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The impact of coastal flooding on conservation areas: A study of the Clyde Estuary, Scotland

Jones, Gareth & Ahmed, Sayeed

Department of Geography, University of Strathclyde, Glasgow G1 1XN, Scotland, United Kingdom;
E-mail chds01@strath.ac.uk

Abstract. This study examines the impact of flooding on land of high conservation value located along part of the southern shoreline of the River Clyde Estuary in western Scotland. This paper hypothesizes that, over the next 50 years, the frequency and extent of coastal flooding will increase due to the gradual effect of global warming and the consequent rise in sea-level and increase in storminess. It is argued that because of the great cost of constructing new flood defence systems it will not be possible to protect all land areas to an equal extent from flooding. A means of ranking different land use will be necessary so that society can make a rational judgement concerning which sections of coastline will be worth protecting. This study provides a methodology that combines an objective ranking of conservation areas using non-economic indicators with a GIS model of flood potential, and permits accurate forecasts of flood losses to conservation areas of different ecological value. The conservation case study used in this paper proposes the use of an ecological weighting value based on five ecological variables each of 10 categories. Tables and maps identify the sites that have been highlighted as consisting of the most 'valuable' conservation sites. The methodology makes extensive use of geographical information systems (GIS) to model the predicted areas of flooding and to calculate conservation weighting values of the land areas.

Keywords: Bird population; Ecological modelling; Geographic information system; Global warming; Habitat evaluation; Sea-level rise.

Introduction

Intertidal and coastal areas form a transitional strip of land between the sea and the land, characterised by distinctive natural or semi-natural ecosystems. Concern has been expressed that these areas will be particularly vulnerable to the relative change in sea-level that is expected to occur over the next 30 - 50 yr as a result of global warming (Anon. 1996, p. 3). However, an element of uncertainty exists over the ability of intertidal areas to adapt to sea-level rise. Research carried out by Stevenson et al. (1986), Reed (1990) and Dijkema (1997) concluded that mud banks and salt marshes in coastal and estuarine settings are frequently able to keep pace with sea-level rise. Dijkema (1997) has shown that salt marshes off the north west coast of The Netherlands can grow vertically at a rate of between 5 and 10 mm/yr, a rate well in excess of most predictions for sea-level rise in the next 50 yr. However, global warming will bring additional changes, for example to wave energy and to the duration and frequency of flooding as well as to the supply of sediment. Estuaries that have valuable land use along the shorelines may be subject to greater frequency of flooding and it is the purpose of this paper to present a methodology for forecasting the location and impact of flooding due to a rise in sea-level. In particular, it evaluates the effect of flooding on units of land with a recognised conservation value.

The River Clyde Estuary

The River Clyde has been continuously dredged for ca. 200 yr and a series of sea walls and embankments, or bunds, have been built on shore to prevent flooding from exceptionally high tides (see Fig. 1). The junction between the estuary and the land in the Clyde Estuary is formed mainly by a sharp boundary between an intertidal mud zone and either a man-made boundary (sea wall or embankment) or a grass-covered slope, exposed in all but the highest tide situations. Only two small salt marsh communities occurred in the estuary.

Many estuaries have become the focus of 'redevelopment', especially so in the case of European estuaries subject to post-industrial renaissance. Major changes to the built environment along the edge of the estuary have resulted in substantial changes to the detailed geomorphology of the estuaries. Since the 1960s the River Clyde has witnessed many ambitious planning projects designed to revitalise the corridor following the demise of the shipbuilding yards (Roe 1979). Despite more than 250 yr of development, some areas of coastal grassland, salt marsh and agricultural land remain in a natural or semi-natural form. The study area comprised 11.3km of estuary shoreline, of which 4.2 km remained in a natural or semi-natural form.

Within 100 m of the estuary edge, 55 % of the land use remained undeveloped. Many of these natural areas have attained considerable local and national value as ecological and ornithological sites.

Those sections of the estuary that have been developed show great variety in form and function. Among the oldest developments are the substantial sea walls, built in the 1850s to protect railway lines. The most recent developments date from the 1960s and 1970s when urban and industrial redevelopment occurred in connection with Erskine New Town and a computer manufacturing plant. The alternation of developed and undeveloped land along the estuary has resulted in considerable spatial variation in both the economic and ecological values of the land.

The area was chosen for detailed study because of its persistent history of flooding, its varied land use, its conservation value, its varied types of flood protection and the threat of future flooding due to sea-level rise. Many of the original sea walls are life expired yet this defence network still provides protection to floods 5 m above Mean High Tide (MHT).

The extent of sea-level rise due to global warming has become clearer in recent years (Anon. 1999), although the expected impacts at a regional level remain difficult to predict. Titus (1993) has examined the regional effects of sea-level rise and Bird (1993) suggested that planners need to begin reorganising coastal land use in coastal areas by drawing 'set back' lines that take account of forecast change. Because coastal ecosystems are the result of a delicate balance between salt and fresh water inundation even slight changes in the flood pattern can be expected to bring about substantial ecosystem change (Peters & Darling 1985). Identifying the areas worthy of protection and those which could be allowed to flood become critical as the value of land and property interact with the time and money needed to construct a strengthened sea defence system. Methodology described in this paper allows the spatial distribution of flood prone areas to be combined with a flood damage index value and allows the impact of flooding to be assessed in terms other than simply identifying the areas most at risk from flooding.

Identifying areas at risk from coastal flooding

This paper assumes that there is already sufficient inertia in the release and accumulation of greenhouse gases in the atmosphere to ensure a commitment to a rise in sea-level until 2050 (Crutzen & Golitsyn 1992). Based on calculations published by the UK Department of Environment (Anon. 1996) it has been estimated that sea-level around the British Isles will rise by 140mm over a 50-yr period. In addition, a warmer atmosphere will produce a greater frequency and intensity of storms (Portney 1991; Wigley et al. 1992), resulting in greater freshwater runoff and an alteration in the rate and distribution of sedimentation. Changes in the flow rate of the River Clyde have already occurred, with peak flow increasing from 670 m^3/sec in 1985 to 830 m^3/sec in 1994, an increase of 24% (pers. comm. West of Scotland Water 1999).

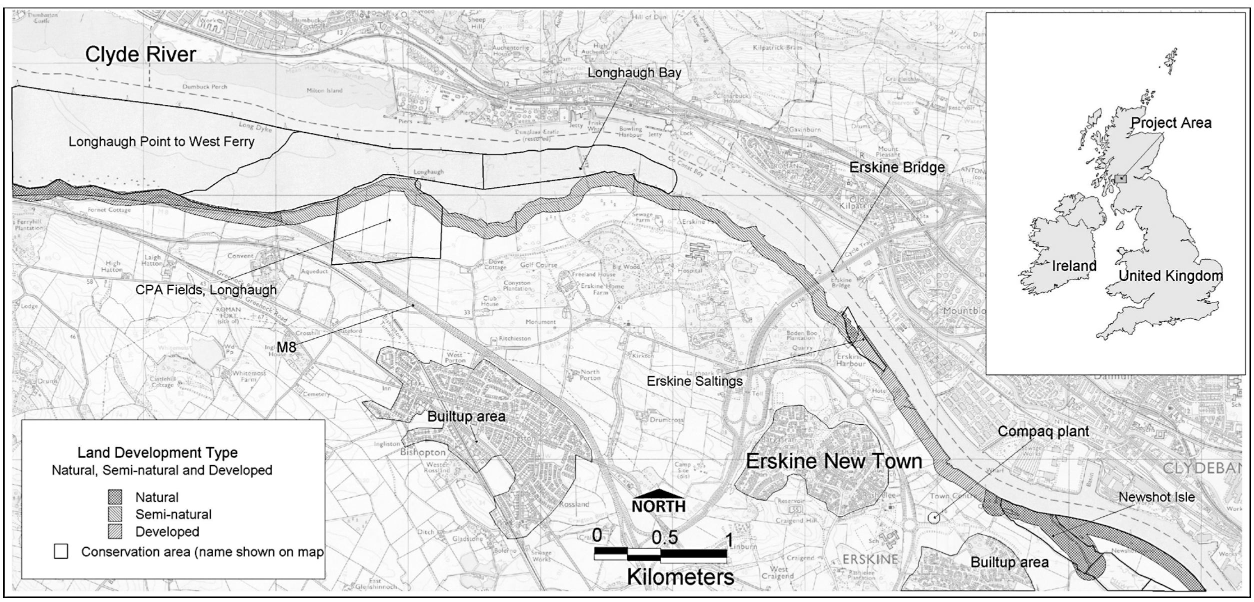

Fig. 1. Location of conservation areas and land development type within 100 m of Mean High Tide, Clyde Estuary study area. Ordnance Survey base map reproduced by permission. Crown Copyright Approved.

Damage caused by flooding will be a function of the frequency and depth to which flooding occurs and the vulnerability of the land use affected by flooding. Fig. 2 illustrates the relationship between these variables. The impact of flooding on areas designated as 'conservation areas' may cause minimal economic and human loss but the impact of salt water on natural or semi-natural ecosystems may result in a substantial mortality of species. Only those species tolerant of halophytic conditions would benefit from inundation. Areas that are flooded infrequently, for example once in 100 yr, may suffer more severely because the ecosystem has a greater intolerance of salt water compared to the species assemblage in areas prone to more frequent salt water flooding.

Land that is used commercially will possess an established economic value. For these areas it is possible to prepare a cost benefit analysis to calculate how much capital investment will be lost if flooding occurs. Economists have attempted a similar exercise for land that is marginal to the economic system, for example marginal agricultural land or land with a conservation value (Macmillan et al. 1996; Hanley et al. 1998). However, designating financial values to conservation land use is problematical and this paper proposes the evaluation of conservation areas by means of an ecological evaluation score based on the degree of interference to the ecology and on the human use of the area. The construction of the index is discussed below.

Methodology used to identify conservation habitats in the Clyde Estuary

Unpublished field work prepared by one of the authors for the Clyde Port Authority in 1989 identified areas of ecological value within the Clyde Estuary. Each conservation area was allocated a 'land value' or weighting and this value was used in conjunction with the depth and duration of flooding to calculate a damage index value. A geographic information system ((MapInfo and Vertical Mapper) was used to overlay map layers (or coverages) and to construct maps showing the distribution of damage index areas. The sites were ranked on a scale of 1 (poorest) to 10 (most valuable) for five criteria shown in Table 1. A composite score, also on a scale of 1 to 10, was derived from the five criteria and used as an indicator for the ecological value of the site. The use of an objective ranking comprising five assessment categories has been proposed as a multi-criteria assessment system similar in objective to that of a land classification scheme (e.g. Bibby & Mackney 1977). The ranking procedure proposed in this paper is subject to development and the objective remains to develop a widely acceptable assessment system that incorporates additional indices such as a biodiversity index, species and community ranking and socio-economic data. The advantage of storing data in spreadsheet format for use in GIS is that revisions or additions to the data base can be made and the model re-run to produce new maps and tabular output.

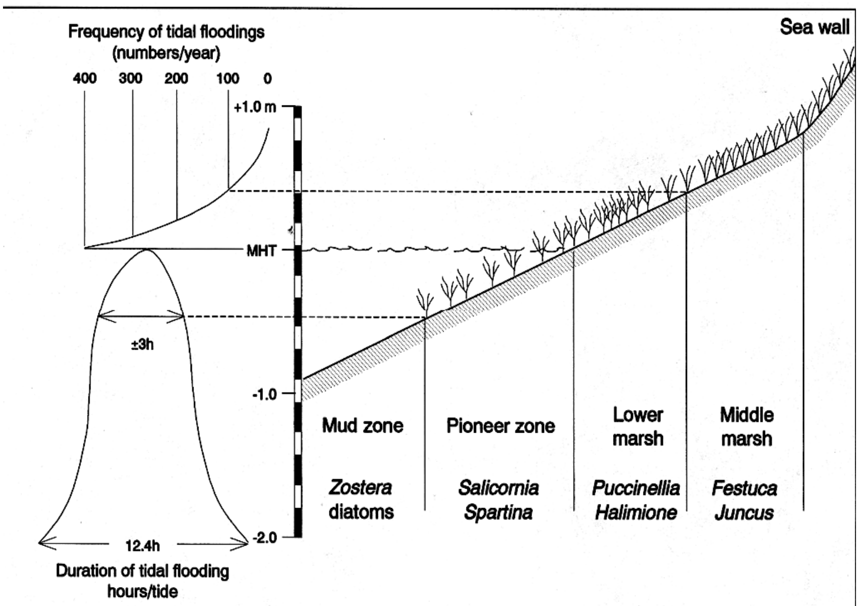

Fig. 2. Stylized zonation of intertidal salt marshes in relation to duration and frequency of tidal flooding. After Erchinger (1985) for the Wadden Sea.

The ecological evaluation scores formed a map layer that was used in conjunction with UK Ordnance Survey Land-Form PROFILE digital data used to construct a digital terrain model (DTM) with a spatial accuracy of 10 m on the horizontal axis and ± 1.0 m root mean squared error on the vertical axis. The DTM was constructed from data obtained in NTF format v2.0 as specified in BS 7567, full details of which are provided in Ordnance Survey Land-form Profile Sample Data User Guide Ordnance Survey 1997. A three-dimensional representation of the DTM is shown in Fig. 3. The study area extended over two standard Ordnance Survey map tiles reference numbers NS47SE and NS47SW, each covering an area of 5km × 5km. For each tile there were 501 columns and 501 rows of data making a total of 501 ×501 ×2, that is, 502002 data points. For the purpose of this study, conversion software for interpretation of the data in NTF format by commercial GIS software was written by one of the authors. The data was imported into MapInfo and the DTM surface was interpolated using an inverse distance weighting (IDW) method using Vertical Mapper software. Resolution of the resulting raster surface was set at 10 m Interpolation within these limits allowed the plotting of detailed contours at 1-m intervals. Additional layers (coverages) of data including physical, environmental, land evaluation and planning data were compiled and used to construct an environmental model in which the sea-level was assumed to rise in intervals of 1m from 0 to 6.0 m above MHT (Mean High Tide). The model enabled the identification of specific areas of the estuary that would become flooded at different stages of sea-level rise. The modelling of sea-level rise and its intersection with polygons for ecological evaluation values allowed a quantification of the ecological losses that would result from a specific depth of flooding. The results of the study could be displayed both in map and tabular output.

Table 1. Scoring system used for the ecological evaluation of study area sites. Method: for each location, allocate the appropriate scoring value in each assessment category. When all five assessment categories have been completed, added the five scores and divide the product by five. This represents the ecological evaluation score for the site. A value of 1 represents the lowest ecological value, a value of 10 represents the highest value.

	Assessment category				
Score	Built environment	Accessibility	Human interference	Agriculture	Ecosystem diversity
1	Full urban landscape	Metalled road leads to estuary	Constant use for human activities	Intensive arable monoculture	Urban landscape
2	Urban edge within 1 km	Rough track leads to estuary	Used for 9 months in 12	Intensive animal husbandry	Formal park land
3	Urban edge within 500 m	Footpath leads to estuary	Used for 6 months in 12	Intensive mixed arable	Exotic species, plantation forestry, shelter belts
4	Isolated dwellings within 500 m	Access via water to mooring point	Used for 3 months in 12	Extensive mixed arable	Evidence of reseeding at an earlier date
5	Single house within 500 m underground pipelines	Occasional use by farmer for access to animals or crops	Used for 30 days in 1 yr	Low intensity management of grassland and woodland	Species-poor natural ecosystems
6	Farm building in use	Cross-country access point used by fishermen or bird watchers	Last used 1 yr ago	Extensive permanent grazing	Native species plantations
7	Farm buildings recently disused	Absence of any access within 0.25 km	Last used 10 yr ago	Low intensity or seasonal grazing	Species-moderate natural ecosystems
8	Abandoned farm buildings	Absence of any access within 0.5km	Last used 25 yr ago	Organic farming	Species-rich ecosystems but showing evidence of modification
9	Fences, posts, radio masts or pylons	Absence of any access within 1km	Last used 50 yr ago	Evidence of agriculture at an earlier date	Unmodified tidal ecosystems, salt marsh
10	Absence of any built structures	No track nor fence, wall or ditch	No evidence of human use within 100 yr	No evidence of agriculture	Species-rich terrestrial natural ecosystems

Assessing flood vulnerability of a site

The vulnerability of a site to flooding will be a function of its horizontal and vertical distance relative to the line of MHT. Consequent upon these two values it would be possible to calculate the depth to which flooding occurs and to estimate the duration of flooding.

Availability of historic tidal records obtained from a tide gauge would allow the frequency of flooding to be calculated. Duration and frequency of inundation are critical to the survival of existing habitats and to the sediment accretion rate and consequently the evolution of the site. Flood protection is currently provided in the most vulnerable stretches of the estuary to a water level of 5.0 m above MHT. At critical times the water level has reached the top of the current defence system. Unprotected coastline has, therefore, already been subjected to inundation of the type predicted in this paper. It is postulated that the water level will exceeded 5.0 m MHT at some point in the next 50 yr as a result of global warming.

The likelihood of an area becoming flooded was calculated in the following manner. The position of the 6-m contour line was calculated from the Land PROFILE data and all locations below this contour line were subtracted from six to give the depth of flooding for each 10m $\times$ 10 m cell. The flood potential matrix was overlain with a second grid containing the corresponding cell values for the ecological weighting values as calculated from Table 1 and a final flood vulnerability score was calculated by the simple rule of multiplying the ecological ranking at every location with the corresponding flood risk score. This method enabled two equally ranked ecological cells to return different flood vulnerability scores depending upon their risk of flooding index.

The use of GIS was essential in providing the capability of preparing and combining the data layers. In addition, GIS provided many other advantages. It allowed many iterations of the model to be performed with different ecological and flood risk values. It would also be possible to include other data layers, for example, political, economic, social, environmental and engineering data layers. It is envisaged that as our knowledge of global warming and sea-level rise improves then also our political, planning and social responses to the threat of flooding will change. The methodology described will allow new data and new weightings to be introduced as necessary and the model re-run in the light of changes in public policy and public attitudes towards coastal flooding and habitat loss.

The conservation sites

The section of Clyde coastline used in this study included four sites of recognized conservation value. The location of the sites is shown in Fig. 1.

West Ferry to Longhaugh Point

This was the largest unit in the study extending over 545 ha and formed an eastern continuation of the Langbank Site of Special Scientific Interest (S.S.S.I.). This site had been assessed in 1985 by Scottish Natural Heritage, the government body responsible for designating and managing areas of ecological and scientific value, as an area worthy of conservation due to its extensive intertidal mud banks used as a feeding ground for large numbers of seabirds and water fowl. The inland boundary was marked by coastal grassland; the inter tidal area was un-vegetated apart from small patches of sea weed. The area provided a major habitat for a wide variety of resident and migrant wetland bird species. In addition, many small woodland and moorland bird species used the area at low tide. Public access to the area was possible although the proximity of a motorway at the western extremity ensured that most humans obtained only passing views of the area as they travelled along the motorway. Despite the area's designation as an S.S.S.I., its aggregate ecological evaluation index value was 4.4. The habitat was marked down for its accessibility and human interference.

	Assessment category
Built environment	5
Accessibility	2
Human interference	1
Agriculture	6
Ecosystem diversity	8

Aggregate score = 22
Ecological evaluation score for the site = 4.4

A rise in sea-level would expose a smaller proportion of the extensive intertidal mud banks resulting in a smaller feeding area for a shorter duration for the birds that occupy this area. A rise in sea-level would push the shore line further inland and erode the grassland immediately above high water.

Longhaugh Bay

This area had no formal conservation designation even though it displayed a variety of intertidal habitats. Exposure to winds blowing up the estuary was higher than in the previous area and coastal erosion was evident along the shore line. A number of brackish water hydrosere communities dominated by *Phragmites* occurred in slack water areas. Ease of access to the site, and major human use resulted in an ecological evaluation score of 4.2. It was an area much frequented by bird watchers and anglers.

	Assessment category
Built environment	6
Accessibility	2
Human interference	2
Agriculture	4
Ecosystem diversity	7

Aggregate score = 21
Ecological evaluation score for the site = 4.2

Continuing eastwards from the previous site the land use changed to an area of agricultural land. During autumn and winter storms the fields provided an important area of shelter for large numbers of birds. A private golf course was the next land use type to be encountered. A large earth and concrete barrier had been constructed at the water's edge to restrict wave erosion. The site had the lowest ecological value with a score of 2.4. The exposed nature of this site would allow wave action to make a major impact on the land ward edge of the site. A raised sea-level could be expected to increase coastal erosion and raised salt water levels impact on the *Phragmites* dominated hydrosere.

	Assessment category
Built environment	4
Accessibility	2
Human interference	1
Agriculture	3
Ecosystem diversity	2

Aggregate score = 12
Ecological evaluation score for the site = 2.4

Erskine Harbour and Salt Marsh

This small site, less than 50 ha, was previously a slipway for one of the many ferries that operated on the Clyde before the advent of modern tunnels and bridges. The ferry service closed in 1962 and the slipway was removed leaving an embayment on the estuary bank. The area had become recolonized by scrub vegetation and assumed the appearance of a natural habitat. The site is now a small salt marsh, one of only two salt marshes in the study area. The species-rich hydrosere is undergoing rapid infilling. Access to the site has become more difficult as it has become increasingly overgrown. Its ecological index value was 7. In the short term, this site is likely to undergo continued plant succession and accretion cause substantial change to this small habitat.

A flood above 2.0 m MHT would substantially alter this highly interesting site. Due partly to its human origin this site has a sharply defined boundary and it would be difficult for migration of the habitat to occur onto adjacent land. This site would be jeopardised if flooding to 2.0 m above MHT became a frequent occurrence.

	Assessment category
Built environment	4
Accessibility	6
Human interference	7
Agriculture	10
Ecosystem diversity	8

Aggregate score = 35
Ecological evaluation score for the site = 7.0

Newshot Isle

Despite its name, this area is no longer an island. Previously, the river branched to form a temporary island. Subsequent infill allowed the island to rejoin the mainland and this area was used as wet grazing land for sheep. Four of the five ecological indicators gave low readings and the ecological index was a disappointing 3.2.

	Assessment category
Built environment	7
Accessibility	2
Human interference	3
Agriculture	2
Ecosystem diversity	2

Aggregate score = 16
Ecological evaluation score for the site = 3.2

On downstream side of the former island a backwater occurred similar to that at Erskine. It, too, was a small area of salt marsh flora dominated by *Phragmites* and was undergoing rapid accretion. This site received the highest ecological index of 9.4. The area does not currently benefit from any formal conservation status. The local planning guide for the area has identified its importance as a salt marsh and recommends the site for protection. The two very distinctive physical habitats at this site compliment each other, allowing birds to move between both areas depending on feeding and roosting routines. An increase in the height of the main river could result in the reopening of the side channel and by so doing would destroy the best conservation site on this stretch of river.

Assessment category	
Built environment	10
Accessibility	8
Human interference	9
Agriculture	10
Ecosystem diversity	10

Aggregate score = 47
Ecological evaluation score for the site = 9.4

While the four sites have been described separately, they form a continuous strip of land 11 km in length. They comprise a series of ecologically connected sites between which bird species can easily move. While each site provides a small conservation habitat, collectively they constitute part of a much more extensive and valuable ecological corridor.

Bird populations in the Clyde Estuary

The preceding section of the paper has referred to the birds that inhabit the estuary. The extensive silt and mud banks provide important feeding and roosting sites for a bird population that is of international significance. Excellent records exist for the types and numbers of birds using the estuary. The Scottish Ornithologists' Club has published annual *Clyde Bird Reports* since 1981, data from the most recent of which has been used in this paper (Gibson 1999), see Table 2.

The total monthly population of birds using the Clyde estuary amounts to ca. 25000 with autumn and winter populations being highest. A raised sea-level would change the extent and exposure of mud flats resulting in local changes in bird populations. As sea-level change is a global phenomenon most estuaries will exhibit changes to the extent of inter tidal areas and flooding and will throw the existence of wetland bird populations into confusion as they adapt to the new regime.

Table 2. Seabird and wader populations; annual counts for Clyde Estuary. Source: Gibson (1999); Clyde Bird Reports, 1998.

Species name	Number of individuals	Comments
Pintail *Anus acuta*	100	Small European population. The Clyde Estuary population is therefore highly significant
Goldeneye *Bucephala clangula*	1900	
Shelduck *Tadorna tadorna*	2000	Mudbank feeders
Dunlin *Calidris alpina*	3250	Occupy inner mudflats
Lapwing *Vanellus vanellus*	8000	Clyde Estuary important in harsh weather
Redshank *Tringa tetanus*	10 600	
Eider duck *Somateira mollissima*	14 000	Population increasing due to less oil pollution
Oystercatcher *Haematopus ostralegus*	27 000	Occupy inner mudflats

Results of the computer model

Two layers of data were used in the environmental model. The first comprised a detailed vector map showing the location of the four conservation areas. The attribute values comprised the final ecological evaluation data produced from the method described in Table 1. The polygon values were converted to raster format with a cell size of 10 m × 10 m. The sharp boundaries produced by this method were subsequently smoothed in an attempt to replicate natural ecosystem zonation. This layer was subsequently overlain on the DTM and the individual pixels in the two layers multiplied to produce a new derived map that allowed the calculation of vulnerable sites at each of the critical flood heights. This map is shown in Fig. 4. The enlargement of the Erskine Salting area shows the high detail that can be obtained from this method. The limitation is set by the scale of the digital elevation data, in this study, each pixel was 10m × 10m. A cross tabulation of all categories was also calculated and the summary data from this exercise is shown in Table 3.

From Table 3 it can be shown that the study area comprised 1517200m^2 grade 7 land or greater on the ecological evaluation scale (47.2 % of the total area) and of this 1188600m^2 (78.3 % of all the grade 7 cells and greater) was located at, or below, Mean High Tide level. All of this area would be lost if the intertidal mud bank accretion did not keep pace with sea-level rise. This scenario represents the single greatest threat to conservation land use in the study area. Reference to Fig. 4 shows the location of the red and orange coloured areas (these being the most highly ranked ecological sites and those most likely to flood). Both areas of salt marsh would be destroyed. Inundation of the land area between 0 and 1.0 m above MHT would eliminate a further 186200 m^2 (12.3% of conservation land of grade 7 or greater). Flooding to 2.0 m above current MHT would affect a further 132200m^2 (8.7 % of all the grade 7 cells and greater). Only 9300m^2 of grade 7 or greater land existed above 2.0m HMT.

The possibility for new conservation areas to form above 2.0 m MHT is therefore extremely limited and in no way can compensate for the loss of 328 600 m^2 grade 7+ land. Flooding of land above 2.0 m MHT makes a proportionately bigger impact on the lower grades of conservation land.

Table 3. Loss of conservation land consequent upon specific increases in sea-level.

Level of sea-water	Number of cells (10 m × 10 m) in each ecological evaluation category lost to sea-level rise. Percentage values in (italics) Ecological evaluation category Ecological evaluation category 1 did not occur in the study area < 2	< 3	< 4	< 5	< 6	< 7	< 8	< 9	9.1-10	Row totals
At or below MHT	0 *(0)*	11 *(0.03)*	2003 *(6.23)*	5247 *(16.32)*	102 *(0.31)*	11209 *(34.87)*	0 *(0)*	0 *(0)*	677 *(2.10)*	19249 *(59.89)*
0-1.0 m a.s.l.	15 *(0.04)*	11 *(0.03)*	982 *(3.05)*	1355 *(4.21)*	25 *(0.07)*	1176 *(3.65)*	9 *(0.02)*	9 *(0.02)*	673 *(2.09)*	4255 *(13.23)*
1.0-2. 0 m a.s.l.	665 *(2.06)*	466 *(1.44)*	465 *(1.44)*	524 *(1.63)*	22 *(0.06)*	491 *(1.52)*	38 *(0.11)*	14 *(0.04)*	779 *(2.42)*	3464 *(10.77)*
20-3.0 m a.s.l.	1304 *(4.05)*	1301 *(4.04)*	31 *(0.09)*	37 *(0.15)*	10 *(0.03)*	70 *(0.2)*	0 *(0)*	0 *(0)*	23 *(0.07)*	2776 *(8.63)*
3.0-4.0 m a.s.l.	934 *(2.9)*	291 *(0.90)*	1 *(0)*	1 *(0)*	0 *(0)*	3 *(0)*	0 *(0)*	0 *(0)*	1 *(0)*	1231 *(3.83)*
4.0- 5.0 m a.s.l.	747 *(2.32)*	225 *(0.7)*	1 *(0)*	0 *(0)*	0 *(0)*	0 *(0)*	0 *(0)*	0 *(0)*	0 *(0)*	973 *(3.02)*
5.0-6.0 m a.s.l.	155 *(0.48)*	37 *(0.11)*	0 *(0)*	0 *(0)*	0 *(0)*	0 *(0)*	0 *(0)*	0 *(0)*	0 *(0)*	192 *(0.59)*
Column totals	3820 *(11.88)*	2342 *(7.28)*	3483 *(10.84)*	7164 *(22.28)*	159 *(0.49)*	12949 *(40.28)*	47 *(0.14)*	23 *(0.07)*	2153 *(6.69)*	32140 *(100)*

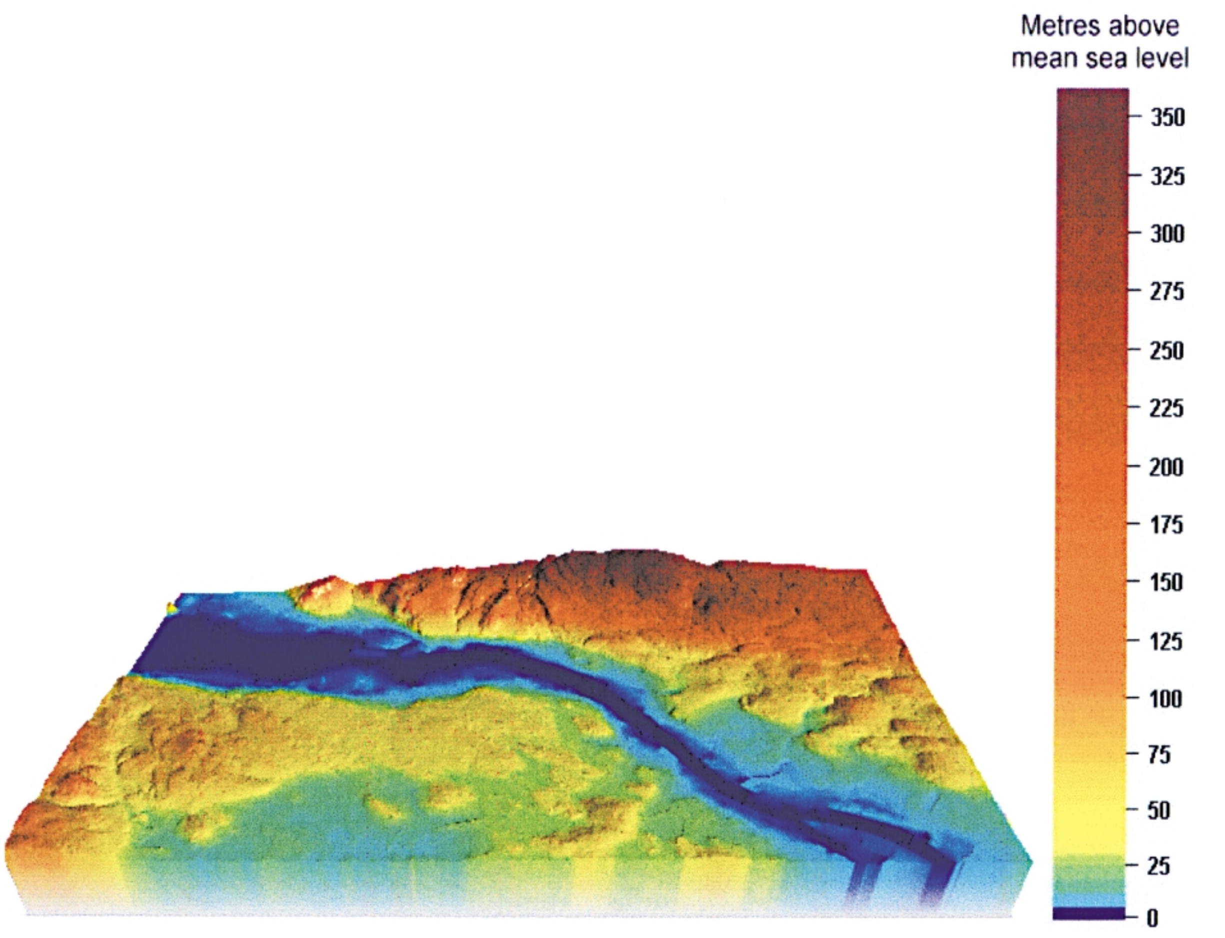

Fig. 3. Digital terrain model of the study area. Computed from OS Landform-PROFILE data. Ordnance Survey digital data reproduced by permission. Crown Copyright Approved.

Fig. 4. Combined flood risk and ecological evaluation weighting showing ecological 'value' of conservation areas lost by flooding to 6.0 m above MHT. Ordnance Survey base map reproduced by permission. Crown Copyright Approved.

Conclusion

The study has identified the implications of sea-level rise on conservation land use in a small section of the Clyde Estuary. Although the predicted maximum rise in global sea-level of 140 mm by 2050 is unlikely on its own to be sufficient to cause major changes to areas that are permanently inundated, the associated changes due to global warming including increased fresh water runoff from heavier winter rainfall and a predicted increase in storminess. In combination, these may be sufficient to alter the frequency, duration and location of flood prone areas.

The problems associated with the use of economic cost-benefit methodology for conservation land has been avoided through the use of an ecological evaluation index that allows conservation land to be given a value of 1 to 10 based on five criteria in a manner similar to that used in a land classification scheme. The advantage of using a GIS model is that changes to the weightings can be easily made and the model re-run.

The use of GIS has enabled the accurate identification of flood prone areas as small as $100m^2$ and these data has been used in conjunction with the data showing distribution of the ecological evaluation index. Together, these data have allowed the accurate identification of the most highly valued conservation sites that will be jeopardised by a progressive rise in sea-level. From evidence presented in Table 3 it is evident that the greatest loss of conservation areas of grade 7 and over will occur if the position of low water becomes permanently raised to that of the mean high tide position. Up to 78 % of all grade 7 conservation land would disappear as the area of inter tidal space would be lost. However, the possibility exists that some of this area can be retrieved through vertical accretion of the mud banks. A further rise in sea-level from zero to 1 m HMT would inundate 13 % of dry land of which approximately 44 % would be conservation grade 7 or greater. Reference to Table 3 and Fig. 4 shows that alternative locations for conservation land of grade 7 and greater do not exist mainly because construction of sea walls or embankments prevents a migration of the intertidal zone. This impediment ensures that the future for conservation land use in the study area and that of the wetland bird population dependent on the intertidal zone is distinctly uncertain.

The methodology developed in this paper allows an impartial assessment of the likely effects of sea-level rise and flooding on estuarine land use. It allows planners, conservation biologists, ornithologists and marine engineers with a powerful modelling tool with which to forecast changes in estuarine flood zones. When combined with established field survey methods and tidal records it provides a realistic means of forecasting changes in the highly dynamic estuarine environment. Over the next 50 yr society will be faced with major policy making decisions regarding the management of coastal flooding. Prioritizing the locations on which flood control measures are required must not be determined solely through the use of traditional economic modelling such as cost-benefit analysis. Inclusion of ecosystem evaluation of a type outlined in this paper will permit an objective broadening of the base on which decisions about estuarine management can be made. The use of GIS methodology allows a number of alternative scenarios to be tested and an optimum strategy identified. The methodology is sufficiently flexible to allow its adaptation to other situations in which significant pressure is being placed on land use.

Acknowledgements. Figures 1, 3 and 4 are based on Crown Copyright data produced by the Ordnance Survey.

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