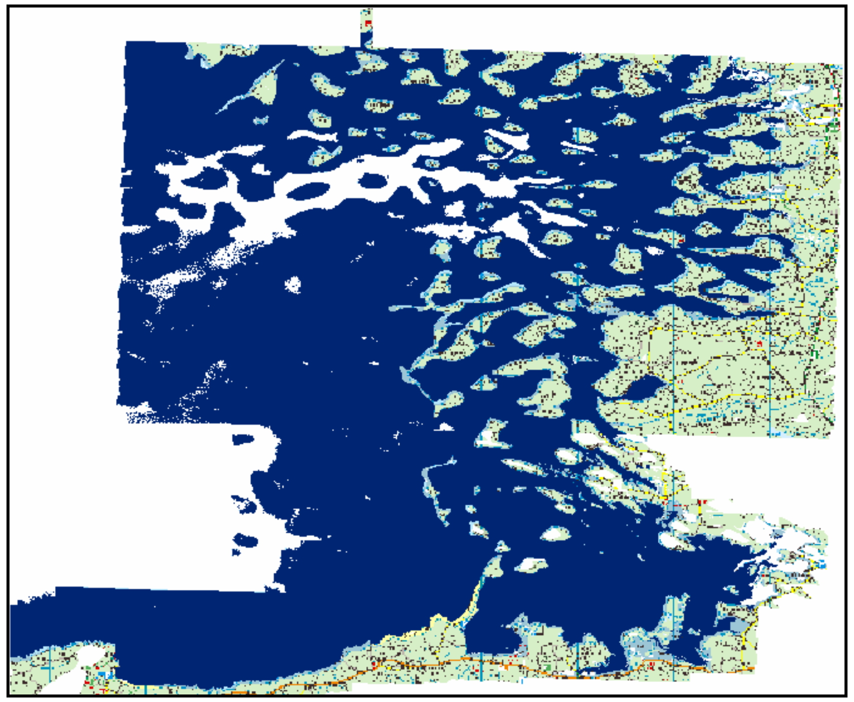
An examination of the flood maps shows that for level 0m OD much of the mud/sand flats in the OS Discovery Series map were exposed, and none of the land was shown to be flooded. At 1m OD most of these mud/sand flats had disappeared, but still none of the land was flooded. At 2m OD some mud/sand flats remained and still the main land areas appeared unflooded. A change appeared at the 3m OD flood level, showing many of the coastal connectivity of remaining mud/sand or possibly rocky shores now inundated, isolating islands from the mainland and other islands. Additionally some significant areas of water appeared inland, for example in the low-lying areas of Claggan and Rosmindle, and at Cravey lough (97,900, 293,350). By 4m OD Annagh Island and other areas containing marsh or saltmarsh had partly disappeared under water, and by 5m OD (the current highest elevation that sea regularly rises to yearly with tides, the more frequent highest tidal level is in the region of 4.7, which is achieved twice per month) very little of these places were still above water. Some smaller islands had disappeared and others were reduced in size.

At this point it is important to point out that apart from areas such as Annagh Island, which have no barriers to inundation, many of the areas that are shown as inundated do not actually flood. Barriers to sea encroachment are in place to prevent this. Annagh Island, however, is a natural area on which the natural communities have developed in harmony with the prevailing inundation regime. There is no human infrastructure that would either be damaged by the sea or that would prevent sea encroachment. In other places where barriers do exist it is useful to examine the extent to which sea can flood the land if the barriers were not there, even with the current tidal extents. Sandy beaches are an important feature of Clew Bay for tourism and recreation, with Bertra beach and Old Head beach being within the study area. There was a discrepancy between the OS Discovery Series map and the DEM in that low tides below 0m were not experienced even on a yearly basis, yet the strand area on the OS map extended quite significantly beyond the 0m line of the DEM (Figure 30). Flooding the map to the level of 5m (approximate level of twice monthly high tide) shows nearly total immersion. Much of these are currently covered by high tides (Figure 30), but with a rise in low tide of one or two metres (to 2 or 3m OD), the area of beach exposed even at low tide would be severely reduced (Figure 31).

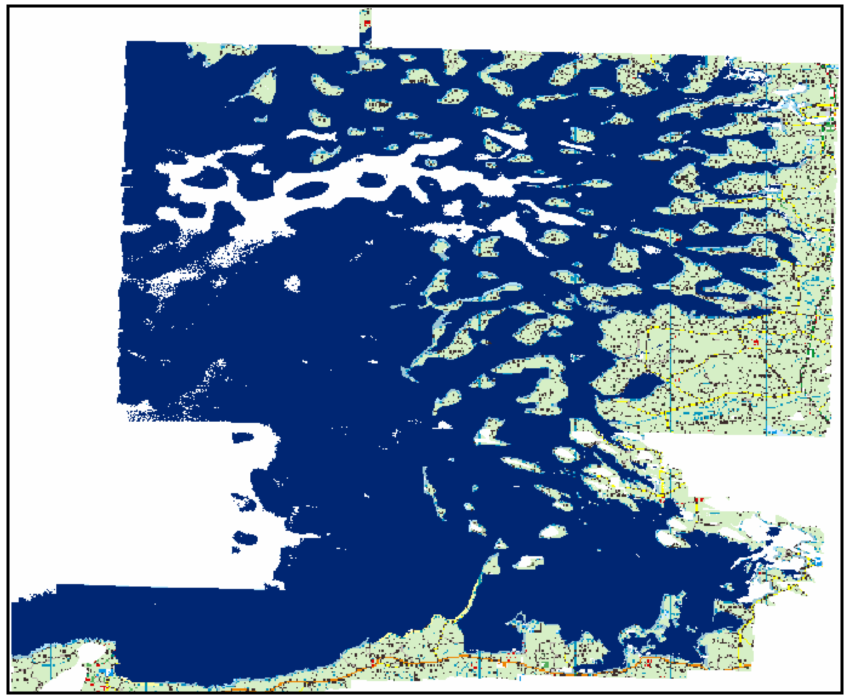
If sea level were to rise by 1m, the highest (annual) tide would be at 6m. At this level a significant part of Bertra spit was covered, Annagh Island was nearly totally under water, the Carrowkeeran peninsula was partly inundated, much of the low-lying areas to the east of the bay had disappeared, such as by Carrowcally, Carrowholly, Moyna, much of Rossmurrevagh and the Rossow river branches (Figure 29). Some



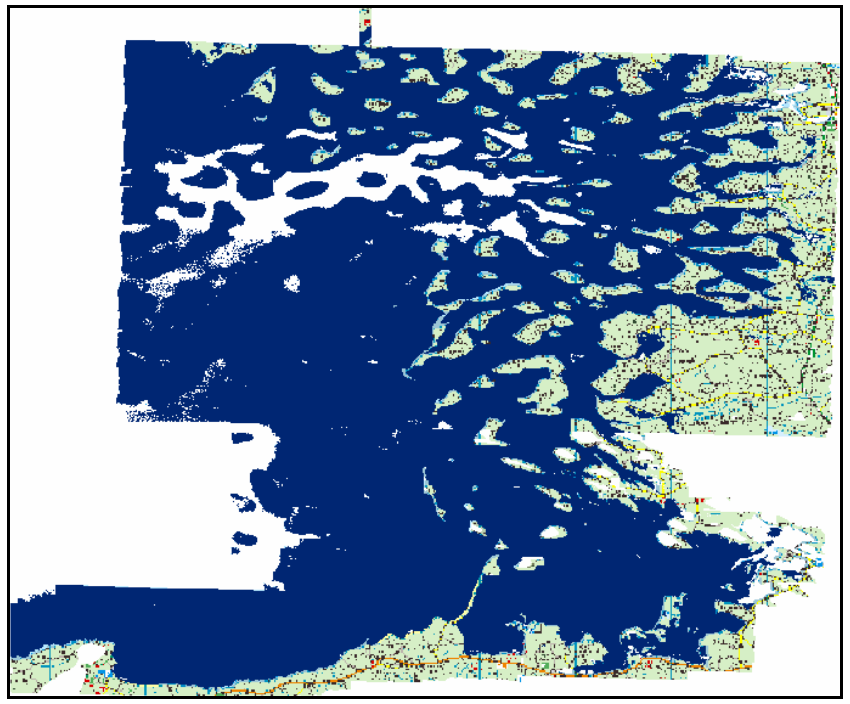
0 OD. Lowest “spring” tide level



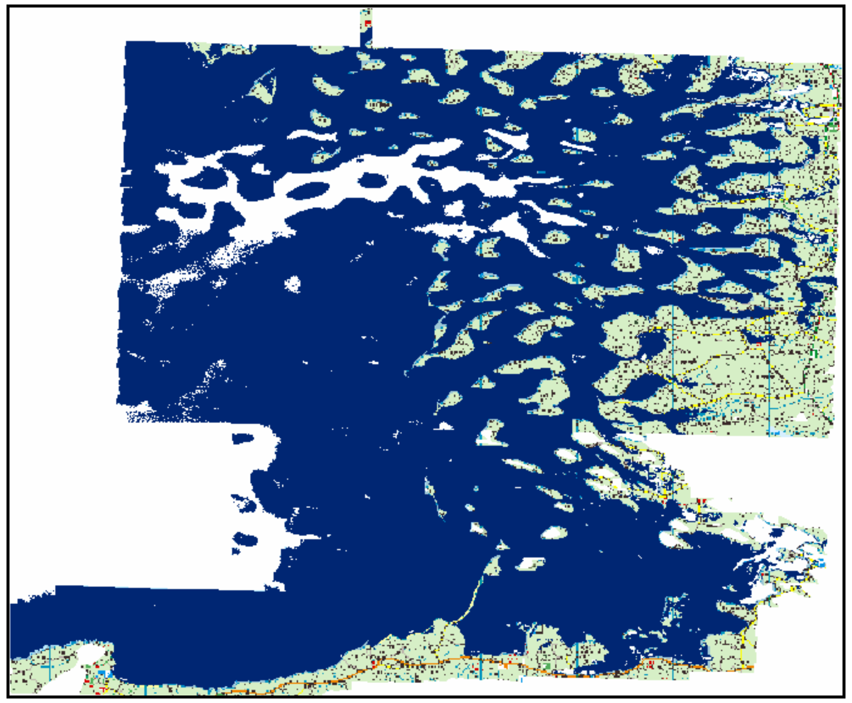
1m OD.



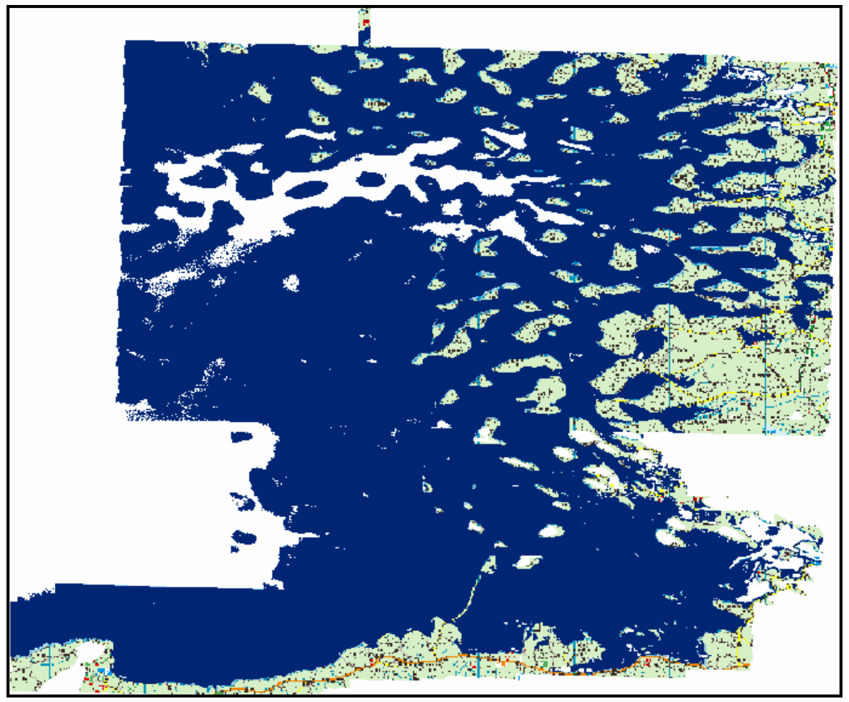
2m OD Lowest “neap” tide level.



3m OD. Highest “neap” tide level.

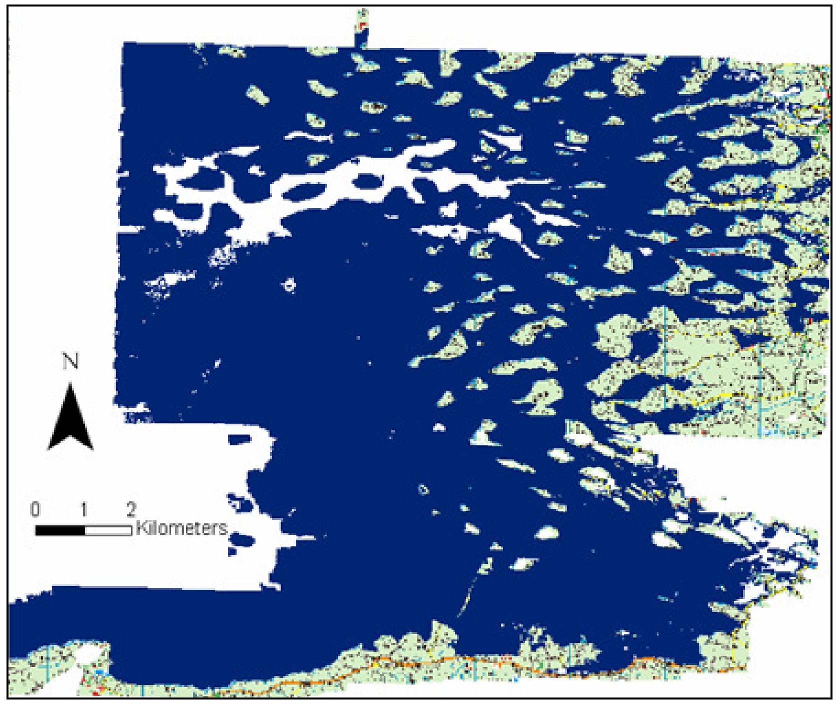


4m OD.

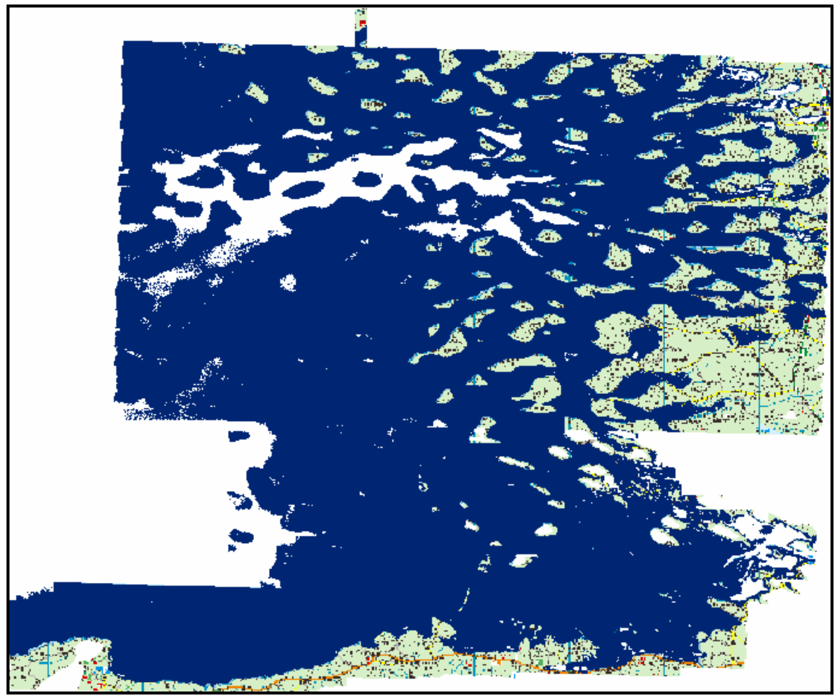


5m OD. Highest “spring” tide level.

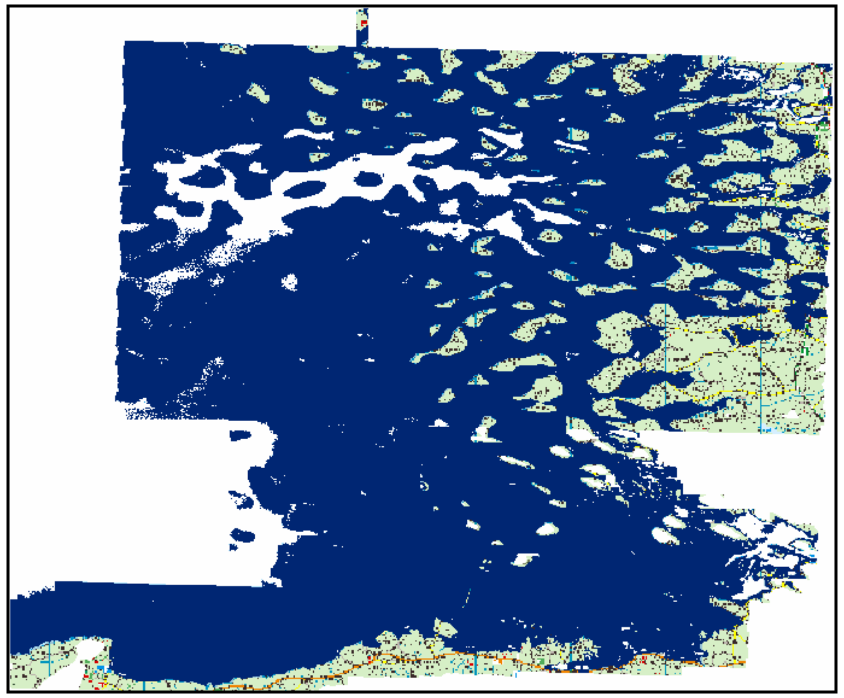
Figure 29. OS Discovery Series maps of study area flooded (dark blue) to levels from 0m to 5m OD. Part 1 of Figure, Part 2 on next page.



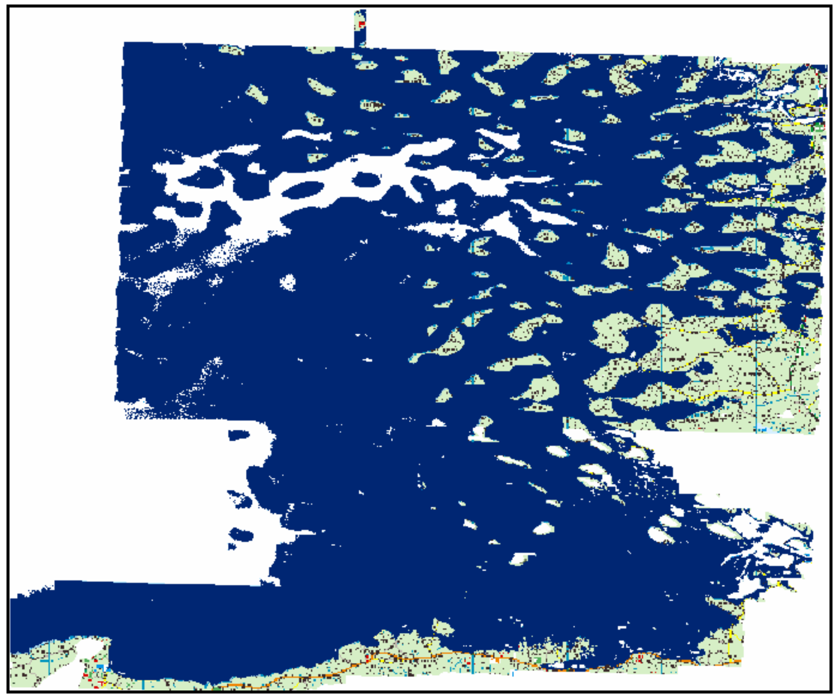
6m OD, highest "spring" tide level with 1m sea level rise.



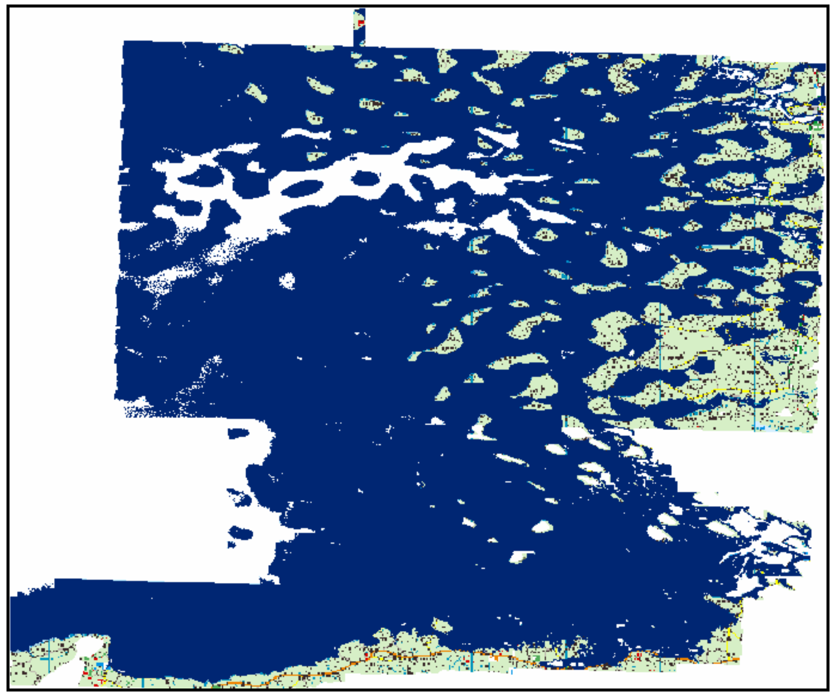
7m OD, highest "spring" tide level with 1m sea level rise coupled with 1m storm surge.



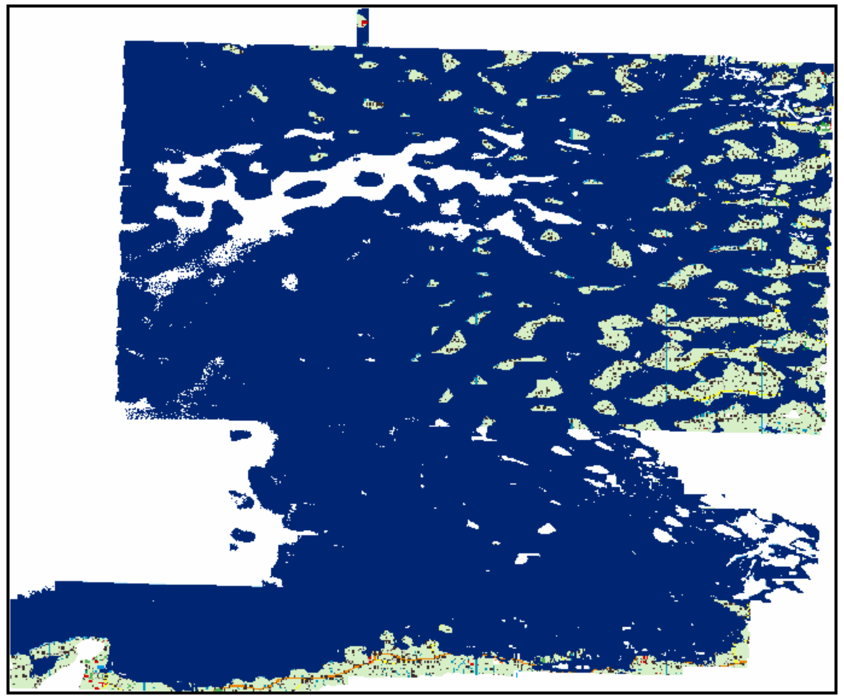
8m OD, highest "spring" tide level with 2m sea level rise coupled with 1m storm surge.



9m OD



10m OD



15m OD

Figure 29. OS Discovery Series maps of study area flooded (dark blue) to levels from 6m to 15m OD. Part 2 of Figure, Part 1 on previous page.

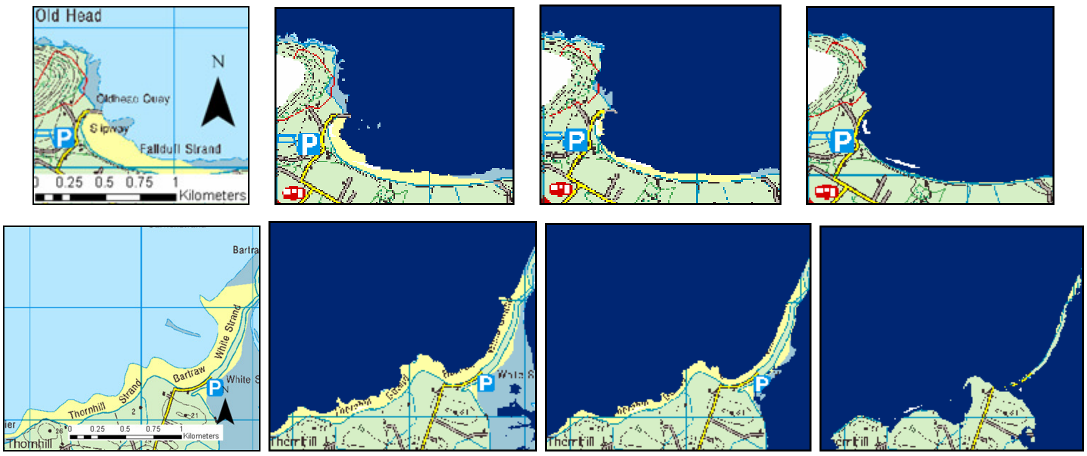


Figure 30. Amount of Old Head (above) and Bertra (below) beaches covered by sea as shown on Discovery Series map, (without flooding on left) with flooding depicted from the DEM, at 0m OD, 1m and 5m (second left to right).

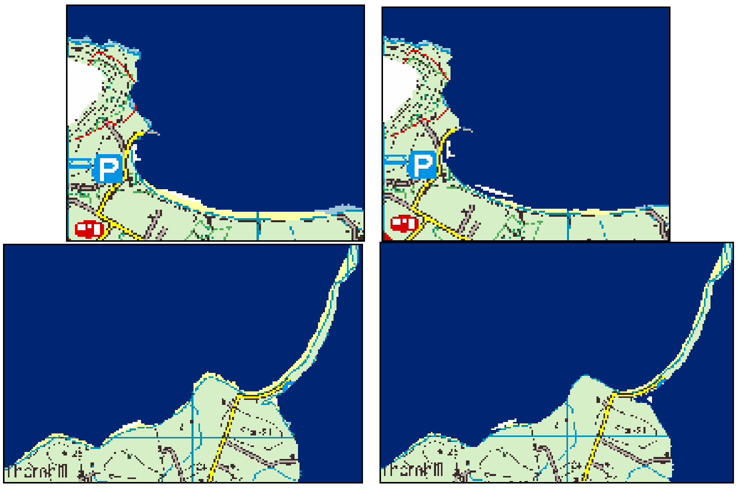


Figure 31. Flooding on Old Head (above) and Bertra beaches showing 2m OD (left) and 3m water levels, with very little of the beach exposed. See Figure 30 for scale.

promontories and islands connected to the mainland by causeways were cut off, including places in the northern part of the study area.

In the real situation some of these areas would have barriers to the sea and so would not be inundated as shown. Figure 32 shows some known barriers to sea movement in the Claggan to Carrowholly areas. A comprehensive survey of barriers and their potential effectiveness is outside for the scope of this project. Some areas had natural barriers in that the land rises towards the sea, as in Moyna.

Figure 32. Known locations of some barriers to sea encroachment in the Claggan to Carrowholly areas (red marks).

The land gradually disappeared and islands got increasingly isolated with the rising sea level from 6m onwards (Figure 29). A rise in sea level of 1m coupled with possible extreme storm surge of 1m would cover the land to 7m. Low-lying areas would become more extensively covered. Areas that were not affected up to this level would now be inundated, including some of the residential suburban area of Rosbeg (Figure 33), which would become an island at high tide. Some barriers which are currently 2m above high tide level would need reinforcing to ensure effectiveness, such as that along the main coastal road at Rosbeg.

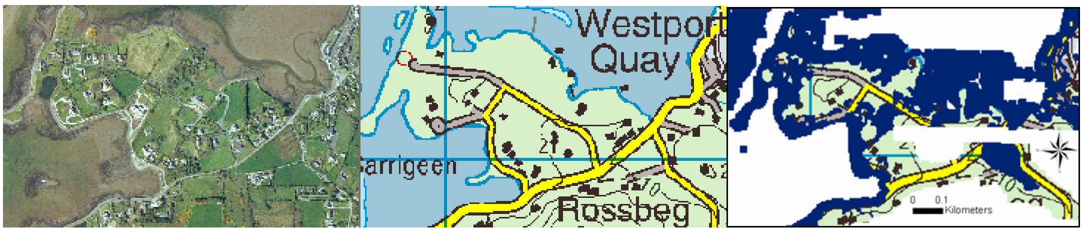


Figure 33. Rossbeg area, which is suburban residential (see aerial photo, left), as shown on OS Discovery Series map (middle) and flooded to 7m by the DEM (white areas are NoData holes in DEM).

With the evidence that sea levels may rise significantly faster than heretofore accepted by the IPCC due to accelerated ice melts (Lawrence *et al.*, 2008), this study should also seriously consider a rise to 8m, that being composed of 2m above the current high (5m) plus 1m possible storm surge. An examination of the 8m flooded figure in Figure 29 showed Annagh Island almost totally under water, the populated areas of Murrisk peninsula and other such promontories such as Rosbeg on the southern coast and Rossanrubble in the east. On examination many of the houses in the eastern and northern peninsulas were situated above this level, whereas the large low-lying tracts of land at Carrowcally and Carrowholly, for example, where there are many houses, showed very extensive flooding. Some of these results were probably affected by the nature of the DEM, which depicted the elevation of dense vegetation or buildings, not the ground (see Section 3.1.2.1), so it is possible that flooding may be more severe in some parts than was depicted on the maps.

Flooding above this height is currently somewhat hypothetical as it very much depends on human responses to climate change (see Section 2.1), or the chance occurrence of a tsunami. However it is interesting to look at the pattern of flooding for the area into the future (beyond 2100) as it will happen (albeit over centuries) if there is not an adequate reduction in emission of greenhouse gases, and for this reason the reader is referred to additional levels of flooding in Figure 29.

Table 6. Area figures for the area defined by the DEM from 0 to 53m OD.

Elevation (m)	Area (km^2)
0	25.3
1	8.9
2	4.0
3	3.3
4	3.6
5	3.0
6	2.2
7	2.0
8	1.9
9	1.9
10	2.0
11-15	9.8
16-20	7.0
21-53	14.9

4.3 LANDCOVER FLOODING STATISTICS.

The study area defined by the DEM (clipped to 0-53m OD) was 89.69km^2. A rudimentary breakdown of the figures by elevation shows that in this coastal area most of the land was low-lying, with the largest area figures occurring at or below 5m. The largest figure was for 0m OD and the second for 1m. The area covered by ground less than or equal to 4m was 48.2km^2: over half the total study area.

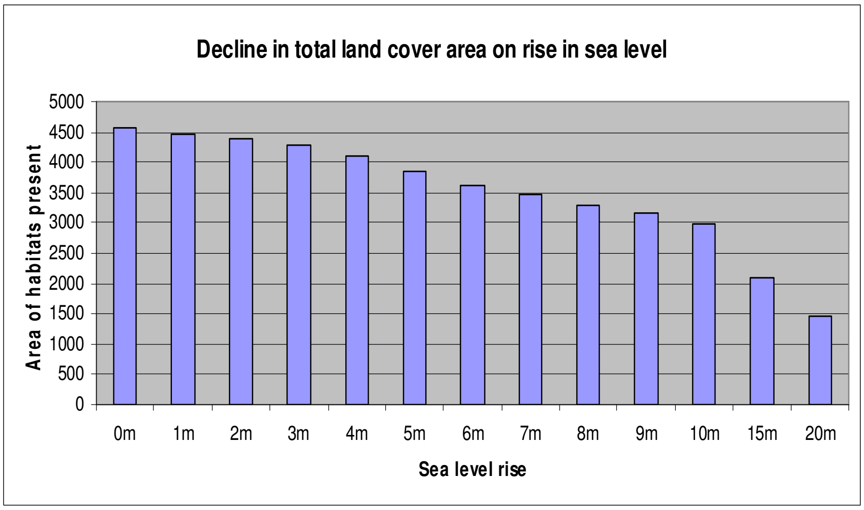


Figure 34. Decline in total land cover area exposed with rising sea levels for the CORINE 2000 land cover dataset.

4.3.1 Statistics from CORINE data.

The overlay of CORINE (2000) with the LiDAR DEM produced statistics showing how much of each land cover type was lost with progressional sea level rise. A progressional loss of overall land cover was observed with increase in sea level, from 4,575ha to 1,450ha (Figure 34), which would be the expected pattern. Each land cover type also lost land as the model increased the sea level (Appendix 5).

Percentages of each land cover type lost in relation to the total extent of the type in the study area, for each increase in elevation, were calculated, and charts for these showed slightly different patterns of loss for each type (Figure 35). The ten land cover types (of 12 in the study area defined by the LiDAR DEM) that were of use to the present study were chosen for the charts: The discounted ones were *Water bodies* and *Intertidal flats*, which were outside the scope of the study or thought to be too inaccurate (see Section 3.1.3.1).

All classes showed an increase in percentage loss with increase in inundation, which was logical as the land disappeared under the sea. The categories *Beaches,dunes,sand*, *Sports and Leisure facilities* and *Broadleaf forest* reached nearly 100% loss with a sea level of 15m. Most sandy communities (the former category) would logically be found at lower elevations, and the *Sports facilities* would include golf courses that occupied low land near the sea. *Broadleaf forest* happened to be below these elevations in this area. Nearly all classes showed cover at below the (annual) spring tide of 5m. This does not need explanation for *Beaches,dunes,sand* but for other categories, it may be an artefact that the CORINE land cover map, which had a minimum mapping unit of 25ha, was so much coarser than the resolution of the DEM (25m^2 or 0.0025ha) that it gave rise to anomalous results. However, field observations confirmed that pastures and agricultural lands may have been below high tide, as grazing occurred on salt marshes and other low-lying parcels of land. The occurrence of *Peat bogs* below 5m was explained by the categorisation of Claggan swamp as *Peat bog* in the CORINE dataset (Figure 36). The land in that area was mainly below 5m, according to Figure 29.

Interpreting the CORINE results for significance in relation to biodiversity was not simple for two reasons. The CORINE dataset was spatially coarse and also very broad in its land cover categories. Some categories that were present in other areas of Ireland that would indicate habitats of biodiversity importance were not in this area of the dataset, namely *Salt marshes*, *Moors and heaths* and *Inland marshes*.

However, some of the results do merit further scrutiny. The *Peat bog* area in Claggan was protected by a barrier that would possibly secure the communities in that area against rises in sea level of 2-3m (field observations). Twenty-three percent of the *Peat bogs* in the area were below a level of 8m. Nearly 20% of pastures were below 5m, and 30% below 8m: certainly some of these would be lost with sea level rise. Forty percent of *Broadleaf forest* was below 5m, and over 60% of it below 8m: This land cover type would not be found below the high water level except if it were in a low-lying area away from the influence of the sea. Most cover of *Transitional woodland and scrub* was above 10m, but this community type can be very important

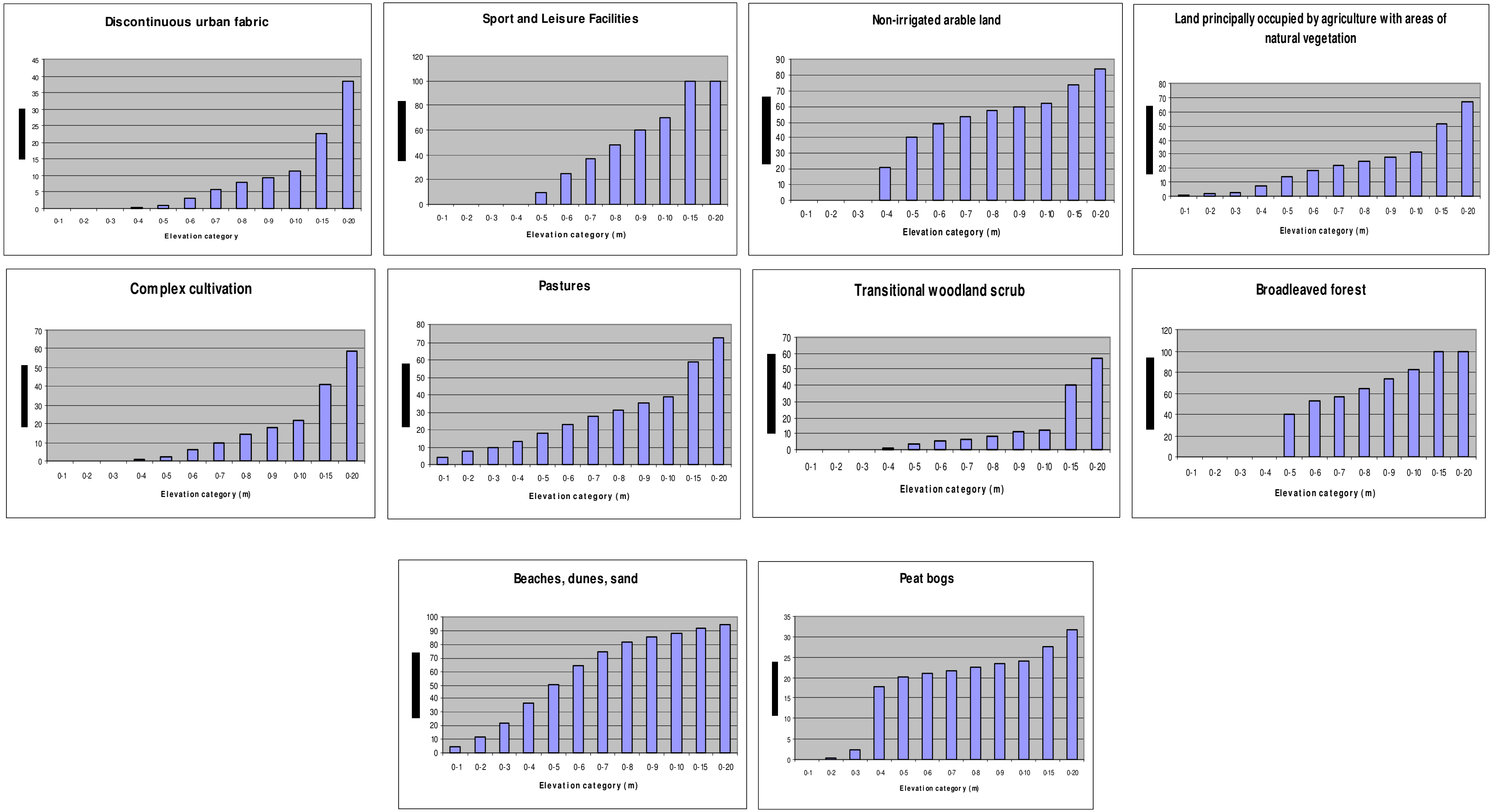


Figure 35. Increasing percentage loss of seven land cover types in the CORINE 2000 data with each increase in sea level ("elevation category"), with the area contained by a rise from 0-1m on the left in each chart and from 0-20m on the right. Note the percentage scale is not the same throughout.

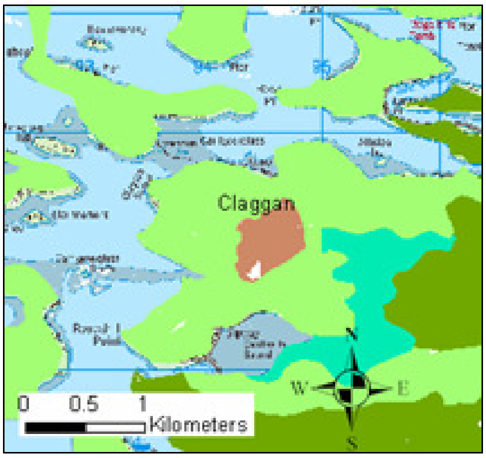


Figure 36. CORINE 2000 dataset showing the *Peat bog* area in Claggan (brown), which is under 5m OD. White parts are NoData areas in DEM and therefore excluded from the study area. OS Discovery Series in background.

for biodiversity as it covers disused or marginal land and wetlands with scrub. *Beaches,dunes,sand* was the most significantly reduced land cover type, with about 50% occurring up to the 5m level, and 80% to the 8m level. A rise in sea level would reduce the cover of this category considerably. The biodiversity impacts of the flooding of categories with more intense anthropogenic origins such as *Discontinuous urban fabric* and the agricultural classes were more difficult to deduce. However, presence of patches and pockets of natural communities among these would be of importance to biodiversity and a loss to the sea would reduce the possible islands of suitable habitat overall.

4.3.1.1 CORINE Land cover changes 2000 to 2006.

There were no changes within the study area between CORINE 2000 and CORINE 2006 datasets, except for *Intertidal flats* that were already discussed in Section 3.1.3.1. Five change polygons occurred just outside the study area: the changes in these were examined for the purposes of seeing what types of changes were occurring in the general area (Figure 20). The results showed that two polygons changed from *Peat bog* to *Transitional woodland and scrub*, but the aerial photos revealed that in 2006 one of these had young forestry and the other ground preparation for forestry. Another polygon changed from *Conifer forest* to *Transitional woodland and scrub* due to felling. Two polygons that were *Principally agriculture* in 2000 changed to

Discontinuous urban fabric (housing and industrial buildings on 2006 photos) and to *Transitional woodland and scrub* (in photos a housing estate, probably should be *Discontinuous urban fabric*). In summary the changes were either (a) from bog to forestry, (b) from one stage of forestry to another and (c) from agricultural land to housing/buildings.

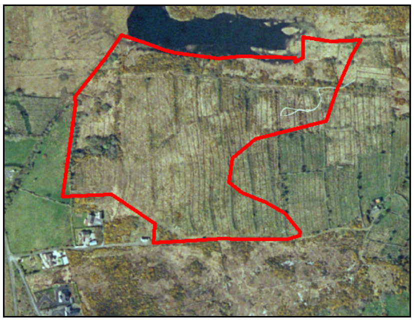


Figure 37. Change parcels near Ballinacarrick Lough, Moyhastin (above) (100300, 282500 approx. coordinates) and near Ardoley (below)(98100, 282100), changed from *Peat bogs* (412, CLC2000) to *Transitional woodland and scrub* (324, CLC2006), shown here overlaid on the 2006 aerial photos.

4.3.2 Results from the Teagasc Habitat Indicator dataset

The Teagasc dataset covered over 45km^2 in the study area. Being a terrestrial dataset, it excluded much of the area covered by tide. As sea level would rise, the Habitat Indicator land cover would decrease with flooding (Figure 38). Under the current tide regime a small area of the Teagasc Habitat Indicator cover existed at levels of between 2 and 4m, with a greater amount between 4 and 6m. The difference between total habitat cover with sea level at 5m and that with sea level at 6m was 241ha. This figure would include habitats normally without inundation that would be inundated regularly by the sea with a rise of 1m, but also those that were more inland and/or shielded from sea level rise.

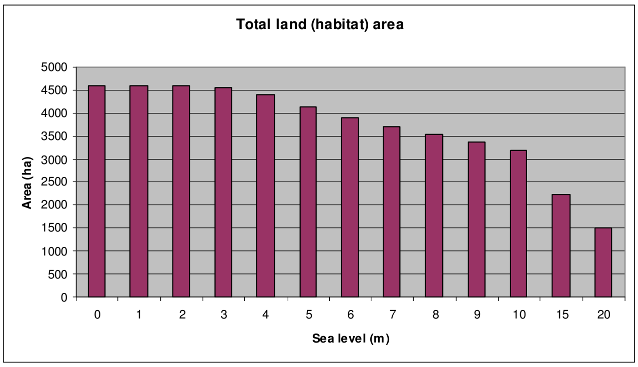


Figure 38. Decline of total Habitat indicator land cover exposed with sea surface at levels from 0 to 20m.

A breakdown of the total area covered by each Habitat Indicator within the study area (Table 7) showed a range from *Rocky complex* at 6ha to *Dry grassland* at 2,504ha (excluding the *Water* category). *Dry* and *Wet grassland* classes covered the greatest amount of land. Area (ha) of each habitat type, with sea level at different elevations from 0 to 20m (habitat area decreases as sea level increases), and total area of land covered by all habitats under the same flooding levels (bottom).

Table 7. Habitat Indicator classes and the areas they cover within the study area.

Habitat	Area ha
Water	1
Rocky Complex	6
Cutover / Eroding Bog	7
Sand	15
Mature Forest	24
Bare Peat & Soil	24
Built Land	29
Coastal Complex	36
Lowland Blanket Bog (LBB)	42
Wetland	65
Reclaimed LBB	90
Forest(U) & Scrub	159
Heath	172
Wet Grassland	1427
Dry Grassland	2504

Rocky complex and *Sand* covered relatively small areas. *Coastal complex* covered more than these but less than *Wetland* or the *Lowland blanket bog (LBB)* classes (except for the *Cutover bog* class). Apart from the grassland classes, the next highest covers were for *Heath*, *Forest (U) and scrub* (which incorporated forests that were not high forest), *Reclaimed LBB* and *Wetland*. *Reclaimed LBB* covered about twice the areas of *Blanket bog* and *Cutover/eroding LBB* together. All classes decreased as the sea level rose in the model (Appendix 6).

Table 8. Thematic classes of Habitat Indicator map showing corresponding Heritage Council classes (Fossitt 2000) as presented by Fealy 2004.

HABITAT INDICATOR CLASS	CODE (Fossitt 2000)
Wet Grassland	GA1, GA2, GS4
Dry Grassland	GA1, GA2, GS1-3, BC1-4
Water	FL1-8, CW1-2
Bare Rock	ER1-4, CS1-3
Rocky Complex	ER1-4, HH1-HH4, HD1
Mature Forest	WN1-7, WD1-4
Forest (unclosed canopy) & Scrub	WS1-5
Built Land	BL3, GA2
Sand	CD1-3
Coastal Complex	CD1-3, L
Fen	PF1-3
Cutover Fen	PB4
Reclaimed Fen	PB4
Raised Bog / Fen	PB1 PF1-3
Cutover Raised Bog / Fen	PB4
Reclaimed Raised Bog / Fen	PB4
Upland Blanket Bog	PB2
Cutover Upland Blanket Bog	PB4
Cutover / Eroding Upland Blanket Bog	PB4, PB5
Reclaimed Upland Blanket Bog	PB4
Lowland Blanket Bog	PB3
Cutover Lowland Blanket Bog	PB4
Cutover / Eroding Lowland Blanket Bog	PB4, PB5
Reclaimed Lowland Blanket Bog	PB4
Heath	HH1-HH4, HD1
Wetland	GS4, GM1, PF1-3, FS1-FS2
Salt Marsh	CM1-2

The relative detail of the bog classes reflected the origins of the data rather than the relative importance of bog in relation to other classes: part of the origins of this dataset was a study of peatland soils. The relation between the Teagasc classes and the widely-used Heritage Council habitats classification (Fossitt 2000) is shown in Table 8.

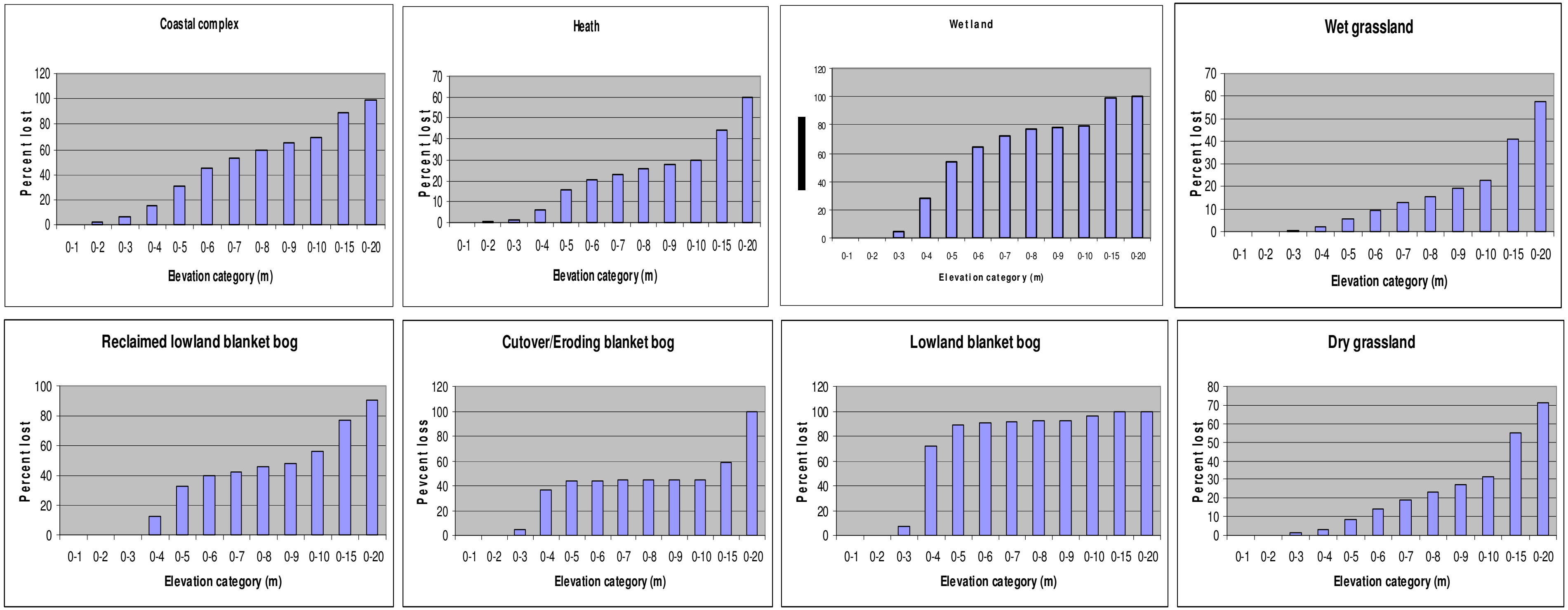


Figure 39. A range of Habitat Indicator classes from the Teagasc dataset and their percent loss to inundation as sea level rises from 0m OD. Some currently exist below tide levels (0-5m OD).

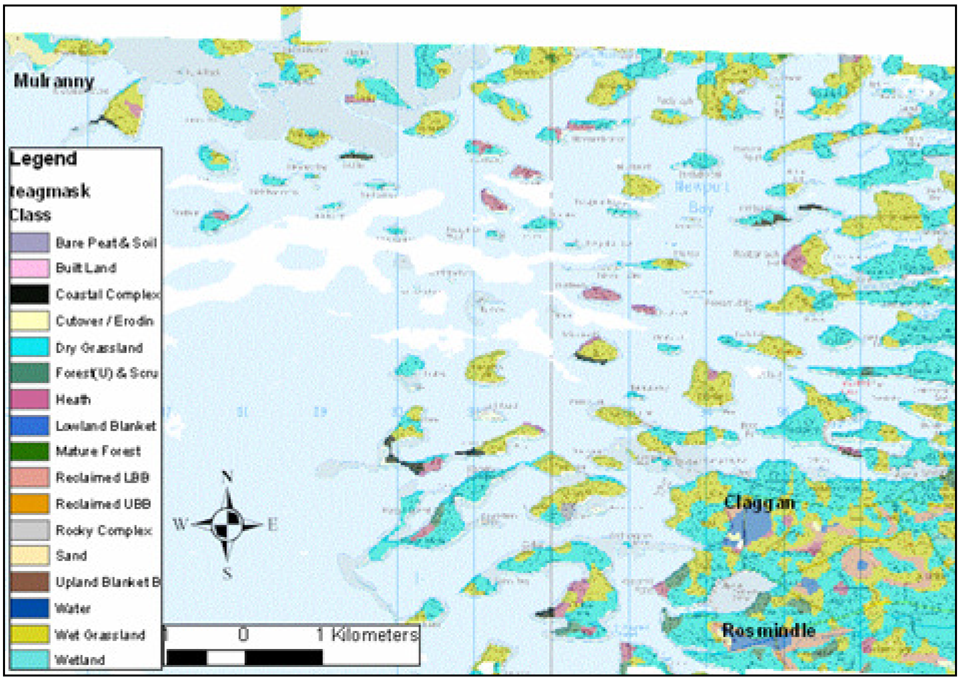


Figure 40. Northern part of the study area with Teagasc classes overlaid on OS Discovery Series map. White areas are NoData in DEM, excluded from study area.

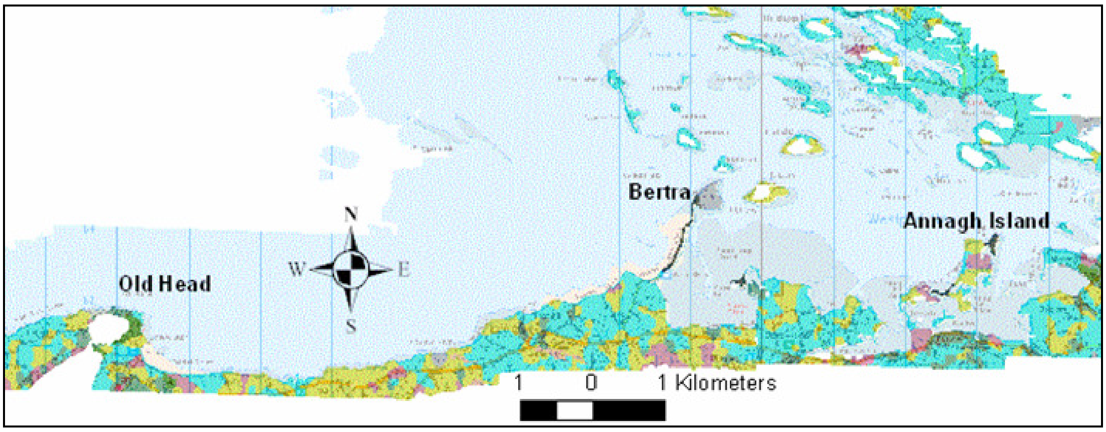


Figure 41. Southern part of the study area with Teagasc classes overlaid on OS Discovery series map. Legend as Figure 40.

All classes in Figure 39 currently exist at elevations below the high tide. However, the bog and wetland classes occurred inland and although they were under high tide levels, they would not be affected by tide due to barriers to sea intrusion (Figure 40). The *Wetland* class illustrates the extent of the range of habitat classes covered by a broad Habitat Indicator class: there were seven Heritage Council classes in this one Teagasc class (Table 8), including types of marsh, fen, wet grassland and swamp

(Fossitt, 2000). Just over 60% of *Wetland* occurred at 6m or less, and 40% of each of *Reclaimed LBB* and *Cutover/Eroding bog* occurred under this level also. About 90% of *Lowland blanket bog* occurred at or below 5m, the remaining 10% occurring at over 9m. The pixels of *Sand* in the study area were exclusively in the Mulranny area (Figure 40), while Bertra spit was not categorised as *Sand* but as *Bare Peat and Soil* (Figure 41). *Coastal complex* occurred along the Spit as well, and also at Annagh Island (Figure 41). Sixty percent of this category was at 8m or less. This class included the Heritage Council habitats of rocky and sandy shores and sand dunes. Twenty percent of *Heath* was at 6m or less, some of which occurred in inland areas. *Wet grassland* and *Dry grassland* had rather similar distributions along the elevation scale (Figure 39), beginning at 3m. Ten percent of *Wet grassland* and 14% of *Dry grassland* occurred at or below 6m. *Dry grassland* included the Heritage Council habitats Flower beds and borders, and indeed the areas included some rural "suburban" localities. A category of *Salt Marsh* defined in the Teagasc dataset was not recorded in the study area of the current project, and so is not represented (compare Table 7 and Table 8 Habitat Indicator classes).

The data show that an amount of habitats exist at low elevations, and many of these are in coastal locations at risk of inundation. Elements of the *Coastal complex* may be more resilient to periodic inundation that a rise in tides would bring: others such as *Heath* and the *Grassland* categories may change in character. Currently the *Wetland* and *Bog* classes would be shielded by sea barriers from a rise in sea level.

4.3.3 Results from the Commonage Habitats dataset

Although this file only covered small patches of land it was of importance because the polygons had been ground-truthed and were reliably classified and drawn using 6" OS maps. The other spatial datasets in this project were based mainly on satellite remote sensing data with pseudo-ground-truthing from aerial photos, so this dataset was more reliable than any of those. Additionally the designation as commonage seemed to have preserved the semi-natural nature of the vegetation, rendering these areas more important for biodiversity than many other areas that had been more impacted by human interference. All the same, this dataset covered only 176ha, whereas the total study area defined by the DEM was 89.69km^2.

Statistics show that the total area of habitats recorded in commonage in the study area declined mainly from a level of about 170ha with flooding at 3mOD to approximately 80ha with flooding to 7m (Figure 42).

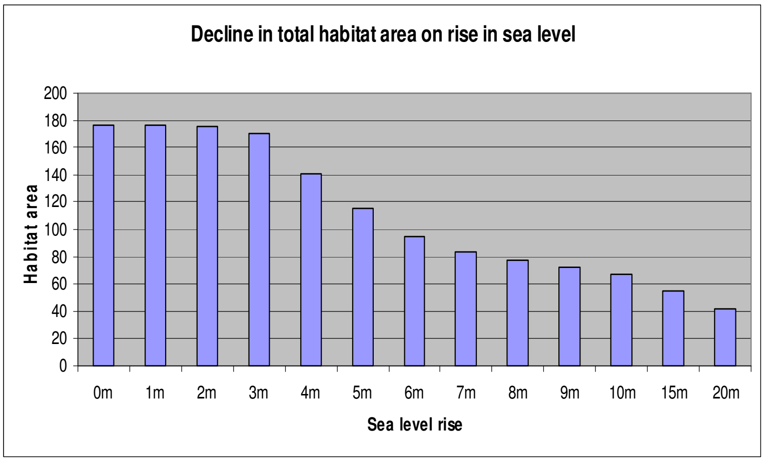


Figure 42. Decline in total habitat area (ha) exposed on rise in sea level for the commonage habitats dataset.

Table 9. Area (ha) of each habitat type, with sea level at different elevations from 0 to 20m (habitat area decreases as sea level increases), and total area of land covered by all habitats under the same flooding levels (bottom).

Habitat	Area 0m	Area 1m	Area 2m	Area 3m	Area 4m	Area 5m	Area 6m	Area 7m	Area 8m	Area 9m	Area 10m	Area 15m	Area 20m
Wet/Dry heath	1	1	1	1	1	1	1	1	1	1	1	1	1
Dry heath/ Unimp. wet grassland	2	2	2	2	2	2	2	2	2	2	2	1	1
Wet heath	3	3	3	3	3	3	3	3	3	3	3	3	3
Dune/ Unimp. dry grassland	5	5	5	5	5	5	5	5	5	4	4	3	2
Wet heath/Dune	5	5	5	5	5	5	5	5	5	4	4	2	1
Wet heath/ saltmarsh	6	6	6	6	6	4	0	0	0	0	0	0	0
Beach/shingle/ reef/shore	6	6	6	5	3	2	1	0	0	0	0	0	0
Unimp. dry grassland/ Saltmarsh	9	9	9	8	7	5	2	0	0	0	0	0	0
Dry heath	9	9	9	9	9	9	9	9	9	9	9	8	8
Unimp. wet grassland	10	10	10	10	10	10	10	9	9	9	9	7	6
Upland grassland	11	11	11	11	11	11	11	11	11	11	11	11	10
Dune/Beach/ shingle/reef/shore	11	11	11	11	10	7	4	2	0	0	0	0	0
Saltmarsh	15	15	15	15	10	2	0	0	0	0	0	0	0
Dune	16	16	16	15	15	13	9	6	4	2	1	0	0
Blanket bog/ Fen/marsh/swamp	18	18	18	16	1	0	0	0	0	0	0	0	0
Unimp. dry grassland	22	22	22	22	19	14	10	9	8	7	6	4	3
Unimp. wet grassland/ Unimp. dry grassland	25	25	25	25	24	23	23	22	21	20	19	13	8
Total	**176**	**176**	**176**	**171**	**141**	**115**	**95**	**84**	**77**	**72**	**68**	**55**	**42**

There were two types of compound classes in the results. One type was designated as a compound class from the outset (it had only one identifying class number, e.g. XII: *Beach/shingle/reef/shore* ("compound classes")), the other mixed two classes, one or both of which may be compound (e.g. VII/XII: *Dune/Beach/shingle/reef/shore* which had two identifying class numbers ("mixed classes"), see Appendix 7). The amount of compound and mixed classes in the dataset meant that it was difficult to see any obvious patterns (Table 9). *Unimproved grassland* comprised 57ha, not including mixed classes that were not grassland (e.g. *Dune/Unimp. dry grassland*). Clearly in the commonage areas grasslands were the most widespread class. Six classes included *Dry* or *Wet heath* (or both), four classes included *Dune*, the largest of which was on its own: *Dune* (16ha). Three categories contained *Saltmarsh*, the largest of which was also on its own (15ha). Six hectares of *Beach/shingle/reef/shore* occurred on its own, and it occurred also as a mixed class with *Dune* (11ha). Six of the 17 classes were reduced to zero with sea level elevated to 8m (Table 9).

The *Blanket bog/Marsh/Fen* category was only present between 3 and 5m, and on investigation this was mainly the area in Claggan swamp, which is currently below high tide levels but has a barrier to inundation (Section 3.1.4.2). Pure *Saltmarsh* was recorded between elevations of 3 and 7m, the latter being surprisingly high. Much of the *Saltmarsh* cover was in the Rossmurrevagh area of Mulranny and in Annagh Island. The cover of the dataset was limited to commonage areas, so other saltmarshes in the study area were not included. Machair systems were included in the category *Unimproved dry grassland* (A. Bleasdale, pers. comm.) and 60% of the pure representative of this was between 3 and 7m (Figure 43 and Appendix 7), and 100% of it had disappeared by 7m in the mix category of *Unimproved dry grassland/Saltmarsh*. These community types would be greatly affected by any rise in sea level. Sixty percent of the pure *Dune* category was recorded between 2 and 7m, although almost 40% of *Dune* occurred between 7 and 10m. Much of the pure *Dune* category was located on Bertra spit, on which the maximum elevation recorded was 11m. *Dune* was also recorded in a mix with *Wet heath*, some of which occurred at 4m but over 60% occurred over 10m (Figure 43). These community types would be affected by sea level rise, but as dunes can build up and persist at elevations several metres above spring tide, the presence of dunes is probably governed more by sea

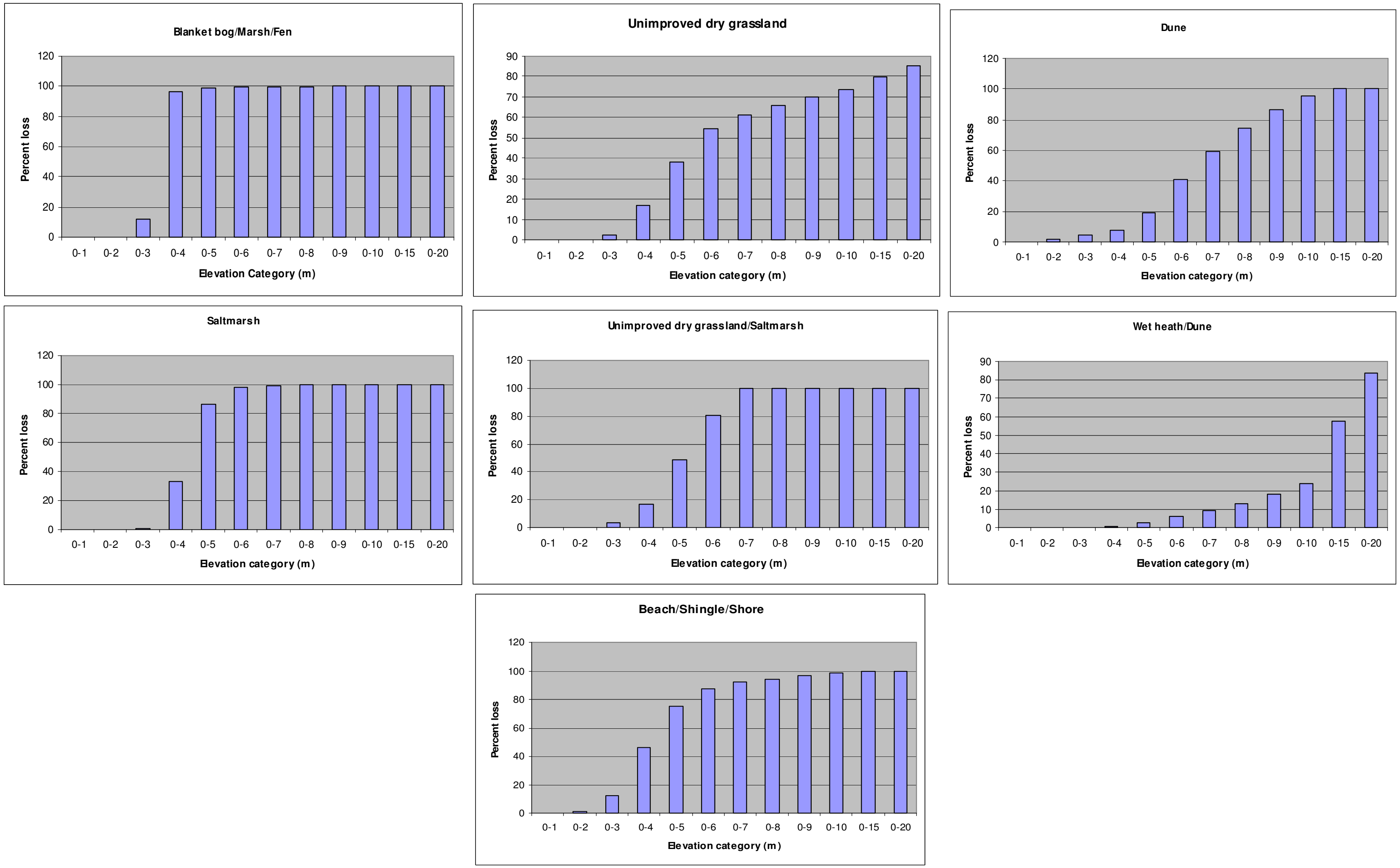


Figure 43. Increasing percentage loss of seven Commonage Habitat combination types with each increase in sea level ("elevation category"), with the area contained by a rise from 0-1m on the left in each chart and from 0-20m on the right. Note the percentage scale is not the same throughout.

currents and wind. The category *Beach/shingle/reef/shore* was recorded from 2 to about 10m, although over 80% of them occur below 6m, meaning they would be impacted by any rise in sea level.

These results show that some communities that exist near the shore and at lower elevations would definitely be reduced in area with a rise in sea level. The commonage areas are a unique resource for habitats, as these can offer a certain amount of protection from change imposed by human activity (building of roads, housing, industrial development). A disadvantage of this dataset for this type of analysis was the use of combined and mixed classes, but this is a problem inherent to mapping natural communities: in many cases the communities form intimate intricate mosaics and even merge one into another so there is no clear mappable boundary.

4.3.4 Results from the classified Landsat image dataset

The distribution of the fourteen classes identified in the image is shown in Figure 44. Total land cover exposed declined from about 5,800ha (sea level at 0m) to less than 4,000ha at 6m and about 3,300ha at 10m (Figure 45). Nearly one third of the dataset lies in the extreme intertidal range (0-5m). The extent of additional land that would be covered if the extreme spring tide were at 6m would be 273ha.

The total area figures for each land cover class show that the highest cover was for the complex class of *Grass/bare ground/rural development* at 1,376ha (Table 10). Next two highest were *Dry* and *Wet grassland* respectively, and then *Sand/mud*. There was a big drop between this and the next largest class, *Broadleaf*, which was followed by *Bog.fen /wet heath* and *Scrub/gorse*. Two hundred and fifteen hectares of water were recorded, which included coastal water as well as inland water bodies (Figure 44). *Saltmarsh* covered 197ha but this figure was probably inflated by erroneous pixels that remained to be reclassified in the image, as had been done for the large tracts of *Saltmarsh* pixels found in the Claggan and Rosmindle areas (see Section 3.1.4.2). *Dune/dry grassland* covered 53ha and *Dense seaweed* nearly the same at 52ha, and *Swamp* was the class with least cover at 41ha.

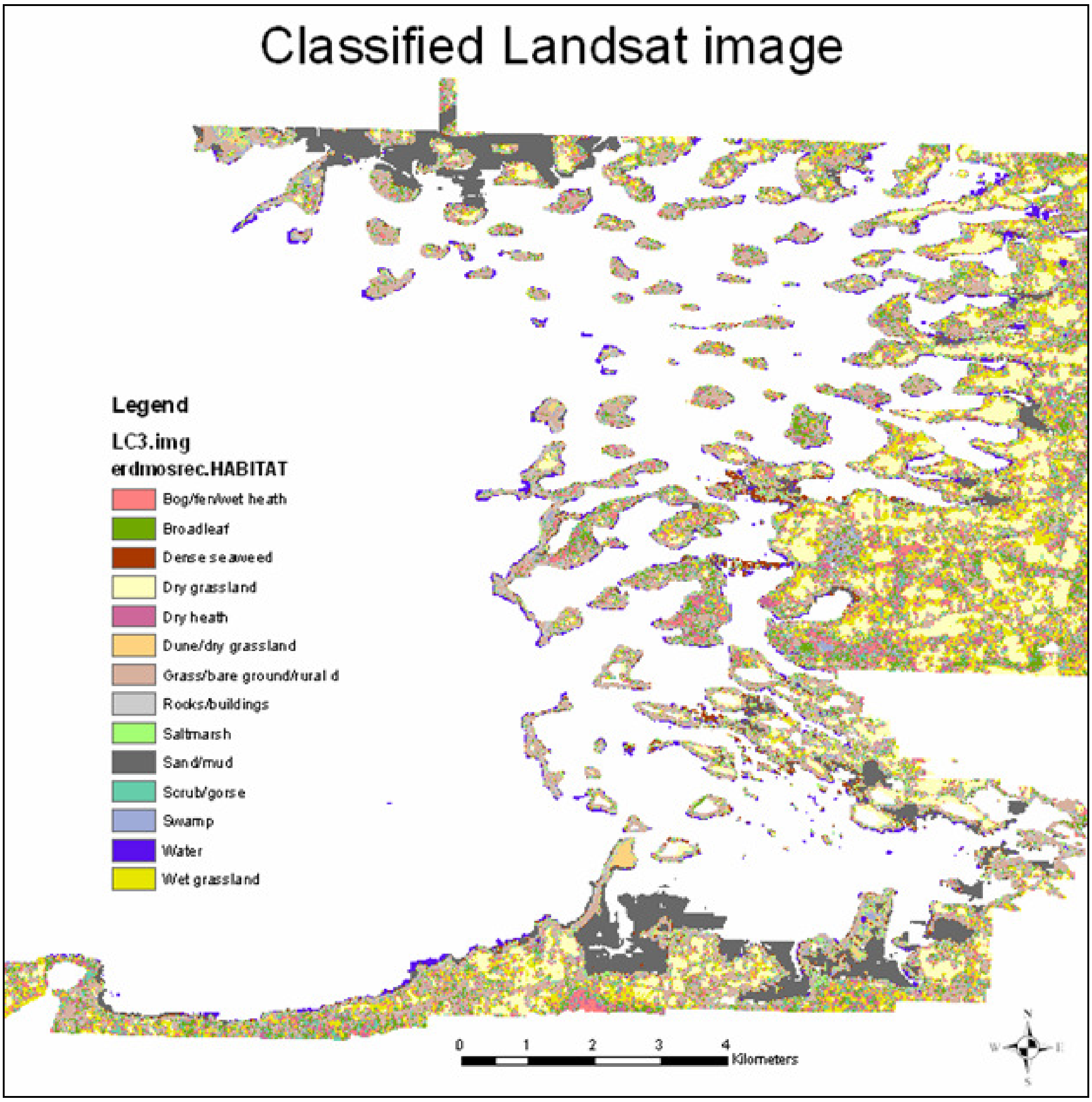


Figure 44. Classified Landsat image created during project.

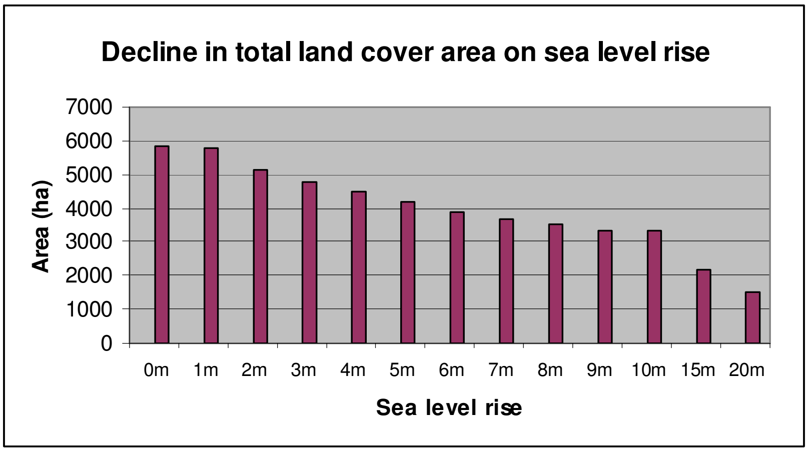


Figure 45. Decline in area of total land cover exposed with rise in sea level for the classified image dataset, excluding the "Water" class.

Table 10. Total area of each land cover class in the dataset, including all elevations from 0 to 53m.

Land cover class	Area (ha)
Swamp	41
Dense seaweed	52
Dune/dry grassland	53
Rocks/buildings	123
Dry heath	179
Saltmarsh	197
Water	215
Scrub/gorse	233
Bog/fen/wet heath	292
Broadleaf	380
Sand/mud	663
Wet grassland	969
Dry grassland	1268
Grass/bare ground/rural development	1376

These areas changed as the level of the sea was set at increasingly higher levels (Table 11). All of *Swamp*, *Saltmarsh*, *Dense seaweed*, *Sand/mud* and *Water* were inundated with sea level at 7m. *Sand/mud* cover plummeted at 2m, and *Dense seaweed* reduced from 51 to 29ha with the same inundation.

Table 11. Area (ha) of each habitat type, with sea level at different elevations from 0 to 20m (habitat area decreases as sea level increases), and total area of land covered by all habitats under the same flooding levels (bottom).

HABITAT/ Land cover	Area 0m	Area 1m	Area 2m	Area 3m	Area 4m	Area 5m	Area 6m	Area 7m	Area 8m	Area 9m	Area 10m	Area 15m	Area 20m
Swamp	41	41	40	37	21	10	3	0	0	0	0	0	0
Dense seaweed	52	51	29	14	6	3	1	0	0	0	0	0	0
Dune/dry grassland	53	53	52	49	43	28	13	4	3	1	1	0	0
Rocks/buildings	123	122	109	90	73	57	42	35	30	26	26	12	7
Dry heath	179	178	172	160	142	127	117	111	104	98	98	65	46
Saltmarsh	197	195	157	114	79	41	16	0	0	0	0	0	0
Water	215	190	68	36	18	7	3	0	0	0	0	0	0
Scrub/gorse	233	233	223	214	200	187	179	172	164	156	156	104	73
Bog/fen/wet heath	292	292	291	288	267	250	241	235	224	215	215	138	86
Broadleaf	380	380	378	374	357	333	320	312	300	288	288	201	142
Sand/mud	663	648	150	35	14	6	2	0	0	0	0	0	0
Wet grassland	969	967	959	949	925	886	855	831	798	767	767	528	368
Dry grassland	1268	1267	1261	1255	1245	1209	1157	1112	1061	1012	1012	672	465
Grass/bare ground/ rural development	1376	1369	1296	1198	1109	1018	938	886	827	771	771	469	299
Total	**6042**	**5986**	**5185**	**4810**	**4499**	**4162**	**3886**	**3699**	**3512**	**3335**	**3335**	**2190**	**1486**

Over 70% of the *Swamp* class was located at or below 5m (Figure 46), which would seem to indicate it would be inundated by tide but on examining the image most *Swamp* pixels were in low-lying areas sheltered from the sea by a barrier (e.g. Claggan). No *Swamp* occurred over 7m OD. *Saltmarsh* showed a similar distribution but with more of it occurring at or below 3m (over 40%, see Figure 46). Very little *Saltmarsh* existed at elevations of 1m and less, so if sea level were to rise by 1m, the area of *Saltmarsh* currently occurring at up to 2m (38ha) would be virtually eliminated. All of the *Saltmarsh* occurred at or below 7m, so unless there were suitable ground available for horizontal migration of habitat the area would be significantly reduced. *Saltmarsh*, *Swamp*, *Dense seaweed* and *Sand/mud* only occurred at elevations of 7m and less.

The area of *Bog/fen/wet heath* occurred at each level steadily increasing until 9m: none occurred between 9 and 10m, then the area rose again to 15 and 20m. Examination of the classified image showed that much of the cover at lower elevations was in areas sheltered from the sea by barriers. Approximately 30% of *Dry heath* occurred at elevations of 5m or less. An examination of the image showed that this class had a very wide distribution and was recorded on many islands as well as the mainland (Figure 44). This class would benefit from further investigation and ground-truthing.

Almost ninety percent of the category of *Dune/dry grassland* occurred at or below 7m (Figure 46), and about 20% at or below 4m. This category would cover a range of separate habitat types including bare sand and dune grassland. A large part of this was on Bertra head (Figure 44). With a rise in sea level the cover of this category would decline. In contrast, less than 15% of both *Dry* and *Wet grassland* were at or below 7m, and more than 50% of each of these occurred over 15m (Figure 46).

Sixteen percent of *Broadleaf* occurred at or below 6m, and 24% at or below 9m. Amounts of the low-lying *Broadleaf* would be away from coasts and sheltered from sea rise by barriers, as would be the case too for *Scrub/gorse*. This latter had 23% occurrence at or below 6m, and 33% at or below 9m.

The *Rocks/buildings* class would include both seashore rocks and also man-made structures, so although 67% of this occurs at or below 6m it is difficult to interpret, as much would be not so important for natural communities. The class *Grass/bare ground/rural development* was made with the purpose of singling out rural housing and farm infrastructure, but the signature for this class was so broad that it included elements of other classes. The result was that this class was over-represented, and further work would be needed to refine it and map it. Gibson and Power (2000) recorded similar misclassification problems with an *Urban and rural settlement* class, for the reason that this was composed of small areas of many different land use types, which confused the classification.

The accuracy assessment was carried out on 20 gridline crosses from the Discovery Series map (Table 12 and see Section 3.1.4.2). The Teagasc Habitat Inventory map, the Commonage Habitats map, the CORINE Land Cover map and orthophotos were used to determine accuracy. Sixteen of the points were definitely accurate, three were possibly other classes that appeared similar (e.g. the *Rural development* class would contain patches of short grassland, but this could also be *Dry grassland*). An issue with using this objective method to choose check points was that not all classes were included in the accuracy assessment, and there was a preponderance of the *Rural development* class (7 of 20 points). Another item to consider was the different dates

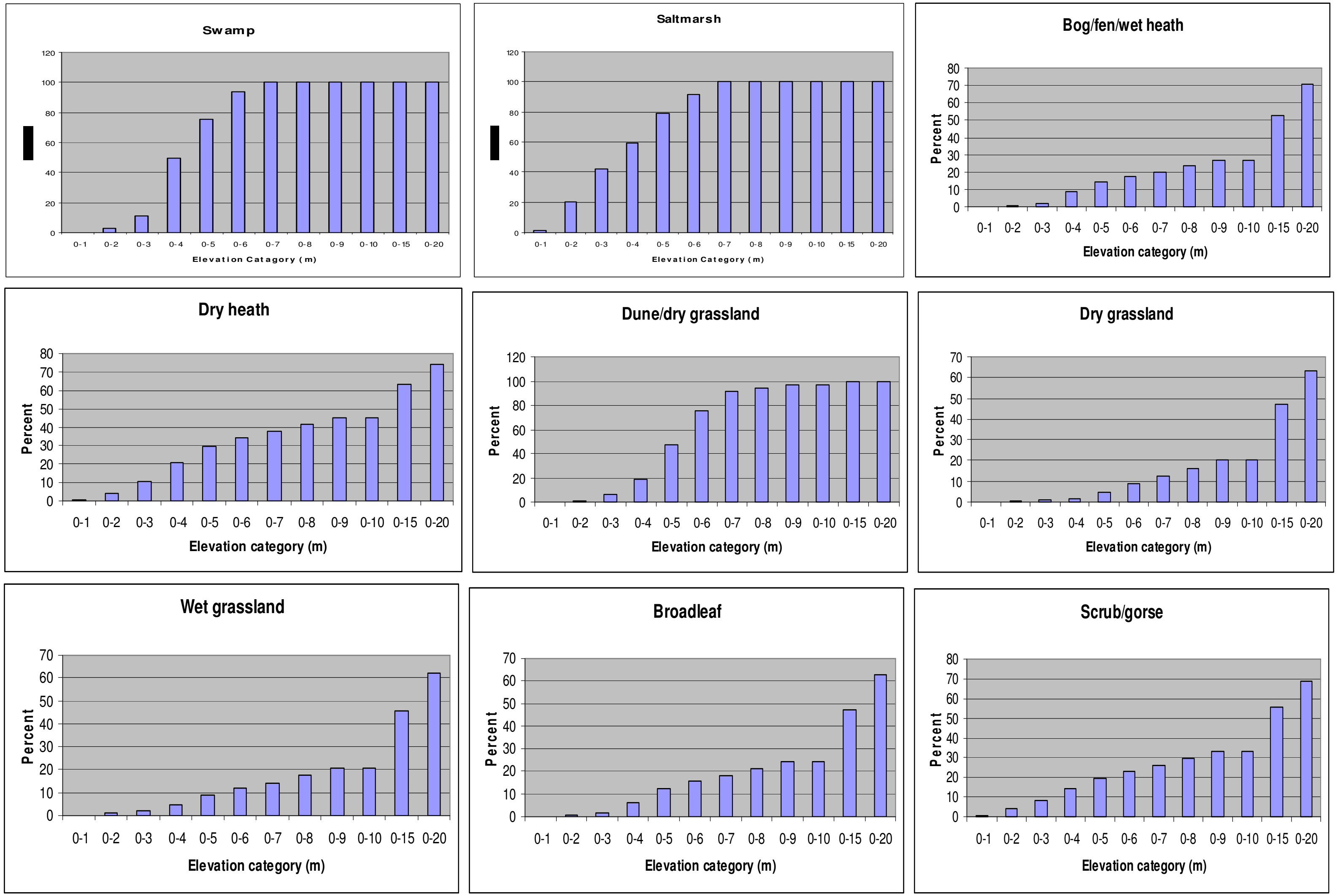


Figure 46. Increasing percentage loss of nine land cover combination types in the classified image with each increase in sea level ("elevation category"), with the area contained by a rise from 0-1m on the left in each chart and from 0-20m on the right. Note the percentage scale is not the same throughout.

of origin of the datasets: the image was from 2002, the photos from 2006, the Teagasc Habitat Indicators from 1995, CORINE from 1998 and Commonage habitats from 2007. In a study of deeper scope it would be necessary to carry out a more comprehensive accuracy assessment.

Table 12. Points used for accuracy assessment, their townland, land cover class and comments re: accuracy.

Grid X	Grid Y	Townland	Land cover	Comments
95000	289000	Castleaffy	Dry grassland	OK
96000	289000	Moyna	Wet grassland	OK
97000	289000	Knockysprickaun	Scrub/gorse	OK
95000	288000	Drumgarve	Wet grassland	OK, scrub has grown
96000	288000	Moyour	Rural development	OK
97000	288000	Buckfield	Rural development	OK
83000	282000	Old Head	Rural development	OK, caravan park
90000	283000	South of Bertra	Wet grassland	OK
92000	283000	Murrisk	Rural development	?OK short grassland near shore
96000	283000	Belclare	Rural development	?OK short grassland near shore
92000	295000	Raigh	Rural development	Probably Dry grassland, from aerial photo
93000	295000	Rossyvera	Sctub/gorse	OK
95000	295000	Gobfadda	Water	OK
96000	295000	Rosgibbileen	Rural development	?OK, maybe Dry grassland
97000	295000	Drumbrastle	Dry grassland	OK
97000	293000	Knockeeragh	Wet grassland	OK, next to Scrub/gorse
97000	292000	Rossanrubble	Dry grassland	OK
98000	292000	Creevaghaun	Wet grassland	OK
96000	291000	Rosbeg	Dry heath	OK
98000	291000	Rossow	Dry heath	OK

5 DISCUSSION.

5.1 DATASET SUITABILITY

This study was limited by availability of suitable datasets, both for the elevation model and for the habitats.

5.1.1 Elevation models

The LiDAR DEM used was suited to the purpose of the study in terms of resolution, but was very limited spatially and had many holes, or patches of NoData, within its extent. Another drawback to the LiDAR DEM was that it was not corrected for presence of objects on the surface such as trees, hedges, buildings. This could have affected the results to a certain extent, particularly the woodland and scrub classes. The LiDAR system of collecting data used in the survey did not use the multipass methods that are now in operation for LiDAR surveys such as those currently being carried out by the Ordnance Survey. The LiDAR beam makes four passes in these, and is able to penetrate accurately to the ground through forest trees (O'Neill, 2009). Another DEM that is now available (November 2009) but was not at the time of commencement of the study, is that from Intermap Technologies, which is gathered using airborne radar technology and provides accuracy to greater than 70cm in the vertical axis (Stanley, 2009).

The DEM used in the current study showed good agreement with the OS Discovery Series contour lines but gave much more detail as these are 10m intervals and the DEM has a 1m vertical resolution. The other datasets available for this study were both too coarse (ERS SAR and SRTM, see Section 3.1.2.2), but the SAR data could have been used to plug holes in the LiDAR except for the echo effect errors at the coast. It was disappointing that Landmap did not have an error-free DEM available for this area. An examination of the statistics of the DEM alone may give some clue as to the effects of sea level rise on biodiversity, as it shows the amount of ground in each separate elevation slice. For example, the statistics for the present study showed that for elevations from 0m OD in the coastal region, the slice 0-1m had the greatest extent by far (25km^2, in an overall space of 90km^2 with elevations between 0-53m represented) (Table 6). If communities existing at this elevation had to move up one metre, they would have to fit into the area contained by the 1-2m slice, which was 9km^2. If they had to move 2m, they would be contained by the area of the 2-3m slice: 4km^2. These are huge area differences. The implications of this for biodiversity can be made from literature as to effects on different species. Mud and sandflats in the intertidal, for example, support a wide diversity and massive numbers of invertebrates which in turn provide food for birds (see Section 5.3). Nationally and internationally important numbers of birds use Clew Bay and depend on these invertebrates (see Section 5.2). Also the otter, for example, which is a species of special conservation concern, uses *Fucus* beds to forage for small fish, and requires a suitable mix of marine, freshwater and terrestrial habitat with heath to exist and breed (Kruuk, 1995). An alteration in configuration of these would affect this mammal, and if the *Fucus* beds were reduced this would be detrimental to its prosperity.

5.1.2 Habitat/Land cover datasets

The datasets available for habitat representation in this study were all limited in their suitability for a study of this nature, both in terms of spatial resolution and classification. What was needed for this study was depiction of habitats that could be used for biodiversity assessment, i.e. entities that would have certain groups of species associated with them and are of themselves coherent ecological units. The broad land cover map of CORINE was too coarse both in terms of the classification and also spatial resolution. It could, however, serve as a first impression of the types of land cover that would be affected by a rise in sea level, which could then be related to more detailed habitat types. The Teagasc Habitat Indicator map was better for this purpose, as it had a finer spatial resolution and certainly the peatland classes were better defined. Additionally this map was produced on a county by county basis, allowing it to be more detailed.

Even finer was the Commonage Habitats dataset, which had been mapped with the aid of the 6" OS maps, and the classification system was more detailed. For example, grasslands were not only divided according to whether they were wet or dry but also included an "improved" category, as well as an "*Upland grassland*". Fens, marshes and swamps were, however, lumped into a compound class, as were coastal elements: *Beach/shingle/reef/shore*. The appearance of these and mixed classes (where one polygon is assigned two classes, see Section 4.3.3) made the interpretation of results difficult. Another drawback to the Commonage dataset for this study was that it only covered commonage areas and so was not useful for drawing any conclusions for the Clew Bay study area as a whole.

Other datasets with drawbacks similar to the latter were the Potential Saltmarsh and other saltmarsh datasets. The areas covered were very small, although this also reflected the amount of that habitat in the Clew Bay area. Additional datasets were in the form of points and were limited in their utility for a spatial analysis.

The dataset created during the project was of suitable spatial resolution but needed more work to refine it and give it more visual clarity. The image itself was far from ideal for habitat mapping being from a date in April, before the growing season, although the use of images from early spring have been used in conjunction with early autumn images for successful land cover mapping in the UK (Lucas *et al.*, 2007). Only grasslands, probably mainly improved ones, would have become actively growing by then, discernable by a vegetation index (O'Connell *et al.*, 2009; O'Connor *et al.*, 2009). It was unfortunate that the image from July 2007 had the banding errors and was unusable (see Section 3.1.4.1): trouble with the same type of banding was reported by Wilson & Rocha (2009). The method, however, shows that it is more than possible to produce a classified image that shows habitat distribution, particularly when used along with ancillary data, essentially the OS maps, aerial orthophotos and other habitat data. Post-classification refinement will always be necessary as the spectral signatures of each habitat type are not mutually exclusive.

This method of habitat mapping has been used extensively in conservation work (Stoms & Estes, 1993). In the UK, the Countryside Survey has used results of this type of mapping in studies of bird ecology, and will be used to calculate carbon accounts for the UK (Countryside Survey, 2009). Recent methodology in the UK has used rule-based classification of multitemporal images, along with cadastral information and Cognition Network Technology software to produce a habitat map (Lucas *et al.*, 2007). The specific advantage of this would be its reproducibility and objectivity, excellent for monitoring exercises. Other studies have used a classified dataset with a protected areas dataset to show the level of protection, or lack thereof, for each habitat type (Grossman *et al.*, 1992; Sobrevila *et al.*, 1992). Other studies focussed on one specific protected area and used the habitat map for management planning (Muchoney *et al.*, 1994; Strand *et al.*, 2007).

5.2 OFFICIALLY RECOGNIZED CONSERVATION VALUE OF THE AREA.

The study area includes much of two areas designated as Special Areas of Conservation by the National Parks and Wildlife Service: Clew Bay Complex and Old Head wood (Figure 47). These sites contain habitats listed on Annex I and species on Annex II of the Habitats Directive (European Commission, 1992; NPWS, 1999, 2001, 2008). This status means that they are particularly important for conservation. The European list of Annexed habitats was defined initially during the CORINE Biotopes project (CORINE, 1991) and used that classification, but the classification has been reviewed and updated to reflect advances in science and in the extent of the European Community (EC DG Environment, 2007). They are much more detailed than the land cover types in the CORINE land cover map used in the current project.

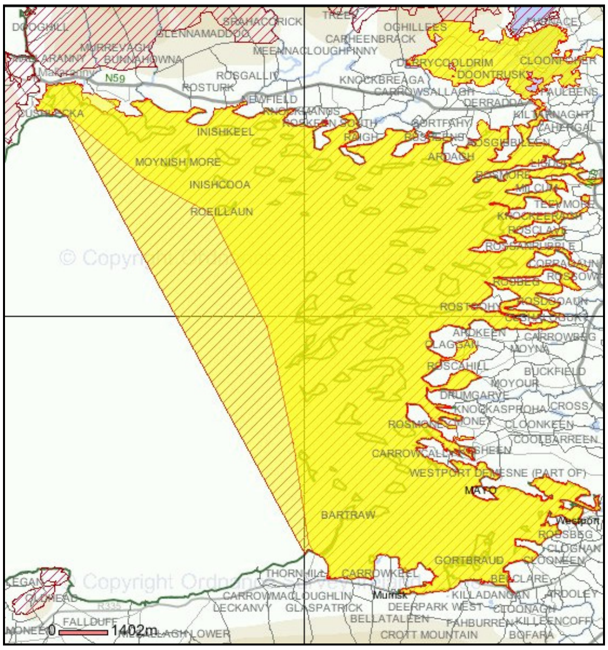


Figure 47. Designated conservation areas in the vicinity of the study area. The area in yellow is the Clew Bay Complex SAC and the small hatched area at the bottom left is Old Head Wood SAC (from NPWS website).

Table 13. List of 16 EC Habitats Directive Annex I habitats recorded in the study area (see text. Priority habitats with asterisk).

Estuaries
Mudflats and sandflats not covered by seawater at low tide
Lagoons*
Large shallow inlets and bays
Annual vegetation of drift lines
Perennial vegetation of stony banks
Salicornia and other annuals colonising mud and sand
Atlantic salt meadows
Mediterranean salt meadows
Embryonic shifting dunes
Marram (white) dunes
Alkaline fens
Silicicolous vegetation on rocky slopes
Machair*
Dry heath
Old oak woods

Ideally a habitat map would use the classification presented by the EC for the Annexed habitats so that the extent of each of these would be clear. This would facilitate monitoring of the extent of these, providing an effective indicator of the success of conservation efforts (Duelli & Obrist, 2003; Noss, 1999). The development of a national habitat mapping scheme which would aid assessment and monitoring of biodiversity was defined as a key priority by the National Platform for Biodiversity Research (NPBR, 2006). However, a habitat map of this detail is not currently available, so correlations must be drawn between the Habitats Directive classification and the categories in the existing maps.

Perhaps the most promising interim method for this is the use of the Teagasc dataset, as it has a documented correspondence to the Heritage Council Habitats (Fossitt, 2000), which in turn provides a cross-referencing table with the EC classification. Through the system of cross-referencing it is possible to determine what a Teagasc Habitat Indicator is in terms of the EC classification. This remains a clumsy method and should be replaced by the drafting of new habitat maps with a minimum mapping unit of at least 1ha, and having a classification that directly corresponds to the EC system. This would fulfil the key priority of the NPBR mentioned above.

Many species of biodiversity value occur in the study area, including two Annex II mammals, the Otter and Common seal. Coastal wetlands, saltmarshes and mud/sand flats are of great importance for bird species (Cabot, 1999). Some are listed on Annex I of the EC Birds Directive, including some tern species, Barnacle Goose, Great Northern Diver and Bartailed Godwit. Clew Bay contains nationally important populations of Barnacle Goose, Red-breasted Merganser and Ringed Plover (Crowe & Boland, 2004).

5.3 INTER-COMPARISON OF THE HABITATS/LAND COVER RESULTS.

Some broad trends were apparent from the results: an overall picture showed the retreat of land as the sea rose, which was to be expected. Because some of the lower-lying areas were inland and protected from the sea by barriers, the loss of habitat to flooding that was registered in the results would not be as great in reality. Some of these areas have already been highlighted, such as the Claggan and Rosmindle wetlands, and low-lying areas in Carrowholly. However, with expected rises of 1m and more, some roads will become inundated, as a number of these already flood at high tide, and there will be a need for more infrastructural barriers. Ideally the low-lying areas should be studied by taking each 1km grid square individually and examining the flood pattern, but this was beyond the scope of this study, and should be done when a more accurate habitat map is available, preferably using the new DEM available from Intermap or Ordnance Survey (minimum accuracy 1m in the z axis). Low-lying areas that are more exposed to the sea will be inundated such as Annagh Island and Rossmurrevagh.

These terrestrial habitats at the coast will be adversely affected and become subject to “coastal squeeze” (Radley & Dargie, 1995). The general countryside in this location is a mix of farms, farmland, rural housing and some natural areas. In the case of the former three, natural habitats at lower elevations will be prevented from expanding into these wherever possible, so loss of habitat will occur. Where there are natural areas available for habitat migration, the habitats present at lower elevations may replace those at higher elevations as sea levels rise and conditions allow (Vos *et al.*, 2008), which would change the picture given by the statistics derived in the current study. However, the statistics give a reasonable first impression of habitat loss due to sea level rise.

It can be assumed that categories that are located at the coast such as saltmarsh and sand or dunes will be directly affected by a rise in sea level, as these do not occur inland. *Dunes* and *Alkaline fens* were among the habitats identified by Byrne *et al*. (2003) as being particularly vulnerable in Ireland to climate change. On the surface it may appear that *Dunes* may be less affected than the lower shoreline habitats because they are found at higher elevations. For example, the Commonage habitats recorded *Dune* even over 10m, and as this dataset was generated by fieldwork, it is reliable. However, 60% of the dunes occurred below 7m, and generally dune systems rely upon the lower ones maintaining the sediment supply to higher, more fixed dunes (Quigley, 1991). The CORINE dataset showed an even spread of the *Beaches/dunes/sand* category among the 1m elevation intervals from 0 to 10m. The Teagasc dataset included dunes in its *Coastal complex* category (according to the cross reference to the Heritage Council classification in Table 8), and about 30% of this was above 10m (Figure 39). A combined *Dune/dry grassland* category from the classified image showed over 70% above 6m.

Two of the EC Annex I dune habitats occurred in the study area: *Embryonic shifting dunes* and *Marram (white) dunes*. Much of the dune habitat in the study area occurred on Bertra spit and head (see classified image, Figure 44), which even now is undergoing rigorous reinforcement work to protect it from being eroded by the sea. In flat sandy areas a related habitat can be found, *Machair*, which is a priority annexed habitat. *Machair* was not singled out in any maps, even in the Commonage Habitats it was included in *Unimproved dry grassland*, which occurred both on its own and as a mixed class with *Saltmarsh*. The most likely areas for it in the study area were on Annagh Island, and near Mulranny (based on the Commonage Habitats dataset and on fieldwork), and in these locations it would be at low elevations. It would be affected by any rise in sea level, although in the Mulranny area any barriers erected to protect the golf course from inundation could be extended to shield some *Machair*.

The Teagasc *Coastal Complex* class included *Littoral rock* and *Littoral sediments* (of the Heritage Council classification, see Table 8). This incorporated *Rocky shores* and *Shingle* (Fossitt, 2000), which in turn translated to the Annexed EC habitats *Annual vegetation of drift lines* and *Perennial vegetation of stony banks* (see correspondence table, (Fossitt, 2000)). Clew Bay has significant shingle areas and has the only examples of incipient gravel barriers in Ireland (on the islands) (NPWS, 2001). About 50% of the *Coastal Complex* of the Teagasc dataset was below 5m, and 60% below 8m, which would indicate that this habitat would be greatly affected by a rise in sea level (Figure 39). The Commonage Habitat dataset also covered these habitats with a mixed class, *Beach/shingle/shore*, and showed that over 80% of this was under 8m (Figure 43). Due to the nature of these classes they would have been included in the *Rocks/buildings* class of the classified image dataset, and not sufficiently separated out to give reliable results in terms of cover. There was no corresponding class in the CORINE land cover dataset; the category was probably lumped in with *Beaches/dunes/sand*. Some birds nest in shingle shores: Common and Arctic tern, Ringed Plover and Oystercatcher (Cabot, 1999).

Most of the low-lying classes of *Mud/sand* and *Dense seaweed* from the classified image were below 5m. With a rise of sea level onto ground supporting other habitats, these others may be replaced by the *Mud/sand* and *Dense seaweed*. This appeared to forecast an extension of these categories by sea level rise, but two issues would most likely cancel this out: (a) the lack of suitable habitat space to migrate into and (b) an elimination of the habitat at the deeper end of the elevations, as this will no longer be uncovered by regular tidal movement, significantly altering the environment. The latter is very significant as the lower elevations were more extensive than the upper ones (at 0m OD there were 25km^2, at 1m, 9km^2 at 2m, 4km^2, and all subsequent elevations were less than this, see Table 6). Some impression of the massive areas of mud flat uncovered by the tide is shown in Figure 48 (higher photo). In the distance are raised areas covered with dense seaweed, beyond which is the sea.

Figure 48. Bawn bay near Carrowholly with tide very low (above) and the same location with tide at 4.7m (below). Note rock with white lichen in right foreground in both photos to aid location. At low tide the sea can only be seen as a small slip in the distance between the distant ridge of dense seaweed and the foot of Croagh Patrick. Most of the area is Mud/sand flat, with saltmarsh in foreground and Dry grassland on hills.

Mud and sand flats are very important for biodiversity in that they support great numbers of invertebrates that provide an important food source for the rich diversity of waders and wildfowl present in Clew Bay (EC DG Environment, 2007; NPWS, 2001, 2008). Included in the *Mud/sand flat* class were the EC Annex I habitats of *Mudflats and sandflats not covered by* *seawater at low tide* and *Salicornia and other annuals colonising mud and sand*. The classified image produced in the current study seems to be the most accurate depiction of the extent of *Mud/sand flats* of Clew Bay to date, albeit limited by the DEM study area.

Saltmarsh was singled out as a separate category in the Commonage habitats and the classified image, but was not recorded for the study area in either the CORINE or the Teagasc datasets (it was present elsewhere in Ireland in these datasets). This was probably due to the limited extent of the stretches of saltmarsh present and the minimum mapping units of the latter datasets, but it is a strong reminder that important remnants of natural habitat can be overlooked or underestimated if spatial habitat datasets are not sufficiently detailed. *Saltmarsh* existed up to 6m in both former datasets. In the Commonage habitats dataset it was recorded as a single class but also as a mixed class with *Unimproved dry grassland* and *Wet heath*. This community type is disappearing in Ireland, even without sea level rise, and is of particular conservation concern (Curtis & Sheehy Skeffington, 1998), being included in the EC Annexed habitats *Atlantic salt meadows* and *Mediterranean salt meadows*. Irish west-coast saltmarshes are different to those on the east coast, due to differences in salinity, substratum and grazing regime, which adds to their conservation importance (Sheehy Skeffington & Curtis, 1998).

Irish saltmarshes were the subject of a systematic inventory and potential and actual saltmarsh maps have been produced ((McCorry, 2007) NPWS data). Many marshes were found to be eroding (according to fieldwork, see Figure 49), and it was noted that sediment supply that builds up the marshes is inversely proportional to storm surge (Curtis & Sheehy Skeffington, 1998). As climate change is likely to bring more frequent and intense surges this bodes ill for saltmarshes. Results from the current study indicate that saltmarshes would be very much affected by sea level rise, agreeing with Simas *et al.* (2001). Where sea level rise exceeds sedimentation the marshes will be inundated. Saltmarsh associated with lagoon was highlighted as a rare type by Curtis and Sheehy Skeffington (1998), and this was recorded by Oliver (2007) for Claggan lagoon within the current study area.

Figure 49. Saltmarshes in Bawn area of Carrowholly showing erosion at borders (above, at low tide) and approximately the same area, saltmarsh almost completely inundated (below), with tide at 4.7m (depth of water did not allow exactly the same area to be depicted in both photos, but scrub at top and fenceposts can be used as locational markers).

Dry heath is listed on Annex I and occurs in the area. The CORINE dataset distinguished a class *Moors and heathlands* (class 322), and although it was present in a number of places in Ireland it was not recorded for the study area. The Teagasc dataset distinguished a *Heath* class but did not distinguish between *Wet* and *Dry*. The Commonage Habitats dataset had both a *Wet heath* and a *Dry heath* class, both of which occurred in mixed classes and on their own. *Dry heath* was identified as a class on its own in the classified image but *Wet heath* appeared as a mixed class with *Bog and Fen*. *Heaths* recorded at lower elevations in the dataset were generally inland and protected by sea barriers. About 30% of the 179ha of *Dry heath* was at or below 5m in the classified image. An examination of this dataset showed the *Dry heath* under 5m to be located on Moynish more Island near Rossmurrevagh and in Rosmindle bog area. The area in Rosmindle is currently protected from sea level rise by barriers but that on the island would not be. Sixty percent of the *Dry heath* class was above 8m, so unlikely to be inundated by sea level rise in the next century. Some of this was found on Old Head mixed with *Broadleaf forest*.

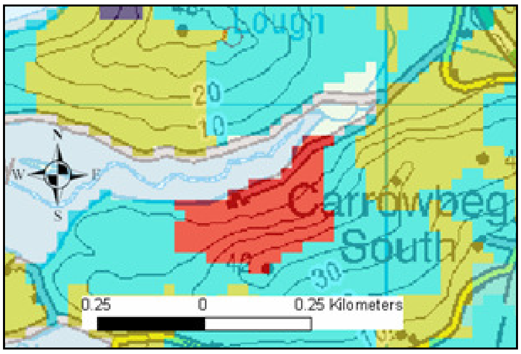


Figure 50. Clips from Teagasc dataset overlaid on OS Discovery series map. Patch of *Forest (U) and scrub* class (in red, top picture) and the same area showing developing forest on the orthophoto (bottom).

The *Broadleaf* recorded in Old Head represented parts of the *Old oak wood* Annexed habitat; Old Head SAC exists because of the occurrence of this. Adjacent to the forest was an area of Commonage that supported *Dry heath* and *Upland grassland*, according to the Commonage habitats dataset. These are not under direct threat from sea level rise as the DEM showed the land above 10m. About 12% of the *Broadleaf* class in the classified image was below 5m: approximately 47ha (Figure 45 and Table 11). The image showed the class was widely dispersed around the study area, including the islands. Much of this occurred as pockets of wooded wetland or "marginal land", and would not be old oakwood, but mainly supported trees such as willows and alder. In the CORINE dataset *Broadleaf forest* was minimal, representing 1.52ha of the entire study area. These were recorded from Westport House Estate: indeed the area included half of Westport House Lough (the other half was the class *Principally agriculture with areas of natural vegetation*). Forty percent of the 1.5ha was at 5m.

There was no forest recorded in the Old Head area in this dataset: represented were *Peat bogs*, *Principally agriculture with natural vegetation* and *Pastures*. The Old Head forest occurred as *Mature forest* in the Teagasc dataset. One other significant area of *Mature forest* occurred in the Teagasc dataset, in the Rossmalley area, which was on the coast but very little of it was below 8m, most being on a hill. Another class in the Teagasc dataset that included woodland was *Forest (U) and Scrub*. This covered 159ha of the study area, with 8ha at 5m and below. Some patches of this were quite large and were probably immature planted forests, e.g. on the south side of the Teevmore channel on Carrowbeg South (Figure 50). The lower parts of this would appear be prone to inundation on sea level rise.

Very little *Peat bog* appeared in the CORINE dataset below 4m, but then there was a sizeable increase as at 4m 18% was represented. This included mainly low-lying inland areas protected from the sea by barriers (Claggan swamp). The *Lowland blanket bog* represented in the Teagasc dataset was recorded around the same area and in Rosmindle bog. As the Teagasc dataset had two other bog classes, both of which indicated a certain amount of interference, it seemed that these areas were indeed intact *Atlantic blanket bog*, which would be an Annexed habitat. This may need further investigation, however, as other communities were recorded from those areas during the classification of the image in the current project, such as

Swamp and *Bog/fen/wet heath*. Similarly in the Commonage habitats dataset, most of Claggan swamp area was classified as a mix of *Blanket bog* and *Fen/marsh/swamp*. *Alkaline fen* is also an Annexed habitat, but it is not clear if the area contains this. Both Rosmindle bog and Claggan swamp are currently protected from sea encroachment by barriers, and these should certainly be maintained at or above the current level to protect the rich habitat mix found in the area. Ireland supports 8% of the world's blanket bogs, and many rare plants and animals occur on them (Irish Peatland Conservation Council, 2009). They have been identified as being vulnerable to climate change (Sweeney *et al.*, 2003).

Both *Dry* and *Wet grasslands* in the study area were largely used for grazing. In the Teagasc dataset they covered far more ground than any of the other classes, and the islands were mainly covered by these, along with much smaller amounts of *Coastal complex* and *Heath*. The *Pastures* and *Land principally occupied by agriculture with areas of natural vegetation* classes in the CORINE dataset covered similarly extensive areas to the *Dry* and *Wet grasslands* in the Teagasc dataset, in the region of 1,500-2,500 ha. In the classified image *Wet* and *Dry grassland* were less extensive (region of 1,000 to 1,300ha), but other areas supporting grass cover were represented by the class *Grass/bare ground/rural development*, which was also very extensive at 1,400ha approximately. Certainly some of these grasslands will be affected by sea level rise as they are so widespread and occur down to the lowest elevations, and in areas without protection from the sea. Their abundance, however, excludes them from being prioritised in conservation concerns at this stage.

5.4 VULNERABILITY AND FLOODING HAZARD.

The central question in this study was what effects would sea level rise have on habitats, and that required an attempt to establish their vulnerability. The IPCC defined vulnerability as the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, and is a function of the character, magnitude and rate of climate change to which a system is exposed, its sensitivity and its adaptive capacity (IPCC, 2001a). The adaptability of habitats to a changed "climate space" governs their prospects for the future, and this is also influenced by the ability to migrate to suitable available space (Berry *et al.*, 2003). The connectivity between habitat spaces has been found to be important for successful migration of habitats and species (Berry *et al.*, 2002). Evaluations of the longer-term prospects for a habitat should inform conservation resource allocation as it may be necessary to accept some loss of habitats with low adaptive capacity in order to save some habitats with better prospects (Berry *et al.*, 2003).

For some habitats the relationship between habitat extent and sea level rise is not straightforward because of the influence of sedimentation pattern (Nicholls *et al.*, 2007b). While the loss of low-lying shore habitats such as beaches and gravel/shingle shores may occur in a predictable pattern on sea level rise, these are also greatly affected by the rates of sediment accretion (Cowell *et al.*, 2006; Orford *et al.*, 2001). Saltmarshes are also greatly influenced by the rate of sedimentation and in some areas that rate will cancel out the inundation effects of sea level rise (Cowell *et al.*, 2006; Hughes, 2004). Areas with high tidal amplitudes (as the current study area; 5m maximum) are more likely to have higher sedimentation rates and therefore may be less vulnerable to sea level rise.

A coastal vulnerability index was derived in the BRANCH project for Northern Europe and tested on saltmarshes and mudflats along coastlines including Ireland (BRANCH Partnership, 2007). A comparison of that work with the current project showed that important habitat areas can be overlooked in regional studies of this nature. This reinforces the importance of higher resolution studies such as in the current report. Datasets for elevation and habitats (land cover) were coarse: the SRTM elevation dataset (assessed for the current project but discarded as being too coarse (Section 3.1.2.2)) and the CORINE land cover dataset. Predictions of sea level rise and 50 year return storm surge events also contributed to the vulnerability index. Indices showed the Clew Bay area as currently being in the High category, and forecasts for 2080 show it is in the Very high category. However, no saltmarshes or mudflats were registered for this area because of their absence from the CORINE dataset (Figure 51). In contrast, the current study found significant amounts of these. This shows the importance of carrying out studies at a more local level and then generalising for a regional overview, rather than using the broad brush approach, which can result in serious omissions (Lund & Iremonger, 1998).

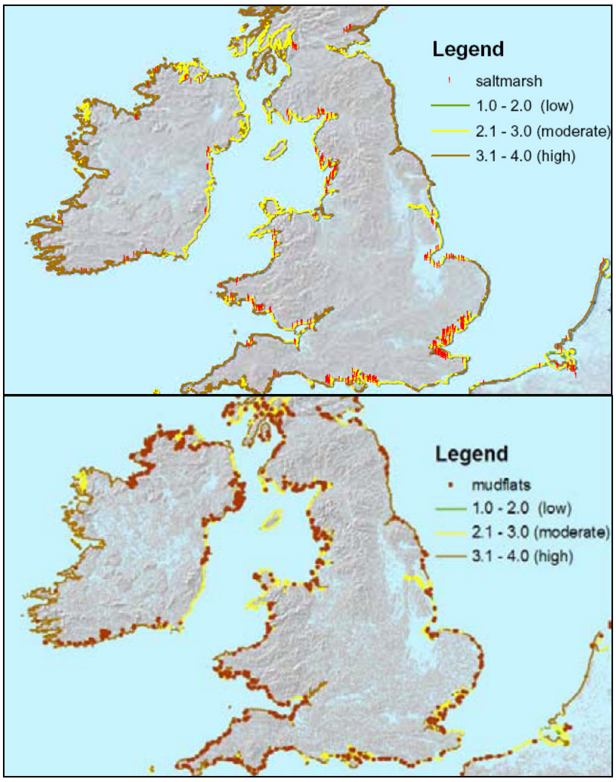


Figure 51. Saltmarsh (top) and Mudflat (bottom) distribution and vulnerability index for Ireland and part of Britain. From: Berry, P.M., Jones, A.P., Nicholls, R.J., & Vos, C.C., eds. (2007) Assessment of the vulnerability of terrestrial and coastal habitats and species in Europe to climate change. Annex 2 of Planning for biodiversity in a changing climate - BRANCH project final report. Natural England, UK.

Comprehensive studies of flood hazard mapping take into account a number of contributing parameters, one of which would be sea level rise (Hall *et al.*, 2005; Holman & Loveland, 2001; Nicholls *et al.*, 2007a). With the increase in flood hazard in many countries due to climate change effects, governments have supported research into flooding. However, most flood hazard studies focus on the economic and social effects of flooding, not on its effects on natural communities (Darwin & Tol, 2001; Evans *et al.*, 2004; Nicholls *et* *al.*, 2007a; Philip Williams and Assoc. Ltd., 2008; Tol, 2007; Yohe *et al.*, 1996). Richards *et al.* (2008) have linked socio-economic futures to habitat viability under climate change, and suggest that land management choices that society makes will be key to conservation of biodiversity. In the coastal Clew Bay area there has been much rural development activity in the past decade, noted in the CORINE change study (Section 4.3.1.1) and by the author (personal observation). Management of this will be important for the maintenance of biodiversity in the area under the additional pressures that climate change will bring (Nicholls & Klein, 2005).

The use of GIS and DEMs have increased accuracy and efficiency in updating and predicting flooding (Hall *et al.*, 2003; Jones *et al.*, 1998). Floods can result from excessive rainfall within a short duration of time; consequent high river discharge damages crops and infrastructures (Sanyal & Lu, 2004). The LISFLOOD model was developed to simulate floods in large European river basins and used potential evaporation, rainfall and daily mean air temperature in addition to land cover and soil parameters to model and forecast flood patterns (De Roo *et al.*, 2003; De Roo *et al.*, 2000). A study of the Lee river catchment in Cork assumed forecasted 20-30% increases in river flow due to climate change (Halcrow Group Ltd, 2008), from precipitation forecasts presented by Sweeney and Fealy (2006). Barriers to sea encroachment can prevent swollen rivers from freely entering the sea, causing flooding inland, as shown in (Figure 7 (Section 2.7)), thus affecting coastal habitats (Leatherman, 2001).

With the new availability of nationwide high-resolution DEMs from the Ordnance Survey and Intermap, it would be possible to carry out a more detailed study of the effects of climate-change-induced flooding on habitats. Flood models that address catchment-level systems could be applied (Liu & de Smedt, 2005). New visualisation tools such as GeoVisionary, developed by Virtalis and British Geological Survey enable the scientist to combine information layers quickly and easily and investigate them in 3D (Virtalis, 2009). GeoVisionary can be combined with ArcMap to extract statistics.

This tool would cut analysis time to a fraction while facilitating more accurate results than were possible before, and is currently available in Ireland (Scanlon, 2009). New methods of classification using multitemporal imagery, segmentation and fuzzy membership should be tested for their potential contribution to vegetation mapping in Ireland (Dean & Smith, 2003; Lucas *et al.*, 2007).

The Clew Bay area has been shown to be an excellent location for a pilot study due to its intimate and intricate land-sea relationship, topography, biodiversity importance and climate. Extending the study to larger areas, even to a nationwide survey, would be possible if resources were made available.

6 CONCLUSIONS

This study showed the possibilities for modelling the effects of sea level rise on habitats in Ireland. Useful data may be derived about the amount of each habitat lost with flooding to increased levels. In the Clew Bay area important extents of mud flats will be lost with an increase of just one metre. Other low-lying coastal habitats will be diminished, such as saltmarshes, rocky and sandy shores and dunes. "Coastal squeeze" will be prevalent in most places as suitable habitat space higher up is not available. Some grassland and wooded areas will also be affected. Swamp, fen and bog habitats currently exist below high tide level, particularly in the Claggan and Rosmindle areas, but are protected from the sea by barriers. These barriers will probably be of sufficient height to keep out the sea with rises of up to 2m. However, with increased rainfall due to climate change these habitats may be adversely affected by flooding from inland sources.

Existing spatial data depicting habitats or land use in Ireland were found to be lacking in sufficient detail to extract meaningful statistics for habitat loss at a local level. The construction of a new habitats dataset for the Clew Bay study area indicated that it was possible to create better habitat maps using Landsat imagery, a high-resolution DEM, aerial orthophotos, other limited fieldwork and existing ancillary spatial datasets. Refining the classified image presented here and extending the mapping to other areas would contribute to satisfying one of the main recommendations of the NPBR. Newly available high-resolution DEMs and geo-visualisation facilities should be used to extend this analysis of the effects of sea level rise on Irish habitats to the entire coastline of Ireland. Socio-economic decisions made about planning land use and the mitigation of climate change effects will impact coastal biodiversity.

APPENDICES

Appendix 1 CORINE land cover 2000 dataset: land cover types in Ireland with areas (from ERA-MapTec (2004)).

Code_00	Cover	Area (km^2)	% of Country Area
111	Continuous Urban Fabric	50.67	0.07
112	Discontinuous Urban Fabric	876.23	1.23
121	Industrial or Commercial	60.85	0.09
122	Road and Rail networks	20.37	0.03
123	Sea Ports	10.79	0.02
124	Airports	22.53	0.03
131	Mineral extraction sites	82.24	0.12
132	Dump	3.43	0.00
133	Construction sites	27.91	0.04
141	Green Urban areas	37.26	0.05
142	Sport and Leisure facilities	163.01	0.23
211	Non-irrigated arable land	5449.47	7.66
231	Pastures	36589.25	51.45
242	Complex cultivation	1235.33	1.74
243	Land principally occupied by agriculture with areas of natural vegetation	4259.59	5.99
311	Broad Leaved forest	308.42	0.43
312	Coniferous forest	2435.56	3.43
313	Mixed forest	223.99	0.31
321	Natural grassland	933.67	1.31
322	Moors and Heaths	590.60	0.83
324	Transitional woodland scrub	3421.18	4.81
331	Beaches, dunes, sand	138.63	0.19
332	Bare rocks	167.26	0.24
333	Sparsely vegetated	201.71	0.28
334	Burnt areas	0.90	0.00
411	Inland Marshes	180.17	0.25
412	Peat Bogs	11461.76	16.12
421	Salt Marshes	31.05	0.04
423	Intertidal flats	454.95	0.64
511	Stream courses	96.68	0.14
512	Water bodies	1228.59	1.73
521	Coastal lagoons	10.11	0.01
522	Estuaries	336.14	0.47
	Total	71110	100

Appendix 2 Metadata for image downloaded.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Appendix 3 Fieldwork results.

Fieldwork took place in July 2009. Results are rudimentary plant species lists and photos. Further work would be required for a more comprehensive survey leading to a well-founded classification. However, there were a number of different plant communities found, mostly mixed in intricate mosaics and difficult to separate out. These included a number of wetland types, from bog and fen to swamp and marsh, as well as some heath. Botanical nomenclature follows Stace (1997).

Claggan swamp (Grid: 94,600, 289,000).
This is divided by a road running approximately North-South, and descriptions below describe the area East of the road and the area West of the road, as well as the community adjacent to the river as it approaches the sea barrier.

East of road: This area is swamp in its main character but includes elements of wet heath in hummocky areas raised above the main flooding height. Patches of scrub and woodland as well as a mix of fen and bog occur. See two photos that follow.

Typha angustifolia	*Irish pseudacorus*
Filipendula ulmaria	*Potentilla palustris*
Ranunculus flammula	*Ulex europaeus*
Mentha aquatica	*Juncus articulatus*
Equisetum sp.	*Succisa pratensis*
Molinia caerulea	*Pedicularis palustris*

Claggan swamp, looking East from road showing pool indicating water table, with swamp areas surrounding this and hummocks supporting heath vegetation.

Claggan swamp, looking East from road, showing the very variable nature of the vegetation from broadleaf woodland and scrub at rear to wet heath and fen/bog in foreground.

West of road: an area of slightly different character, with very wet areas including pools around the main water bodies, and drier areas of bog where the ground is higher. See photo that follows.

The wetter areas have swards of monodominant sedge and rush, *Scirpus lacustris* and *Bolboschoenus maritimus* (subject to confirmation), with few other species among which were *Myosotis scorpioides*, *Ranunculus flammula, Equisetum* sp. and *Cardamine pratensis*.

West of Claggan swamp road including areas of bog and of dense rushes beside pools. The bog areas support sedges at about 40% cover, 30 cm high, rushes at 15% and moss cover at 40%, but not *Sphagnum* moss. Other plants were:

Salix aurita	*Stachys palustris*
Salix cinerea	*Mentha aquatica*
Galium palustre	*Equisetum sp.*
Carex nigra group spp.	*Vicia cracca*
Succisa pratensis	*Holcus lanatus*
Potentilla erecta	*Luzula multiflora*
Oenanthe crocata	*Pedicularis palustris*
Calluna vulgaris	*Orchid* sp.

Community along river approaching sea barrier: some brackish water occurs. Habitats support wet grassland grading into marsh with saline influences. In shallow water and mud a diminished form of *Fucus* seaweed occurs, in parts it cloaks the mud around swards of small rushes.

Claggan riverine area where river flows towards the sea, showing diminished forms of *Fucus* spp. and swards of Juncaceae and Cyperaceae.

Rosmindle area (Grid: 94500, 287,600).
This contains reedswamp and wetland with bog and fen characteristics.

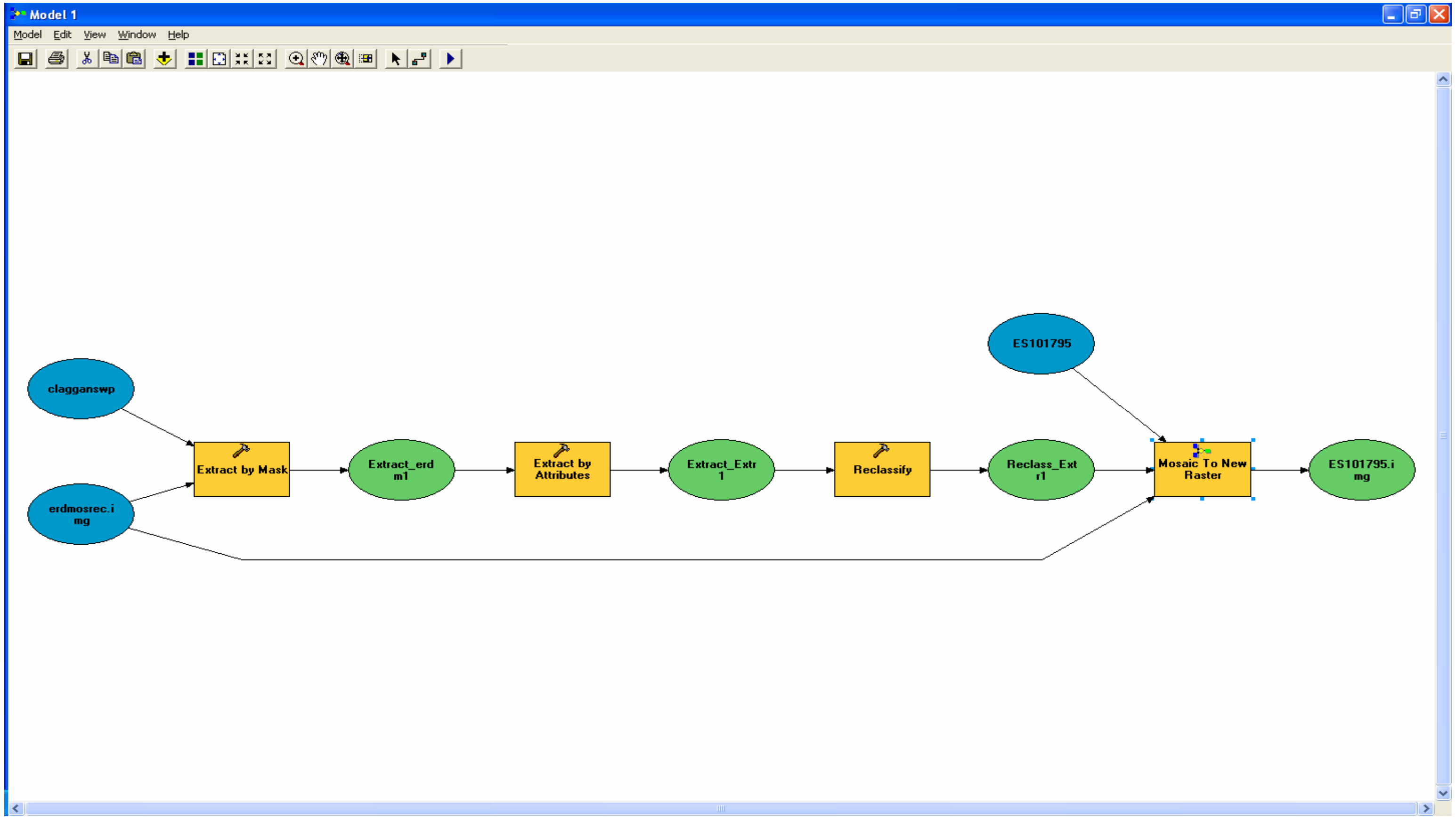
The reedswamp contains mainly *Phragmites australis*. The bog/fen area contains plants such as:

Menyanthes trifoliata	*Schoenus nigricans*
Calluna vulgaris	*Salix aurita*
Succisa pratensis	*Molinia caerulea*
Potentilla erecta	*Mentha aquatica*
Filipendula ulmaria	*Parnassia palustris*
Iris pseudacorus	*Scirpus lacustris*
Erica cinerea	

Rosmindle bog/fen

Rosmindle reedbed (swamp)

Appendix 4 Model in ArcMap for reclassifying certain pixels in a classified image.



The model above is in ArcMap and clips out a polygon-delineated area of the image, reclassifies pixels from one class to another in the clipped piece and then mosaics it back into the original image.

Appendix 5 Area (ha) of each habitat type in the CORINE dataset, with sea level at different elevations from 0 to 20m (habitat area decreases as sea level increases), and total area of land covered by all habitats under the same flooding levels (bottom).

Land cover	Area 0m	Area 1m	Area 2m	Area 3m	Area 4m	Area 5m	Area 6m	Area 7m	Area 8m	Area 9m	Area 10m	Area 15m	Area 20m
Broadleaved forest	2	2	2	2	2	1	1	1	1	0	0	0	0
Sport and Leisure facilities	16	16	16	16	16	15	12	10	8	6	5	0	0
Non-irrigated arable land	35	35	35	35	27	21	18	16	15	14	13	9	6
Beaches, dunes, sand	68	65	60	53	43	34	24	17	13	10	8	6	4
Discontinuous urban fabric	78	78	78	78	78	77	76	74	72	71	69	61	48
Complex cultivation	109	109	109	109	109	107	103	99	94	89	86	64	45
Peat bogs	128	128	128	125	105	102	101	100	99	98	97	93	87
Transitional woodland scrub	220	220	220	220	219	212	209	205	201	196	193	131	94
Land principally occupied by agriculture with patches of natural vegeation	1641	1631	1617	1591	1520	1410	1337	1284	1234	1182	1121	795	546
Pastures	2278	2191	2112	2052	1981	1873	1752	1652	1565	1484	1403	946	621
Total	**4575**	**4475**	**4376**	**4279**	**4100**	**3852**	**3633**	**3458**	**3301**	**3151**	**2996**	**2105**	**1450**

Appendix 6 Area (ha) of each habitat type in the Teagasc dataset, with sea level at different elevations from 0 to 20m (habitat area decreases as sea level increases), and total area of land covered by all habitats under the same flooding levels (bottom).

Habitat	Area 0m	Area 1m	Area 2m	Area 3m	Area 4m	Area 5m	Area 6m	Area 7m	Area 8m	Area 9m	Area 10m	Area 15m	Area 20m
Water	1	1	1	1	0	0	0	0	0	0	0	0	0
Rocky Complex	6	6	6	6	6	5	5	4	4	4	4	3	3
Cutover / Eroding bog	7	7	7	7	4	4	4	4	4	4	4	3	0
Sand	15	15	15	15	12	8	4	2	1	0	0	0	0
Mature Forest	24	24	24	24	24	23	23	23	23	22	22	20	17
Bare Peat & Soil	24	24	24	24	23	22	19	16	14	11	9	4	2
Built Land	29	29	29	29	29	28	26	23	21	19	16	7	3
Coastal Complex	36	36	35	34	31	25	20	17	15	13	11	4	0
Lowland Blanket bog (LBB)	42	42	42	39	12	5	4	4	3	3	2	0	0
Wetland	65	65	65	62	47	30	24	18	15	14	13	0	0
Reclaimed LBB	90	90	90	90	78	60	54	52	48	47	40	21	9
Forest(U) & Scrub	159	159	159	158	155	151	147	143	139	134	128	99	79
Heath	172	172	171	169	161	145	136	132	127	124	120	96	69
Wet Grassland	1427	1427	1425	1418	1395	1344	1290	1245	1202	1151	1103	842	603
Dry Grassland	2504	2502	2497	2476	2425	2293	2147	2028	1921	1820	1716	1118	724
Total	**4599**	**4597**	**4589**	**4550**	**4401**	**4142**	**3901**	**3711**	**3537**	**3365**	**3188**	**2216**	**1507**

Appendix 7 Percent loss of each habitat combination for the Commonage Habitats file, on rise in sea level.

Habitat Code	Habitat Name	% lost 0-1m	% lost 0-2m	% lost 0-3m	% lost 0-4m	% lost 0-5m	% lost 0-6m	% lost 0-7m	% lost 0-8m	% lost 0-9m	% lost 0-10m	% lost 0-15m	% lost 0-20m
VII	Dune	0.00	1.56	4.84	8.03	19.31	40.50	59.45	74.42	86.55	95.40	100.00	100.00
II/III	Wet/Dry Heath	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
II	Wet Heath	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
VIII	Un. Wet Grs.	0.00	0.00	0.47	1.76	3.30	4.40	5.86	7.95	10.71	12.72	26.35	42.10
IX	Un. Dry Grs.	0.00	0.18	2.38	16.63	38.38	54.64	61.16	65.71	70.07	73.57	79.94	85.53
III/VIII	Dry Hth/Un. Wt Grs.	0.00	0.42	1.79	3.58	5.16	7.38	11.06	14.54	19.49	24.66	49.74	70.71
VII/IX	Dune/Un.Dry Grs.	0.00	0.05	0.10	3.50	6.62	8.37	9.93	11.92	13.92	16.98	37.52	63.89
XII	Beach/Shingle/Shore	0.00	1.24	12.39	45.97	74.97	87.40	92.18	94.18	96.51	98.76	100.00	100.00
VIII/IX	Un. Wet/Dry Grs.	0.00	0.36	2.44	6.39	9.05	11.48	14.22	17.53	21.41	25.71	47.85	68.44
I/X	Bl Bog/Marsh/Fen	0.00	0.00	12.10	96.00	99.10	99.52	99.70	99.79	100.00	100.00	100.00	100.00
III	Dry Heath	0.00	0.16	0.62	1.38	2.54	3.30	3.90	4.52	5.44	6.47	9.47	15.97
XI	Saltmarsh	0.00	0.00	0.34	32.90	86.58	97.85	99.53	100.00	100.00	100.00	100.00	100.00
II/VII	Wet Heath/Dune	0.00	0.00	0.00	0.33	2.75	6.21	9.20	13.00	18.03	23.67	57.54	83.63
II/XI	Wet Heath/Saltmarsh	0.00	0.00	0.00	2.40	30.84	99.84	100.00	100.00	100.00	100.00	100.00	100.00
IX/XI	Un. Dry Grs./Saltmarsh	0.00	0.09	3.59	16.97	48.43	80.18	99.66	100.00	100.00	100.00	100.00	100.00
IV	Upland Grs.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	2.45	6.30
VII/XII	Dune/Beach/Shingle/Shore	0.00	0.00	1.32	13.69	35.29	60.84	82.74	97.07	99.98	100.00	100.00	100.00

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