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(NATURAL ENVIRONMENT RESEARCH COUNCIL)

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COMPARATIVE STUDIES OF SALT MARSH PROCESSES

Results from the UK Site at Old Hall Marshes, Essex

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DRAFT FINAL REPORT

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I. OBJECTIVES

1. To estimate the primary production of the salt marsh vegetation and the role played by the different species and components of the standing crop.

2. To assess changing patterns in the exchange of organic matter and the exchange of mineral nutrients between upper and lower salt marsh, mud flats and adjoining estuarine water.

3. To assess the changing role of sediment transport in salt marsh development.

4. To analyze the data collected under the above headings especially in relation to the interactions between different processes and parameters.

5. To interpret these processes in relation to the management of coastal resources especially in relation to sea level rise.

6. To write a report and appropriate scientific papers on the results achieved both nationally and internationally.

EEC CONTRACT:

COMPARATIVE STUDIES ON SALT MARSH PROCESSES

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2. SITE DESCRIPTION

2.1. Geomorphology

Approximately one fifth of the total area of British salt marshes occurs in East Anglia. The coastal counties of Norfolk, Suffolk and Essex are fringed by salt marshes amounting to nearly 9000 ha of which approximately half (4492 ha) occur in the county of Essex. The marshes of Essex are under intensive study for their importance as sea defence as well as for their conservation and scientific value. The marshes are decreasing in area as a result of a number of different environmental pressures, including the sinking of the land relative to the sea, at a rate of at least 3mm per year, the result of isostatic adjustment following the last glaciation.

1073 ha of the Essex marshes occur along the Blackwater estuary. The Tollesbury marshes cover 146 ha between the village of Tollesbury to the south and the reclaimed Old Hall Marshes to the north. An area of 38.45 ha was chosen for the study as it is drained by a single creek in an embayment at the west end of the marshes (Fig. 2.1.1.). The study area forms a single watershed with no interchange with surrounding areas during neap tides and only limited interchange during the overmarsh spring tides. Cross flows along the marsh watersheds were observed to be very limited. There are two potential freshwater inflows to the system in the form of field ditches with sluices through the sea wall. Water flow only occurs during the wettest months and no effect on the marsh fauna or flora has been observed.

At Tollesbury and the adjoining areas there is a tidal range of 2.6 m during neap tides and 4.6 during springs. For all practical purposes tidal heights at Old Hall Creek, Tollesbury are the same as those at West Mersea for which tidal predictions are available.

2.2. Vegetation map and species distribution

2.2.1. General Description of vegetation

The salt marsh vegetation was divided into two categories, Lower Marsh and Upper Marsh. The vegetation of the Lower Marsh varied from pure *Salicornia* species (*Salicornia herbacea* agg. with *Salicornia dolichostachya*) along the lower zones to various mixtures of *Aster tripolium*, *Salicornia* (various species including some *Salicornia perennis*) and *Suaeda maritima* on the higher areas together with occasional individuals of the Upper Marsh species. However there was no clear pattern of variation between the different sites and thus the vegetation of the Lower Marsh sites will not be described separately. The 'Lower Marsh' as recognised and describe for the British Study Site corresponds more to the vegetated mud flat or pioneer marsh category on the mainland sites.

The vegetation of the Upper Marsh was dominated by Halimione portulacoides and Puccinellia maritima but in varying proportions (Fig. 2.2.1.1.). Limonium vulgare was the next most noticable species. The higher parts of the marsh were characterised by the appearance of Inula crithmoides and Artemisia maritima. Along the edge of the marsh adjoining the sea wall Elytrigia repens is the dominant species. The edge of the Elytrigia zone marks the upper limit reached by normal spring tides. Apart from these higher areas the area described as 'Upper Marsh' corresponds to the general European 'Low Marsh' category but as the Essex site has these two clearly defined zones they will be referred to in the British parts of this report as 'Upper Marsh' and 'Lower Marsh'. In addition to the two major vegetation zones two mud flat zones were recognised. These are referred to as Upper Mud Flat and Lower Mud Flat. The Upper Mud Flat category comprises the rather firmer and often steeply sloping areas of bare mud found along the margins of creeks and pans. The Lower Mud Flat category comprises the level or gently sloping areas of soft mud occurring along the beds of the larger creeks and as the bottom of the pans in the marsh. As far as levels are concerned the creek bed Lower Mud Flats are generally very much lower than the Lower Mud Flats that occur in the marsh pans but intermediate areas do occur and no clear distinction exists between the two sub-categories.

The total areas of the marsh system (32.48 ha) and of the main creek (5.97 ha) were determined from the aerial photographic cover using a Calcomp digitiser. The proportions of the site area contributed by the four vegetation and mud flat zones described above were determined. The zones along the main creek could be distinguished on the aerial photographs and a series of transects was drawn on the photos and used to estimate the relative contribution of the different zones. It was not possible to deliniate these zones in the complex system of marsh and creeks. At each sample site a series of four 25m transects (N, S, E & W) were taken from each point and the intercepts of the different zones recorded. The proportion of the zones so obtained was then applied to the total area to give the area of each zone. The two sets of figures was then combined to give totals for the whole site (Table 2.2.1.1).

Table 2.2.1.1. Areas of the four habitat types at the Study Area, Tollesbury, Essex in hectares.

Habitat Type	Upper Marsh	Lower Marsh	Upper Mud Flat	Lower Mud Flat
Main Creek	0	0.18	1.41	4.38
Marsh System	20.02	7.03	3.29	2.14
Whole Site	20.02	7.21	4.70	6.52
% contribution	52.07	18.75	12.22	16.96

2.2.2. Sample Sites

The Upper Marsh sites varied considerably in altitude and thus tidal regime, the lowest (Site 5) was some 180 mm lower than the highest (Site 10). The ten sites could be divided into three groups with Sites 3, 5 and 6 as low sites, Sites 1, 2 and 4 as medium sites and Sites 7, 8, 9 and 10 as high sites. The Lower Marsh sites were generally steeply sloping and there was as much variation between the altitudes of sub-plots and replicates within each site as between sites. They were generally some 400 to 800 mm lower than the Upper Marsh sites.

The following adjectives are used to describe the general height of the vegetation:- short = 50 mm and less, medium = 50 - 150 mm, tall > 150 mm. The Upper Marsh sites are dominated by either _Puccinellia_ or _Halimione_ or mixtures of the two, in which case the first-named species is the overall dominant.

2.2.3. Site Descriptions

Site 1.

The vegetation was medium height _Puccinellia_/_Halimione_ with more _Halimione_ around the creek edges but with two patches of dense _Puccinellia_. Associated species were _Triglochin_, _Cochlearia_, _Limonium_, _Aster_ and _Plantago_. In addition there was a small central patch of short _Puccinellia_ and _Limonium_. Over the two years of the study this patch increased in size.

Site 2.

The vegetation was medium height _Puccinellia_/_Halimione_ with

Halimione dominant around the creek edges. Associated species were Aster, Triglochin, Plantago, Spergularia and Cochlearia.

Site 3.

The vegetation was medium height Puccinellia/Halimione but by the end of the study there were some patches of short Puccinellia. Associated species were Triglochin, Limonium, Spergularia and Aster. There were clumps of Inula along the eastern edge.

Site 4.

The vegetation was generally medium height Halimione/Puccinellia with patches of dense Halimione especially by the creek to the south. By the end of the study the balance had switched from Halimione/Puccinellia to Puccinellia/Halimione. Associated species were Limonium. Triglochin, Plantago, Aster, Spergularia and Cochlearia. To the north there were patches of short Limonium/Puccinellia.

Site 5.

The vegetation was generally medium height Puccinellia/Halimione with patches of Halimione/Puccinellia but only small patches of Puccinellia. Over the course of the study these areas of more or less pure Puccinellia became more extensive with a reduction in Halimione/Puccinellia. Associated species generally were Limonium, Triglochin, Plantago, Aster and Spergularia. There were also small patches of short Limonium/Puccinellia.

Site 6.

There were two types of vegetation at this site. Along the main channel the vegetation was dominated by Spartina with Limonium, Triglochin and Halimione. The rest of the site was dominated by tall Halimione and some medium height Halimione/Puccinellia. During the study this changed to Halimione/Puccinellia overall that varied in height from tall to medium. Associated species were Triglochin, in considerable quantities, Limonium, Aster and Plantago.

Site 7.

There were two types of vegetation at this site. The central area was of short Limonium, with Armeria, Triglochin, Spergularia and Puccinellia. The area surrounding was tall Halimione/Puccinellia and some Puccinellia/Halimione. By the end of the study the balance had switched in favour of Puccinellia/Halimione. Associated species were Limonium, Aster, Cochlearia and Spergularia together with scattered clumps of Inula and Artemisia.

Site 8.

The vegetation was mainly tall Puccinellia/Halimione with Halimione/Puccinellia along some creek edges, but along the main creek to the west Puccinellia was dominant. By the end of the study Puccinellia had increased at the expense of Halimione with only clumps of Puccinellia/Halimione. Associated species were Limonium, Triglochin, Cochlearia, Aster and Juncus maritimus and also scattered Artemisia on the highest areas.

Site 9.

The vegetation of this site was predominately tall Halimione/Puccinellia and pure Halimione, however there were also patches of Puccinellia/Halimione and some pure Puccinellia. As with some of the other sites the balance switched during the study in favour of Puccinellia. Associated species were Limonium, Triglochin, Aster, Spergularia and Cochlearia. On the highest areas, along the creek edge, there was also Juncus maritimus and Artemisia.

Site 10.

To the south the vegetation was short and Limonium-dominated with Armeria, Puccinellia, Triglochin and Plantago. The north and the edges of the site were medium to tall Puccinellia with Puccinellia/Halimione and some pure Halimione around the edges. Associated species were Limonium, Plantago, Cochlearia, Aster and Spergularia and scattered Juncus maritimus.

The occurance of species through the ten sites is summarised below (Table 2.2.3.1).

Table 2.3.3.1. Species composition of upper marsh sample sites.

	Site Number									
Species	1	2	3	4	5	6	7	8	9	10
Armeria							+			+
Artemisia							+	+	+	
Aster	+	+	+	+	+	+	+	+	+	+
Cochlearia	+	+		+			+	+	+	+
Halimione	+	+	+	+	+	+	+	+	+	+
Inula			+				+			
Juncus								+	+	+
Limonium	+	+	+	+	+	+	+	+	+	+
Plantago	+	+		+	+	+				+
Puccinellia	+	+	+	+	+	+	+	+	+	+
Salicornia	+	+	+	+	+	+	+	+	+	+
Spartina						+				
Spergularia		+	+	+	+		+		+	+
Suaeda	+	+	+	+	+	+	+	+	+	+
Triglochin	+	+	+	+	+	+	+	+	+	+

2.3. Species behaviour

2.3.1. Seasonal Changes.

In normal seasons growth has commenced by April and ends in October (Fig. 2.3.1.1.). The loss of leaves of most species occurs with the first major frost which is usually between late October and early December. The only truly evergreen species present is *Armeria maritima* whose rosettes remain green throughout the year. In mild winters some growth can occur at any time between November and March. This is particularly true of *Puccinellia maritima* and *Aster tripolium*. Seed germination is normally in late March but it can be up to a month earlier or later depending on the weather. In hot dry years drought and hypersalinity can limit plant growth between June and August, but growth is generally resumed with September rainfall. Generally growth in the lower marsh starts and finishes later than in the upper marsh because of the influence of the sea water that is slow to warm in the spring and slow to cool in the autumn. The low marsh is less affected by summer droughts than the high marsh.

Table 2.3.1.1. Phenology of salt marsh species at Tollesbury, Essex.

	MONTHS IN AVERAGE YEAR		
Species	Vegetative	Flowering	Fruit
Armeria maritima	1 - 12	4 - 8	5 - 8
Artemisia maritima	4 - 10	8 - 10	9 - 10
Aster tripolium	3 - 10	7 - 9	8 - 10
Cochlearia officinalis	4 - 8	4 - 8	5 - 8
Halimione portulacoides	5 - 10	7 - 10	8 - 10
Inula crithmoides	4 - 10	7 - 10	8 - 10
Juncus gerardii	4 - 10	6 - 7	7 - 8
Limonium vulgare	4 - 8	6 - 8	8 - 9
Plantago maritima	4 - 10	6 - 9	7 - 10
Puccinellia maritima	3 - 10	6 - 7	7 - 8
Salicornia herbacea agg.	4 - 10	8 - 9	9 - 10
Spartina anglica	4 - 10	7 - 10	8 - 10
Spergularia media	3 - 9	5 - 9	6 - 9
Suaeda maritima	4 - 10	8 - 10	9 - 10
Triglochin maritima	4 - 9	5 - 8	6 - 9

2.3.2. Longevity.

Nearly all these species are perennials, some of them, such as Limonium, can be very long lived indeed. Only two are annual, Salicornia herbacea and Suaeda maritima. While Aster tripolium can be quite long-lived, much of it occurs in the lower marsh where it is generally rather short-lived. The upper marsh is generally a rather stable community of long-lived species.

2.3.3. Leaf loss.

As mentioned in the opening paragraph leaf loss occurs with the first serious frost of the winter, that is if drought has not intervened earlier. In particularly mild winters there can be both the retention of leaves and the growth of new ones but this does not often occur. Halimione portulacoides is normally an evergreen shrub, except in severe winters, with the new leaves appearing rather late in the spring. In the winter of 1991-92 most of the Halimione leaves were shed after the hard frost that occurred on December 14th (-6°C). However this did not affect the Halimione growing in the highest marsh areas and along the drift line. It would appear that the areas unaffected had not been covered by the tide around this time but this has to be an observation rather than an explanation. This leaf loss had not occurred in 1990/91 but -6°C was only reached on January 25th and there was snow cover at the time. The effect appeared to be particularly severe as even in May the bushes affected were only showing very limited recovery to the extent of new leaf buds appearing on the older parts of the shoots. By June it was clear that that the last two years of shoot growth had been lost.

2.3.4. Zonation of salt marsh plant species.

Previous studies in the area (in 1986) had shown that the vertical zonation of the major salt marsh plant species in relation to the fringing Elytrigia repens was showing considerable annual variation so these measurements were continued for 1990 and 1991. While the normal ranges of the various species remained fairly constant the restricted ranges they exhibited in certain parts of the marsh varied considerably (Table 2.3.4.1.). These observations are broadly in agreement with the results obtained for other Essex salt marsh sites.

Table 2.3.4.1. Variations in the zonations of major salt marsh plant species 1986 - 1991 (metres below the lower limit of Elytrigia repens).

Species	Area	1986	1990	1991
Limonium vulgare	Normal	0.5	0.8	0.6
Puccinellia maritima	Normal	0.7	0.8	0.8
Aster tripolium	Normal	1.0	1.2	1.2
Aster tripolium	Restricted	0.7	1.2	1.0
Salicornia spp.	Normal	1.7	1.7	1.6
Salicornia spp.	Restricted	0.7	1.2	1.3

PART TWO

1. METHODOLOGY

1.1. Primary Production

1.1.1. Selection of Sample Sites

The sampling was based on ten sample sites selected at random within the study area. These sites were chosen using a grid and random numbers, and located in the field using aerial photographic cover of the area. Because of the dissected nature of the marsh some of the random points were rejected on grounds of inaccesability. Checks from aerial photographic cover and in the field confirmed that the rejected sites did not differ significantly from those selected. The ten sites finally selected covered both landward and seaward parts of the marsh. Five sites were chosen north of the main creek and five to the south.

During the summer of 1991 each site was marked by a 1.5 m galvanised steel tube driven in to the ground until the top was within 100-150 mm of the marsh surface. At each of the sample sites, ten subsample sites were located by taking random compass bearings (Lower Marsh 5 x 9 sites) and random random bearings and distances (up to 25m - Upper Marsh 5 x 10 sites) from the site marker. The sub-sites were marked with bamboo canes. Each site was levelled as were reference points along the sea wall. These levels were tied in with the national system (Ordnance Datum - Newlyn).

Meteorological data was collected from October 1990 using a Didcot Instruments Automatic Weather Station coupled to a Campbell Scientific CR10 Data Logger. The parameters recorded include solar radiation, wind speed and direction, barometric pressure, rainfall, temperature and humidity.

1.1.2. Sampling Methods

The first trials of the vegetation sampling were made in May 1990 and the regular monthly sampling commenced in June. The selection of the ten sample sites has been described in Part 1., Section 2.2.1. Vegetation was cut from five sub-sample sites in the Upper Marsh and five sub-sample sites in the Lower Marsh at each of the ten primary sample sites, using a square quadrat of 0.10 m^2. The quadrats were cut in a regular sequence around the primary point and the location of each quadrat cut was recorded.

This procedure was modified in August by dividing each quadrat into two - one half was totally harvested as before while the other half was also harvested but the litter and standing dead was returned to the plot. The dead material that was returned was collected the following month to determine its rate of disappearance. The samples were taken to the mobile laboratory situated immediately behind the sea wall and the fresh weights recorded. The samples were then returned to Monks Wood where they were deep-frozen for sorting and weighing at a later date.

The vegetation sampling was further modified after the March 1991 meeting in Rennes. From April 1991 onwards sampling was reduced from five to three replicates. This resulted in only a small increase in standard error of totat dry weight, but a considerable saving of time.

The methodology of returning the dead material to plots to determine rate of decay was also modified. Since April 1991 quadrat-sized pieces of 5 mm plastic mesh and pins were used to anchor the material to the relevant half of the harvested plot. This was done because there were problems with dead material being irregularly removed by the tide. This was considered to be the best method that could be devised to substitute for the anchoring properties of the living material that was harvested. Winter sampling was done in January 1991 and the regular monthly sampling was resumed in March and continued to October together with a final sampling in January 1992.

Samples of drift line material were collected in January 1991 and 1992. The length of the sea wall was measured on the map and divided by ten to determine the sampling interval. A random point on the sea wall was taken to determine the location of the first sampling point. Samples were than taken every 200 m. The whole length of the sea wall was covered using nine samples. Dry weights and ash-free dry weights of the material collected have been determined.

Two traps to catch floating litter were erected in October 1991 using 5 mm plastic mesh. They are cross shaped with each arm measuring 2 m long by 0.75 m high, and stand parallel and at right angles to the creek. Dry weights and ash-free dry weights of material collected was determined.

1.1.3. Processing of Samples

The harvested material was sorted into species and components. The components were green (the current year's green tissues), woody (lignified living material - e.g. old stems of <u>Halimione</u>, rhizomes of <u>Aster</u> etc.), standing dead (dead material still attached to living) and litter (not sorted into species). Dry weight was determined by drying at 80°C to constant weight (usually overnight). Loss-on-ignition and thus ash-free dry weight was determined by heating at 500°C for a minimum of three hours.

Material harvested during sampling was sent to Soil Survey for chemical analysis on a composite sample basis. Species from all Upper Marsh replicates within a site were mixed to form composite samples of total live, litter, standing dead and the previous months' dead material for the site. The same happened with Lower Marsh vegetation. Material of individual species also was sent to Soil Survey for chemical analysis.

1.1.4. Calculation of Results

Dry weights (DW) and ash-free dry weights (ADW) were transferred to an IBM PS2 Computer and entered into Minitab work-sheets and coded for species, component, and site. Plant nutrient data will be dealt with similarly when the results of the chemical analyses are available. For this report dry weight values for species and components were summed at each of the ten sample sites and the means and standard errors over the ten sites calculated.

In agreement between the four teams, Net Annual Primary Production, (NAPP)of the Upper and Lower Marsh and of key species, was estimated using Smalley's method (Linthurst & Reimold, 1978).

1.2. Exchange Study

1.2.1. Sampling Methods used

In order to measure and sample the water going in and out of the marsh during various tidal cycles a jetty was constructed extending out to the deepest point in the main creek at the outer margin of the area under study. The jetty was constructed on eight pairs of poles driven 4m into the mud and extending upwards some 6m, to a level above Extreme High Water Spring Tides. The working platform of the jetty extended 20m and it was planked 2m wide. The planking was based on three longitudinal members approximately 200mm x 75mm in cross-section. The end of the jetty supported a tide pole calibrated 0 - 6 m, a ladder for access to the bed of the creek at low water, a winch for raising and lowering a current meter and a table for equipment. Water velocity measurements were made using two Armfield H37 electromagnetic current meters. The sensing heads were fitted with fins to ensure they remained parallel to the water flow. One of the sensors was set at 0.5 meters form the bottom of the creek and one suspended 0.5m below the surface of the water. Preliminary studies had shown that this method gave a good indication of the overall mean creek velocity.

Because of the large tidal range (approximately 5m for a high spring tide) it proved difficult to pump water up to the jetty while the tide was low so water sampling was done from a 6m motor boat anchored near the jetty. Water samples were taken by using a submersible electric pump on a flexible hose that could be set at different depths. To obtain a representative sample of the water column water samples were taken at 0.5m above the bottom and 0.5m below the surface of the water and at 1.0 m intervals between, when water depth allowed this (thus up to six sub-samples were taken). At the start of the study the individual samples were kept separately. However to reduce the total number of samples for analysis the replicates taken at different depths at the same time were combined into a single sample. Two replicates were taken of each water sample; one went to Soil Survey for chemical analysis and the other was brought back to Monks Wood. In addition to the water samples described above, simultaneously 501 of water was filtered through a 50µ plankton net to separate the coarse particulate matter.

Sediment traps were used to determine the much higher sediment load moving near the bed of the channel. Each sediment trap consisted of an inner acrylic sample tube, 0.00621 m2 in cross section area, set in an outer tube buried in the bed of the channel.

The eight traps were set up in pairs at four levels between the level of the bed of the main channel and the level of the lower edge of the main marsh (corresponding to Low Water Spring Tide and Mean High Water). The traps were set up at Low Water and one of each pair was left open to catch the Flood sediment load while the other was left corked. At High Water the set of open traps were retrieved by means of the nylon cords attached to each sample tube; simultaneously the corks were removed by cords from the other set of tubes to activate the traps and thus sample the Ebb sediment load.

Tidal data was recorded continuously using a pneumatic (bubbler) type of water level recorder set up some 200m above the jetty with the control module and air supply situated in the mobile laboratory.

The cross-section area of the creek at the jetty was determined in the spring and autumn of 1991 by levelling with reference to the jetty which had been tied in to the UK national levelling system (Ordnance Datum - Newlyn). The two different profiles obtained only showed minor differences and so the mean of the two profiles was used in further calculations relating cross-section area to tidal height.

The areas of the four zones used for the productivity studies (Upper Marsh, Lower Marsh, Upper Mud Flat, Lower Mud Flat) was determined as described in Part 1., Section 2.2.1. The heights of the boundaries between these zones and thus the tidal regimes had already been determined.

In addition to the direct measurements made of sediment transport a study was also made of direct erosion and accretion of the main marsh surface. Four two-metre transects were set out in January 1991 with deeply anchored reference blocks at each end. Measurements to the soil surface were made at 100mm intervals from a portable aluminium beam between the two reference points. The transects were situated at intervals across the marsh between the jetty and the sea wall and readings were made at intervals of approximately one month.

1.2.2. Measurements Made

The basic cycle of measurements and the water sampling was repeated every half hour throughout one (12.5hr) or two (25hr) tidal cycles. Measurements of current speed and water height were made every ten minutes during the half hour before and after high water and low water. When the water depth was insufficient to measure current speed with the bottom current meter the measurements halted. The amount of water still leaving the marsh at that time was negligible. The value of current speed recorded from each meter was the mean velocity (with standard error) calculated over four minutes.

One set of water samples was taken to Monks Wood and the pH and salinity determined. The other set of water samples were analyzed, by Soil Survey, for total dissolved phosphorus, ammonium nitrogen, nitrate nitrogen, nitrite nitrogen also POM. The samples of coarse sediment (>50μ) were analyzed by Soil Survey for DWT, LOI, total phosphorus and total Nitrogen.

Between May 1991 and February 1992 a total of 12 tidal cycles were studied. In addition, on the 9th April, 1992, a set of water samples were taken every 200 m from the head of the main creek, past the jetty and on to the open sea, a distance of some 8 km. These samples were treated in the same way as the water samples taken from or near the jetty.

1.2.3. Calculation of Water Budgets

The water discharge was calculated by taking the average current speed (Fig. 1) with the mean cross-section area of the water during a time interval (normally half an hour but 10 minutes during the turn of the tide). For the determination of the current speed the average of the surface and bottom current speeds was used.

Water discharge (m^3s^{-1}) = Current Speed (ms^{-1}) x Cross Section Area (m^2)

The cross-section area corresponding to a particular water level was determined graphically from the profile of the creek bed. A clear relationship was obtained between the water level in the creek and the cross-section area of the water column (Fig. 2).

The irregular pattern of creeks in the marsh made it difficult to measure creek profiles. Information on this was obtained indirectly from the relationship of flood volume to water level (Fig. 3). Below the level of the main creek system and above the main marsh level the relationship between water level and flood volume was approximately linear being related to water depth. The areas and levels of each of the zones being known it was possible to relate water level to the percentage area covered (Fig. 4). As the zone boundaries varied from place to place the picture is a generalised one, however it is possible to say that the rise in cover between -75cm and -50cm represents the flooding of the edge of the lower marsh and the rise between +10cm and +50 represents the flooding of the upper marsh surface.

Finally a total water budget was calculated from the water discharges of each of the tidal cycles that were measured. Multiplying the volume of total water transport during a half hour measurement with the mean concentration of a particular substance during the same half hour gave the transport of that substance. By summing the half hour periods a budget figure for each flood or ebb tide was obtained.

1.2.4. Analysis of Water Samples

(to be supplied by Soil Survey)

2. PRIMARY PRODUCTION

2.1. Changes in total plant material at Old Hall Marshes in 1991

2.1.1. Upper Marsh

There was a gradual increase in green material during the early part of the growing season. Levels remained relatively constant from June to August (800 DW g/m^2), then declined over the winter months (Fig. 2.1.1.1). Woody material, largely *Halimione portulacoides*, was at quite high levels early in the season but then declined, levels being particularly low during the dry months of July, August and September (Fig. 2.1.1.2). When the results for green and woody material were combined to give total live material, one could detect only a very slight increase in material until October, followed by a sharp decline over the winter months (Fig. 2.1.1.3).

The amount of standing dead material remained relatively constant until midsummer, when it increased to a peak in September, and then remained relatively high through to January (Fig. 2.1.1.4). Litter declined quite markedly over the year (Fig. 2.1.1.5). The decline, however, only resulted in autumn levels similar to those of autumn 1990, suggesting a build up in litter between January and March 1991. When the results for standing dead and litter were combined to give total dead material, levels fluctuated somewhat between high winter levels and rather lower levels in early summer (Fig. 2.1.1.6).

2.1.2. Lower Marsh

There was a slow increase in green material from March to July, after which the amount of green material increased sharply to a peak of over 1250 DW g/m^2 in September (Fig. 2.1.2.1). This corresponded with seed production by *Salicornia herbacea* agg. (see Section 2.3.2.). After that the green material declined to very low levels in January 1992. As expected the levels of woody material in the Lower Marsh were low (Fig. 2.1.2.2). Woody material in the lower marsh is made up from the occurrence above ground of partially exposed *Aster* rhizomes and the occasional occurrence of woody Upper Marsh species. With woody material at a low level, the changes in total live material corresponded closely with those in green material (Fig. 2.1.2.3).

The amount of standing dead increased slowly during the late summer and early autumn, then increased steeply following the death of the season's growth (Fig. 2.1.2.4). Litter levels were around 400 DW g/m^2 during the spring and early summer and then declined steadily during the rest of the year (Fig. 2.1.2.5). When the results for standing dead and litter were combined, it was clear that dead material was at its minimum during the summer and increased during the autumn and early winter (Fig. 2.1.2.6).

2.2. Total Net Primary Production

2.2.1. Upper Marsh

The NAPP in the Upper Marsh in 1991 was 975 DW g/m². Monthly growing season figures varied between 0 and 320 DW g/m². April productivity was probably by algae. A drop in productivity in July was probably due to drought (Table 2.2.1.).

MONTH	DW LIVE MATERIAL	DW STANDING DEAD	NMPP
March	1197±297	495.9±56.8	-
April	1234±215	570.0±101.0	111.1
May	1106±208	466.0±115.0	0
June	1304±182	362.4±51.9	198.0
July	1277±128	472.7±61.8	83.3
August	1359±140	534.8±45.7	144.1
September	1321±157	894.0±102.0	321.2
October	1438±202	727.6±52.1	117.0
January	844±168	856.0±74.7	0

Table 2.2.1 Net Primary Production of Upper Marsh at Old Hall Marsh in 1991.

2.2.2. Lower Marsh

The NAPP in the Lower Marsh in 1991 was 1031 DW g/m^2. Monthly growing season figures varied between 0 and 450 DW g/m^2. April productivity was, again, probably the result of algal growth. Productivity on the Lower Marsh was not so affected by summer drought. Nutrient availability was probably the limiting factor that caused a reduction in productivity between August and September (Table 2.2.2).

MONTH	DW LIVE MATERIAL	DW STANDING DEAD	NMPP
March	405.2±98.7	45.6±15.5	-
April	569.8±85.4	43.2±22.1	164.6
May	514.9±95.1	23.2±22.3	0
June	535.7±68.4	15.47±4.99	20.8
July	614±144	61.2±39.2	124.0
August	1039±192	83.0±23.2	446.8
September	1267±153	129.6±31.50	274.6
October	1159±125	210.6±30.2	0
January	75.8±15.7	860±155	0

Table 2.2.2 Net Primary Production of Lower Marsh at Old Hall Marsh in 1991.

2.3. Performance of Major Species

2.3.1. *Halimione portulacoides* (Upper Marsh)

The changes in the levels of green plant material of *Halimione* followed a similar pattern to that of green material for all species combined. There was a gradual increase in material through the growing season, followed by a decline over the winter months (Fig. 2.3.1.1). As *Halimione* is an evergreen shrub, green material usually does not completely die off over the winter. *Halimione* makes up most of the woody material on the Upper Marsh and therefore follows the same pattern of changes as total woody material (Fig. 2.3.1.2). There was an overall decline in the total amount of live material between March 1991 and January 1992 (Fig. 2.3.1.3). This has yet to be explained.

There was a gradual increase in standing dead *Halimione* over the year. This increase was most rapid during the dry summer months, which corresponded with the drop in the amount of woody material at this time, but was not large enough to account for it (Fig. 2.3.1.4).

The NAPP of *Halimione* in 1991 was 561 DW g/m², which was 58 % of total NAPP on the Upper Marsh. *Halimione* production was low until June. Peak production of *Halimione* was reached in October, resulting from renewed growth in the autumn (Table 2.3.1).

MONTH	DW LIVE MATERIAL	DW STANDING DEAD	NMPP
March	1008±310	60.3±16.1	-
April	1013±228	40.5±11.2	5
May	790±232	45.6±28.3	0
June	917±212	64.3±23.0	145.7
July	725±166	100.3±23.9	0
August	870±170	132.7±28.0	177.4
September	831±147	204.1±63.4	32.4
October	1031±236	199.1±51.7	200.0
January	653±170	231.4±73.0	0

Table 2.3.1. Net Primary Production of *Halimione portulacoides* (DW gm^{-1}) at Old Hall Marsh in 1991 (Upper Marsh).

2.3.2. Salicornia herbacea agg. (Lower Marsh)

The changes in the levels of plant material of Salicornia displayed a typical growth curve for an annual plant. The most rapid increase in green material was between August and September, which was probably due to seed production (Fig. 2.3.2.1).

Changes in standing dead Salicornia also followed the expected pattern. The rapid increase in material between October and January corresponded with the rapid decline in green material over the same period (Fig. 2.3.2.2).

The NAPP of Salicornia was 761 DW g/m², which was 74 % of total NAPP on the Lower Marsh. Productivity of Salicornia began in May and increased until September. The high September value was largely due to seed production at that time (Table 2.3.2).

MONTH	DW LIVE MATERIAL	DW STANDING DEAD	NMPP
March	12.7±12.7	22.87±7.16	-
April	5.67±2.17	22.38±9.84	0
May	71.9±38.4	19.9±19.9	66.2
June	78.2±13.7	1.93±1.91	6.3
July	176.2±26.4	0.0±0.00	98.0
August	285.2±60.7	0.0±0.00	109.0
September	630±93.3	10.40±8.91	356.6
October	698±121	69.0±28.2	126.2
January	0.0±0.00	638±181	0

Table 2.3.2. Net Primary Production of Salicornia spp. (DW gm^{-1}) at Old Hall Marsh in 1991 (Lower Marsh).

3. EXCHANGE

3.1. Water budgets

3.1.1. Discharges

The tidal curves in the estuary of the Blackwater are relatively symmetrical in the main channels, however in the major creeks, such as at the Tollesbury site the flood is rather longer than the more rapid ebb. The shape of a typical spring tidal curve is given in Fig. 5 and that of a neap tidal curve in Fig. 6. With a neap tide both flood and ebb velocities rise quickly and then remain relatively constant. In the case of spring tides the flood reaches a peak velocity at about one hour after low water, then decreases for most of the rise before reaching a second peak just before high water. However the ebb tide reaches a peak soon after the turn of the tide and then decreases steadily until low water.

3.1.2. Total Budgets

The results of the calculations of tidal volumes are presented in Table 1. The tides include a wide range of spring and neap tides and the calculated volume varies between 2.0 and 7.4 million cubic metres of water. There are considerable differences between the calculated volume of corresponding flood and ebb tides. In the tides studied the difference between the flood and the ebb volumes varying between -30% and +4% of the flood volume. The differences tended to be greater with spring tides than for neap tides and this could be explained by some of the flood tide coming in directly over the marsh but ebbing through the channel. However this explanation could not apply to those neap tides where flood volume was exceeded by that of the ebb as the main surface of these marshes is not attained by neap tides. On average the difference between flood and ebb volumes was -17%. This means that over all tidal cycles there is a net water export of 17% of the averaged flood volume.

3.1.3. Annual Budgets

The annual budgets are calculated on the basis of multiplying the mean net tidal budget by the annual number of tides (702). The results must be regarded with extreme caution both because, even with the full data set, not all months are represented and, probably more significantly, storm tides, not represented in the UK data set, make a major contribution to the annual situation.

Date (1991,1992)	High Water Level (cm+/-MHW)	Flood(F) (m^3)	Ebb(E) (m^3)	F-E (m^3)	% of Flood
16 May	93	461243	597750	-136507	-30
17 May	97	471201	599159	-127958	-27
30 May	40	294683	379268	-84585	-29
3 Jun	29	329361	315157	14204	4
4 Jun	21	258479	302601	-44122	-17
27 Jul	-8	197201	195611	1590	1
5 Aug	-3	229223	255294	-26071	-11
6 Aug	-2	216161	264398	-48237	-22
20 Feb	100	(538347)	711997	-173649	-32
21 Feb	109	744373	(921707)	-177334	-24
25 Feb	0	277799	(282730)	-4931	-2

Table 1. Total water budget of all measured tides.
N.B. () indicates an estimated value.

3.2. Water Analyses

3.2.1. Organic Matter

The waters of the Blackwater estuary are noted for their clarity; there were times, during calm weather in the summer, when it was possible to see the bottom clearly at a depth of 2m or more. Not surprisingly the concentrations of fine particulate material (particle size <50µ) were very low. The POM were mostly below the limits of detection of the methods of analysis used for the size of water sample taken. Results were, however, obtained for coarse particulate material (>50µ) as these were determined from 50l water samples.

For the year as a whole the mean flood concentration of coarse organic material (COM) exceeded the mean ebb concentration indicating a net import of COM (flood = 0.29 mg ADW l^{-1}, ebb = 0.25 mg ADW l^{-1}). There was however considerable variation between the different sets of readings and the different months (Fig. 3.2.1.1). The ebb concentrations were higher than those of the flood on three out of ten tides studied. This was sometimes the result of lower than average flood COM levels and some times higher ebb levels.

3.2.2. Carbon

It was anticipated that, with respect to fine material (<50µ), the very low concentrations of POM implied that the levels of POC would also be very low. The levels of COC would be as implied by the levels of coarse organic material.

3.2.3. Nitrogen

The concentrations of ammonium-nitrogen were vary variable but the annual mean flood concentration (12.2 µmols l^{-1}) exceeded the annual mean ebb concentration (8.2 µmols l^{-1}). For both flood and ebb the individual tidal means varied between zero and over 30 µmols l^{-1} Both the highest and the lowest results results occurred in the early summer months (Fig. 3.2.3.1). In June the picture was particularly confused; the apparently normal level in the first flood measured (27.6 µmols l^{-1}) was succeeded by very low levels in the succeeding ebb (1.9), flood (0.4), ebb (0.0),flows.

For nitrate nitrogen the flood and ebb concentrations were similar (annual mean flood = 67.4 µmols l^{-1} , annual mean ebb 63.3 µmols l^{-1}). As with ammonium-nitrogen, nitrate nitrogen concentrations were at their highest in May and June (fIG. 3.2.3.2). These peak levels were about 100x those found offshore and up to 10x those found in adjoining coastal waters. The transect of samples seawards showed that there was a distinct front between the nitrate rich marsh water and the lower concentrations seaward with a five-fold increase over a distance of 200 m.

Concentrations of nitrite nitrogen were very low, usually less than 2 µmols l^{-1}. Because of this the total dissolved nitrogen (TDN) was assumed to be approximately equal to the sum of ammonium and nitrate nitrogen.

As might be expected the concentration of TDN was much less variable. The annual mean flood levels (79.6 µmols l^{-1}) were marginally higher than those for the ebb (71.5 µmols l^{-1}). Usually the flood and ebb levels for particular tides were similar with most of the variation occurring between different tides (fIG. 3.2.3.3). However the May ebb TDN concentrations were consistantly higher than the flood (flood 104 µmolsl-^{1}, ebb 137 µmolsl-^{1}). This was parttialy offset by the high flood tide nitrogen concentrations shown by the first June tide.

In view of the low concentrations of particulates it was considered that the concentrations of PON would also be very low but no measurements were made.

3.2.4. Phosphorus

There appeared to be a net import of dissolved phosphorus with the mean annual phosphate concentration for the flood tide of 0.39 µmols l^{-1}, as compared with the mean ebb concentration of 0.31 µmols l^{-1}. There were however considerable variations within these figures. The data for May show a mean phosphate concentration of 0.23 µmols l^{-1} during the flood tide and 0.07 µmols l^{-1} during the ebb tide. This indicated a small but significant net export (Fig. 3.2.4.1). Subsequent data for June, and July showed rising phosphate levels. In June, for example, the mean flood concentration was 0.47 µmols l^{-1} while the mean ebb concentration was 0.65 µmols l^{-1}, indicating a significant export. In August however levels had declined (mean flood 0.33 µmols l^{-1}, mean ebb 0.25 µmols l^{-1}) and although the figures suggested further small imports the differences were not significant. Subsequently the phosphate levels remained low for the rest of the year.

The July peak had been observed elswhere in the Blackwater (National Rivers Authority - unpublished data). The background levels of dissolved phosphate in the marsh creek were only marginally higher than those in the adjoining coastal waters, although these were 10x those further offshore.

There is also a phosphorus exchange associated with the COM. The concentrations are very low so that although there is a net export of COM the effects on the phosphorus levels and budgets overall are negligable.

3.2.5. Silica

Found to be very low and not subsequently measured.

3.2.6. Suspended Sediments

As described in 3.2.1. the sediment load was generally rather low except for the coarse material. Preliminary results suggest that there are no significant differences between the inorganic content of the coarse material between flood and ebb (See 3.2.1).

While the average suspended sediment loads throughout the water column were low the near bed loads were considerable. The bed exchangeable particles (beps), as determined by this technique, amounted to 75.7 g m^{-2} on the flood tide and 115.0 g m^{-2} on the ebb tide. This difference of 52% amounts to a net export of 39 g m^{-2} per tide. There was no significant difference between flod and ebb beps regarding their organic content which was arount 25%.

The export of beps is not evenly distributed between the different trap levels. It is concentrated at the level of the higher creek mudflats just below the bottom of the cliffed edge of the marsh along the main creek. Here the sediment flux is estimated at -121 g m^{-2} (50.8 g m^{-2} on the flood and 171.4 g m^{-2} on the ebb) evidently a major, if local, source of erosion. At the highest trap level, equivalent to the lower marsh, there appeared to be a small net import although the differences were not statistically significant. However the material being exchanged at this level had a significantly higher organic content (40%0 compared with the beps elswhere (25%). This suggests a local origin to the material being exchanged at this level.

However general observations on accretion and erosion show that this is not the whole story. The evidence of surface changes in the general marsh level shows considerable seasonal variation. From March to June the mean erosion was 3.5 mm although this occurred at rather different rates across the marsh. From August to January there was an average gain of 2.5 mm. These gains were however offset by an average erosion of 3.5 mm during the period from January to April (Fig. 3.2.6.1).

3.3. Material Budgets

3.3.1. Organic Matter

The impact of the net export of water considerably modified the effect of the flood and ebb concentrations of organic material. In general it could be said that, because of the negative water budget (Section 3.1.2.) there had to be, on average, a difference of at least +17% between flood and ebb concentrations for there to be net import. For COM this meant that while mean annual flood concentrations were higher the differences in water volumes meant that there was overall a net export of material (flood mean 108 kg/tide, ebb mean 136 kg/tide) (Fig. 3.3.1.1). The variation between tides were considerable. The first measured tide in May showed a large net export of COM estimated at 263 kg.

This was partly replaced by the following tide which showed a net import of 35 kg. The largest exchange recorded was during a spring tide in February when the flood imported 517 kg, but the following ebb exported 559 kg. Wind induced variations in tidal flows and levels and local wind driven currents can have major effects on the exchange of coarse organic material.

3.3.2. Carbon

The picture can only be inferred from the behaviour of the organic material describe above (Section 3.3.1.).

3.3.3. Nitrogen

The tidal budget for ammonium nitrogen showed a net import with a mean import of 81 kg on the flood tide as compared with a mean export of 60 kg on the ebb. The different sets of data show that there considerable tidal exchanges of ammonium nitrogen in both directions especially in the early summer (Fig. 3.3.3.1).

In contrast for nitrate-nitrogen there were higher nitrogen levels and a net export of nitrate nitrogen (mean flood import 393 kg/tide, mean ebb export 423 kg/tide). The largest exchanges were again in May and June (Fig. 3.3.3.2).

The TDN budget showed a mean input of 474 kg/tide on the flood offset by an export of 483 kg/tide on the ebb. This occurred mainly in the early summer (Fig. 3.3.3.3).

3.3.4. Phosphorus

The tidal budgets showed a net import of dissolved phosphorus, with a mean flood import of 4.7 kg/tide against a mean ebb export of 3.5 kg/tide. The major imports appeared to be associated with high spring tides independant of the summer build-up of phosphate when the budget is more or less balanced.

3.3.5. Silica

Not calculated as data insufficent.

3.3.6. Suspended Sediments

Not calculated as data insufficent.

3.4. Annual Budgets

3.4.1. Organic Matter

The annual budget of COM for the Old Hall site amounts to an estimated export of 20 tonnes (ADW) or 52 g m^2 yr^{-1}. When related to the area of the (vegetated) marsh this would be equivalent to 73.5 g m^{-2} yr^{-1} (ADW). It it is interesting to note that this represents an export of 7-8% of the NAPP.

3.4.2. Carbon

From the export balance of COM it can be inferred that there is also a net export of carbon.

3.4.3. Nitrogen

The ammonium-nitrogen budget showed that there was a net import of 15000 kg per year equivalent to 39 g m^2 yr^{-1}. In contrast there was an annual net export of 20900 kg of nitrate-nitrogen, equivalent to 54 g m^2 yr^{-1}. Overall the nitrogen budget (TDN) showed a small net export of 5800 kg yr^{-1}, equivalent to an export of 15 g m^2 yr^{-1}.

3.4.4. Phosphorus

The annual budget for dissolved phosphorus showed a small net import of 840 kg yr^{-1}, equivalent to 2.2 g m^2 yr^{-1}. However in view of the variation in the data this figure should be regarded with caution.

3.4.5. Silica

Not calculated as data insufficent.

3.4.6. Suspended Sediments

Not calculated as data insufficient.

PART THREE

WILDFOWL GRAZING

Ten exclosures and ten control areas measuring 1 m x 1 m were set up on areas of Old Hall Marshes where brent geese (Branta bernicla bernicla) were known to have grazed and which were accessible and easy to observe. Vegetation was cut in October 1991 from ten 0.1 m x 0.1 m squares located at random within each quadrat. Total dry weight of the material harvested and dry weight of individual species were measured. A further ten randomly selected 0.1 m x 0.1 m squares were cut in March 1992 when the majority of geese had left the area. Numbers of geese grazing the marsh were recorded within five areas A - E at approximately weekly intervals over the winter.

There was a significant difference in the cover of Salicornia spp. in one treatment. There were no other significant differences between exclosures and controls. The significant reduction of Salicornia spp. in plots 6 - 10 in Area A can be partly explained by the observational results which show this area was more heavily grazed than Area B, which contained plots 1 - 5. One area received a higher level of grazing per hectare than Area A and it is possible that more significant results would have been obtained if plots had been located there. This area was rejected, however, as it was thought to be very prone to human disturbance. In the event, although disturbed and moved by walkers in November, by February the geese were not disturbed.

Over 1991/1992 the marsh was grazed by up to 25 % of the total brent goose population in the Tollesbury area (Old Hall Marshes RSPB, pers. comm.). Whether there is a relationship between the numbers of geese in the area and numbers using the marsh is not known. Any further work on saltmarsh processes at the site should be accompanied by monitoring of grazing levels as populations of all geese, including brents, have increased rapidly over recent decades.

The results of this study indicate that wildfowl grazing did not have a significant effect on the vegetation on Old Hall Marshes over the winter of 1991 - 1992. It must be stressed that this study did not cover the most heavily grazed area of the marsh and did not include the growing season of the plants at the site, when the effects of excluding grazing may be more apparent.

As the level of grazing is believed to have been lower in the winter of 1990 - 1991 (L.A Boorman, pers. comm.; M. Stott, pers. comm.; A. StJoseph, pers. comm.) the effect of wildfowl on carbon and nutrient budgets of Old Hall Marshes could be said to be negligible over the period of the present EC project. Further study is necessary over a longer period of time and over a greater area of the marsh before any real conclusions can be made on the effects of wildfowl grazing on the plant communities of the saltmarsh.

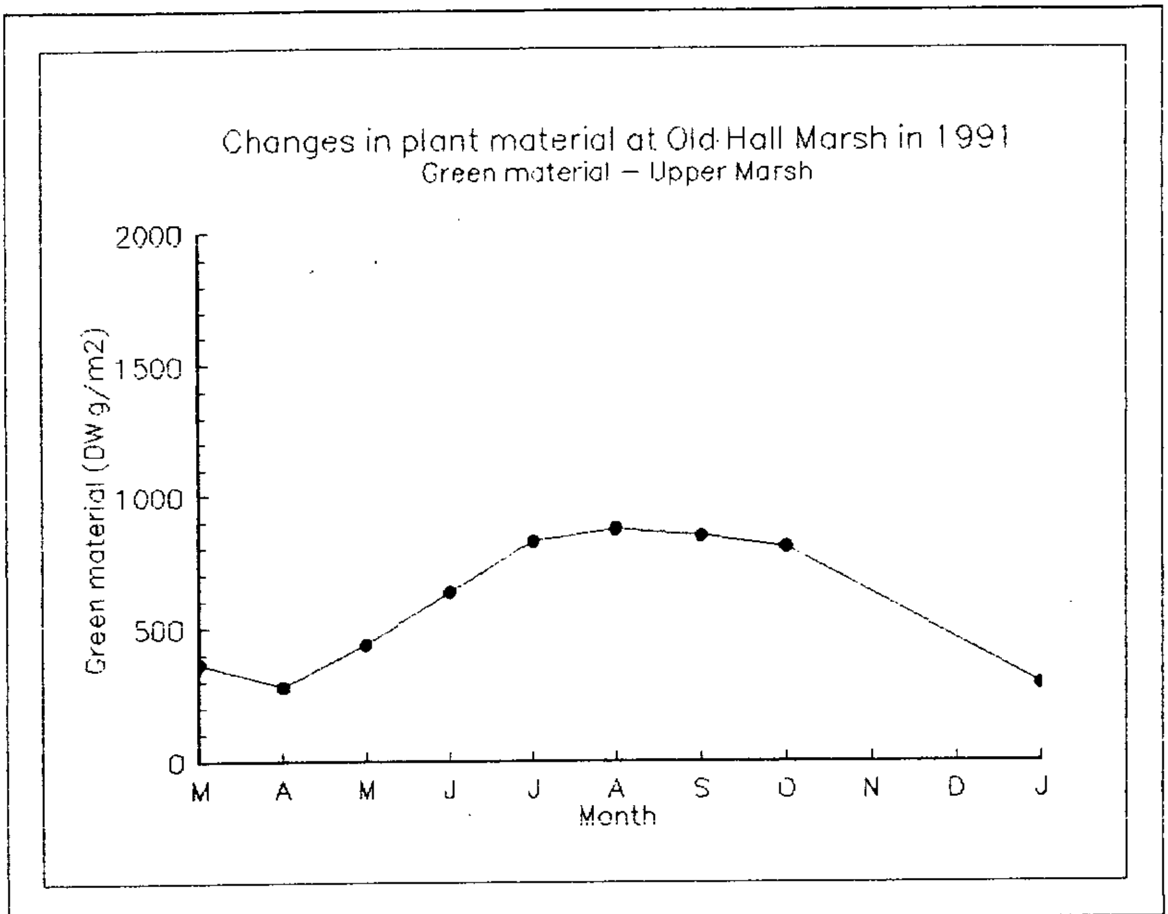

Figure 2.1.1.1 Changes in green material in the Upper Marsh

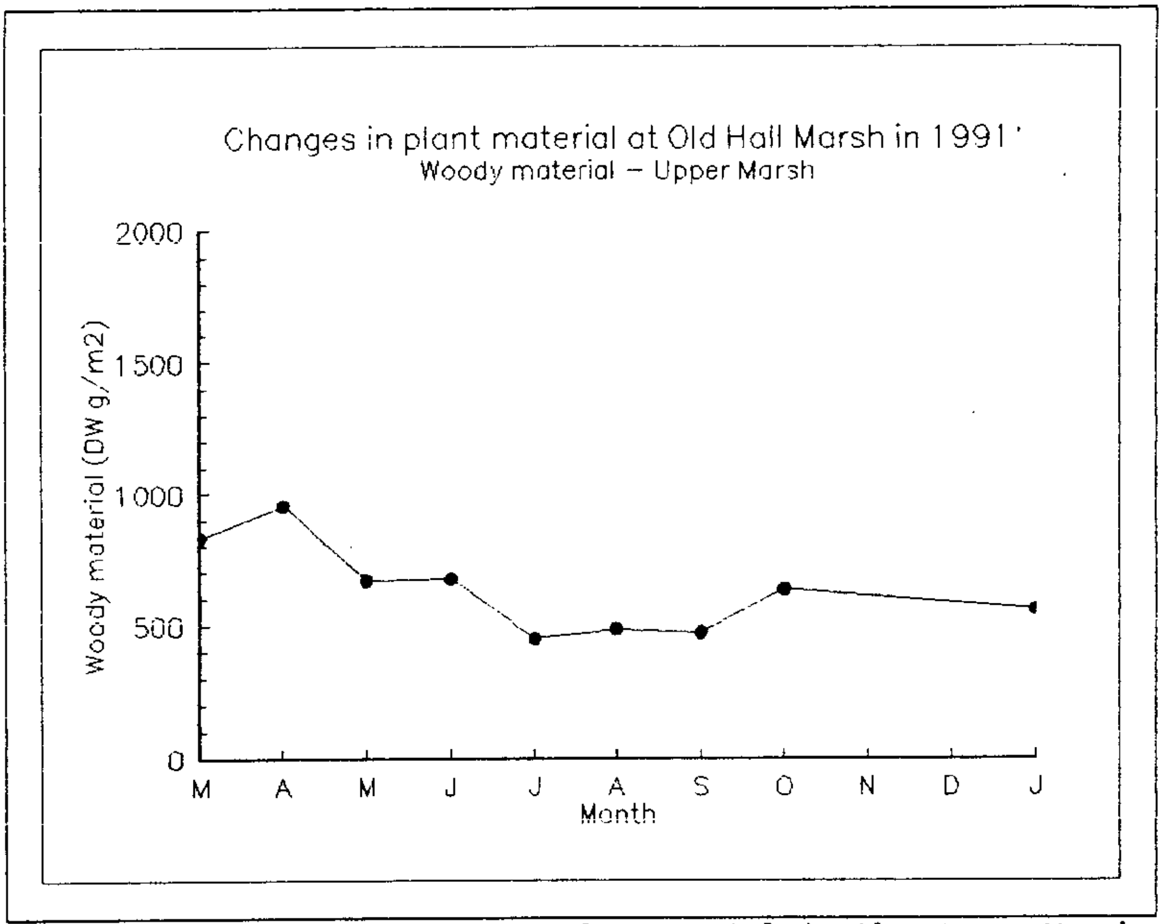

Figure 2.1.1.2. Changes in woody material in the Upper Marsh

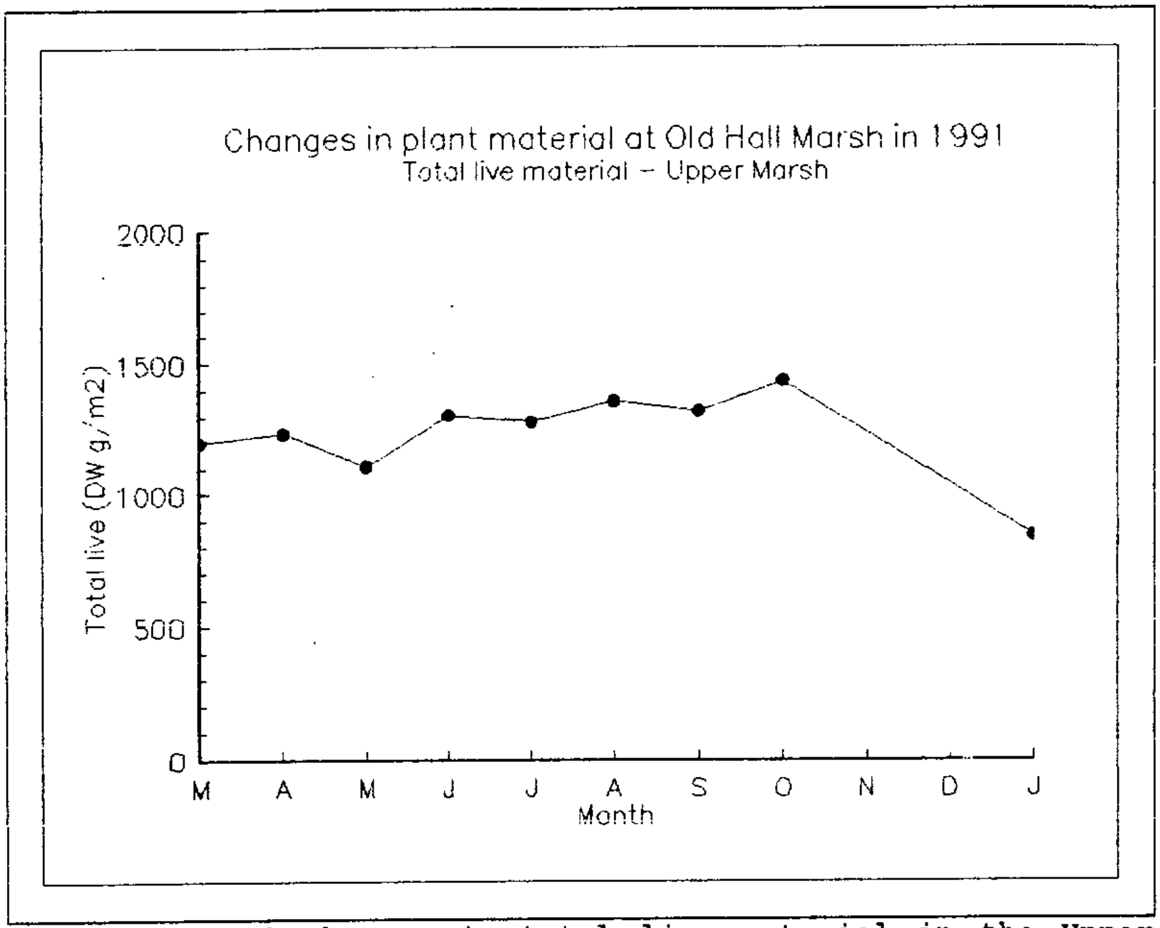

Figure 2.1.1.3 Changes in total live material in the Upper Marsh

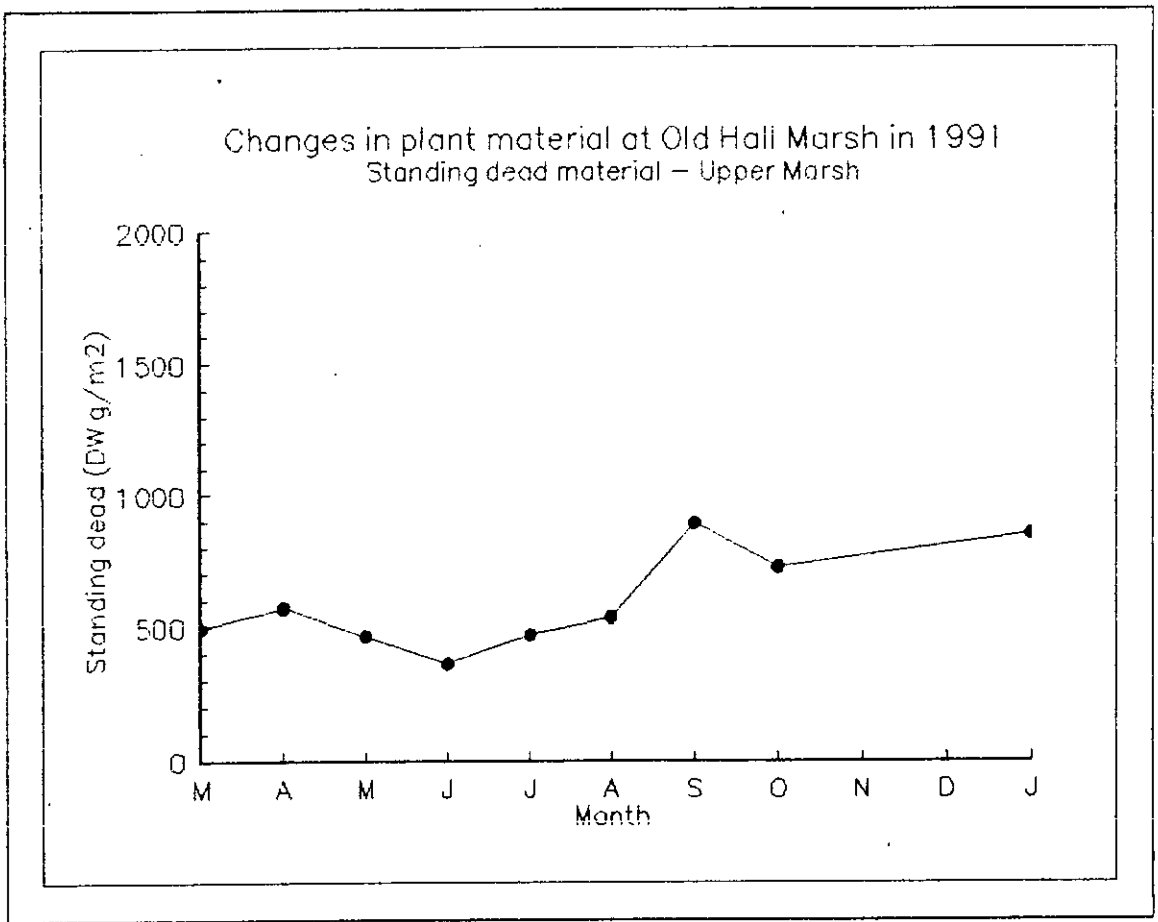

Figure 2.1.1.4 Changes in standing dead material in the Upper Marsh

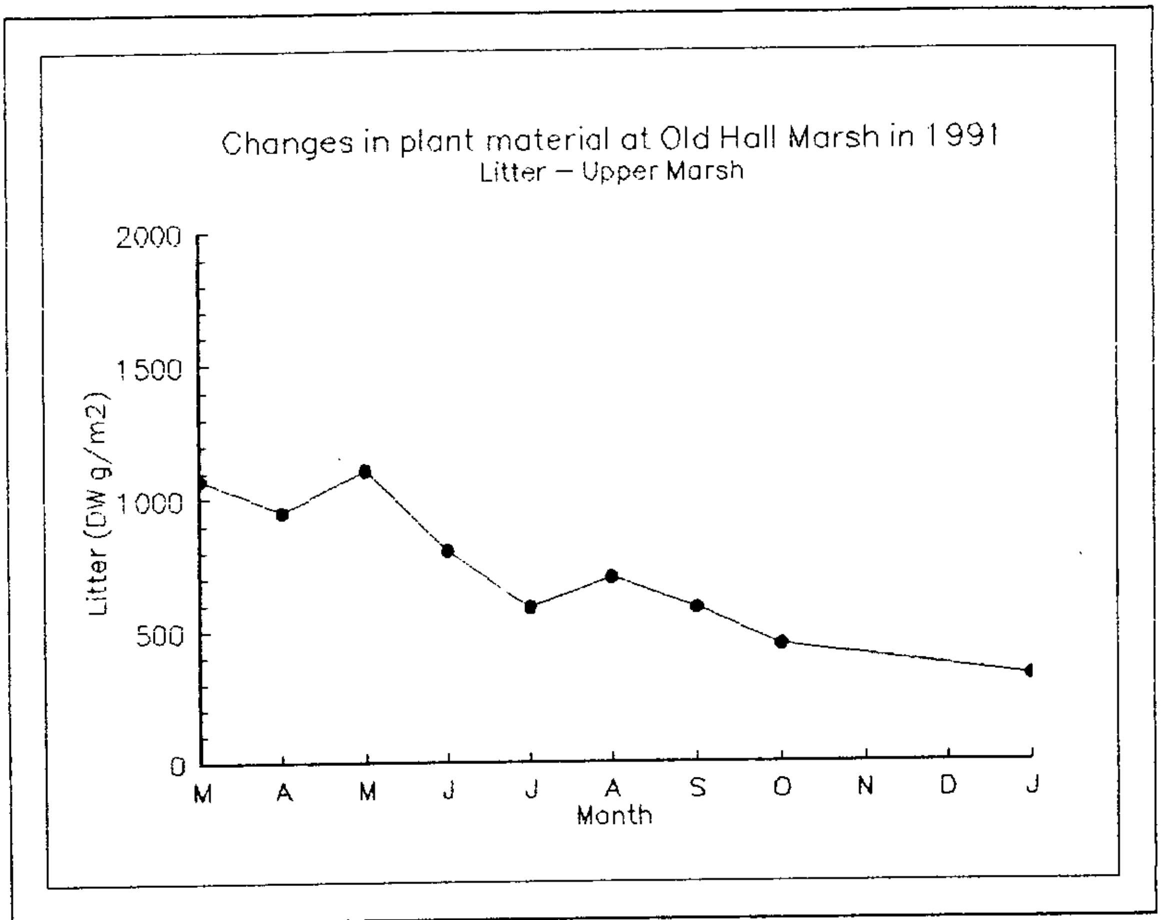

Figure 2.1.1.5 Changes in litter in the Upper Marsh

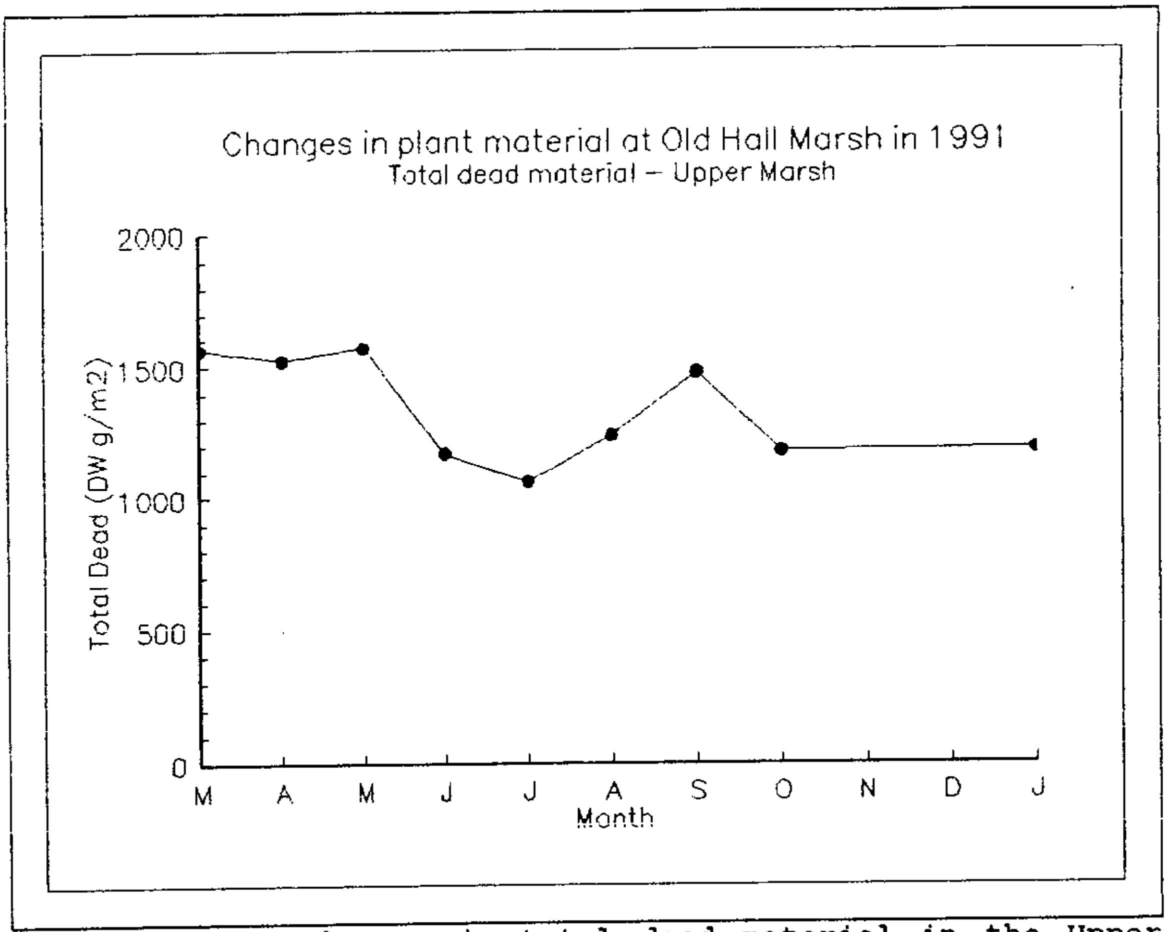

Figure 2.1.1.6 Changes in total dead material in the Upper Marsh

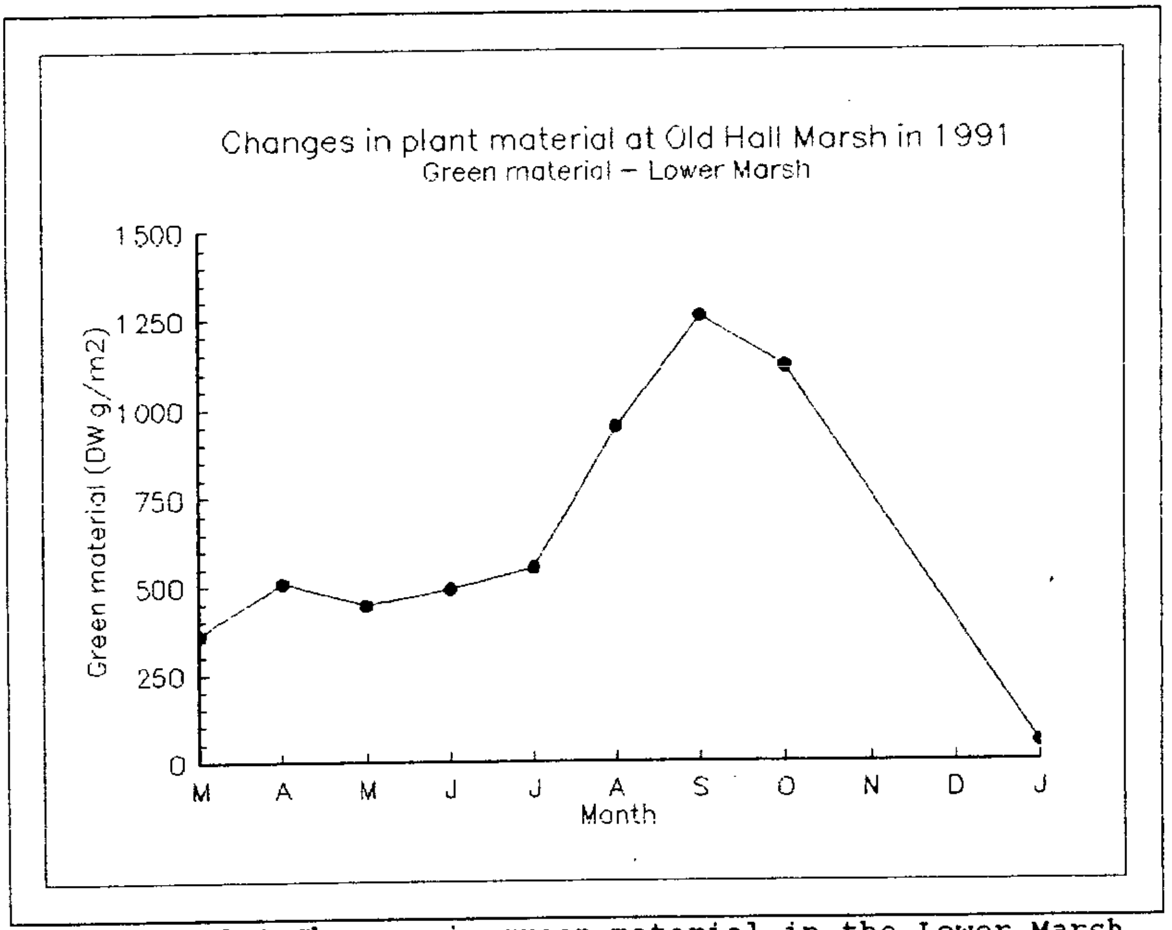

Figure 2.1.2.1 Changes in green material in the Lower Marsh

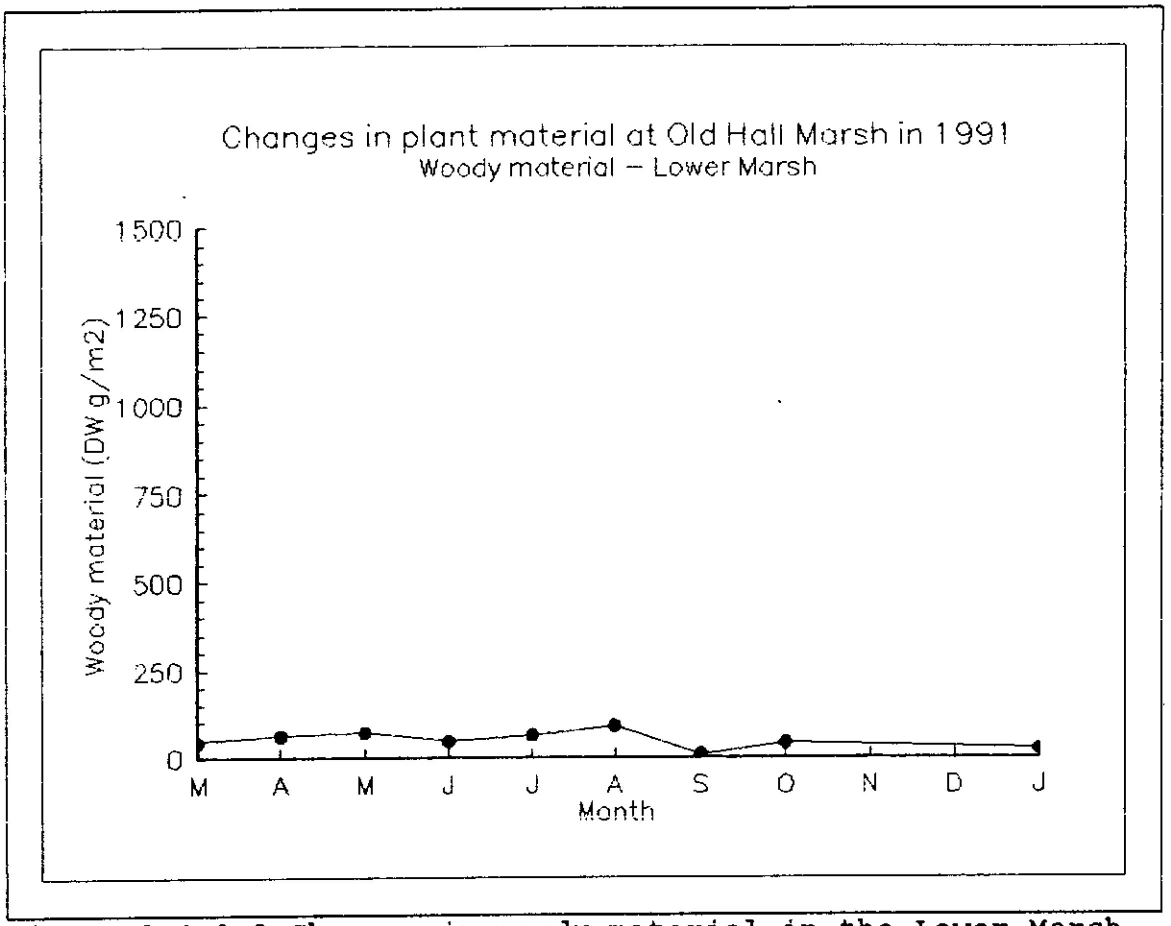

Figure 2.1.2.2 Changes in woody material in the Lower Marsh

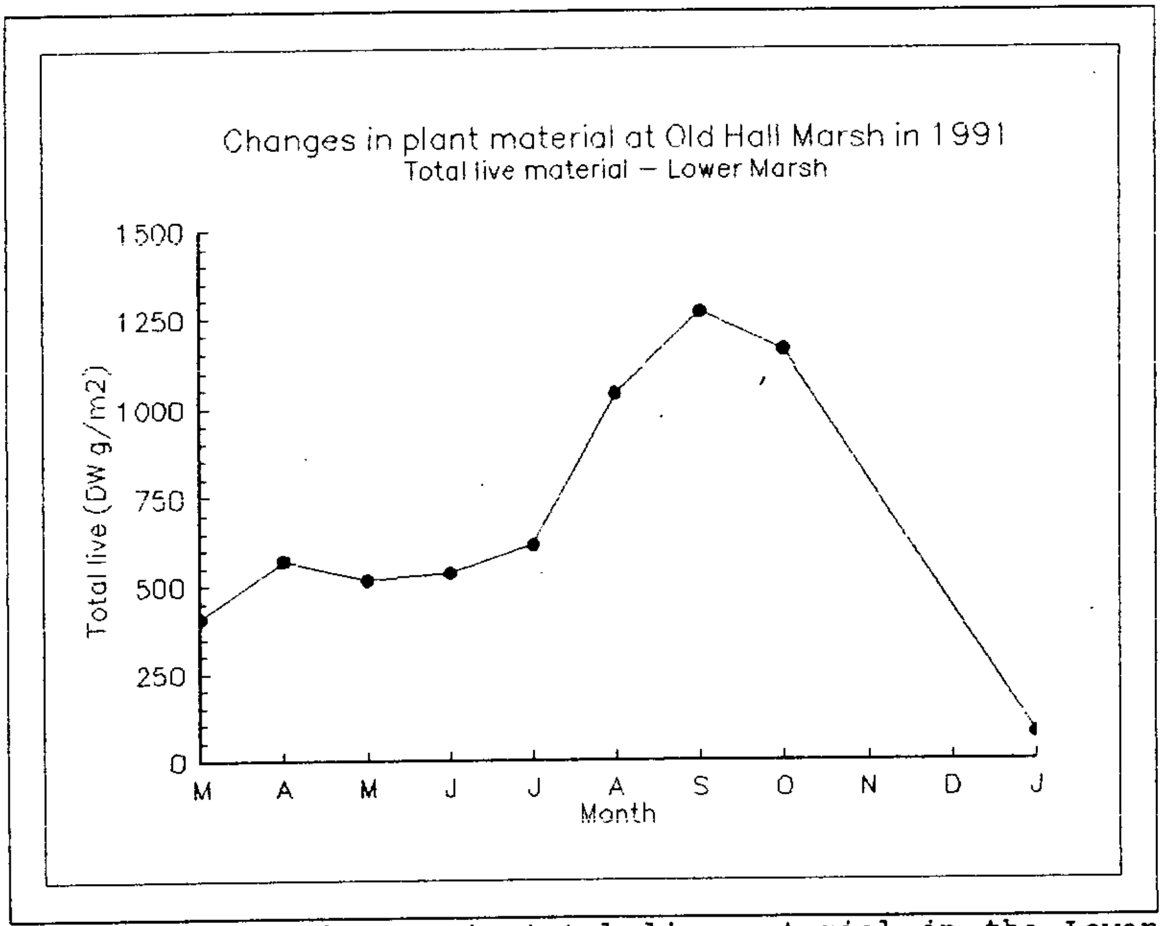

Figure 2.1.2.3 Changes in total live material in the Lower Marsh

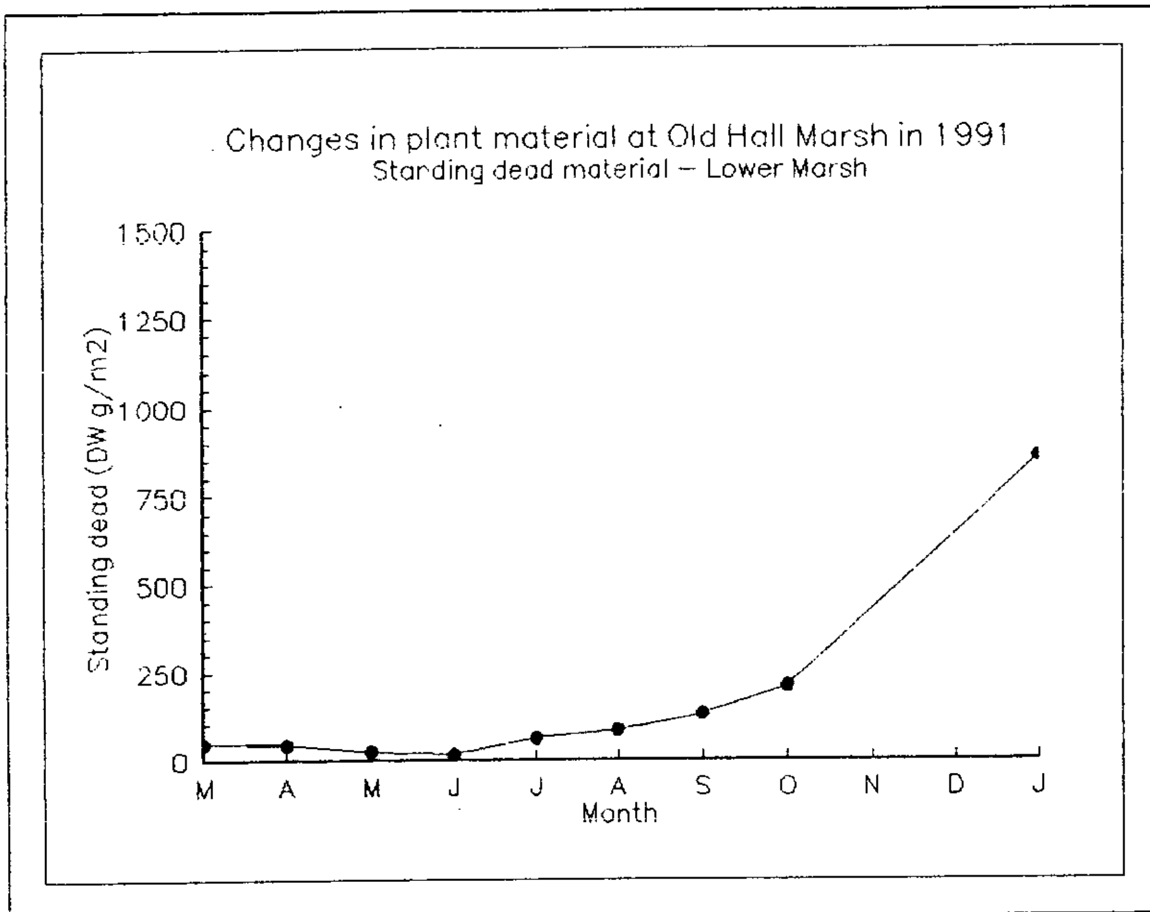

Figure 2.1.2.4 Changes in standing dead material in the Lower Marsh

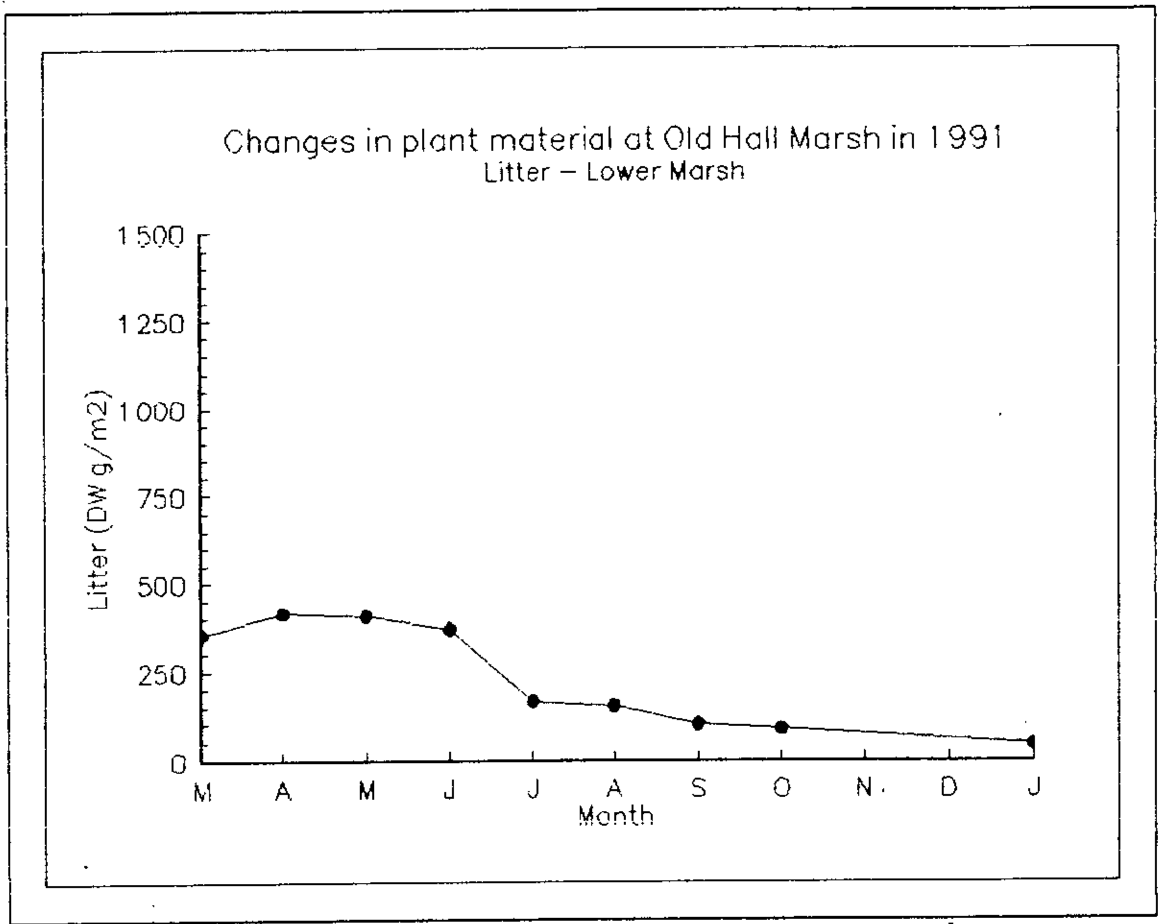

Figure 2.1.2.5 Changes in litter in the Lower Marsh

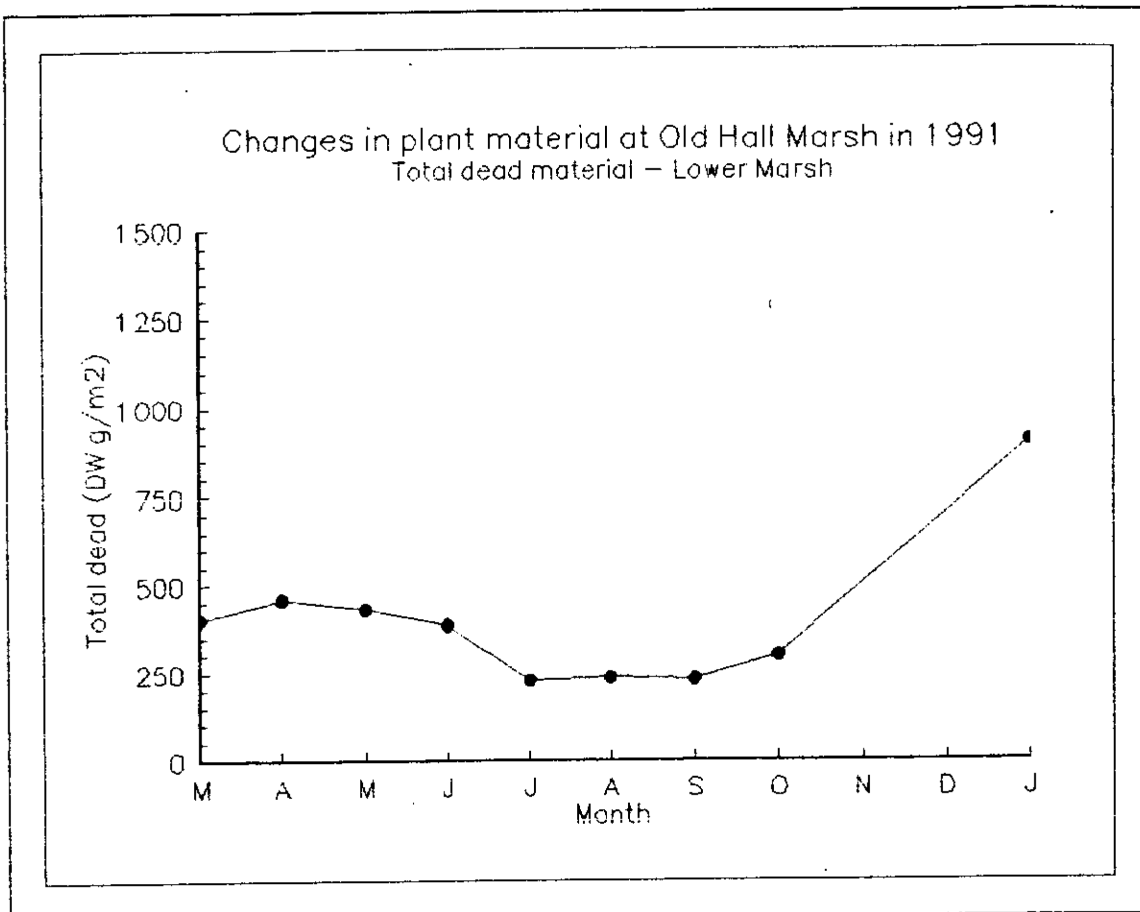

Figure 2.1.2.6 Changes in total dead material in the Lower Marsh

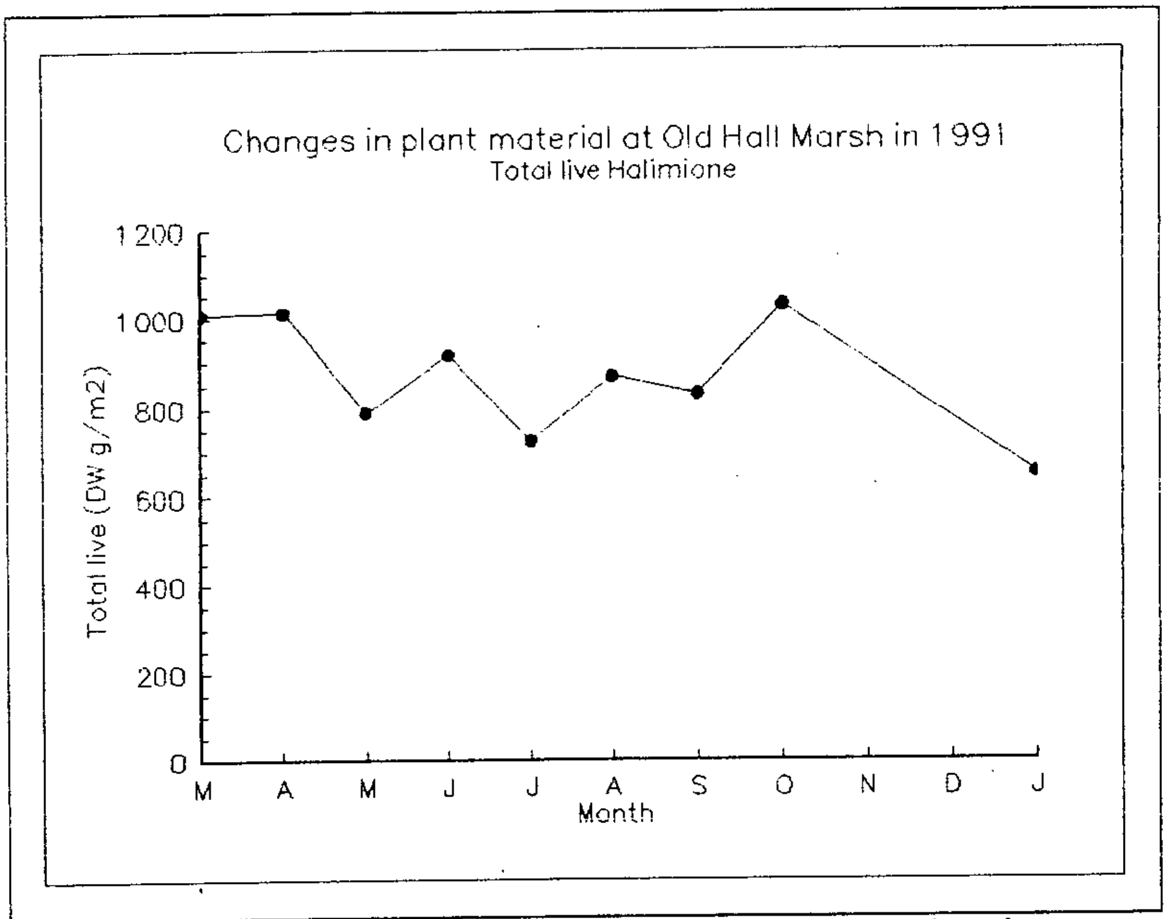

Figure 2.3.1.3 Changes in total live Halimione in the Upper Marsh

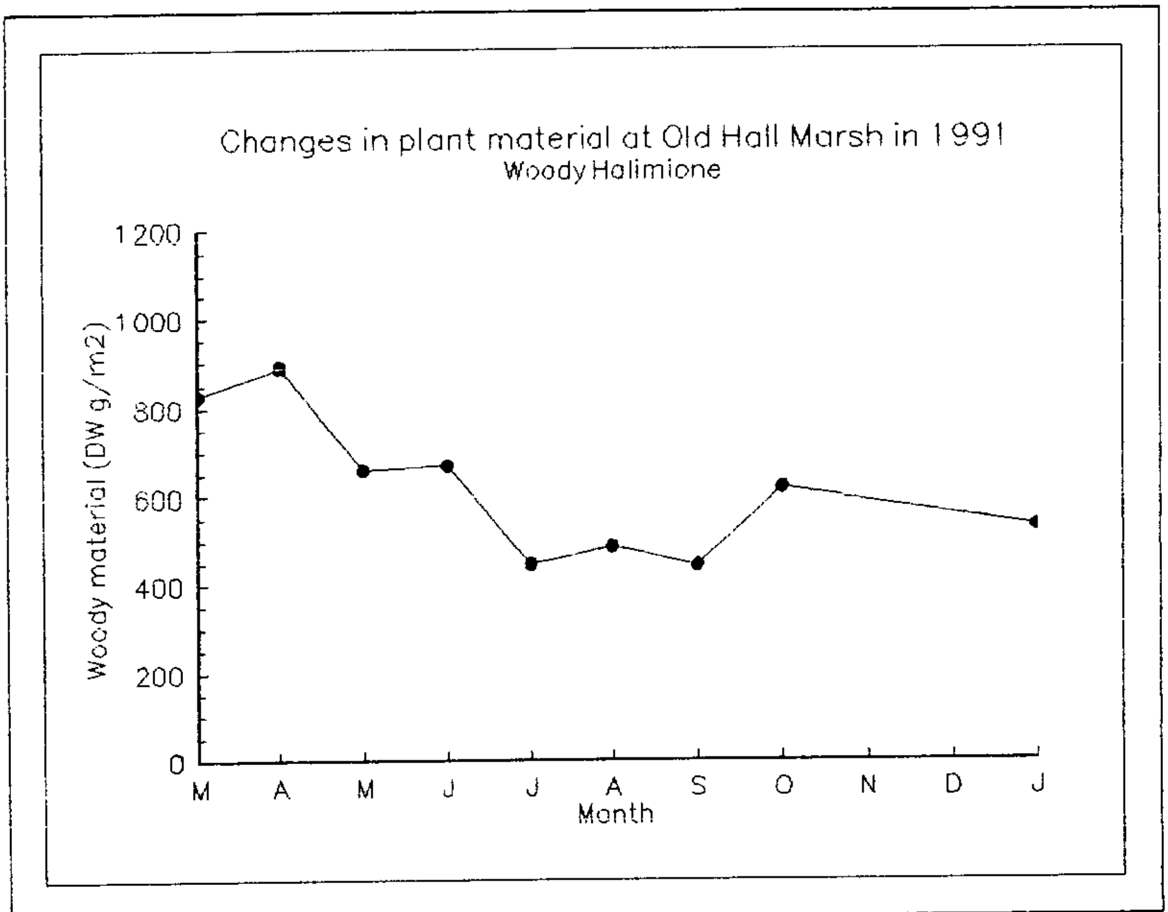

Figure 2.3.1.2 Changes in woody Halimione in the Upper Marsh

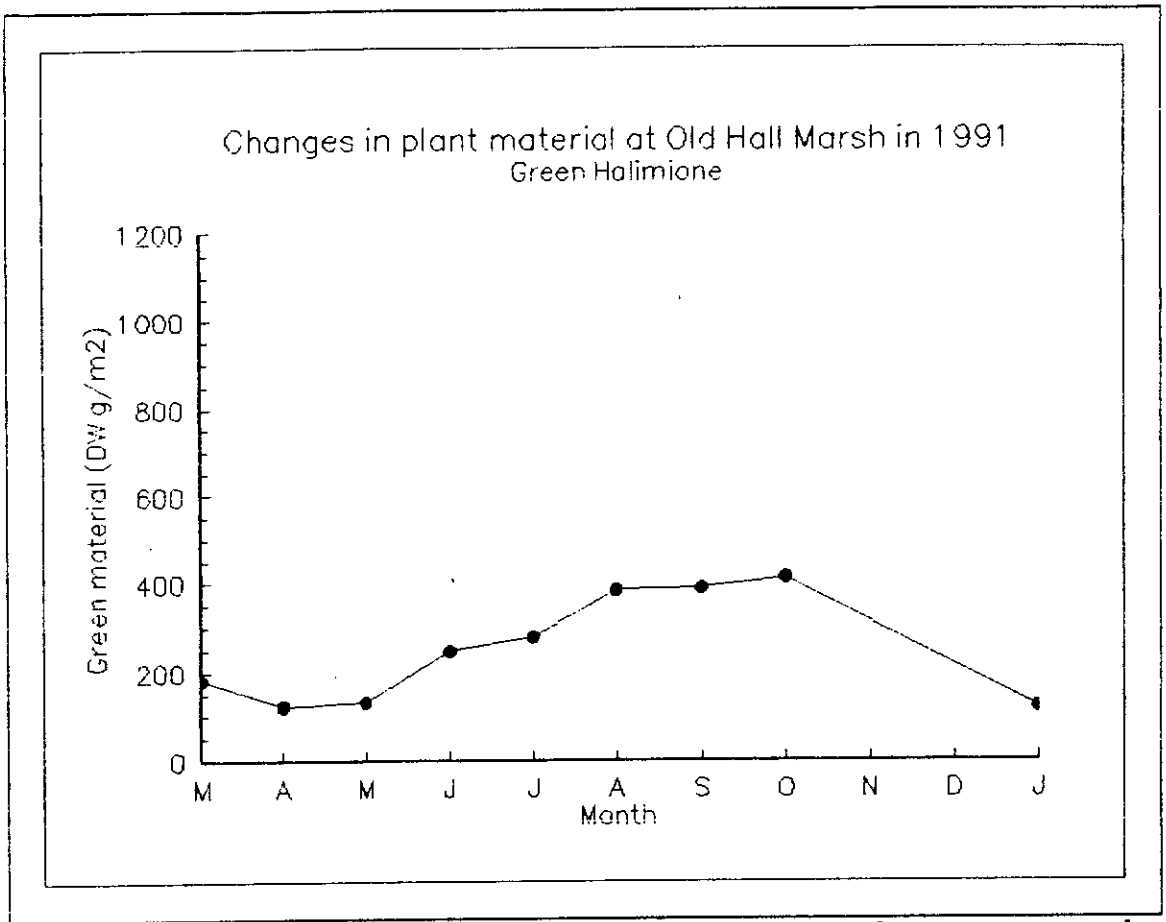

Figure 2.3.1.1 Changes in green Halimione in the Upper Marsh

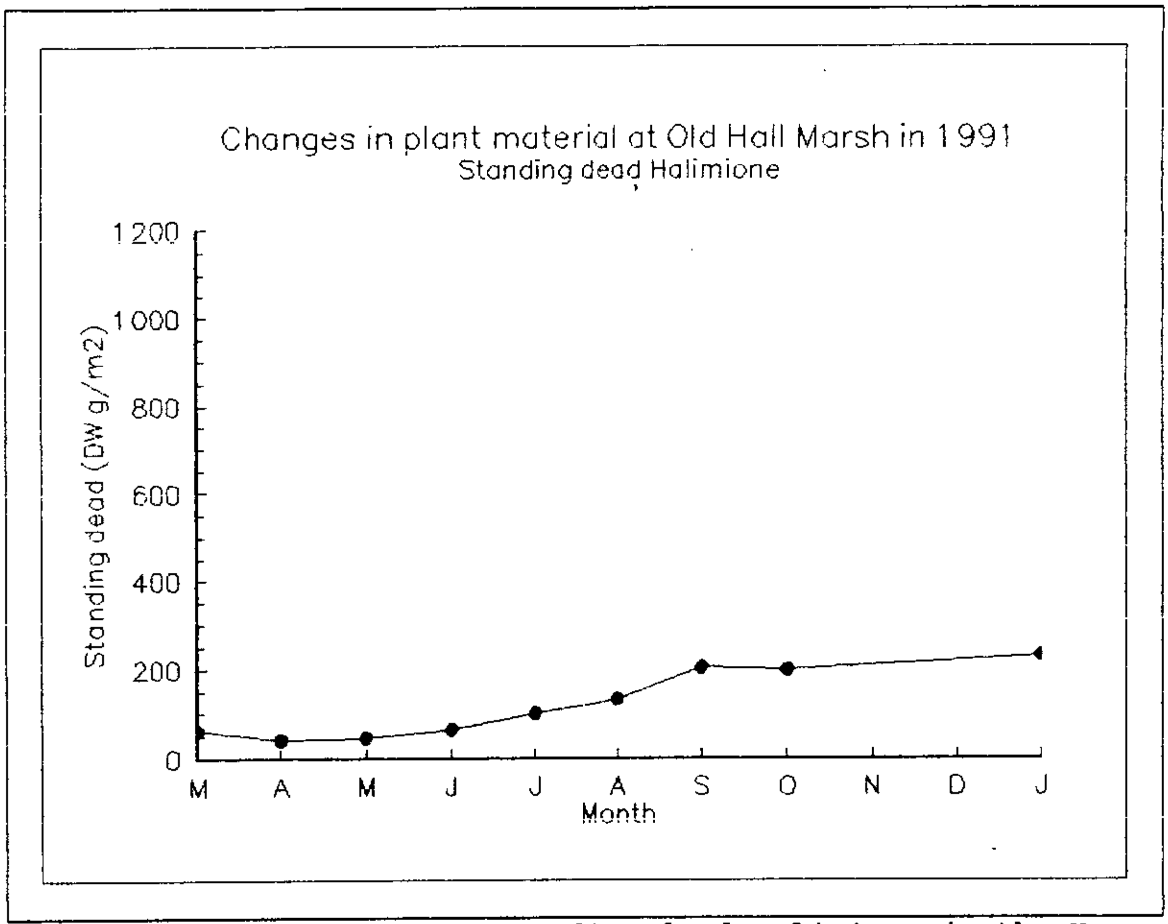

Figure 2.3.1.4 Changes in standing dead Halimione in the Upper Marsh

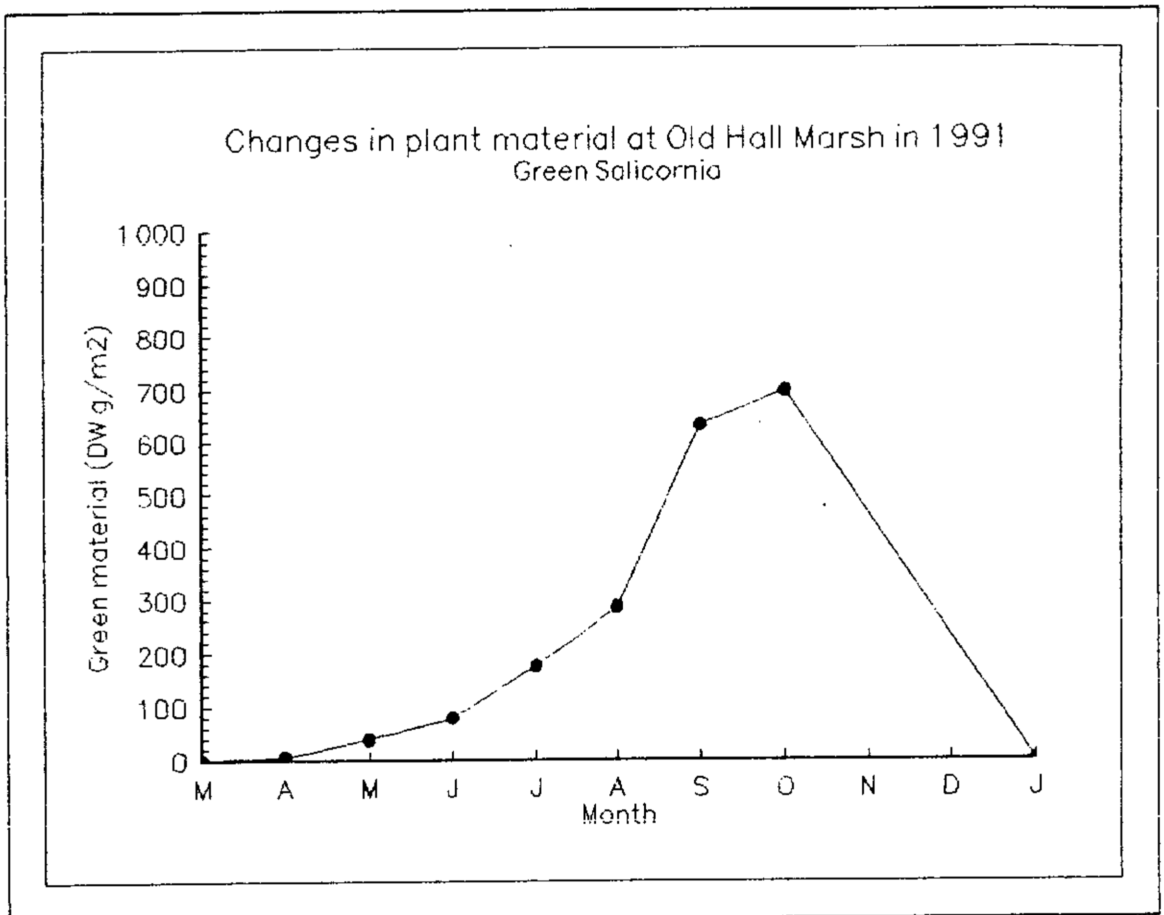

Figure 2.3.2.1 Changes in green Salicornia in the Lower Marsh

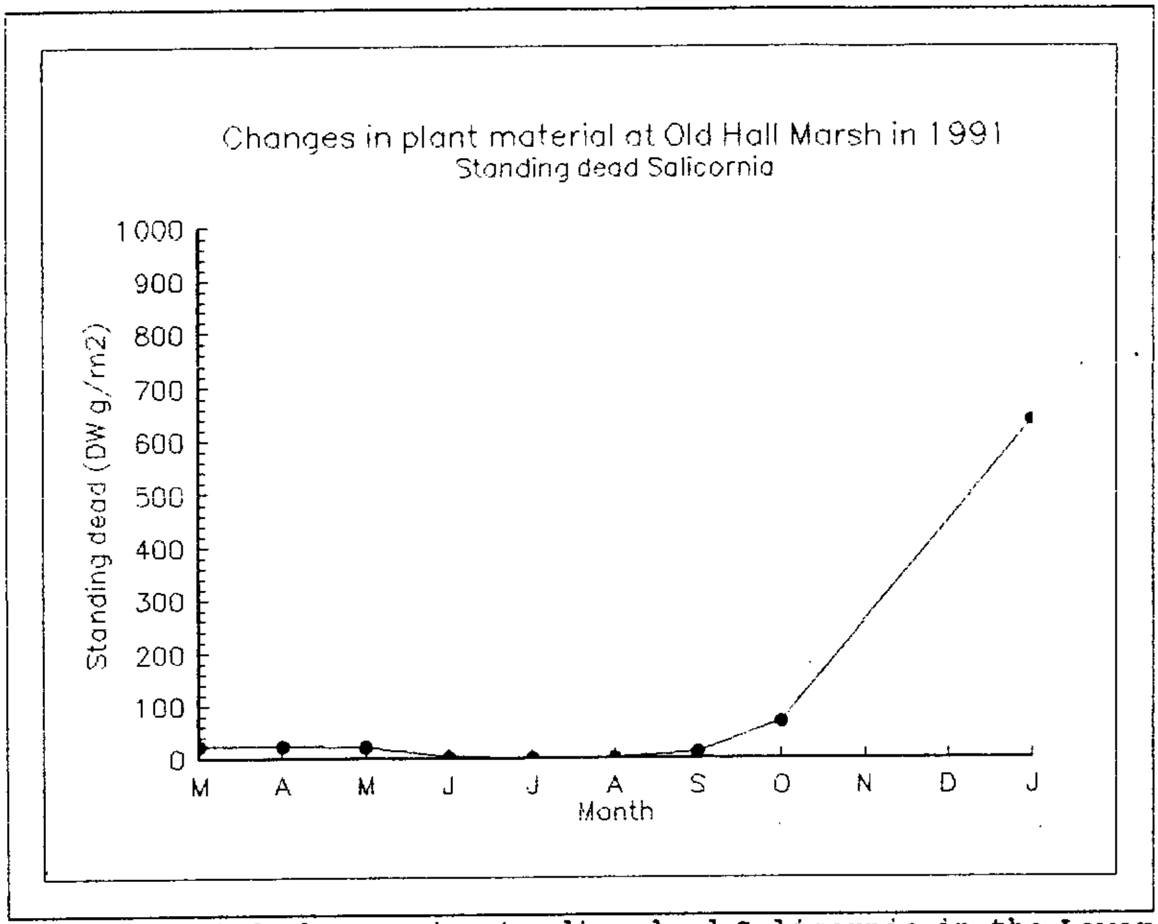

Figure 2.3.2.2 Changes in standing dead Salicornia in the Lower marsh

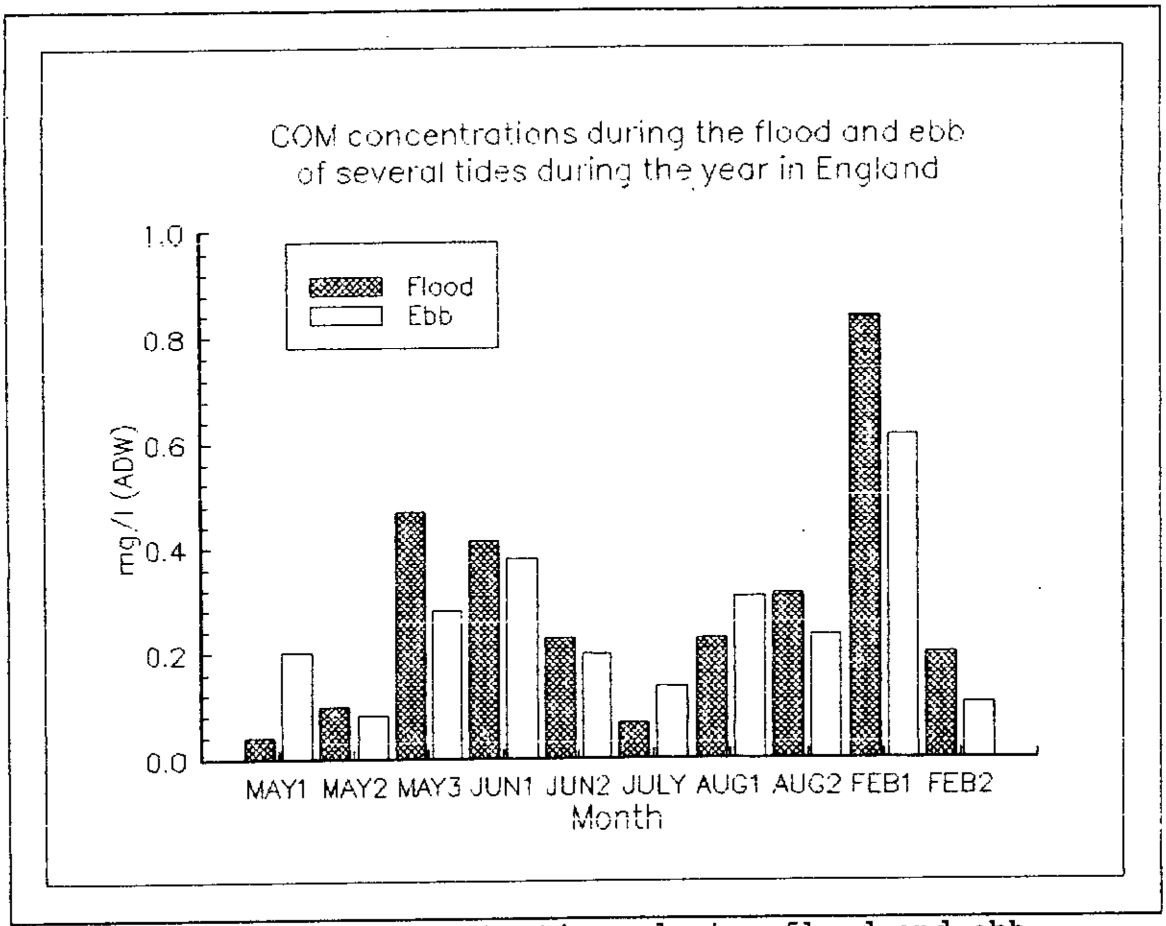

Figure 3.2.1.1 COM concentrations during flood and ebb

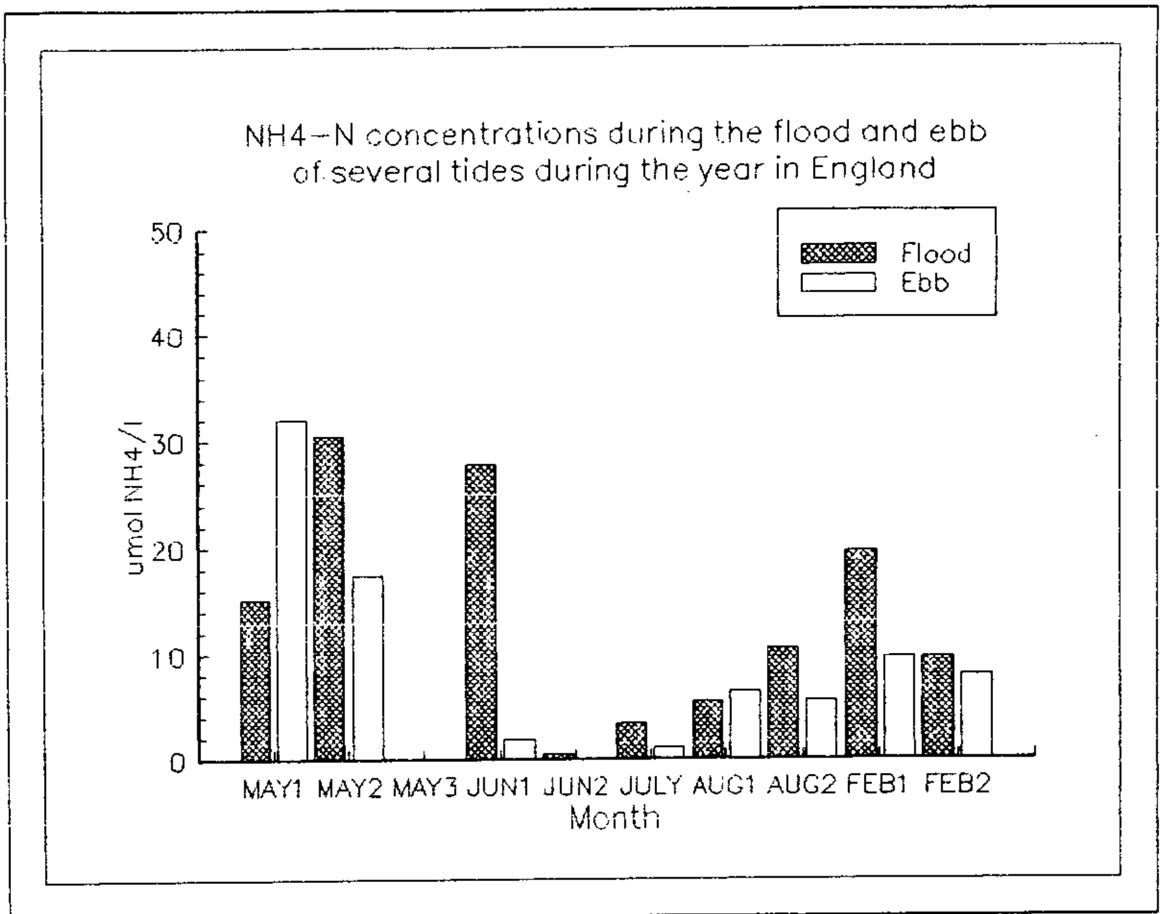

Figure 3.2.3.1 Ammonium nitrogen concentrations during flood and ebb

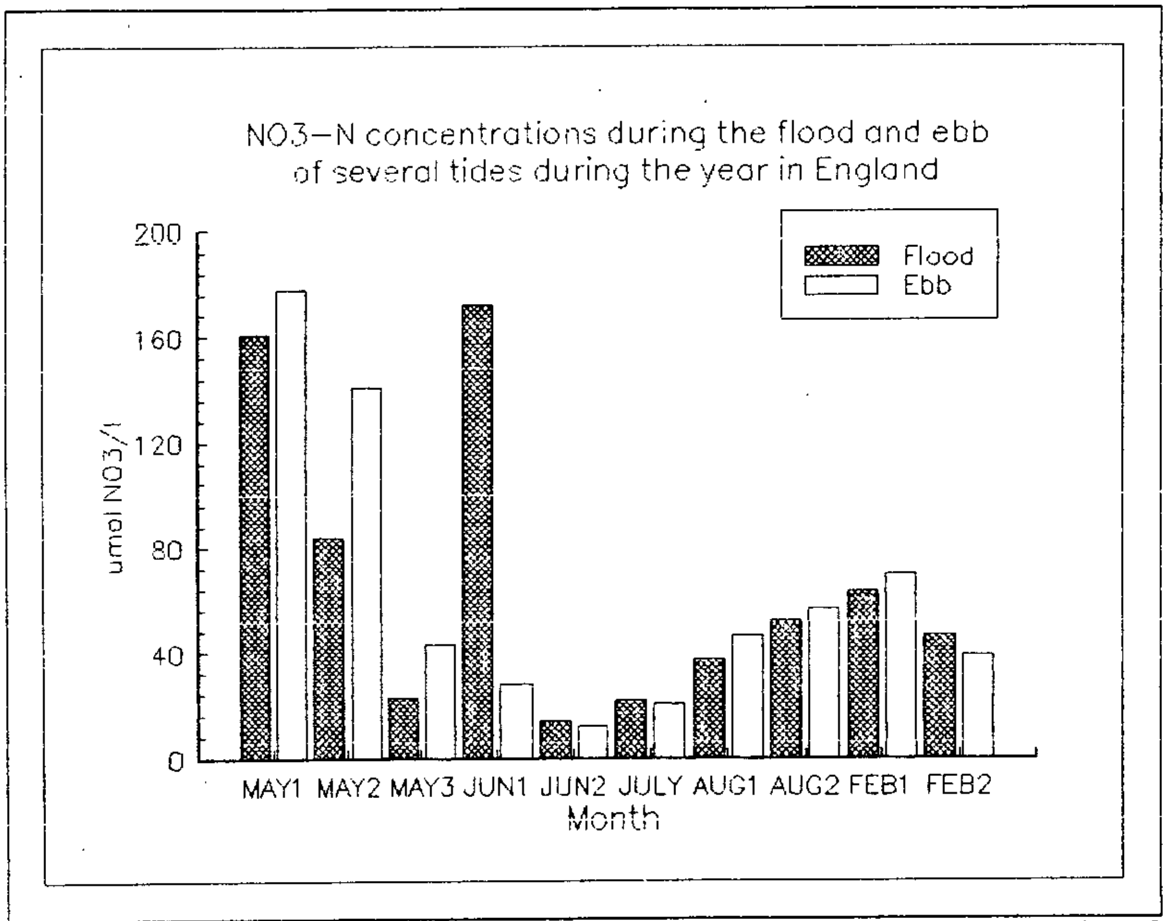

Figure 3.2.3.2 Nitrate nitrogen concentrations during flood and ebb

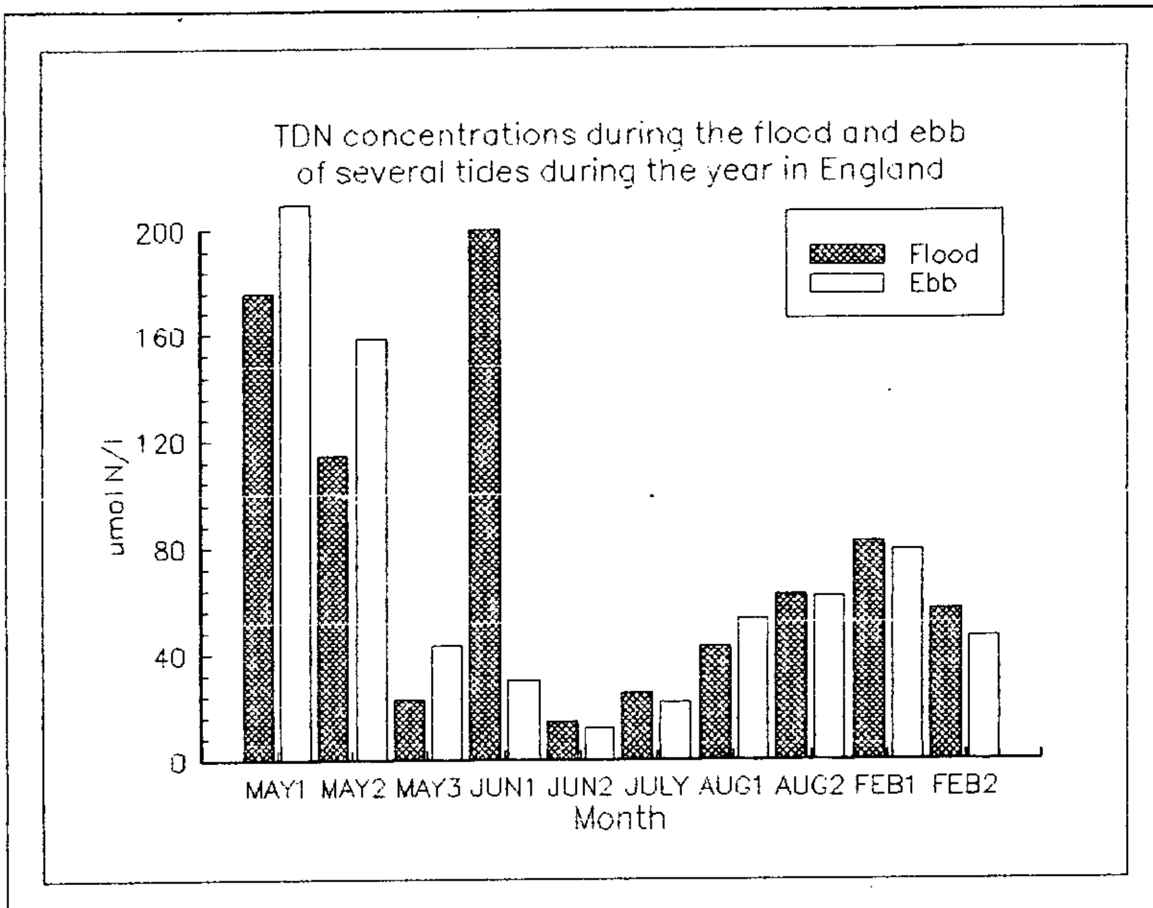

Figure 3.2.3.3 Total disssolved nitrogen concentrations during flood and ebb

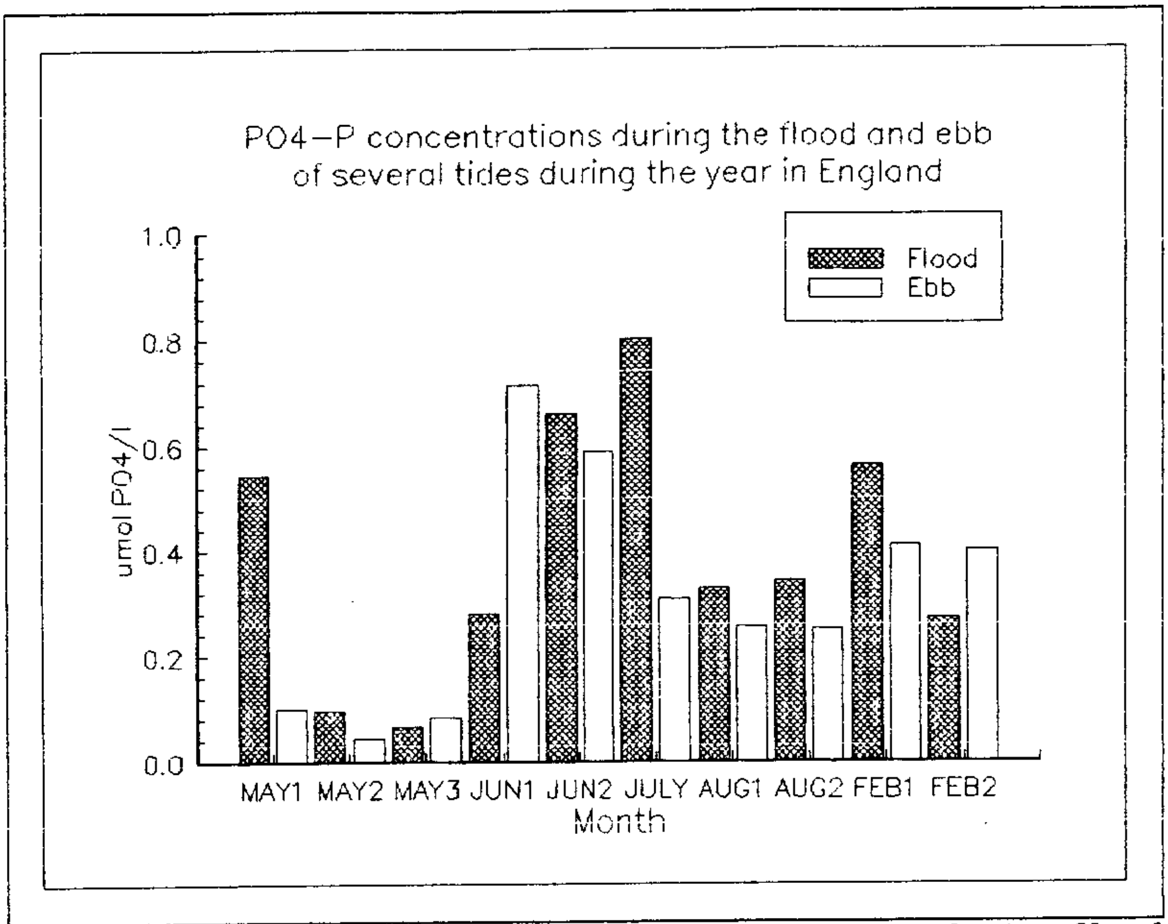

Figure 3.2.4.1 Dissolved phosphorus concentrations during flood and ebb

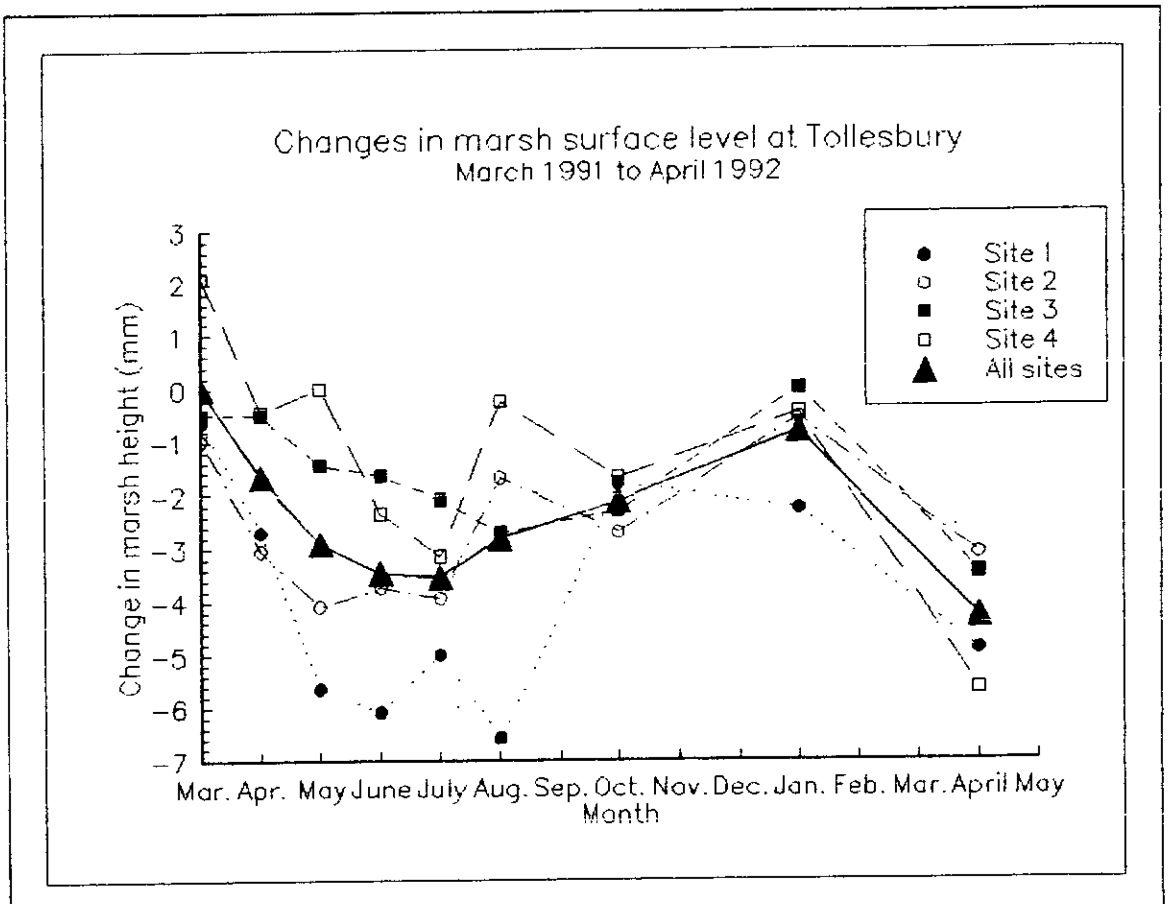

Figure 3.2.6.1 Changes in marsh surface level

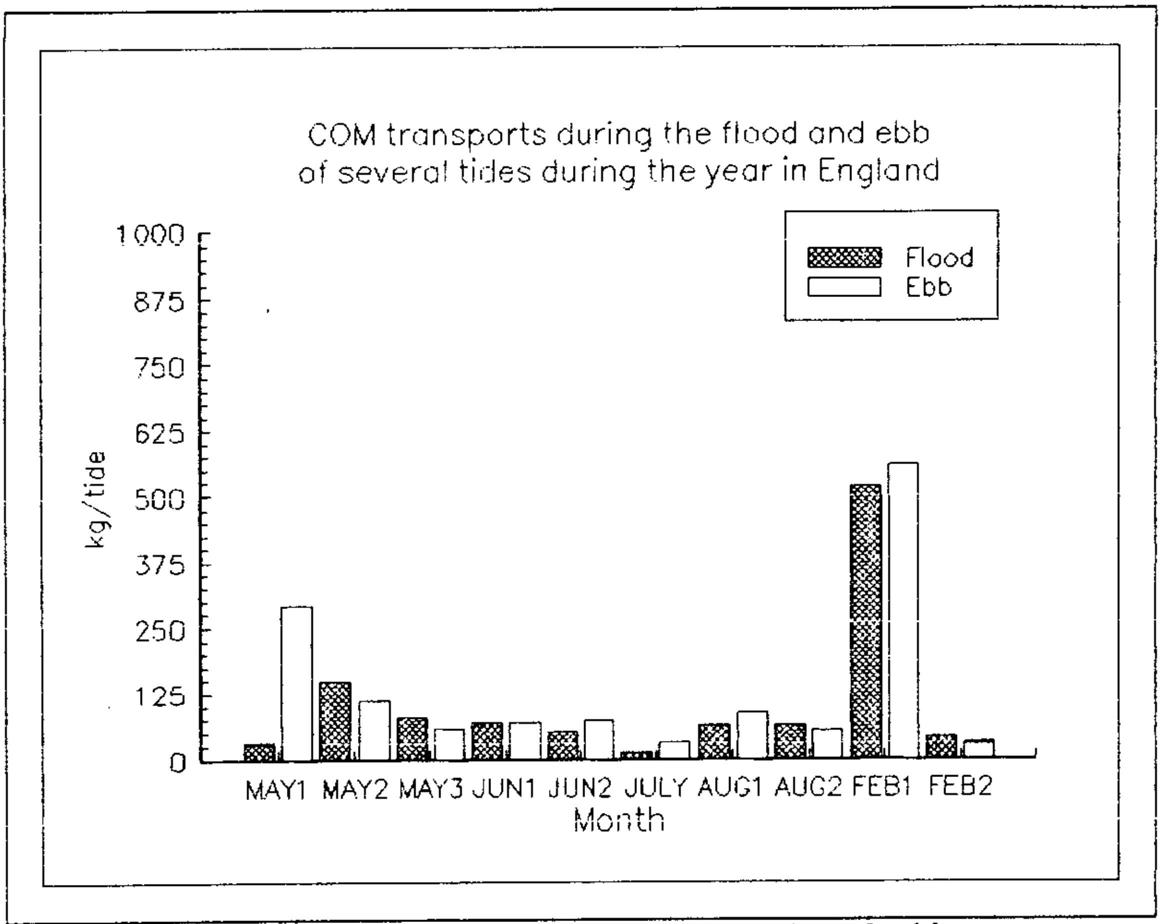

Figure 3.3.1.1 COM transports during flood and ebb

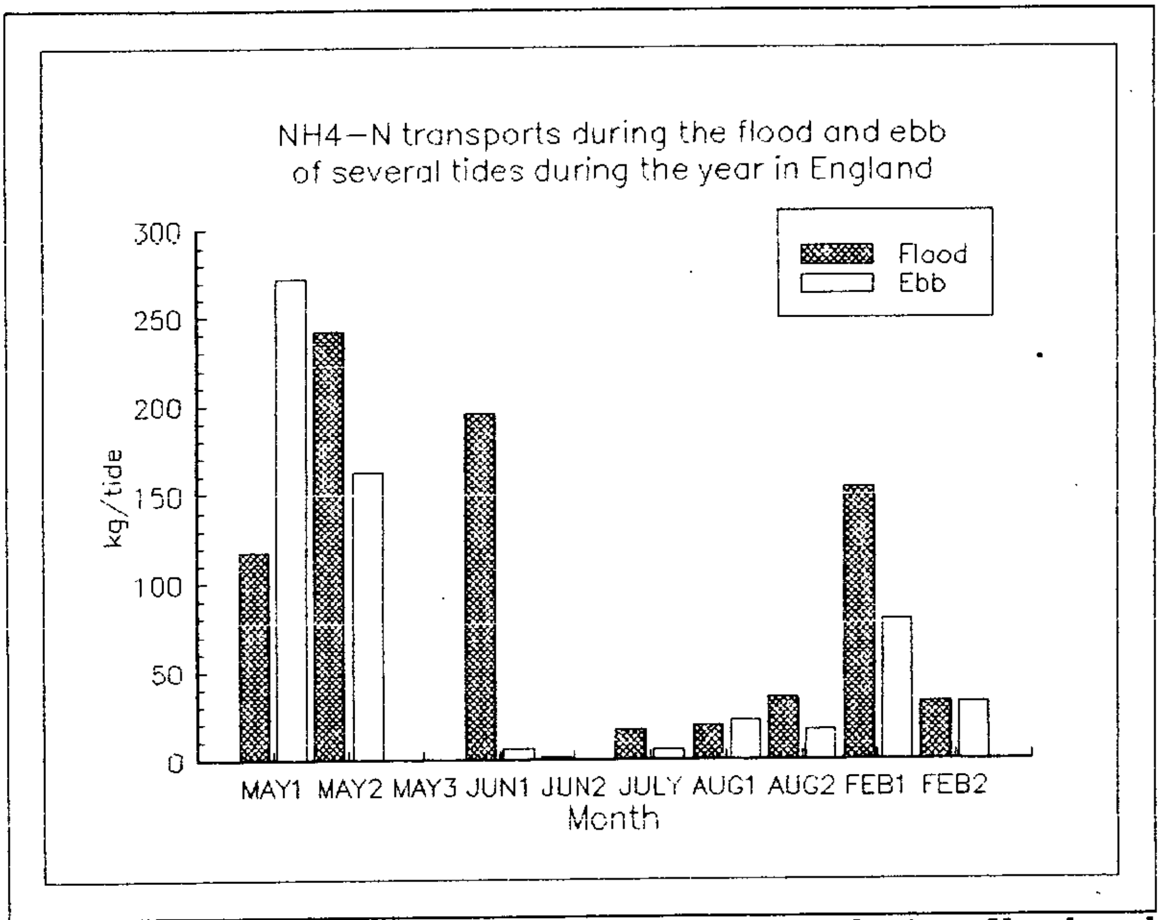

Figure 3.3.3.1 Ammonium nitrogen transports during flood and ebb

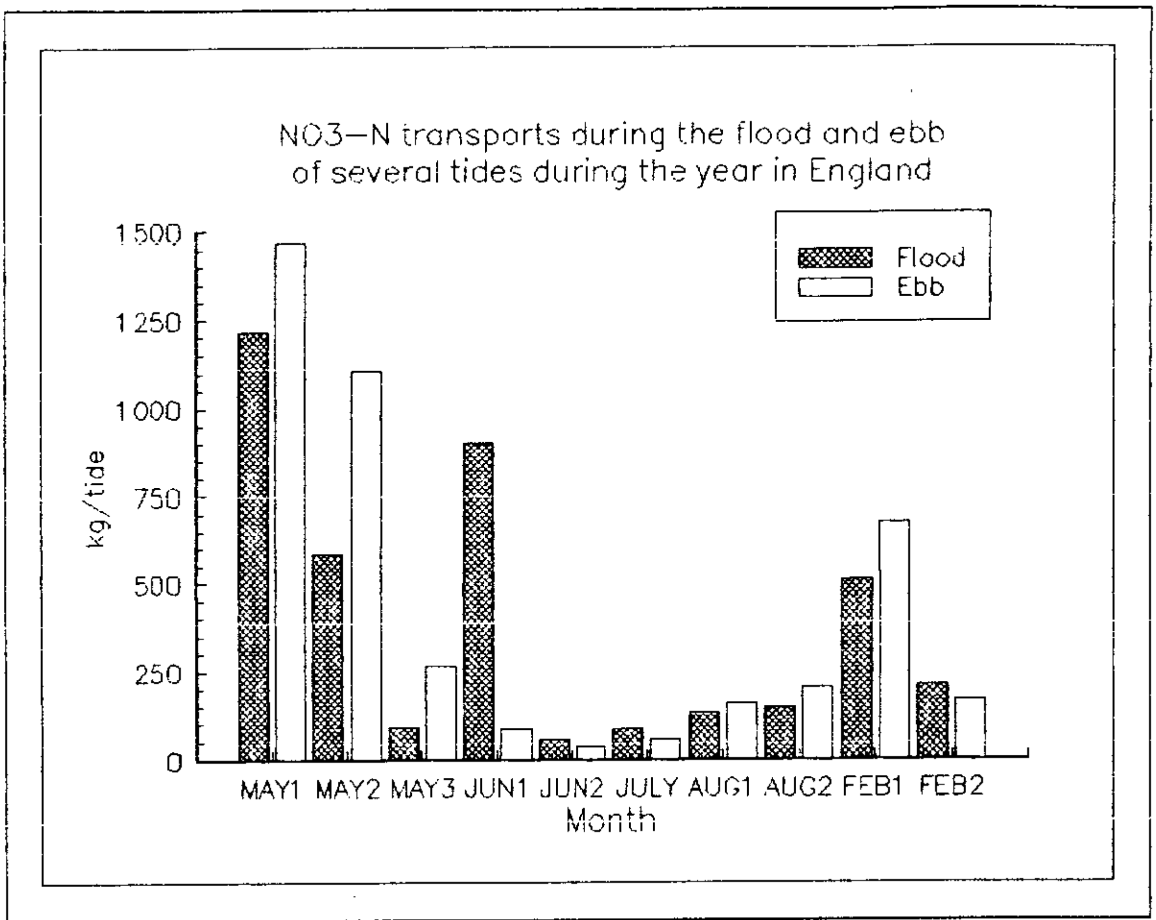

Figure 3.3.3.2 Nitrate nitrogen transports during flood and ebb

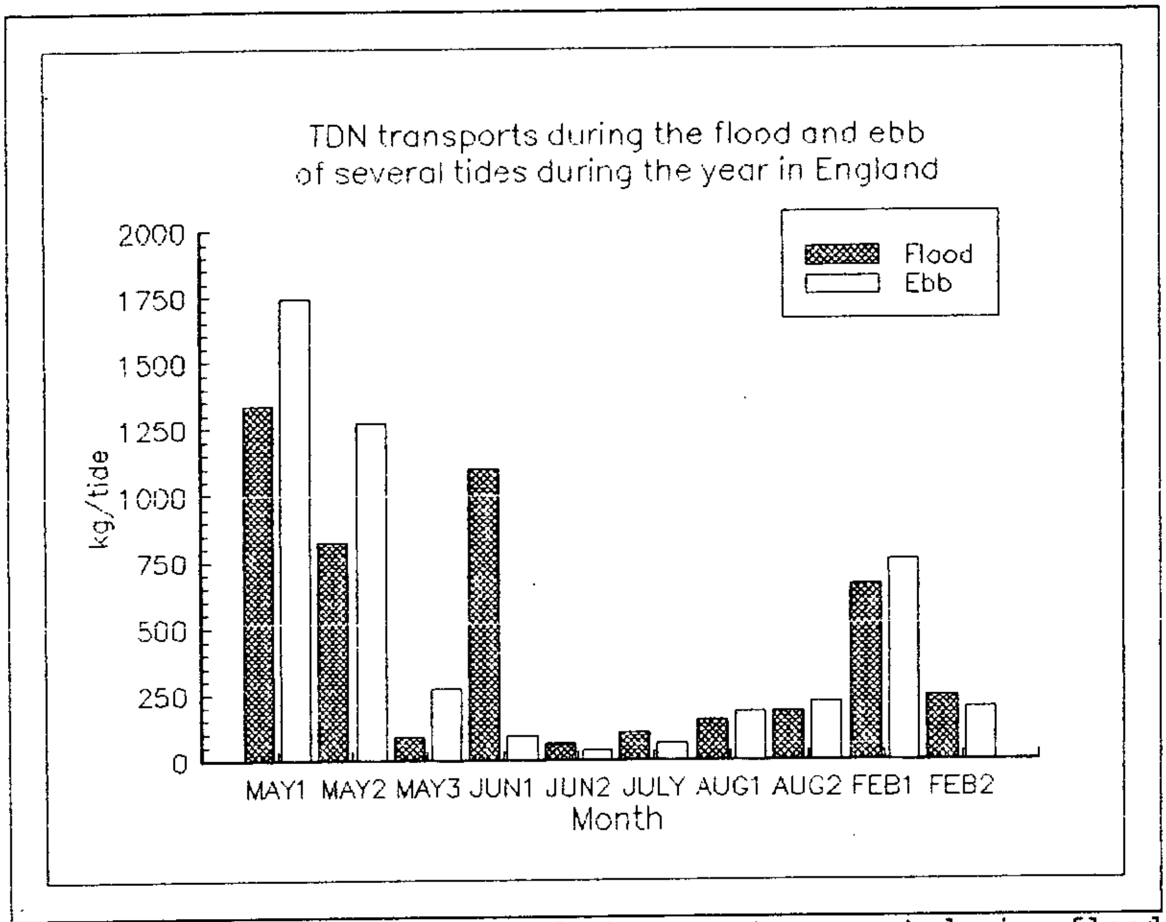

Figure 3.3.3.3 Total dissolved nitrogen transport during flood and ebb

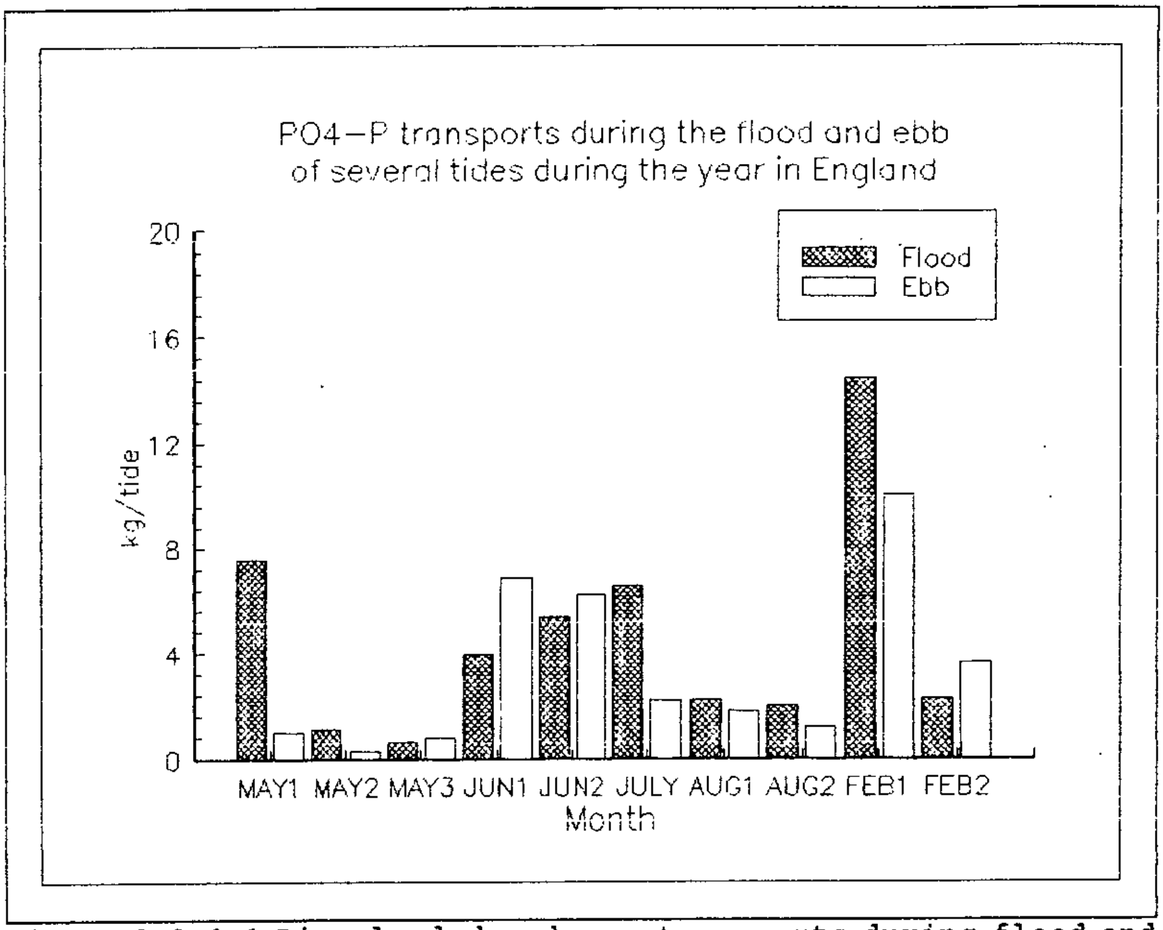

Figure 3.3.4.1 Dissolved phosphorus transports during flood and ebb