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25 years of salt marsh erosion in Essex: Implications for coastal defence and nature conservation

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Abstract. This paper presents the results from a study which was undertaken to monitor, map and quantify salt marsh change along 440 km of shoreline within the county of Essex, south-east England, between 1973 and 1998. Results indicate that during this 25-yr period, 1000 ha of salt marsh has been lost in Essex, primarily due to coastal erosion. This figure represents ca. 25 % of the total salt-marsh area originally present in Essex in 1973. The salt marshes of Essex are important nature conservation areas, with many sites designated as Special Protection Areas under the EC Birds Directive (79/409/EEC) and as Special Areas of Conservation under the EC Habitats Directive (92/43/EEC). Salt marshes are also natural features which significantly dissipate wave and tidal energy, thereby playing an important role in contributing to effective coastal defence. The large-scale loss of salt marsh in Essex has, therefore, implications for both nature conservation and flood defence. Potential hypotheses for, and implications of such losses are discussed in this paper, together with the identification of potential management approaches to alleviate the losses.

Keywords: Aerial photography; Coastal squeeze; GIS; Sea level rise.

Abbreviations: NCC = Nature Conservancy Council; ITE = Institute of Terrestrial Ecology.

Introduction

The county of Essex is located in south-east England and comprises a total shoreline length of 440 km. This shoreline is characterised by short sections of open coast interspersed between a series of estuaries and tidal inlets which form components of the larger Outer Thames estuary complex (Fig. 1).

The coastal salt marshes of Essex are a valuable international, national, regional and local natural resource due to both their inherent coastal defence and nature conservation properties. The importance of these salt marshes as natural forms of coastal defence has long been acknowledged by the Environment Agency (who is the body responsible for the provision of flood defences in England) (Leggett & Dixon 1994; Anon. 1994). This is due to the significant wave attenuation which has been proven to occur over the intertidal profile, and especially over the salt marsh surface (Möller et al. 1996). Furthermore, the majority of the salt marshes in Essex are awarded designated conservation status as Special Protection Areas (under the EC Birds Directive 79/409/EEC) or as Special Areas of Conservation (under the EC Habitats Directive 92/43/EEC), and in total account for 10 % of the UK national salt-marsh habitat. Despite the importance of these areas to the natural sustainability, coherence and integrity of the Essex shoreline, salt marsh has not in the past been routinely assessed for changes, despite the potential vulnerability to sea level rise of the order of 6 mm/yr in Southeast England and their sensitivity to inappropriate management activities. Indeed, the figures often quoted for the rates of salt marsh erosion in relatively recently produced shoreline management studies and strategies (e.g. Anon. 1997) are now out of date, with changes being last recorded to 1988.

The most comprehensive previous assessment of salt marsh change in Essex was undertaken for the (English) Nature Conservancy Council (NCC) (Burd 1992). The results from this work indicated that significant erosional changes occurred in the Essex salt marshes between 1973 and 1988.

This paper presents the results from a contemporary study which was undertaken in order to produce a timely update of the previous NCC study, thereby investigating and quantifying salt marsh changes in Essex between 1988 and 1998. The study results give an accurate and reliable figure of contemporary salt marsh change and also allow a broad degree of assessment of the shoreline management activities which have been undertaken with the intention of checking or offsetting erosion rates. These include the implementation of 'managed retreat' schemes which involve the breaching of existing flood defence structures to allow tidal inundation for purposes of habitat re-creation (as in Fig. 2), or the construction of offshore wave breaks to reduce erosion of existing salt

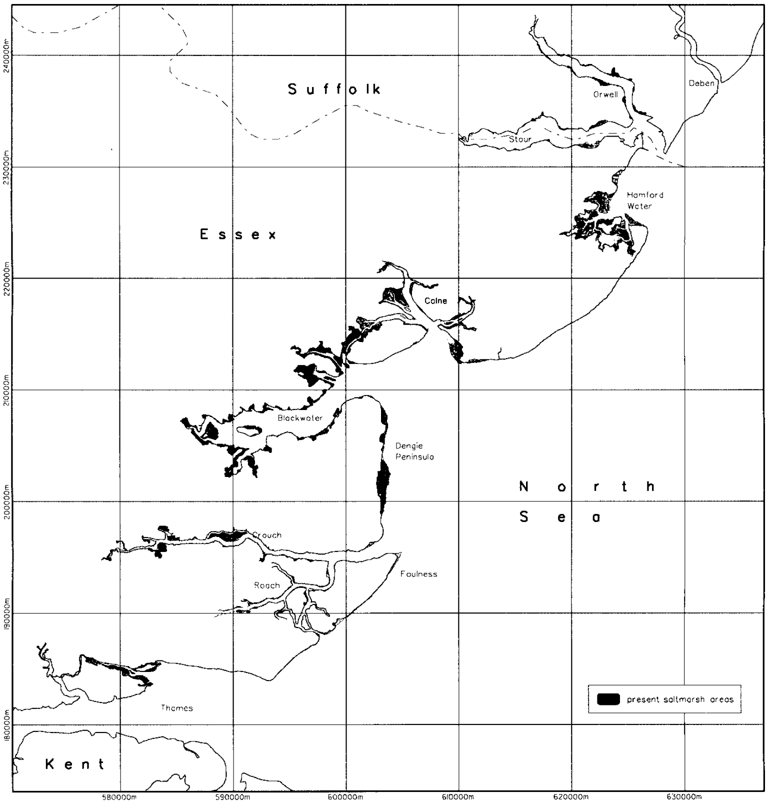


Fig. 1. Location map of Essex and the Outer Thames Estuary.

marshes (as in Fig. 3). Furthermore, when combined with the results from the NCC study, information is now available on the changes within the Essex salt marshes over a 25-yr period, from 1973 to 1998. The results from this paper are currently being applied by shoreline managers to ensure that current and future management practices are undertaken based upon up-to-date and reliable data.

Previous studies of salt-marsh change in Essex

In order to identify and quantify the changes in salt-marsh area in Essex, it was first necessary to establish a baseline survey against which the contemporary data which were available could be compared. In the case of Essex, two previous baseline surveys exist and are described below.

The 1973 study

In 1973, the Institute of Terrestrial Ecology (ITE) undertook ecological studies of a number of coastal areas in Essex. One of the specific objectives of their project was to “provide information on the species, amount, distribution and habitats of the most important elements of the natural fauna and flora of the area”.

In order to achieve this objective, the salt marshes of Essex were mapped using panchromatic vertical aerial photographs which were flown for the study at 1:10560 scale. From these aerial photographs, the area of salt marsh was traced directly onto Ordnance Survey base maps. Area calculations were made from the resulting tracings. Results from this study were output in hard-copy report and figures format (Anon. 1974).

The 1988 study

The (English) Nature Conservancy Council (NCC) published a report (Burd 1992) which identified and quantified the rates of erosion on Essex salt marshes between 1973 and 1988. This study used the maps from the 1973 ITE study as a baseline and derived data from specially commissioned panchromatic aerial photographs (1:5000), flown in 1988.

The following methodology was adopted during the course of the NCC study:

– The 1973 baseline survey was digitized into a Geographical Information System (GIS);

– The area of salt marsh present in 1988 was traced from the 1:5000 scale aerial photographs and the resulting maps were digitized into the GIS, overlaying the data

Fig. 2. Managed retreat at Orplands in the Blackwater Estuary.

files corresponding to the 1973 survey;
– A sequence of 'spatial analysis queries' was processed on the GIS in order to: (1) quantify the area of salt marsh present in Essex in 1988; and (2) calculate the differences in salt-marsh area between 1973 and 1988;
– Results were presented in report format (Burd 1992), as digital GIS files, and as a set of salt marsh change maps. These data formats were suitable to accommodate future repeat surveys.

The information gained from the 1988 NCC study contributed to the national debate on reasons for the erosion of Essex salt marshes. It highlighted that sea level rise was a potentially influencing factor, particularly in locations where salt marshes were backed by flood defence structures or high ground and were progressively being lost due to a process known as 'coastal squeeze'. It also provided guidance on NCC's future policy in relation to various shoreline management strategies.

Results from the 1973 and 1988 studies

The results from the previous studies identified that salt marshes in all of the study areas considered within Essex (namely Rivers Orwell and Stour, Hamford Water, Colne and Blackwater estuaries, Dengie Peninsula, River Crouch and River Thames north bank; Fig. 1) experienced net loss between 1973 and 1988. Actual statistics are presented in Table 1.

Whilst the results presented are undoubtedly significant, it was acknowledged in the NCC report (Burd 1992), that some of the results may have been affected by the limitations of the methodology used in the project. Of particular importance are the following potentially limiting factors:

- both the 1973 ITE and 1988 NCC studies used unrectified aerial photographs;
- the scales of the aerial photographs used for both studies were different;
- the 1973 study involved mapping of the general salt marsh outline and primary creek systems only, whilst the 1988 study extended the mapping to include most creek systems visible on the 1 : 5000 scale aerial photographs;
- the discrepancies in scale and level of detail mapped may have given rise to considerable 'apparent losses' of salt marsh between 1973 and 1988 which are greater than the 'actual losses' experienced.

It is also worth noting that the statistics from the NCC study which are most frequently quoted in relation to the changes in salt marshes in Essex are the percentages of the 1973 baseline which were subject to erosion by 1988. However, when considering actual rates of change in salt-marsh area, both the losses due to land claim and the natural changes due to accretion should additionally be incorporated in calculations in order to identify overall net change.

Despite the factors outlined above, the 1988 NCC study is considered to have provided good quality, highly detailed mapping which is suitable for use as a baseline

Fig. 3. Wave breaks (sunk barges) within Hamford Water.

Table 1. Summary results of salt marsh erosion in Essex between 1973, 1988 and 1998.

	Total salt-marsh area in 1973 (ha)	Total salt-marsh area in 1988 (ha)	Total loss 1973 to 1988 (ha)	Total accretion 1973 to 1988 (ha)	Net Loss 1973 to 1988 (ha and %)	Total salt-marsh area in 1998 (ha)	Total loss 1988 to 1998 (ha)	Total accretion 1988 to 1998 (ha)	Net Loss 1988 to 1998 (ha and %)	Net Loss 1973 to 1998 (ha and %)
River Orwell[1]	99.5	69.5	39.9	9.9	30.0 (30.2%)	53.7	25.0	9.2	15.8 (22.7%)	45.8 (46.0%)
River Stour[1]	264.2	148.2	129.5	13.5	116.0 (43.9%)	107.4	51.4	10.6	40.8 (27.5%)	156.8 (59.3%)
Hamford Water	876.1	765.4	170.6	59.9	110.7 (12.6%)	621.1	172.0	27.7	144.3 (18.9%)	255.0 (29.1%)
Colne Estuary	791.5	744.4	97.7	50.6	47.1 (6.0%)	694.9	97.0	47.5	49.5 (6.6%)	96.6 (12.2%)
Blackwater Estuary[1]	880.2	738.5	200.2	58.5	141.7 (16.1%)	683.6	144.5	89.5	54.9 (7.4%)	196.6 (22.3%)
Dengie Peninsula	473.8	436.5	46.7	9.4	37.3 (7.9%)	409.7	32.8	6.0	26.8 (6.1%)	64.1 (13.5%)
River Crouch	467.1	347.4	146.1	26.4	119.7 (25.6%)	307.8	80.0	40.5	39.6 (11.4%)	159.3 (34.1%)
Roach / Foulness	No data presented	No data presented	No data presented	No data presented	No data presented	218.4	No 1988 data	No 1988 data	No 1988 data	No 1973 data
River Thames (North bank)[2]	365.9	307.0 (original) 197.0 (revised)	105.6	46.7	58.9 (16.1%)	181.0	35.2	19.2	16.0 (8.1%)	Different limits

[1]Salt-marsh areas and changes for the Blackwater, Stour and Orwell represent 1997 areas (not 1998 areas). This was due to lack of aerial photography data available in 1998 for these three locations. [2]The North Thames (Essex) does not have 1998 geographical limits which are consistent with the 1988 baseline, due to the extent of aerial photography coverage that was available in 1998. Consequently, in order to enable direct comparisons between the 1988 and 1998 surveys, the area of salt marsh present in the 1988 data set has been recalculated within revised geographical limits. This means that the revised 1988 salt-marsh areas presented here differ from the original 1988 salt-marsh areas presented in Burd (1992). This recalculation process has not been possible, however, with the 1973 data because it was not available in digital format.

for repeat studies.

Methods of the 1998 study

The contemporary study was undertaken during 1999, although the majority of aerial photographs used in its preparation were flown in 1998. Fig. 1 shows the geographical area which has been covered in this study. The salt marshes in the following areas of Essex have been mapped: River Orwell, River Stour, Hamford Water, Colne Estuary, Blackwater Estuary, Dengie Peninsula, River Crouch, River Roach, Foulness and River Thames (north bank). Due to the more limited extent of aerial photography coverage that was available in 1998, the area of North Thames salt marsh present in the 1988 data set was re-calculated within revised geographical limits which are consistent with the 1998 data.

For the majority of the study areas, aerial photographs at 1 : 5000 scale taken in 1998 have been used. For those study areas where 1998 data did not exist, namely the Blackwater Estuary and the Rivers Stour and Orwell, 1997 1 : 10 000 scale aerial photographs have been used as an available alternative.

The area of salt marsh present on each individual aerial photograph was mapped onto tracing paper, the areas of algae or eel grass (*Zostera* spp.) were excluded. Only the central 80% of each photograph was mapped in order that the errors at the edge of photographs, caused by angular distortion, were minimised. Complete geographical coverage was ensured due to the fact that considerable overlap existed between adjacent photographs.

Once the salt marsh had been mapped in this manner, the salt-marsh areas were digitized directly into the GIS, whilst the 1988 baseline was displayed on the computer screen as a ‘reference file’. Upon completion of digitization, the line work was quality assured to ensure that all salt-marsh areas were represented by distinct enclosed polygons within the GIS. The line work was then attributed with appropriate nomenclature (e.g. flood embankment, salt marsh polygon) and each polygon was attributed with a centroid in preparation for the spatial analysis exercises.

Results of the spatial analysis

The spatial analysis can be described as a computerised assessment method to identify and measure certain themes, in order to:

1. Identify and quantify all of the salt-marsh area present in 1998 (or in 1997 in the case of the Blackwater, Stour and Orwell);
2. Identify and quantify all of the salt-marsh areas which were subject to erosion or accretion between 1988 and 1998 (or 1997), as well as identifying and quantifying areas of stable salt marsh.

Output from the spatial analysis comprised maps depicting locations of stable salt marsh, locations of salt marsh erosion and locations of salt marsh accretion and also quantification (in hectares) of salt-marsh areas and salt marsh changes.

This section presents the summary statistics from the studies of salt marsh changes within Essex between 1973, 1988 and 1998 (or 1997). Tables 1 and 2 present summary statistics of the salt marsh changes within each

Table 2. Average annual rates of changes between 1973, 1988 and 1998. (n.l.) = net loss. River Roach/Foulness and River Thames (North bank) have been excluded from Table 2 due to lack of available data and differences between geographical limits, respectively.

	Average annual rate of change						
	1973 to 1988			1988 to 1998 *			1973 to 1998 *
	Loss (ha/yr)	Accretion (ha/yr)	Net change (ha/yr)	Loss (ha/yr)	Accretion (ha/yr)	Net change (ha/yr)	Net change (ha/yr)
River Orwell *	2.7	0.7	2.0 (n.l.)	2.8 *	1.0 *	1.8 (n.l.)*	1.9 (n.l.)*
River Stour *	8.6	0.9	7.7 (n.l.)	5.7 *	1.2 *	4.5 (n.l.)*	6.5 (n.l.)*
Hamford Water	11.4	4.0	7.4 (n.l.)	17.2	2.8	13.9 (n.l.)	10.0 (n.l.)
Colne Estuary	6.5	3.4	3.1 (n.l.)	9.7	4.8	4.9 (n.l.)	3.9 (n.l.)
Blackwater Estuary *	13.3	3.9	9.4 (n.l.)	16.1 *	9.9 *	6.1 (n.l.)*	8.2 (n.l.)*
Dengie Peninsula	3.1	0.6	2.5 (n.l.)	3.3	0.6	2.7 (n.l.)	2.6 (n.l.)
River Crouch	9.7	1.8	8.0 (n.l.)	8.0	4.1	3.9 (n.l.)	6.3 (n.l.)

*Salt-marsh areas and changes for the Blackwater, Stour and Orwell represent 1997 areas (not 1998 areas). This was due to lack of aerial photography data available in 1998 for these three locations.

of the individual sites considered in Essex. These statistics are also represented in Fig. 4.

Fig. 4a identifies the amount of salt marsh which, between 1973 and 1988, was: (1) subject to erosion or land reclamation; (3) experienced accretion; or (3) remained stable. Fig. 4b identifies the amount of salt marsh which, between 1988 and 1998 (or 1997): (1) experienced loss; (2) experienced gain; or (3) remained stable. In Fig. 4b, the area of salt marsh present in the north Thames has been re-calculated within revised geographical limits. This means that the 1988 salt-marsh area quoted for the north Thames differs between Figs. 4a and 4b. Fig. 4c identifies the reduction in total salt-marsh area within each site from 1973, through 1988 to 1998 (or 1997).

From the results, it can be seen that all of the eight sites for which both 1988 and 1998 (or 1997) data existed (i.e. excluding the River Roach and Foulness) experienced net salt marsh loss between these dates. Of these sites, Hamford Water experienced the greatest absolute net loss (139 ha) whilst the Rivers Stour and Orwell experienced the greatest percentage net losses of their original area (28 % and 23 % respectively). The changes within the Stour and Orwell are particularly concerning because this net loss was experienced over a period of only nine years (since 1997 data were used). Although the Colne, Blackwater and Crouch experienced relatively large absolute net losses, these figures represented only moderate percentage net losses of their original areas. Dengie peninsula experienced the lowest percentage net loss of all of the Essex complexes considered, with 6 % (or 27 ha) net loss recorded.

Whilst the Blackwater estuary experienced a similar major order of erosion to Hamford Water, significant accretion was also recorded, thus reducing the net effect. Some of this accretion was due to the implementation of managed retreat schemes leading to intertidal habitat re-creation within the estuary, such as that at Orplands (Fig. 2). Considerable accretion was also recorded in the Colne and the Crouch.

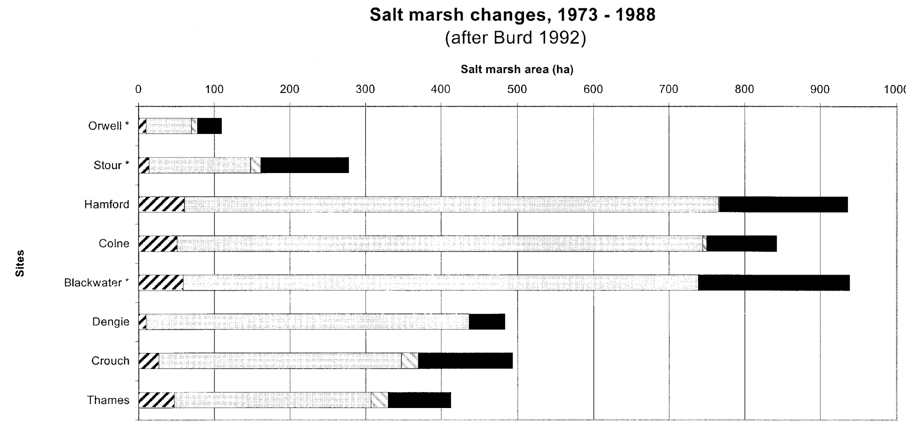
It is evident from the results in Tables 2 and 3 and Fig. 4 that similar general patterns of salt marsh change were observed between 1988 and 1998 as were observed in the NCC study between 1973 and 1988. The only major exception to this generalization is the increased rates of accretion which were recorded, particularly in the Blackwater, but also in the Crouch, although in the case of the Blackwater the average annual (gross) erosion of salt marsh between 1988 and 1998 (16 ha/yr) exceeded that observed in the NCC study (13 ha/yr), thus having the net effect of continued salt marsh loss. Additionally, some of the observed accretion in the Blackwater was due to the implementation of managed retreat schemes (13 ha), as opposed to natural accretion, thus indicating that in the absence of these schemes, the net loss in the Blackwater would have been greater.

Discussion

The total amount of salt marsh present within the combined Essex complexes of the Rivers Orwell and Stour, Hamford Water, Colne and Blackwater estuaries, Dengie peninsula and River Crouch has been calculated for 1973, 1988 and 1998. The results presented below indicate that significant loss of salt marsh has occurred throughout the 25-yr period:

- The total salt-marsh area in these complexes in 1973 was 3852 ha;
- The total salt-marsh area in these complexes in 1988 was 3250 ha;
- The total salt-marsh area in these complexes in 1998 was 2878 ha.

The total salt marsh loss in these complexes between



	Thames	Crouch	Dengie	Blackwater *	Colne	Hamford	Stour *	Orwell *
■ Erosion (ha)	83.3	124	46.7	200.2	92.5	169.4	116.2	32.4
□ Reclamation (ha)	22.3	22.1	0	0	5.2	1.2	13.3	7.5
□ Remaining (ha)	260.3	321	427.1	680	693.8	705.5	134.7	59.6
Accretion (ha)	46.7	26.36	9.4	58.52	50.58	59.9	13.5	9.87

Fig. 4a. Salt marsh changes, 1973-1988.

1973 and 1998 was 974 ha. If statistics for the River Roach and Foulness and the north Thames were also included in the above calculations, it can be estimated that the total salt marsh loss in Essex would have exceeded 1000 ha over 25 yr. This equates to an average annual rate of approximately 40 ha/yr. The hypotheses for, and implications of such a large-scale loss of salt marsh are discussed in the following sections.

Reclamation for port developments

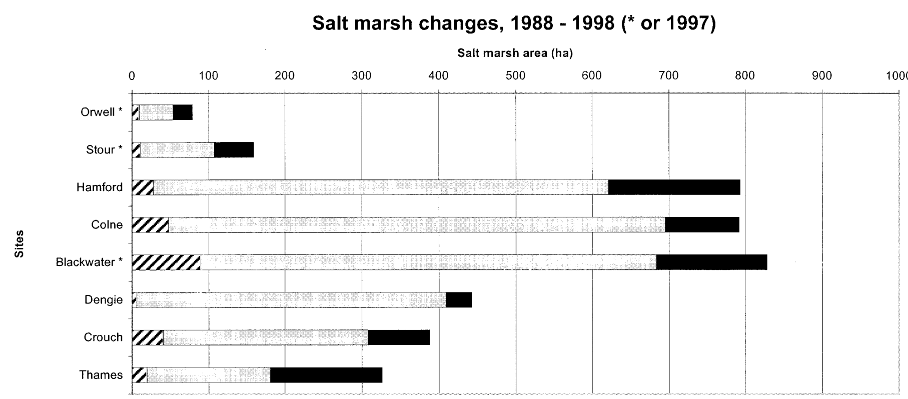
Reclamation of salt marshes for port developments has occurred in some complexes between the dates considered within this study. Clearly, this leads to a direct loss of salt marsh and may also have effects on the tidal prism and tidal asymmetry of the estuary (discussed later). However, direct loss due to reclamation only accounts for only 5% of the observed loss in Essex over 25 yr from 1973 to 1998.

Long-term estuarine response to sea level changes

Evidence from previous UK east coast estuary studies (e.g. Pethick 1996; Lowe 1999) suggests that the natural estuarine response to sea level rise is for the entire estuary morphology to ‘roll-over’. In summary, the increase in water depth associated with a sea level rise which outpaces sedimentation rates results in:

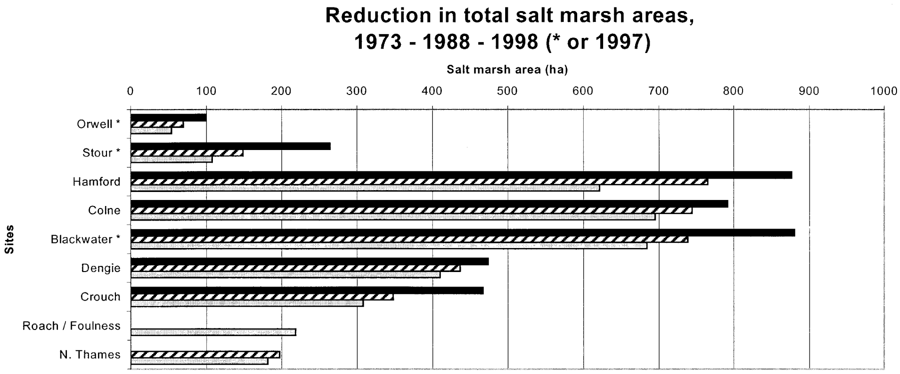
1. An increase in wave energy towards the landward limit of the intertidal zone, resulting in erosion of the upper mudflat and salt marsh edge (Fig. 5A);

2. A decrease in the shear stress on the bed of the subtidal channels, resulting in a net accretion of sediment here. Most of this sediment is generally eroded from the



	Thames	Crouch	Dengie	Blackwater *	Colne	Hamford	Stour *	Orwell *
■ Loss (ha)	145.24	80.02	32.8	144.46	97.02	172	51.4	24.97
□ Remaining (ha)	161.76	267.34	403.7	594.06	647.36	593.4	96.8	44.5
Gain (ha)	19.24	40.46	6	89.54	47.54	27.7	10.6	9.2

Fig. 4b. Salt marsh changes, 1988-1998.



	N. Thames	Roach / Foulness	Crouch	Dengie	Blackwater *	Colne	Hamford	Stour *	Orwell *
■ 1973			467.1	473.8	880.2	791.5	876.1	264.2	99.5
▨ 1988	197		347.36	436.5	738.52	744.38	765.4	148.2	69.47
□ 1997 or 1998	181	218.4	307.8	409.7	683.6	694.9	621.1	107.4	53.7

Fig. 4c. Reduction in total salt-marsh areas, 1973-1998.

upper intertidal zone by wave action and swept down the intertidal slope by tidal currents (Fig. 5B);

3. An increase in tidal energy enters the estuary due to the deeper water at the estuary mouth and in the near-shore zone. The result is that sediment recently deposited in the sub-tidal channel is swept landwards to be deposited in the inner estuary, upon the intertidal zone if possible (Fig. 5C);

4. The overall morphology of the estuary undergoes a spatial translation in two directions: landwards and upwards to maintain its position in the energy frame (Fig. 5D).

Therefore, such a ‘roll-over’ transgression is likely to result in natural salt marsh erosion towards the mouth of an estuary (or the mouth of its creeks) and natural salt marsh accretion towards the head of an estuary (or the head of its creeks) as its morphology attempts to move landwards and upwards within the tidal frame in response to rising sea levels.

Inhibition of estuarine ‘roll-over’ by the presence of flood defences

Inhibition of the ‘roll-over’ transgression process by intervening flood embankments causes the intertidal area to be progressively ‘squeezed’ between the static engineering structures and the rising sea level, resulting in direct loss of salt marsh and mudflat (Pethick 2001). In many Essex estuaries there have been significant anthropogenic alterations to the morphological form of the estuary which affect and constrain the way in which the estuary can dissipate energy and ‘roll-over’. The presence of flood defences can also reduce the amount of intertidal which is available in the inner-estuary to receive the sediment which is eroded from the outer-estuary. The response is that available sediment has to be deposited in the remaining sub-tidal channel, rather than on the intertidal, thus decreasing the estuary depth. However, decreasing the depth of an estuary, without a corresponding increase in width, results in an increase in the tidal velocity, increasing the potential for erosion. If a sufficient buffer zone of mudflats and salt marsh were available for the deposition of sediment on each bank, then it is more likely that a sustainable estuary morphology would be achieved and less salt marsh erosion would be observed.

Long-term estuarine response to land reclamation

It should be noted that the effects of land reclamation are manifest over time scales of decades to centuries and can have serious implications both within the estuary and on the adjacent open coast (Pethick in press). The historic reclamation of large areas of intertidal zones of estuaries (as previously practised widely in Essex) has often resulted in:

- a modification to the geometry of the flood and ebb channels (perhaps ‘squeezing’ existing salt marsh against the flood embankments);
- changes to the asymmetry of the tidal velocity curve (perhaps giving a tendency for ebb dominance and hence causing or exacerbating salt marsh erosion);
- changes to the tidal prism of the estuary (discussed below).

Reduced natural protection offered by ebb deltas

Reducing the tidal prism of an estuary (the volume of water which enters and leaves the estuary on each tide) through land reclamation can lead to a decrease in estuary length and a consequential withdrawal landward of the associated ebb-tide delta. This may in turn lead to increased exposure of the outer estuary, the adjacent open coast intertidal area and engineered defences to wave

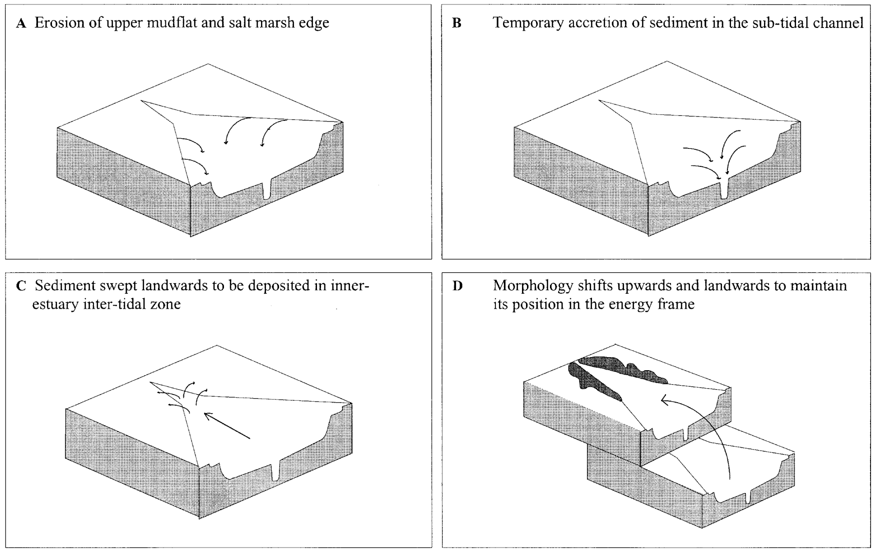


Fig. 5. Stratigraphic 'roll-over' model for estuarine response to sea level rise.

attack as the modified ebb-tide delta offers less natural protection to the shoreline (Pethick 2001 in press).

Cyclic behaviour of coastal systems

Cycles of erosion and accretion of the Essex salt marshes (as hypothesized by Greensmith & Tucker 1966), may occur within some complexes. However, any such changes are likely to be superimposed upon an underlying unidirectional change (Ranwell 1972). In the case of Essex, this clearly appears to be an erosional change.

Changing wave conditions

Salt marsh erosion within Essex may also be due to changing wave conditions, for example increasing storminess or changing wave refraction patterns under different sea level and/or bathymetric conditions. For example, Greensmith & Tucker (1966) observed the landward migration of a chenier ridge offshore from Dengie. This morphological response to rising sea levels may affect the wave refraction characteristics over the ridges and alter forcing parameters at the shoreline. Direct wave action at the salt marsh / mudflat boundary is considered to have been a major source of the observed erosion in Essex.

Geomorphological functioning

The following geomorphological factors could all potentially account for some degree of variation in the salt-marsh area present within Essex:

1. Pethick (1999) postulated that salt marshes 'function' within a self-regulating feedback system. He suggested that when a zone of salt marsh is sediment-starved (e.g. at a point on the marsh which is too far from the nearest creek to receive sediment, but still receives tidal water), the marsh elsewhere (e.g. nearer to creek) continues to accrete because it continues to receive sediment. Over a period of time, the result of this will be a ponding of tidal water within the lower areas of marsh. This can then lead to headward erosion from the ponded area, a process which then forms a new creek across the marsh. The newly-eroded creek then allows sediment to be transported to the topographically lower points on marsh, which then accrete and hence catch up and keep pace with surrounding marsh accretion.

2. Pethick (1999) postulated that on marshes with little cross-shore gradient, 'coils' are created within the marsh. These features function like a tidal meander in terms of achieving tidal energy dissipation, but are created only on marshes with little or no gradient. Additionally, it is suggested by Pethick (1999) that outer estuary sections are generally characterised by relatively mobile salt marsh/mudflat boundaries, but inner estuaries are generally characterised by relatively stable salt marsh/mudflat boundaries because these locations are fetch-limited (i.e. little wave action exists).

Legal and biodiversity implications

The continued loss of salt marsh within Essex has considerable implications for nature conservation, in both biodiversity and legal terms. Firstly, the salt marshes of Essex represent ca. 10% of the national habitat total. The observed rates of loss of these marshes clearly has both local and national implications in terms of the direct loss of a nationally scarce natural resource which supports a wide range of flora and fauna. However, the loss of salt marsh additionally has a wider implication in terms of UK compliance with the EC Habitats Directive (through the associated UK Conservation Regulations). This is of relevance to coastal managers since the presence of flood embankments along much of the Essex shoreline causes existing salt marsh to be progressively squeezed between rising sea levels and static flood defence structures. It must be considered that the loss of such extensive areas of salt marsh within Essex is likely to have significant adverse impacts on the integrity of the internationally designated sites of nature conservation interest (which are present throughout Essex). Consequently, given the rates of loss which have been recorded, management action needs to be taken in order to maintain the overall integrity of these sites. This may best be achieved through the 'balancing' of losses and gains on a wide scale through the implementation of habitat management strategies such as land banking.

Over 25 yr (1973-1998), the observed amount of salt marsh loss in Essex has exceeded 1000 ha. This equates to an mean annual rate of over 40 ha/yr. Therefore, in order to simply 'compensate' for the losses anticipated from this day forward, a total of 40 ha/yr would have to be re-created. This figure assumes no increase in rates of sea level rise and does not even take into account the extent of historic loss due to land reclamation and erosion up to the present time, but it does exemplify the scale of the management issues facing the Essex coastline, particularly when considering that the total amount of 'managed retreat' (intertidal habitat re-creation schemes) undertaken has amounted to ca. 80 ha, of which only a relatively small proportion has, to date, been colonized by salt marsh species (13 ha), with the majority being intertidal mudflat. This means that the annual amount of salt marsh re-creation required in order to simply make good anticipated losses from this day forward is significantly greater than the *total* amount of salt marsh re-creation that has ever been undertaken in Essex (or indeed the UK) through the implementation of managed retreat (or salt marsh creation) schemes.

Implications for coastal defence

Along many shoreline frontages in Essex, the strategic coastal management plan, named the *Essex Shoreline Management Plan* (Anon. 1997), identified a preferred short-term (up to 10 yr) management policy of 'hold the existing line of structural defences' combined with further monitoring, modelling and economic evaluation in order to identify sustainable defence policies for the longer term. However, given the results from both the NCC (Burd 1992) and present (Cooper et al. 2000) studies, it must be anticipated that considerable losses in salt-marsh area will continue to be observed under a policy of 'hold the existing line of structural defences', even if this is only a short-term policy for the next 10 yr.

Additionally, mudflats and salt marshes are features which dissipate wave and tidal energy. As such, they must be considered as natural forms of coastal defence. Experiments in North America have shown that the passage of waves through salt marsh vegetation may reduce wave height by 71% and wave energy by 92% (Frey & Bason 1978). Similar field results were obtained at Stiffkey marsh in Norfolk, England, indicating that salt marsh surfaces can decrease wave energy from between 50 - 100% (Möller et al. 1996). However, in Essex, the continued erosion of salt marsh, coupled with sea level rise, is likely to result in progressively less wave attenuation over the salt marsh surface, resulting in progressively more direct wave action on the existing flood embankments. The resulting implications may be manifest through increasing damage to, and maintenance costs of the structural defences.

Possible management approaches

In order to address the issue of salt marsh loss within Essex, a range of management approaches are possible. These include:

- Allowing more space for landward migration of the salt marshes in response to sea level rise (e.g. managed retreat through the removal or breaching of existing coastal defences – see Fig. 2);
- Decreasing the wave activity impacting upon the marshes (e.g. through the placement of offshore wave breaks – see Fig. 3);
- Increasing the suspended sediment concentrations reaching the salt marshes (e.g. through supplying a sediment-starved estuary or coastal area with sediment, often derived from navigation channel dredging);
- Increasing the trapping efficiency of existing marshes (e.g. through the construction of polders or groynes) although the effectiveness of this technique has been critically debated (Bakker et al. 1997);
- Engineering (relatively dense) creek systems on managed retreat sites (in order that most locations on the site are able to receive sediment).

Conclusions

This paper has investigated the erosion of the salt marshes of Essex between 1973, 1988 and 1998. It has been found that net erosion occurred during this time period in all of the coastal and estuarine complexes which have been considered. Furthermore, over the past 25 yr, it has been estimated that over 1000 ha of salt marsh has been lost from Essex. This net loss has been due to both reclamation for port developments and erosion. Potential hypotheses for this large-scale erosion have been identified as follows:

- Inhibition of the long-term estuarine 'roll-over' in response to sea level rise and resulting coastal 'squeeze' between rising sea level and existing flood defences;
- Long-term morphological response to land reclamation, resulting in reduced protection offered by natural features;
- Internal dissection of existing marshes;
- Cyclic behaviour of coastal systems;
- Changing forcing conditions;
- Self-regulating nature of geomorphological systems.

The implications of the observed losses have been discussed in both nature conservation and coastal defence terms. It is suggested that the current management practice of 'hold the existing line of structural defences' (as identified as the preferred shoreline management policy for the next 10 yr throughout many parts of Essex) is not sustainable in the longer term, and continued salt marsh loss will occur as long as this policy is implemented. This will ultimately result in increasing damage to existing engineered defences, increasing loss of internationally important habitats, and increasing pressure on relevant authorities under the EC Habitats Directive and UK Conservation Regulations to ensure that the integrity of the internationally designated conservation sites is maintained or enhanced.

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