CHAPTER 4 INTERPRETATION

Chapters 2 and 3 described the experiments carried out in the present study and presented their results. These results will now be interpreted in the light of work elsewhere, and the similarities and differences in the processes and responses between the Holderness and other coasts identified.

The interpretation aims to assess whether the results obtained in the experimental work have enabled the initial aims of the research to be fulfilled, and whether the hypotheses advanced can be upheld or rejected. It is valuable first of all to review the more specific aims of this chapter. Having established a sediment transport model, an assessment of its accuracy has to be made, and an attempt made to identify the effects of tidal currents and assess their significance for sediment movement on this coast. The beach work aimed to establish the relationship between beach morphology and intertidal and nearshore conditions, and the relationship between beach morphology and cliff erosion. After identifying the "gaps" in previous models of beach evolution, the present research sought to establish whether the model presented for Holderness adequately predicted behaviour throughout the year. A comparison of present beach observations and other Holderness studies was also to be undertaken to enable any differences along the coast to be identified. Work also aimed to establish the variations in beach sediment characteristics and their relationships with offshore conditions. In order to assess the effectiveness of the sediment transport model, tracer experiments were carried out to determine the directions and rates of sediment movement in the field. The cliff work aimed to establish temporal and spatial variations of retreat and relate them to prevailing conditions, and to assess whether rates are significantly different from other coasts. The sediment budget incorporated results from all the coastal sub-systems. This interpretation seeks to determine whether it is backed up by field observations, and discuss the implications for the coast. Limitations of earlier studies will be identified and the ways in which the present study sought to overcome them explained. Suggestions for a number of improvements to the research will be made.

Chapter 4 has a similar structure to Chapters 2 and 3, with the three coastal sub-systems being considered separately, followed by a section on the sediment budget. The individual experiments, e.g. beach profile work and sediment tracer experiments, will be dealt with in turn and each section will be interpreted in a common fashion. Firstly the broader context represented by previous studies will be considered, including the development of relevant approaches and methods described in the literature. This will be followed by an interpretation of the Holderness results, comparing them with previous work and discussing the implications of both sets of results. The suitability of the experimental methods will be assessed and any suggestions for improvements made before the conclusions from each section of work are presented.

Before considering the implications of the results of the present study it is worth assessing the representativeness of the Holderness study period, and the possible effects of extreme but unrecorded events on this coast.

Conditions During the Study Period and the Effects of Extreme Events

In order to test whether the winds and waves of the year October 1983 to September 1984, during which most of the field work was carried out, were representative of the general wind and wave conditions on the coast, the most satisfactory comparison would be between the wave heights and directions recorded during the previous twenty years or so. However, the wave data obtained in the present study constituted the longest wave record available for this stretch of coast, and Dowsing Light Vessel was considered to provide only a remote reflection of conditions nearer the shore. There is therefore no really rigorous method of testing the representativeness of the wave climate during the study period.

Although it may not be satisfactory to derive wave data from winds (Appendix 4.1), the only possible comparisons of long-term data and data collected during the study period are for wind records. It was decided to "test" whether the proportions of winds from the north-east, east and south-east, the directions which would have the greatest effect on wave directions, occurred with the same frequency during the study year as they had done during previous years. Long-term wind records are available from the Monthly Weather Records (HMSO 1960-1983) for further south on the Holderness coast; the recording station was originally at Kilnsea, and from 1977 at Spurn Head. Unfortunately the 1984 data have not yet been published so 21 years up to the end of 1983 were analysed to produce the results shown below. Had they been available, it would have been more satisfactory to compare the 1983/84 Spurn data, with the means over the preceding years. However, the only recent wind records available were for a location about 1 km inland from the field site near Atwick, 46 km north-north-west of Spurn Head. Thus the proportions of winds from the north-east, east and south-east recorded at the field site during 1983/84 are also shown below.

	Winds recorded on S. Holderness		Field Site Winds
Direction	Mean %	Standard Deviation %	1983/84 %
NE	7.21	1.65	12.20
E	10.02	2.95	9.21
SE	9.00	2.03	9.92

The long- and short-term easterly and south-easterly winds are similar but at Atwick during the year 1983/84 the proportion of north-easterly winds was slightly higher than the mean further south during the previous 21 years. It is likely that, because of the distance between the two stations, the north-easterly winds on the field site were not drastically different from the general conditions. Though it may not be satisfactory to draw any conclusions about wave conditions from wind data, there is no strong evidence for the 1983/84 study period being atypical.

As well as testing the representativeness of the study period it is useful to consider the effects of extreme conditions on the coast. High energy events, not actually recorded during the present research, could have devastating effects,allowing huge quantities of sediment to be moved, the beach to be laid bare and accelerated erosion to proceed. Such events might include storm surges and although Holderness is a cliff coast the coincidence of high energy storm waves, spring tides and elevated sea levels resulting from low atmospheric pressure, may enable water to reach some height up the cliff, eroding large portions within a few hours or a day. These conditions did not coincide during the study period, though frequently over half of the cliff face was wetted by waves and spray, and sections of cliff were sometimes removed rapidly over limited lengths of coast.

There are two main ways in which extremes may be considered. The first is to determine the heights of extreme waves which are likely to occur with a certain frequency on this coast, and the second is to calculate the amount of sediment which might be moved by relatively high energy waves.

An estimate of the maximum waves which might be encountered on the coast over a number of years can be obtained by extrapolating a graph of wave height against frequency, or probability of occurrence, for one year. Estimates using the wave recorder data from the present study (September 1983 to September 1984) produced the following results for 10 and 25 year waves etc.

Wave	Wave Height, H_0 (m)
1 year	3.20
10 year	4.40
25 year	4.92
50 year	5.42

Such extremes were not recorded in the present study and so do not contribute to the results.

Before moving on to the offshore section concerned with modelling sediment movement it is valuable to consider the amount of sediment movement caused by some extreme waves which are likely to occur with a greater frequency than those mentioned above. The largest waves recorded in this study were just over 3 m, and persisted for less than 0.25% of the time. It was decided to calculate the longshore sediment transport induced by 3.5 m waves, waves likely to occur every 19 or 20 months. There is little point in producing estimates for higher waves as they would almost certainly strip the beach of sediment completely. Because of the short time for which such waves are likely to be sustained the hourly sediment transport rates are presented:

Wave height	Wave direction	Sediment Transport Rate ($x10^3$ m^3/hr)
3.5 m	NE	1.50 - 2.27
3.5 m	E	0.74 - 1.60
3.5 m	SE	1.40 - 2.70

For a rough comparison these gross hourly values are one half to one fifth of the net potential transport which might occur during an entire season. Such extreme rates may enable large areas of beach to become depleted and hence increased cliff erosion to proceed.

Although it was impossible to establish with total reliability whether the conditions during the study period were representative of the general conditions on the Holderness field site over a number of years, it is likely that the modelled period was not atypical. When 1984 wind data are published for Spurn Head a more satisfactory comparison will be possible. It is always important, however, to bear in mind the sort of extreme, if short, events which might occur, and the effects that they may have on sediment transport rates, beach morphology and cliff erosion.

4.1 THE OFFSHORE ZONE

There are two parts to this interpretative section - the first is a consideration of modelled sediment transport rates (to maintain consistency with the sub-system sections in previous chapters), comparing the results obtained on Holderness with those of other studies. The second part is a discussion of the currents recorded on Holderness, and their influence on sediment movement.

4.1 a SEDIMENT TRANSPORT

The interpretation of sediment transport results is presented in the "offshore" section because potential rates were derived from data gathered in the offshore zone. The detailed results were presented in Section 3.1.a, and are interpreted here in the light of the rates produced in other studies. Most work elsewhere produced potential results from offshore or hindcast meteorological data, rather than the measured field results which are considered in Section 4.2.c.

The aim of this interpretation is to review sediment transport modelling in order to identify the main fields of work, and to consider examples of sediment transport rates which have been established elsewhere. An interpretation of the results of the present Holderness study will be made with reference to previous findings, placing it in perspective.

4.1 a (i) Previous Sediment Transport Studies

For decades researchers have attempted to determine rates of sediment transport on beaches. A mere description of beach changes was no longer satisfactory and there was a need to calculate rates of change over large areas from easily obtained variables, instead of having to carry out laborious tracer work. It has long been recognised that sediment movement depends upon the amount of work done by waves and currents, however the necessary data are often limited and various surrogates (usually meteorological) have been used.

Two basic types of "model" have been produced:

1. Simple mathematical models produced in early studies involved calculations based on the relationships among variables such as wave height, sediment particle size and beach slope. At this stage when the calculation of sediment movement was so time-consuming it was regarded as an end in itself.

2. Models based on wave refraction were derived when the advent of computers allowed large volumes of data to be handled, and the repetitive procedures involved in wave refraction to be undertaken with ease. Computer models based on equations derived in earlier studies are capable of incorporating variable influences throughout the offshore system, and along great lengths of coast.

The derivation of sediment movement rates is now seen as a tool for producing sediment budgets, predicting beach morphology changes and planning coastal defences. Table 4.1 contains a number of potential sediment transport rates obtained in a variety of studies.

1. Simple mathematical models: Empirical formulae have been derived from offshore data obtained world-wide, and many have subsequently been included in refraction programs . Most sediment transport predictions have been based on energy flux methods (CERC, 1975);

Table 4.1 Potential sediment transport rates from the present and previous studies

	Reference	Location	H_o	Total breaker wave power $Jm^{-1}s^{-1}$	Longshore wave power $Jm^{-1}s^{-1}$	Sediment transport rate m^3/yr
Simple mathematical models	Dally and Bryant (1984)		1.0 - 2.0			.018 m^3/s - .027 m^3/s
	Phillips (1964)	Holderness (south)	3.4 m max			8.95 x $10^3 m^3/day$
Observations	Fitsgerald (1984) *et al.*	W. Germany		4.4 x 10^3		2.7 x 10^5
Computer models	May and Tanner (1974)	Theoretical	.25 m		2.5 - 15.0	
		Florida			< 10.0	
	Nummedal and Stephen (1978)	Alaska				200 x 10^4 gross 140 x 10^4 net
	Vincent (1979)	East Anglia				2 x 10^4 - 36.5 x 10^4
	Davidson-Arnott and Pollard (1980)	Nottawasaga Bay, Ontario		1 - 18 x 10^3	0 - 4 x 10^3	
	Allen (1981)	Sandy Hook, New Jersey				36 x 10^4
	Davidson-Arnott and Amin (1983)	L. Ontario			.077 x $10^9 Jm^{-1}yr^{-1}$ -.85 x $10^9 Jm^{-1}yr^{-1}$ 2.44 $Jm^{-1}s^{-1}$ -2.70 $Jm^{-1}s^{-1}$	0.09 - 0.33 x 10^4

Table 4.1 Continued

Reference	Location	H_o	Total breaker wave power $Jm^{-1}s^{-1}$	Longshore wave power $Jm^{-1}s^{-1}$	transport rate m^3/yr
Komar (1983c)	E. India				
	Paradip				100×10^4
	Madras				50×10^4
Nummedal *et al.* (1984)	Great Lakes		deep water 556	12.7 -172	$3 \times 10^4 - 21 \times 10^4$
Present Study	Holderness			35	3.3×10^4

e.g.

$$P = ECg = \frac{\rho g H^2}{8} Cg$$

P = wave power
E = wave energy, per unit surface area
Cg = group wave velocity
ρ = water density
g = acceleration due to gravity
H = breaker wave height

This requires repeated measurement of Cg and H, and to establish sediment transport rates empirical constants have been derived (see appendix 1.1). Most expressions are similar to that produced by Komar (1976a):

$$I_l = 0.77\ (EC_n) \sin\alpha_b \cos\alpha_b$$
$$= 0.77\ P_l$$

α_b = angle of wave approach at breaking
I_l = sediment transport
Ec_n = wave energy flux
P_l = longshore wave power

Many studies are theoretical and only present expressions for calculating sediment transport rates; they rarely report the results obtained from these equations. However, Dally and Dean (1984) produced values of between 0.018 m^3s^{-1} and 0.027 m^3s^{-1} in the breaker zone.

Rates of sediment transport on the east coast of England have been presented by Phillips (1962) and Cambers et al. (1978). Phillips used simple expressions based only on wave height to produce rates equivalent to a maximum of 8.95 m^3/day on the Holderness coast. Cambers et al. carried out field calibration of a sediment transport equation based on the calculation of total wave energy from wave height. If these equations were to be used elsewhere a new calibration, involving tracer experiments, would have to be carried out. This defeats the object of trying to model rates, but would be suitable for continued work in one area.

Although many basic expressions include site-specific constants, they do have the advantage of being based on true wave heights and directions, and not on surrogate data. Most are therefore suitable for use over short stretches of beach but may be inadequate for larger areas. These methods would not generally be used where sediment transport rates are required as a step in some further investigation.

2. Sediment transport rates from computer models: The earliest large-scale computer models of littoral wave power based on wave refraction (e.g. Fairchild, 1966) considered a range of wave energy conditions at breaking by refracting different hindcast waves over the nearshore zone. Such studies, in calculating the alongshore wave energy and calibrating it against measured sediment transport, paved the way for more recent models in which sediment movement is calculated directly from wave refraction results.

An important development occurred when May (1974) expanded a wave refraction model to determine alongshore wave power, P_l, and to delimit coastal cells. It could not, however, model sediment transport transverse to the shore. For waves of 0.25 m May (1974) produced P_l values from 2.5 to 15.0 $Jm^{-1}s^{-1}$, and went on to calculate the differences between adjacent points alongshore, and hence to identify areas of relative erosion and deposition. The direction of induced sediment movement varied according to the direction of wave approach. Many subsequent studies have used the same refraction program (Orford, 1977; Vincent, 1979; Davidson-Arnott and Pollard, 1980). The delimiting of littoral "cells", especially in connection with the derivation of sediment budgets, has been carried out frequently; for example Lowry and Carter (1982) identified areas of wave concentration and diffusion, and hence established sediment transport paths and cell boundaries.

In the past most studies presenting potential sediment transport rates have depended upon derived wave data. Armon and McCann (1977), in establishing an inshore wave climate and sediment transport rates from wind data, point out that this should be limited to areas where swell is insignificant. Appendix 4.1 presents a comparison of wind and wave records obtained on Holderness and emphasises the problems which arise when deriving wave data from winds. The techniques for working out overall energy alongshore used by Armon and McCann (1977) were similar to those used in the present research, i.e. obtaining records of wave variables, and weighting refraction results according to the frequency of occurrence.

Working on the Great Lakes, Nummedal et al.(1984) used more refined modelling techniques. Although still predicting sediment movement rates from wind-derived wave data, they calibrated longshore power distribution with field measurements. This would be valuable in producing predictive formulae for use in the same location but would be worthless elsewhere. They produced sediment transport rates of around 30 000 m^3/yr and occasionally up to 209 000 m^3/yr in the most exposed areas (Table 4.1). Wave refraction studies on high energy coasts have been virtually compelled to incorporate wind-derived data because field studies and even basic data gathering are difficult (Nummedal and Stephen, 1978; Komar, 1983c). Even in less hostile environments with a history of coastal research field data are often difficult and expensive to record and consequently data are woefully inadequate world-wide.

Some studies have been carried out on coasts which have similarities to Holderness. For example, Davidson-Arnott and Pollard (1980) studied longshore sediment transport patterns on till-cliff-backed beaches in Nottawasaga Bay, Ontario. Wave power was derived from various wind-based parameters with P_ℓ values from 0 to 4000 $Jm^{-1}s^{-1}$ being recorded, however no specific transport rates were given. This model included further approximations in that best-fit lines represented trends in the longshore component of wave power and may have masked some important spatial variations.

Successive studies have attempted to produce more realistic sediment transport models. Allen (1981) used a rigorous model in his attempt to describe and predict the shore dynamics of Sandy Hook, New Jersey. Improvements included the use of a wave refraction program which filters bathymetric information accurately. Allen's wave data had actually been recorded in the field over a seven year period but comprised only 200 breaking wave heights; deep water wave heights were available for one ten-month period. A general "ten-condition offshore wave climate" was generated for the area incorporating five directions, eight periods and seven wave heights. This example illustrates that although improvements were being made, most models had a number of shortcomings, a function of the data available and the nature of the program used. When Allen's refraction diagrams are inspected, they reveal a number of complicated areas of crossing rays which suggest problems in energy distribution, and may partly invalidate the results. The program calculated the differences between the amount of material entering and leaving a cell, and used the results to calculate shore-line advance or retreats of up to 0.3 m/day.

Improved models have been used increasingly to predict the response of coasts to various conditions, and to help solve a number of coastal problems. For example, Davidson-Arnott and Amin (1983) applied computer modelling techniques to shore erosion problems in south-west Ontario, an area with some similarities to Holderness, where beaches are backed by rapidly retreating low till cliffs. Comparisons of sediment supply from the cliff and potential transport were used to deduce areas of sediment deficiency or surplus. Total annual P_l values (Table 4.1) far exceeded the energy required to move all the available beach material and the potential volumes of longshore sediment transport varied from 0.9×10^4 m^3/yr to 3.37×10^4 m^3/yr.

Most of the sediment transport models referred to so far have been from North America; few modelled rates have been presented for continental Europe, although off the coast of West Germany Fitsgerald et al., (1984) recorded high wave energy and morphological evidence for movement of 2.7×10^5 m^3/yr. Some sediment transport models have been produced in Britain. Potential rates for sand transport on the East Anglian coast were presented by Vincent (1979). The refraction diagrams produced in the study showed a complicated pattern likely to give erroneous results; some rays stopped at sand banks and never re-formed. The distance between the rays was 1 km but results proved to be so irregular that averages were taken over 5 km, an area within which considerable natural variation may occur. Wave data were partly derived from wind data, though it is doubtful whether this is appropriate on an east-facing North Sea coast where prevailing winds are from the west and south, (reference may be made to Appendix 4.1). The winds were correlated with a four-month-long wave height record, and then extrapolated to provide wave heights and directions for a thirteen-year period, despite the unlikelihood of a four-month wave record being representative of all the wave conditions for a year. Rates of sediment transport ranged from 20 000 m^3/yr to 365 000 m^3/yr for a number of 25 km stretches of coast.

In summing up the general position of, and results obtained from littoral drift modelling it should be re-emphasised that only potential rates for sediment movement are produced, whether they are obtained from simple calculations or from complex computer models. A number of assumptions, some with far-reaching consequences, are made. Wide ranges and highly variable values of P , P_l and hence sediment transport rates have been obtained, depending upon the area modelled - its wave climate, exposure, duration of wave attack on the beach and the nature of the beach material. However, the large number of studies which use the May and Tanner program ensures comparability. The many studies based on hindcast or wind-derived wave data instead of "field" data are more likely to produce erroneous and unreliable models, particularly on exposed coasts which have long fetches, offshore prevailing winds and variable wave climates, such as the east coast of Britain.

There is a surprising, but distinct, lack of published transport rates, despite the declarations made in the titles of many articles!; there has been a tendency to concentrate instead on the general trends in direction, and relative volumes of sediment movement based on P_l values. This may reflect the unreliability of many models and a consequent lack of confidence in them. Often the step of calculating transport rates has been by-passed and shore changes produced directly, the former results are no longer seen as the ultimate object of most studies. Instead, work now concentrates on predicting shore erosion and morphological beach changes.

There are inevitably errors involved in these equations and models, particularly if the new environment differs from that for which a sediment transport model or expression was derived. The errors which may be encountered in the present study will be presented in detail in section 5.3 e but may be $\pm$ 30% - a maximum error of $\pm$ 65 m^3/day, and would obviously have a considerable effect on the sediment budget. For example, if the equation put forward by Komar (1983) had been used, then figures 170% greater than those presented here would have been obtained.

The literature review in Chapter one lists a number of studies which produced sediment transport equations. These were derived in a variety of ways - some had a purely theoretical basis (e.g. Bagnold, 1963 and Komar and Inman, 1970); some were based on physical models, while others calibrated them against measured sediment transport rates (Cambers *et al*., 1978, CERC, 1975). Even measured sediment transfer may have been determined in a number of ways - from observing changes in beach profiles (Thornton, 1968) and/or plan, or from tracer experiments (Ingle, 1966). They have been derived on a wide variety of coasts in Europe, North America, Asia and Australasia, and on a number of types of coast, of varying sediment grade, some with cliffs, some barrier coasts, and, perhaps most important of all, of varying exposure, experiencing widely varying wave energies. Further equations were based entirely on the regression of field measurements (Harrison *et al*., 1965; Harrison, 1968); no attempt to model from these site-specific equations should be made, as the resulting errors are likely to be large.

There are of course formulae which could have been used which do not depend directly upon P_l, such as those presented by Willis (1977), equation 3 in Appendix 1.1 (CERC, 1975), and Allen (1980). Others include variables such as significant wave height and water depth as well as P_l and a proportionality constant (Thornton, 1968), and so the scope for errors to arise is even greater. The use of such equations was not suitable for the present study because of the form of the data from the wave refraction model. It is unfortunate that few studies in the literature record the quantitative errors which have accumulated as a result of using the chosen equations. In many experiments which involved calibration of equations (e.g. Thornton, 1968) no mention was made of whether the experiment was repeated to check the results. The coefficients obtained by Fairchild (1966) may have accumulated great errors, being based on hindcast wave data. Coefficients would not only have depended upon geographical location and associated sediments but also the conditions prevailing at one particular time.

The influence of the coefficients in sediment transport expressions should never be overlooked - in many studies they provide data for the sediment budget and would hence have a marked effect on the budget. Even relatively minor errors on finely balanced coasts might lead to a section of coast which has a sediment deficit being modelled as having a surplus, and vice versa. Thus, if great care is not taken then the fundamental nature of a coast may be totally misrepresented.

As Allen (1981) pointed out, few models have been truly corroborated in the field, and there are factors affecting beach sediment transport which are seldom modelled. For example:

1. Sediment movement by tidal currents is rarely acknowledged; most studies neglect to say whether such currents were investigated and found to be insignificant, or simply ignored.
2. Very few (if any) models include sediment transport perpendicular to the shore; large amounts of sand may be moved directly offshore accounting for some of the difference between material supplied from the back-beach and potential longshore transport rates.

Having explained the development of sediment transport prediction from simple formulae to computer wave refraction models, and having presented rates obtained by other workers (Table 4.1), a more detailed discussion of the results obtained on the Holderness coast in the present study can be presented. The present research applied a widely used refraction program, but the quality of the data and experimental method constituted a considerable improvement on previous studies.

4.1 a (ii) Research on Holderness

The aim of this offshore research was to produce potential longshore sediment transport rates which could be:

1. Used, along with details of sediment supply from the cliff, to calculate a sediment budget for the area,

2. Compared with sediment transport rates measured on the beach in order to test the accuracy of the sediment transport model,
3. Compared with morphological beach changes and beach development, and
4. Used to assess any similarities between the study beach and coasts elsewhere.

Detailed results for each beach cell for both general and field site data were presented in Section 3.1 a, Tables 3.4 and 3.9 to 3.11 and are summarised in Table 4.2. Inspection of the original tables reveals variations in rates and direction of sediment movement.

Table 4.2 Summary of sediment transport rates for the Holderness coast

A. General Refraction $\bar{Q}_l$ range of results with respect to a northwards movement

	Minimum	Maximum	Net
Winter	2.53 x 10^2 m^3/day	4.14 x 10^2 m^3/day	3.43 x 10^2 m^3/day
Spring	0.77 x 10^2 m^3/day	1.85 x 10^2 m^3/day	0.90 x 10^2 m^3/day
Summer	1.05 x 10^2 m^3/day	3.04 x 10^2 m^3/day	2.22 x 10^2 m^3/day
Autumn	3.12 x 10^2 m^3/day	6.20 x 10^2 m^3/day	5.19 x 10^2 m^3/day
Year	6.44 x 10^4 m^3	12.31 x 10^4 m^3	10.89 x 10^4 m^3

-ve; movement towards the south: +ve; movement towards the north

B. Field Site Refraction $\bar{Q}_l$ range of results with respect to a southwards movement

	Minimum	Maximum	Net
Winter	21.06 x 10 m^3/day	-2.34 x 10 m^3/day	8.57 x 10 m^3/day
Spring	-7.48 x 10 m^3/day	-12.42 x 10 m^3/day	-6.78 x 10 m^3/day
Summer	-.01 x 10 m^3/day	-5.84 x 10 m^3/day	-2.41 x 10 m^3/day
Autumn	3.17 x 10 m^3/day	-12.39 x 10 m^3/day	-2.09 x 10 m^3/day
Year	35.83 x 10^3 m^3	-28.6 x 10^3 m^3	-2.8 x 10^3 m^3

-ve; movement towards the south: +ve; movement towards the north

In the first general experiment, using Dowsing data, the net sediment movement was always towards the north, whereas the more reliable and appropriate data measured by the field-site wave recorder produced a net annual southwards movement made up, however, of both northerly and southerly drifts in different cells and in different seasons.

From the general refraction results (Table 3.4) there is no discernable pattern in the alongshore variation of P_l, and the size of the fluctuation may reflect, in part, the absence of any smoothing of the P_l data. The movement towards the north may reflect the overestimation of waves approaching from the south-east and east. The lowest modelled rates of sediment movement occurred during summer (July, August and September), approximately the same as those recorded in spring (April, May and June), and half those recorded in autumn and winter (October, November, and December; January, February and March). This reflects the greater proportion of high energy waves during autumn and winter. The direction is probably erroneous; the same proportion of wave directions may not prevail off Hornsea or Flamborough Head as at Dowsing, and there is also greater opportunity for errors to accumulate during this long refraction operation. The data used in this refraction model are similar to, or even of better quality than, those used in many published studies where data were not available close to the study area.

Field Site Results were presented in Tables 3.9, 3.10 and 3.11. The effects of weighting and smoothing were discussed when the results were presented in Chapter 3 (3.1 a) and here the final results presented in Table 3.11 and summarised in Table 4.2 are discussed. The northwards drift in winter, despite a net annual drift to the south, is somewhat surprising but can be explained by a period of high energy waves from the south-east, and by the very high proportion of waves from the east. In general there is no particularly strong trend in sediment movement rates, with both northwards and southwards drifts occurring along much of the modelled coast. In cells (iii) and (vi), on either side of the Skipsea to Atwick field site, northwards drifts are observed. As for the field site itself, a southwards drift was always recorded in cell (iv) in the north, while the southern half (cell v) experienced a small southwards drift in all seasons but winter when there was a northwards drift. There was some seasonal variation in the direction of sediment movement from cell to cell. While cells (ii), (iv) and (vi) experienced a constant sediment drift, cells (iii), (v) and (vii) exhibited reversals from season to season. The smallest drifts, i.e. lowest sediment transport rates, were recorded in summer; spring and autumn values were up to twice those recorded in summer, while in winter gross rates were almost double those recorded in spring and autumn reaching 210 m^3/day The annual rates are summarised in Fig. 4.1.

The difference in the direction of net sediment movement between the general and field site refraction experiments has already been mentioned; some of the assumptions made in the general model may have been invalid, e.g. the wave record was probably an abstraction of a very complex wave climate. The wave recorder data were more accurate in that wave rays commenced their "journey" at almost exactly the equivalent distance from the shore for which the real data had been recorded.

Previous studies, the results of which may have been slightly larger than those in the present study, also had longer refraction paths and consequently inaccuracies would have been magnified; there was no indication as to whether wave rays were started from the points for which their data had been recorded.

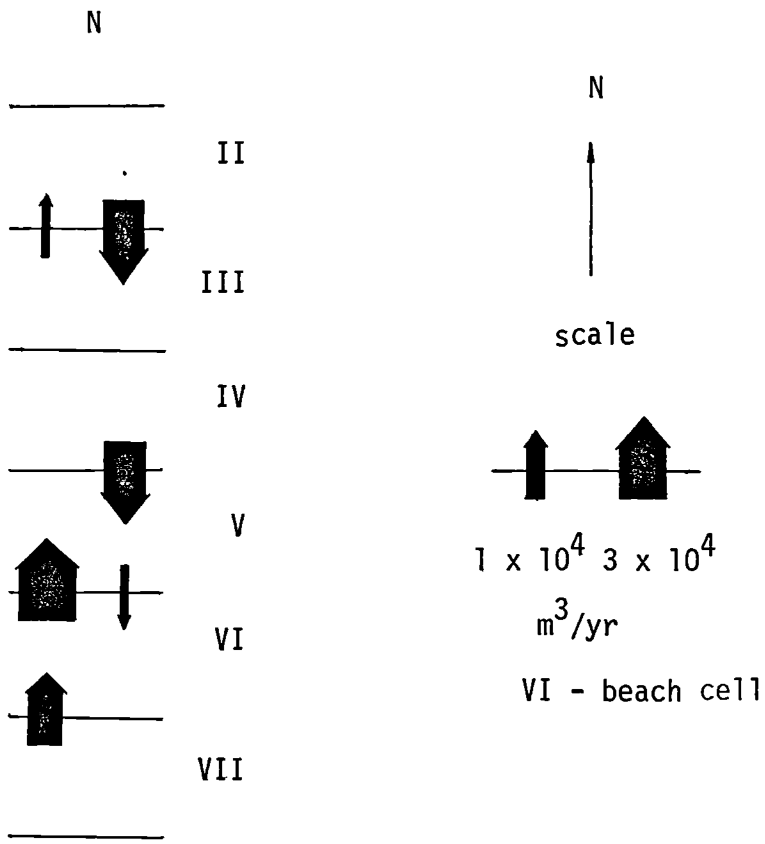
Implications for the Coast

The juxtaposition of the sediment transport values in various cells has implications for the build-up and depletion of the beach, which, according to season, will reflect variations in the occurrence of different wave heights and directions. These implications will be considered when a sediment budget is presented. Cell (iv) according to the wave recorder results would, over a year, suffer considerable depletion (ignoring the supply from the cliff). It is losing 28.25 x $10^3 m^3$ a year while receiving nothing from the cell to the north which has a net northward drift. This will lead to a depleted beach, while cell (v) has a large supply and should, based on sediment transport studies alone, accrete. Cell (iv) corresponds to the northern half of the Atwick to Skipsea field site, an area of flatter "combed down" beaches. Cell (v) coincides with the southern half of the field site (profiles A to E) where the beach profiles are much fuller and have more distinct upper and lower beaches. These beaches have developed as a result of the sediment movement patterns prevailing for the particular offshore bathymetry and wave conditions of the last few years. Fig. 4.1 summarises the gains and losses of each cell.

Previous work further south on Holderness has suggested that sediment movement is predominantly towards the south

(Phillips 1962, 1963, 1964), supplying material for the development of Spurn Head: in the north there must be some northwards drift as it may be assumed that there is no major supply from the chalk cliffs and shore platforms of Flamborough Head, yet there is a wide

Fig. 4.1 Summary of net Annual Sediment Transport Rates



sandy beach at Bridlington and for some distance south of the town. It is unlikely that all of this material has come from the relatively stable banks offshore and so some of the sand must therefore be supplied from the south. A further reason for expecting some northwards movement is the sheltering effect of Flamborough Head. In this area of the North Sea the highest waves are usually those from the north-east, but Flamborough Head will prevent such waves reaching the coast, from Skipsea northwards. Refraction of waves from the N.E. and E.N.E. may also mean that they approach the northern part of Holderness from a more easterly direction. Such evidence, and observations of the beach morphology, suggest that the northern half of the Holderness field site is part of a transition zone where the effects of Flamborough Head on the wave climate and hence beach character begin to be felt.

Because of the variation in direction of movement it is perhaps unrealistic to compare the net rates obtained in the present study with those obtained elsewhere, where more uniform wave approach directions prevailed and where small changes in direction were not as critical in changing the drift direction. It will be more useful to compare seasonal rates obtained in individual cells, though even they are aggregations of local movements. With reference to Table 4.1 it can be seen that the rates obtained on Holderness are much lower than those obtained on the most exposed coasts (e.g. Nummedal and Stephen, 1978 and Komar, 1983c) but the P_ℓ values of 2.5 - 15 $Jm^{-1}s^{-1}$ which Tanner (1974) modelled in Florida are much lower than all but the lowest summer values for Holderness. In winter P_ℓ values of over 80 $Jm^{-1}s^{-1}$ were modelled for Holderness, conditions being much more variable than those in Florida and also of higher energy. The rates obtained by Allen (1981) on the New Jersey coast were considerably larger than the average gross rates of around 33000 m^3/yr on Holderness, however detailed inspection of the Sandy Hook data revealed significantly different wave conditions, representing a higher energy environment. Allen recorded "calm" conditions ($H < 0.9$ m) for 58% of the time, and $H > 3.0$ m for around 2.5%, while waves below 0.25 m never occurred; the mean value was 1.0 m. On Holderness calm conditions ($H_0 \leqslant 0.05$ m) prevailed for approximately 18% of the time, and waves were 1 metre or lower for 92% of the year.

Despite such apparent differences, there are coasts which are similar in morphology, wave climate and sediment characteristics to Holderness, e.g. the Great Lakes of Canada and East Anglia. A representative P_ℓ value for all the Holderness field site cells over the year is 35 $Jm^{-1}s^{-1}$, equivalent to a gross annual longshore power of 1.1×10^9 Jm^{-1}, slightly higher than the maximum of 0.85×10^9 Jm^{-1} presented by Davidson-Arnott and Amin (1983) for south-west Lake Ontario. This reflects the fact that Holderness is never ice-bound, and is less sheltered. Nummedal et al. (1984) reported an average modelled sediment transport rate of 30 000 m^3/yr on the Great Lakes, again only slightly lower than the gross rates on Holderness. Gross field site rates compare fairly well with other North Sea coasts, e.g. Vincent (1979) in East Anglia obtained mean rates from 20 000 m^3/yr but a more representative value might be around 50 000-60 000 m^3/yr, reflecting a greater exposure to north-easterly waves.

In comparison with other rates obtained on Holderness, the results of the present study are rather low. Phillips (1964) recorded maximum P_B values of 7 500-8 900 $Jm^{-1}s^{-1}$ which suggests a breaker wave height of over 4.25 m (using the formula from which the results were calculated); this would produce a large sediment transport rate of approximately 8.93×10^3 m^3/day. In any case recorded deep water wave heights during the fifteen month-record of the present study never exceeded 3.5 m and it is possible that the effects of north-easterly, and to some extent easterly, waves were overestimated by Phillips, while those from the south-east may have been underestimated.

The possible reasons for the modelled sediment transport rates on the north of the Holderness coast being different from those further south presented by Phillips (1962) may be summarised as follows.

1. The proportion of higher waves in the wave record as a whole, and from the north-east in particular, is lower in the north, leading to a decrease in gross sediment transport rates. The maximum wave heights, according to Phillips, occur over the maximum fetch which is between 350^{o} and 10^{o}; on the northern stretch of coast these waves are cut out completely by Flamborough Head.
2. A proportion of waves from the east and north-east will be refracted by offshore banks to approach the shore from a more easterly direction.
3. Phillips did not mention any northwards drift whereas in the present study, not only was a northwards drift modelled for certain seasons and locations, but was observed in the field and confirmed by tracer experiments (Sections 3.2 c and 4.2 c).

Despite the fact that a number of improvements could be made to the model used on Holderness (these will be described later), it produced results which are more realistic than previous studies. The advantages over previous studies fall into two categories, those concerning the data used throughout the modelling, and others pertaining to the experimental method.

1. <u>Data</u>:

a. The depth matrix of the field site grid was finer than those used in many studies - it had units of 375 m, compared with 420 m in Davidson-Arnott and Pollard's (1980) model and 1 km in Vincent's (1979). The bathymetry, extracted from the most recent Admiralty charts, was relatively simple and detailed, and as a result adjacent wave rays crossed only once in the field site model. Crossing rays in many studies (e.g. Vincent, 1979; Allen, 1981) have caused considerable errors.

b. In both the general and field site models the wave ray origins were placed at the equivalent distance offshore for which data had been recorded.

c. A wide range of 36 combinations of wave period, height and direction were used to obtain the P_l values from the refraction program.

d. Real wave height and direction data were used to weight P_l : these had been recorded continuously for over a year, and records suggested that the year's data which were used for the weighting were not atypical. No hindcasting from wind information was involved in the field site model, though it was occasionally used in the general model when there was no swell. Many studies used wind-derived wave-heights (Fairchild, 1966; Armon and McCann, 1977; Nummedal and Stephen, 1978; Davidson-Arnott and Pollard, 1980), while most deduced wave directions at least, from wind directions (e.g. Davidson-Arnott and Amin, 1983), even when the environment was not strictly appropriate, for example on an open coast.

e. Data were non-subjective and consistent in the Holderness research. A few studies, though using real wave data (Cambers et al., 1978; Vincent, 1979), had obtained them in a less satisfactory manner; wave heights had been estimated by eye against marker posts at most twice a day by different amateur observers. Often wave directions were measured at the shore with no indication of the corresponding deep water orientation. In the present study wave height and period were recorded on a pressure transducer wave recorder, a twelve-minute sample being taken every three hours. Wave directions were estimated by the same observers (coastguards) for a distance approximately 1 km offshore, i.e. equivalent to the wave recorder position.

2. Experimental Method

a. Two separate wave refraction experiments were carried out, the first covering a wider area allowed the general refraction patterns in the area to be derived. The second was more detailed, using specific field site data and more rigorous analysis (additional weighting and smoothing). These allowed a comparison of resulting energy distributions for two different refraction distances to be made, indicating the magnification of errors in the first, general model.

b. Each season was considered separately, allowing comparisons to be made, and the identification of important times for sediment movement; most studies present only net annual rates.

c. Later testing against field measurements (3.2 c and 4.2 c, (iii)) indicated that the model produced accurate results. Few studies have attempted to test the accuracy of their sediment movement rates.

d. The present study was carried out on a field site where human disturbances are minimal and so a comparison of modelled and measured results is admissible.

e. The possibility of sediment transport by tidal currents and in an onshore/offshore direction, while not being included in the model, was acknowledged, and discussed in other sections of the work.

It should not be forgotten that only potential sediment transport rates are produced in this and other studies; the overall response of the beach will depend upon there being sufficient material available to fulfil this potential. Long-term beach changes will reflect the supply of material over time, and changes in the prevailing wave climate and offshore bathymetry. In an area which receives a constant supply of material from the back of the beach, varying potential transport rates will have important implications for the development of the beach, not just in one year, but well into the future.

Improvements

The methods adopted in the present study compared favourably with those of previous studies, and the results were similar to those on partly sheltered coasts elsewhere, e.g. the Great Lakes and East Anglia. However, there are a number of improvements which would increase their accuracy.

1. Tidal current effects could be taken into account, but when they are discussed later (4.1 b) their effects are found to be minimal.
2. Better quality direction data could be obtained and incorporated in the model.
3. In both the general and field site models the high northwards drift may be enhanced or overestimated as a result of the orientation of the coast. Waves from a small sector of the compass ($5\frac{1}{2}^{o}$) will induce a northwards drift in the model but a southwards drift in the field, and so some allowance could be made for this. (The same problem must apply to many studies).
4. A series of wave recorders alongshore would improve the quality and quantity of available wave height data. In the present

study, as in many others, the same wave height was assumed throughout the field site under the same prevailing conditions.

5. An overall increase in the quality and quantity of data would reduce errors arising from generalisation but would use a great deal of computer time. The only substantial and worthwhile improvement on Holderness would involve recording wave direction data frequently at each available wave recorder site.

Despite the fact that some improvements could be made, few highlight problems specific to the Holderness research, indeed many of the features of the model were superior to previous examples. Most improvements would involve the acquisition of still more detailed field records, particularly for wave direction. Of course any improvements in the wave refraction program which reduced the approximations and assumptions involved (outside the scope of this research) would be extremely useful.

Summary

This interpretation of potential sediment movement derived from offshore data discussed the results of the present study in the light of previous findings, comparing sediment transport rates on the Holderness test site with those for other coasts. The implications of the Holderness results were considered and the scope and advantages of this research summarised. Finally some suggestions for improvements were made. To sum up:

1. The methods used in this modelling exercise could be used on virtually any coast; the only difficulty would be in obtaining as high quality data as were collected on Holderness.
2. The results obtained on Holderness (e.g. gross sediment transport of 33000 m^3/yr) are representative of similar partly protected environments elsewhere, i.e. those in medium energy situations with some protection from the full force of the highest energy

waves, such as parts of East Anglia and the Great Lakes in Canada.

3. Flamborough Head provides shelter for the north of the Holderness coast.
4. Provided that the existence of tidal-current-induced and onshore/offshore sediment movements are recognised, the modelled potential rates are adequate for inclusion in the sediment budget presented in Chapter 3 (3.4).

The following section discusses the effect of tidal currents. The sediment transport results obtained in the offshore zone are incorporated in the budget which is discussed in Section 4.4.

4.1 b CURRENT EXPERIMENTS

The previous section on modelled potential sediment movement from offshore wave data indicated that the models had two main shortcomings; they did not take into account onshore and offshore sediment movement, or consider the contribution of sediment transport by tidal currents. Experiments were undertaken to assess the effects of these currents on the Holderness coast. Before interpreting the Holderness results a brief review will be made of previous work on currents, relevant to the present study.

4.1 b (i) Previous Work

Of the numerous studies which have examined the effects of currents, relatively few have physically measured them; most current patterns have been deduced or modelled from wind records. Still fewer have concentrated on tidal currents in nearshore areas, and virtually no estimates of sediment transport by these currents have been presented. On most coasts wave-induced transport dominates on the beach, intertidal and nearshore zones, while further offshore tidal currents are more significant.

In most current studies in the North Sea, workers have concluded that there is a residual southwards flowing current off the Holderness coast (e.g. Sundermann and Lenz, 1983). Results were mainly values derived from wind and tide data; generally current data are scanty and may involve a number of inconsistencies, as the term "residual current" has not been uniquely defined. For measured data, MAFF have records for a number of locations in British waters (Jones, 1982), most of which are short and often incomplete. Most investigations have been in deep water but some trends may be similar to those measured further inshore. Tryggestad et al. (1983) reported speeds of up to 90 cm s^{-1} recorded off Teeside, 3 m above the bed in 70 m of water, and up to 50 cm s^{-1} near the Ekofisk oil field in the central North Sea, also at 70 m depth. In both locations the resultant current was dominated by semi-diurnal tidal currents with velocity amplitudes of 10-20 cm s^{-1} at Ekofisk, and 15-40 cm s^{-1} at Teeside. Fluctuations in these records were common, however; for example, the residual current at Teeside during one week of extremely strong winds was between 10 and 20 cm s^{-1}. The most dramatic increases in tidal currents were a result of storms and periods of high winds, though it was pointed out that at this depth wave effects should be minimal.

4.1 b (ii) Holderness Currents

The aims of the current experiments carried out off Holderness in the present study were to determine net and residual current velocities at a distance from the shore, to determine what component of this could be attributed to the tide, to determine what grades of sediment could be transported, and to decide whether these currents would be important in influencing beach sediment transport. Measurements were made at approximately 500 m and 1000 m from the shore in experiments one and two respectively, and in mean water depths of 5 m and 7 m ± 2.5 m. The results were dominated by the semi-diurnal tidal currents, detailed results of which were presented in 3.1 b.

In the first experiment recorded currents ranged from 0.05 to 0.45 ms^{-1}, with a mean of around 0.21 ms^{-1}; this mean current would be capable of entraining material with a b-axis of between 25 and 500 μm. The duration of the first experiment was insufficient for the calculation of a daily residual current. Maximum velocities recorded in an area may enable many grades of sediment to be moved but they may be sustained for such a short time that only a very small quantity would be moved. The greatest potential for moving the largest size-range of material occurs just after mid-tide when velocities are at their highest. The values in experiment one should reflect currents purely as a result of the tide since wave effects were negligible and the mean value of 0.21 ms^{-1} is similar to the rates recorded elsewhere; they are probably somewhat lower than those for Teeside because of friction effects being greater in the shallower water off Holderness, where the currents were measured closer to the sea bed (≑ 1 m).

On the lower beach the influence of tidal currents is greatest at high tide, i.e. when deep water extends further inshore; this does not however coincide with the times of maximum current speeds. It was found that lower beach material could be moved for about one fifth of the tidal cycle if it had been at rest originally. However, it is important to consider not only the mean conditions and particle sizes, but more extreme events, e.g. storm surges which were mentioned earlier.

In considering current velocity there are a number of errors which may have arisen. Apart from the problem of using a variety of mean values for sediment size and for velocity, the very sampling of the currents may lead to inaccuracies. To obtain a more accurate picture of the effects on the beach it might have been helpful to take readings further inshore but there the wave influence would be more marked. The main object of this first experiment was, however, to provide a general view of conditions in the area in preparation for the second, longer, experiment.

Experiment two used an identical recorder to that used by Tryggestad et al (1983) and provided a much longer record of current velocities, coinciding with a variety of wave and weather conditions. Again, minimum velocities occur as the current direction changes, about 1¼ to 1½ hours after low and high tides, and the semi-diurnal tidal current periodicity dominates both direction and velocity records. The modal net velocities of 0.15-0.20 ms^{-1} in either direction are similar to values recorded at Ekofisk, and are slightly lower than those for Teeside (Tryggestad et al., 1983), allowing the entrainment of material from 125-500 µm. Some wave-induced effects would be felt in experiment two. On some days there would be a net movement in one direction (Figure 3.7 in Chapter 3) while on the following day this might be reversed. It is only during periods of very high and sustained current speeds that large quantities of beach material would be moved but invariably most would be moved back on the opposing tide. The mean residual current over the month was 0.651cm s^{-1} to the south; for the week of 23/5 to 30/5, this would be considerably higher, over 1.0 cm s^{-1}. Off Holderness the general flow was from only 1.0 cm s^{-1} to the north to 2.0 cm s^{-1} towards the south. It thus seems reasonable to exclude tidal current effects from the longshore sediment model as the resulting errors will be small. The two tidal streams are, at this position and depth, very similar, though they still reflect the established overall southwards residual flow. It is not appropriate to compare these values with the only residual value quoted by Tryggestad et al. (1983), which was recorded in extremely high energy storm conditions; during experiment two waves over 1.0 m were recorded for 2% of the time and waves under 0.5 m for 60% of the time.

Some effects of the wave climate on the current can be deduced from Figure 3.7 in Chapter 3 by considering the wave height and direction data, which have been added to the graph of daily residuals. Currents towards the south were more common during wave approach from the north-east and east-north-east, and the size of the velocity residual is greater during periods of higher waves. In this case waves enhance the residual tidal current, whereas waves from the south-east reduce its impact. Similarly, higher waves add to the basic resultant tidal current to give a larger overall current value.

It is difficult to separate wave- and tide-induced longshore currents, though during calm conditions (i.e. minimum value for wave-induced sediment transport) residual values of less than 0.5 cm s^{-1} towards the south were recorded, suggesting that this is the tidal component. The remainder, even at 1 km from the shore, could be attributed to waves, the effects of which are already incorporated into the sediment transport model. When the absolute values of the daily residuals are considered, the net sediment movement achieved would be very small. On the beach itself, which is of primary interest in this study, the tidal sediment transport would be negligible. The current record obtained in this study, while representing only just under a month, is somewhat longer than those obtained in other research projects where recordings were made over a couple of ebb and flow tidal cycles, or over a few days; even then the records were not always complete or error-free and did not represent continuous sampling. The present study used sampling at 10-minute intervals.

Tidal contributions to sediment movement are likely to be more significant further offshore where the effect of waves is much reduced. Here currents will be important in evacuating material which has been washed out of the littoral and nearshore zones. Much of this material, on Holderness at least, will be fine silts and clays which are not incorporated into the beach, though there will inevitably be some sandy sediment which may travel at right angles to the beach. Once out of the littoral zone this material may be transported southwards, perhaps ending up in some of the finer grained estuarine deposits at the mouth of the Humber.

A short section on suspended sediment patterns will be presented in Section 4.4 (iii). This might include the suspension of fines beach grade material under severe waves and strong tides, and its subsequent deposition. The suspended material off Holderness which can be seen in large plumes offshore comprises silt and clay fractions which do not contribute to the beach.

<u>Summary</u>

Current experiments on Holderness established that:

1. Velocities were similar to those elsewhere in the North Sea.
2. Tidal currents would have a negligible net effect on moving beach sediments.
3. Very fine material would be suspended and experience a small net southwards drift. This material would not be incorporated into the beach and so need not be included in the beach sediment

transport model.

4. Omission of tidal currents from the sediment transport model is justifiable provided that their existence is recognised and velocities quantified.

Summary of Offshore Work in Section 4.1

This "offshore" section has provided an interpretation of sediment transport results produced from offshore data. Both wave- and tide-induced movements have been considered, though the latter is of minor importance on Holderness. Comparisons with the methods and results of previous studies have allowed the scope of the present study, and the quality of the model, to be assessed. It established the patterns of sediment movement on Holderness and produced similar sediment transport rates to those reported on partly sheltered coasts elsewhere. The modelling of sediment movement incorporated a number of important improvements on previous methods, especially in terms of the quality and quantity of real data which were available.

The following section is an interpretation of the Holderness beach work, part of which comprises a comparison of sediment transport rates modelled from offshore data and rates measured in the field.

4.2 THE BEACH

Section 4.2 is an interpretation of the results of work carried out on the beach sub-system. It is presented in three sections, the first of which deals with the morphology of the beach, its evolution and behaviour under certain wave conditions. The second section deals with the characteristics of the beach sediment, and finally sediment transport rates obtained from field tracer experiments are discussed and compared with results which were modelled using offshore data.

Within each section the interpretation will follow the same pattern; after the aims of the research have been established, a summary of the development and present state of relevant beach work will be presented. A more specific interpretation of the Holderness results will be made in the light of the findings of previous studies and some suggestions for improving the experimental method made. Finally, the advantages and scope of each section of work will be summarised.

4.2 a BEACH EVOLUTION

Beach evolution is central to the general aim of the present research as put foward in Chapter 1 (Section 1.1), i.e.

"To explain the processes governing beach variability and its interaction with till cliff erosion".

Before the relationships and inter-relationships involving morphological changes could be explained, and further changes eventually predicted, some rigorous, objective and consistent classification of the beach was required. This would enable the identification of changes or transitions among different beach types, associated with specific nearshore or cliff conditions. In order to detect spatial and temporal beach variations it was necessary to monitor its profile, revealing the relative rise or fall in various sections of the surface and hence the potential for wave energy to reach the upper stretches of the shore or the cliff.

In accordance with the more specific aims put forward in Section 1.1 and with special regard to beach morphology, profile monitoring helps:

1. To establish the relationships between beach morphology and intertidal and nearshore conditions,
2. To establish the relationships between beach morphology and

till cliff erosion, and

3. To establish a probability model of beach behaviour.

A probability model is valuable in that it enables formal, objective descriptions and predictions of beach behaviour to be made, in terms of specific profile types or classes. This may in turn enable changes in the sediment budget to be forecast, thus supplementing fieldwork and reducing the amount ultimately required. Such models have advantages over many deterministic models in that they require no wave or associated data, and allow the effects on the sediment budget of certain, so far unrecorded, extreme events or critical conditions to be predicted.

2.4 a (i) Previous Beach Models

In order to place the Holderness results in perspective, and to assess the quality of the model it is necessary to consider previous work on beach development. Many studies of beach changes have been carried out but few have produced a comprehensive model, and fewer still have considered the continued development and evolutionary stages of a beach in terms of profile changes from one state to another. Most studies modelling beach changes have concentrated upon sediment transport as a function of wave conditions, and virtually all have been deterministic. Models have usually described and predicted the results of particular events but have ignored the longer, less active periods which dominate on most coasts.

There has been an increasing desire to model and predict beach changes as part of the new management approach to coastal problems, and in an attempt to take all possible variables into account. The studies reported in the literature are of three types, firstly the beach response models which though deterministic do not define any specific beach "states" or "types", and secondly deterministic models which consider evolution among a number of defined beach types, the beach evolution models. This second type, which includes models describing and predicting patterns of evolution in response to wave conditions, will be considered in more detail as they have similarities to the Holderness model. Finally there are the probabilistic Markov-type models which most resemble the model presented for Holderness.

Beach Response Models

One of the first process response models of beach behaviour was produced by Davis and Fox in 1972. It was almost purely descriptive and comprised a time-series of superimposed topographic contour maps which showed bar migration varying with offshore conditions represented by derivatives of barometric pressure. This type of model might be useful for predicting the trends of beach evolution for a given set of wave conditions at the site for which it was developed, but otherwise its applications are limited.

Many workers concentrated their work on the long-recognised seasonal periodicity of beaches (e.g. Dubois, 1973; Winant et al., 1975; Aubrey, 1979) but most, with the exception of Inman and Rusnak (1976), modelled bulk changes in beach volume or shore line position, and did not allow for deposition at one point on the profile and erosion at another. Sometimes models comprising a winter and summer type beach were proposed, but this hardly constituted a rigorous beach classification (Owens, 1977).

Apart from seasonal variations, a number of studies recognised beach cycles and other non-seasonal changes, frequently associated with a specific event. Davis et al. (1972) and Owens and Frobel (1983) presented models designed to explain a limited sequence of events in beach recovery following storm wave erosion. Other more comprehensive models have described a whole storm cycle; for example, using a wave index derived from barometric pressure, Fox and Davis (1971) presented a combined probabilistic and deterministic model which was empirically fitted to the data, but which gave no indication of profile evolution. They later modelled rhythmic beach forms (rips and bars) using similar techniques (Davis and Fox, 1972; Fox and Davis, 1976).

More direct measures of wave conditions were used by other workers, e.g. Wright et al. (1982) who even more significantly recognised that the surf zone processes varied across the beach profile as local gradient and degree of reflectivity changed with changing tide level. This suggested that the present nature of the beach does determine its response to waves, perhaps hinting at Markov behaviour.

There was a progressive movement during the 1970s towards classifying beaches into specific types and more particularly to identifying the cycles among them. Wright et al. (1979) came close to this; each of their two general beach states (dissipative and reflective) had an associated beach appearance (concave with no berm, and well developed with a berm), and was later subdivided to give a total of six types. It is important to note that it was still each state (not transition) that was associated with particular wave conditions, i.e. the emphasis was still on form rather than process. A "surf-scaling" parameter, ϵ , was used as an indication of wave conditions associated with beach states, and was a function of incident wave amplitude, beach slope and wave period. There was still no formal statement of the importance of the state of the beach, though the presence of beach slope as a variable suggested that it may be important.

These beach-response type models are useful for establishing some of the relationships involved in beach behaviour, though most are deterministic and consider a limited set of conditions. Little importance has been attached to transitions among beach states, the emphasis being on erosion or deposition associated with particular wave conditions. Few studies considered the full cycle of beach evolution over a range of prevailing conditions, and no models allowed a reversal before this often limited cycle had gone to completion. Neither did they give any indication of the time scales involved, nor the frequency with which events occurred.

Some of these shortcomings were eliminated in two studies which presented models having characteristics of both beach response and beach evolution models. Bowman and Goldsmith (1983) concentrated on the transitions among certain morphologies and sets of wave conditions throughout the year. Dean and Maurmeyer (1983), while not defining beach types, recognised an inertia in the system which confirms suggestions that their evolution may be described in Markov terms.

Beach Evolution Models

The major studies which have investigated the evolution of beaches among a series of specifically defined beach types, and have been particularly concerned with the variation of the beach profile, are those by Short (1978, 1979, 1980), Wright and Short (1983), and Wright et al. (1985). The models are still deterministic, based on wave parameters, but the importance of the previous state of the beach in determining present conditions is acknowledged (Wright and Short, 1983),

> ".. permitting the evolution of morphodynamic regimes which are free to varying degrees from complete forcing by deep water wave conditions."

Many previous models assumed that whether a beach eroded or accreted depended solely on the height and steepness of the waves; the same set of waves may, however, erode a reflective beach whilst producing accretion on neighbouring dissipative stretches. This suggests that previous studies which used wave power (or height) as the sole determinant of beach behaviour simplified the system considerably. It also serves to emphasise that until a very accurate description of beach morphology is built into wave refraction sediment transport models, results will not be very realistic. The models were now based on beach investigations during the entire year, and recognised the existence of modal beach types. The number of beach states in one model had been increased so that at last a classification was possible. Wright and Short (1983) defined six "morphodynamic" beach states, the features of which could be recognised by eye in the field. They could also be distinguished by different values of the "surf-scaling" parameter ϵ, the intermediate members being far more complicated than the reflective and dissipative end members. In an attempt to produce better predictions of beach type a new summary statistic for wave conditions, Ω , was introduced (Wright et al., 1985) which depended upon breaker wave height, beach gradient, and the fall velocity of beach sand. Predictions made using this model were still less than satisfactory (a success rate of 23.4%). Better predictions (68% correct) were obtained, but only by classifying within three types instead of six. Such models did however, accommodate interuptions of the cycle.

Short's work (1978, 1979) concentrated on the changes among beach states, rather than on the states themselves. These changes he designated "beach stages" and presented a ten-stage cycle incorporating six main beach types which could be subdivided according to whether the beach was accreting or eroding. This cycle portrayed continuous beach change but allowed reversals in the system, and was thus much more realistic than previous attempts at modelling. Morphological states were identified in the field, and again the influence of present beach state on that in the future was acknowledged. For the first time a distinction was drawn between the scales of erosive and accretionary transitions. Short (1979) found that erosion required more energy than accretion, and therefore that similar beach states could exist under widely differing wave conditions, depending upon whether they were part of an eroding or an accreting phase. He also considered the length of time over which beach changes occur, and not unexpectedly found a disparity between the two main sequences; a full eroding sequence could be achieved nine times quicker than the reverse accreting sequence. In 1980 Short went on to relate beach transitions to specific waves.

It is apparent from the examples of beach models cited (Short, 1979; Dean and Maurmeyer, 1983; Wright and Short, 1983; Wright *et al*., 1985) that some work had indeed suggested the important influence of existing beach type on future development, even if it had not been stated formally.

Probabilistic Models

Very few probabilistic models of beach development have been derived. In 1973 Sonu, as part of a wider study on rhythmic topography, presented a model which appeared to have Markov characteristics, and involved assigning the beach profile to one of six states by eye. These simple states were: linear (B), concave (A) and convex (C) profiles, each with (') and without (^{o}) a berm. Accreting and eroding sequences were defined and importance attached to the preceding beach state.

The concept of a beach depending on its previous stage (Sonu, 1973; Short, 1978, 1979; Wright and Short, 1983; Wright *et al*., 1985) was incorporated into a formal Markov model by Sonu and James (1973). The authors, using the same beach types as Sonu (1973) and Sonu and Young (1971), assigned probabilities to the transitions from one beach type to another. So simple was the evolution model that the beach could only "move" to one of two other states in one transition; therefore four elements in each row and column of the transition matrix would be zero, and as A^o and C' were end members it was possible to move only one way from either of those states, i.e. the associated probability was 1. The model was further limited in that no time scale was imposed on the change, so the length of "real" time for which the beach remained in one state was unknown.

The study went on from this Markov-type model in which the existing beach state was a probability function of its former state to investigate the length of a full beach cycle, not in terms of actual time but in terms of the number of beach transitions in a sequence from one end member state to the other. It is doubtful whether there is any real benefit in being able to model sequence length in the way Sonu and James did, it only shows that beach evolution is not a straightforward progression from one extreme beach form to another. The fact that this study was based on only one profile location, against which the model was tested, limits its use; unless beach profile types are simplified beyond all recognition different stretches of beach will not exhibit the same range of profiles. Similarly, if one beach type was defined under unusually severe wave conditions, the full cycle may never be completed during less extreme periods.

Despite these important drawbacks the study was useful in that it pointed out the non-random nature of beach development, and laid down a first, albeit extremely simple, probabilistic model for beach evolution.

There was, and still is plenty of scope to improve Markov probability models by considering more than one beach profile location, by including some measure of time in the model and by basing the transitions on examples which have occurred and do occur in the field. In 1973 field data may have been rather scarce but the last decade has seen an enormous increase in beach monitoring projects which could provide the necessary data.

Summary of previous work: Previous beach morphology models have been predominantly deterministic, and only comparatively recently has the importance of the existing beach state in beach evolution been recognised and the need to study beach profile change been acknowledged. There has been little or no development of the model presented by Sonu and James in 1973. As modelling work progressed improvements were made but they tended to be piecemeal, and no systematic, cumulative advance was made. What was required was the combination of some of the best features of a number of models. The most important improvements would be:

1. The inclusion of a temporal element so that the speed and frequency of beach changes could be represented,
2. A more rigorous and objective way of classifying beach profiles, and of later assigning profiles to these classes consistently,
3. An emphasis on beach transitions, and
4. An ability to model without wave data.

The work on Holderness sought to produce a model which would overcome the problems of previous studies and incorporate the improvements listed above. An interpretation of the results follows.

4.2 a (ii) Profile Evolution on Holderness

The aims of examining beach profiles in the present study were:

1. To establish characteristic beach forms of the Holderness coast and the transitions among them.

2. To produce a probabilistic model of beach evolution, based on the established forms and transitions, which does not depend upon wave conditions.
3. To investigate the variations in beach behaviour alongshore.
4. To establish the relationships between a range of defined beach morphology and offshore variables; this will be considered in section 4.2 a (iii).

In order to fulfil the first two aims the beach had been monitored at nine positions along the field site beach and assigned to members of a beach classification system. The present research produced a beach model based on these states and the application of the probabilistic Markov approach, thus incorporating some techniques of previous studies, and developing others. Probably the most important new features of the Holderness work were the introduction of a regular profile sampling period, and the emphasis on beach transitions.

Identification of Beach Profile Types

In the field it was apparent that beach evolution did indeed depend upon the existing beach state, certain profile types were preferred at certain locations along the shore (Section 3.2 a) and, irrespective of prevailing conditions, some areas would never exhibit a "fully developed" profile. Some previous workers had specifically described this dependence, while others had hinted at it (Sonu, 1973; Sonu and James, 1973; Short, 1978, 1979; Wright *et al.*, 1979; Dean and Maurmeyer, 1983; Wright and Short, 1983; Wright *et al.*, 1985). If there was not some dependence on existing beach types, i.e. if one set of wave conditions gave rise to one specific profile type, then after one storm of uniform longshore intensity, the beach would exhibit the same cross-sectional profile throughout its entire length. This is clearly not the case.

In the production of the Markov model some observations were made which accord with the results of previous workers, for example the occurrence of "preferred" profile types at certain locations. Wright and Short (1983) indicated the existence of modal beach types around which variations may occur, reflecting modal environmental conditions and a range of possible conditions. This indicates an inertia in the beach system which prevents a particular profile from exhibiting a wider range of states with equal frequency. The present study found that though each beach location exhibited a range of profile types, each end of the field site exhibited a different range of profile types under similar offshore conditions. Chapter 3, Section 3.2 a (ii) and Fig. 3.10 illustrate the frequency of different beach types along the shore. At profiles A and B the modal beach is of type O; at C, E and G it is type N, while at D, M-types are observed most frequently. Profiles F' and H have modal beaches of types P and Q respectively. As far as the ranges of profiles are concerned, profile A exhibits mainly O and R types, profiles B, C, D and E, M, N and O types while at F and F' types O and P dominate. Type O and to a lesser extent types Q and R dominate at profile G.

Production of the Model

A number of methods used to produce the present Holderness model were improvements of those described in the literature. Beach types were not assigned by eye as they had been in most studies; nor at later stages in the development of a model were they determined by some parameter representing wave conditions (Wright and Short, 1983; Wright *et al.*, 1985). All previous studies used field observations or aerial photographs to determine subjectively the existing beach state, and even using plotted surveyed profiles it is difficult to be consistent in the allocation of a classification, particularly when the differences involved are slight. As a result many workers have presented types to which it would be difficult to allocate real, complex, beach profiles.

In the present study the beach was classified using cluster analysis so that each beach type has a set of values assigned to a set of variables. Once these variables had been measured for profiles they could be placed in the pre-determined classes. Thus beach profiles were classified objectively, and consistent allocation, with minimal observer error, was possible. The classification was based on, and therefore reflected, the range of *real* beach profiles (unlike the Sonu and James (1973) classification of possible beach profiles). The most important development in the present model was that it incorporated a "time" element, i.e. profile surveys had been carried out regularly and the model based on the results. It thus reflected real beach evolution, even when "evolution" meant that the beach was unchanged for some time.

Model Results

Tests indicated that the Holderness beach transitions do indeed exhibit Markov properties, and that the probability transition matrix model described and predicted the transitions which occurred along the beach and over different time intervals (Section 3.2 a). In all the probability matrices the highest values are observed on the "diagonals", indicating a certain equilibrium or inertia in the system, i.e. a beach profile will have a greater probability of remaining in the same state than of changing to another state. Such an equilibrium was identified by Dean and Maurmeyer (1983) and by Wright and Short (1983), and confirms the observations about modal profile states.

When profile data were collected for a second (winter) period comparisons were made between the frequencies of beach states and beach transitions for the two seasons. Generally the same profile locations were dominated by the same "families" of beach type (i.e. the modal beach types were similar in winter and summer), though many O-type profiles were replaced by N-types, again indicating the importance of antecedent beach conditions. The most significant change, allowing for the introduction of X and Y-type beaches, was the reduced percentage of O profiles in winter. This reduction in the linear upper beach/linear lower beach profile was compensated for by the presence of X and Y profiles which reflected combed down, high energy, winter conditions.

When the first matrix was used to predict transitions during the second period it was fairly successful but "significant" differences between observed and predicted transition frequencies were apparent. A greater variability in profile behaviour was revealed, reflecting a greater range of wave conditions during winter (Table 3.20). In Poisson tests, of 161 transitions predicted only 12 proved to be outside two standard deviations of the expected values.

It was considered that a still better prediction could be obtained if a second matrix was prepared and this proved to be true. Comparisons of the two matrix models confirmed the existence of more variable conditions in winter, coinciding with high wave energy. The values in the diagonal cells of the matrix were lower, indicating a less static beach. In winter, transitions occurred in which the upper beach remained linear or became concave as a result of higher energy waves moving material seawards. The lower beach on the other hand tended to gain material. Such behaviour occurred with a greater frequency than before (Table 4.3). Wright and Short (1983) also found that any state and transition could occur during any season but they did not establish the increased proportion of certain transitions at different times of the year.

All of these model predictions were made without reference to wave records, but seemed to be compatible with present knowledge of wave action. The predictions were also within a range of defined states and did not simply represent erosion or accretion among myriad, unclassified, unique states (Fox and Davis, 1972; Inman and Rusnak, 1976).

In considering beach transitions, the present study reflected beach processes. Previous models could not deduce

Table 4.3 Comparison of Winter and Summer Transitions

Increased freq. in winter	Decreased freq. in winter	Increase in transitions from	Decrease in transitions from
M —— N	M —— O	linear UB & concave LB →linear UB & convex LB	linear UB & concave UB →linear UB & linear LB
N —— M	N —— N	linear UB & convex LB →linear UB & concave LB	linear UB & convex LB →linear UB & convex LB
O —— N	O —— O	linear UB & linear LB (steep) →linear UB & convex LB	linear UB & linear LB (steep) →linear UB & linear LB (steep)
P —— Q	P —— P	v. concave UB & linear LB →less concave UB & linear LB	v. concave UB & linear LB →v. concave UB & linear LB
Q —— P	Q —— Q	less concave UB & linear LB →v. concave UB & linear LB	less concave UB & linear LB →less concave UB & linear LB
R —— O	R —— R	linear UB & linear LB (gentle) →linear UB & linear LB (steep)	linear UB & linear LB (gentle) →linear UB & linear LB (gentle)

UB - upper beach LB - lower beach

how the beach came to exhibit the form it did. However, when wave activity is considered (Section 4.2 a (iii)) it will become apparent that offshore conditions acting over a period of time produce beach changes between an already established selection of profile types.

Time Scale and Tesing of the Model

The Markov model presented in this study, important in that it had a temporal framework, was based on two time intervals - fortnightly and daily. These were considered to be the most important time scales for studying beach evolution and are scales at which the effects on man's activities would be greatest. They are also the most practical scales for field investigation. However, it should be remembered that the results necessarily depend upon these time scales. It is important therefore that the chosen time scale should be appropriate to the beach study.

A number of different time scales may be considered. A shorter survey interval could be used to produce a model describing and predicting beach changes from hour to hour, within a tidal cycle. Undoubtedly this would be interesting for investigating intermediate beach forms, but for predicting the longer term behaviour, possibly with a veiw to devising a protection scheme, it would be of little use. In addition, such a study would pose practical difficulties, requiring underwater surveys to determine the beach profile over complete tidal cycles.

At the other extreme a model could be based on four-monthly, six-monthly or annual surveys. However, for the beach behaviour to be established over, for example, 12 transition periods, a study would have to last for at least 3 or 12 years (for 4-monthly and yearly examples respectively). Again, such a long-term model would be interesting but, particularly if it was based on yearly data, would not be very useful. It would take so long to collect the data necessary for the model that the conditions governing beach evolution may have changed significantly over the study period. Predictions would then be based on the results of processes which no longer prevailed. From the field data it is not really satisfactory to investigate the beach on a monthly time interval; insufficient transitions would have been recorded.

Certainly from a practical point of view, the daily and fortnightly scales used in the present model are the most satisfactory - it does not take too long to accumulate sufficient data, and conditions are unlikely to have changed drastically over the period.

The basic fortnightly sample interval was chosen here to reflect spring tide cycles when, as well as the maximum expanse of beach being exposed, consistency was maintained with other elements of the study. The surveyed profiles always reflected the same stage of the 24 hour tidal cycle; similarly, except during periods of intense field work, the stage during the fortnightly tidal cycle was constant. Determing the causes of beach variation and establishing a systematic evolution of profiles is only admissible when making comparisons under similar conditions: even when "daily" profiles were compared difficulties were encountered. For this reason it was felt that a weekly time scale was inappropriate, and was impractical with the data available where at most three successive weekly surveys were available.

The fortnightly time interval is also that over which the most significant variations occur. Spring tides are critical for beach behaviour, especially as they may compound the effects of high energy waves; waves exert their influence over the entire beach width and erosion, of the cliff and beach, is likely to be greatest. It is important therefore that the nature of the beach is established at this time. One problem of the fortnightly time scale is that it does preclude any study of tidal effects. However, if longer records of fortnightly profiles were obtained a study at this scale would eventually allow yearly or six-monthly analyses to be effected.

The standard chi-squared test for memory used in this study was appropriate to the profile data, which comprised a matrix of beach transitions. It tested whether a multi-variate data set exhibited significant differences at different times. The nature of the memory was the same when daily and fortnightly sequences were used as it was for the Bulk data, though only the test results for the last case were presented in Chapter 3 to illustrate the use of the test,and it is possible that if a different time scale were used, the memory might differ. This would be tested if more data are acquired.

Finally, it is useful to emphasise that while the first six months' data were used to generate the beach profile types, the second set of data was assigned to the already established classification. It could be argued that the tendency to remain the same or in a similar form, might be expected for the first six months for this reason. The results for the second data set refutes this argument - they did not generate their own classification.

Improvements Introduced in the Holderness Model

When comparing this and previous models, both in terms of methodology and results, a number of improvements are apparent in the present model. They can be summarised as follows:

1. The present study confirmed that the beach exhibited first-order Markov behaviour.
2. The present model is probablistic, rather than deterministic as most previous studies have been.
3. The beach classification,and later the allocation of beach profiles to these type classes,was objective and consistent in the Holderness modelling, and reflected more subtle changes in the

profile shape than previous models had allowed.

4. The data used to produce the probability transition matrix were real field data, not simulated data as used in Sonu and James' (1973) probablistic model.
5. By identifying beach <u>transitions</u> a pattern of beach evolution could be established. Many previous studies had concentrated on the existence of a certain beach shape at a specific time.
6. One of the most important improvements in the present study was was the inclusion of a temporal element; this had been omitted from all previous models. Although the Markov results depend upon the chosen time interval, the association of each transition with a specific time interval enabled modal beach types and equilibrium profiles to be recognised, whilst

the presentation of "summer" and "winter" models allowed the whole year to be modelled, not just responses to isolated events as in the models of Fox and Davis (1971), Davis and Fox (1972) and Owens and Frobel (1983).

7. Wave parameters were not required to produce the Holderness model which thus avoided the inaccuracies in other models based on wave surrogates or summary wave statistics.
8. Unlike others, the Holderness model could incorporate interuptions and reversals of the beach cycles, and did not require full beach cycles to be executed.
9. The prediction of beach types by the present model seems to be more satisfactory in predicting one of seven or nine states than Wright et al.'s (1985) model was for six or three states, and than previous two-class, winter or summer, full or depleted, beach models have been.

Summary

The results presented in Section 3.2 a (iv) and discussed above enable a number of conclusions to be made, the first two of which accord with Sonu and James' (1973). The present study has established that:

1. Beach behaviour exhibits Markov properties.
2. Beach development can be described by the relevant probability transition matrix or matrices.
3. The model adequately describes and predicts the spatial and temporal distribution of profile transitions.
4. A greater variability among profile states is encountered in winter than in summer, supporting the trend observed by Dolan and Hayden (1983) that alongshore variation in shoreline changes are smaller than temporal variations.

5. In predicting beach changes, it is therefore possible to predict profile states. Refinements involve the use of different matrices for different times of year.

This work was undertaken so that a more realistic model of beach evolution could be produced which did not depend upon a knowledge of wave conditions. Previous beach modelling had been limited and unrealistic. Various techniques needed to be combined, principally the definition of specific beach types, the concentration on transitions between these types, the probability approach to modelling and the use of real beach data. This work was also undertaken so that another primary aim of the research could be fulfilled, i.e. to establish the relationships between beach morphology and offshore conditions.

These relationships are investigated and discussed in the following section when the modelled transitions are compared with coincident wave conditions.

4.2 a (iii) Relationships between Beach Transitions and Wave Conditions

Earlier sections have shown how most workers derived beach models which depended upon wave heights. In Chapter 3 where different winter and summer beach models were presented it was suggested that during winter, when waves are higher, the beach exhibits greater variability. Though the models were not based upon a knowledge of waves they necessarily reflect wave influence on beach behaviour. This interpretative section seeks to investigate the nature of the variations associated with different wave conditions and will enable the beach evolution results obtained in the present study to be compared with the more deterministic models put forward before.

Previous Work

Often when beach changes have been directly related to wave conditions, the plan position of the shore has been investigated rather than the beach profile shape. Generally as wave height (and hence energy) increases,the amount of material which can be moved increases and is moved seawards,building up the lower beach and near-shore zone at the expense of the upper stretches of beach (Short, 1978, 1980). When wave heights fall a full upper beach develops and has been linked to bar formation by Davis and Fox (1972), Fox and Davis (1976) and Owens and Frobel (1983). The relationships are not straight forward, and it has been found that for a highly accreted state to exist a pulse of higher energy is required (Bowman and Goldsmith, 1983). Previous workers (Wright and Short, 1983; Wright et al., 1985) have attempted to relate various wave-derived parameters to specific beach states. The present work aims to associate simple trends in wave heights with specific transitions between beach types, and variability in these transitions.

Holderness Work

Sections 3.2 a and 4.2 a revealed that certain beach transitions occurred more frequently in winter, and others in summer. It is possible to identify these differences, presumably related to wave conditions, by determining the way in which transitions coinciding with specific wave conditions varied from a uniform distribution which assumed no dependence on wave height. Since it is the amount of wave energy available rather than wave direction which is of prime importance in determining sediment transport rates only wave height is considered here. On Holderness, waves from the north-east coincided with periods when the beach was more active, simply because these waves generally possess the highest energy.

To investigate the relationships between wave height and beach conditions four data sets were considered:

1. Summer fortnightly beach transitions.
2. Winter fortnightly beach transitions.
3. March intensive beach transitions.
4. Daily beach transitions in July.

For each, the beach transitions and the coincident wave conditions were tabulated, and the transition frequencies expected from a uniform distribution calculated in the usual way - row total x column total/grand total. The wave conditions used were those which were dominant during the transition interval. The observed and expected data were compared, and the main differences summarised in Table 4.4, i.e. the transitions which occurred more or less frequently than expected for a particular wave height were identified. Briefly, as wave heights increased the beach became more dynamic, altering its state rather than remaining the same. Static profiles prevailed during calm conditions and although the frequencies of individual transitions differed between "summer" and "winter" there is no difference between the behaviour exhibited under the same prevailing wave conditions in each season. In winter, however, the range of wave conditions is much greater allowing the transitions which occur under higher waves to be identified.

Not only are the types of transitions more variable in winter but transition frequencies are different from those that might be "expected"; summer behaviour is more uniform. It was recognised that there might be some delay in profile changes reflecting prevailing wave conditions, but this could only be investigated for daily transitions in July, when only one days wave data were associated with the observed transition. For fortnightly transitions it was impossible to impose a lag on what was a representative

Table 4.4 Transitions which occur more or less frequently than expected

	Winter			Summer	
Wave H_o(m)	More	Fewer	H_o(m)	More	Fewer
0-0.5	NN ON OO	MO NS PO RO	0-0.33	MM MN NN NO	ON OO PP RO
	OP	SN	0.34-0.66	OO RO	MM NO RR
0.51-1.0	NO PO PY	MO NN NS	0.67-1.00		NN
	RO SN XQ	OM OP ON YX			
1.01-1.5	MO PP				
>2.0	NN NS YX	OO			
Wave dirn.					
NE	PO NS	OO	NE	MN ON PO	MM NN OR
E	NM OO OP	NN NS PO	E	NN	MN ON PO
	PP RO SN				
SE	NN	OO	SE		
March			July		
H_o(m)	More	Fewer	H_o(m)	More	Fewer
0-0.25	SN		0-0.25	OO PP QQ RR	NN NO OP OR
0.26-0.50	NM XN	MM QQ	0.26-0.50	NN OP	OO
0.51-0.75	MN		0.51-0.75		
0.76-1.0	MM QQ	NN	0.76-1.0		
direction			direction		
NE	NN SN XN XX	MM MN NM QQ	NE	NO	MM OO QQ
E	MM NN NM QQ	NN SN XN XX	E	NN	PP
SE			SE	MM OO PP QQ	NN
				RR	

wave height. The range of wave heights during July was so small that similar patterns were observed between the non-lagged data and waves, and between waves and transitions which had been lagged by 24 hours. Further detailed work would be required to establish the existence and length of significant lags in the system.

Waves from the north-east, those possessing most energy, exhibited more M—O, O—N and P—O transitions , indicating a transfer of material to the lower beach at the expense of the upper beach. Waves from the east and south-east were accompanied by a more stable beach.

Beach Transitions and Wave Height

With low waves static "transitions", i.e. no change in beach type, occur more frequently and only rarely are transitions such as N—O, O—P and R—O encountered, in which the upper beach is depleted. This is in accordance with the findings of other workers and confirms the observations of the diagonal elements of the summer matrix being larger than the equivalent winter figures. With waves around 0.5 m the upper beach could be built up, perhaps representing the pulse of energy that Bowman and Goldsmith (1983) found to be necessary for a fully accreted beach to develop. As wave heights increase the beach becomes more dynamic and fewer "static transitions" are observed; there are exceptions such as Q—Q which may involve the continued depletion of the upper beach. When waves exceeded 1 m, transitions occurred which involved a transfer of material from the upper to the lower beach, e.g. M—O, N—S, Y—X, as well as P—P and N—N which can represent a continued transfer of material in the same direction, leading to more "extreme" profiles of the same type. These observations confirm, in part at least, the first-two hypotheses put forward at the end of Section 3.2 a (iv).

1. The first hypothesis stated that higher energy conditions will lead to a "combing down" of the upper beach and a building up of the lower beach, and is confirmed by the increased frequency of M—O, P—P, N—N and Y—X transitions for waves over 1 m. The most marked build up of the lower beach coincides with waves over 2 m, e.g. N—N and Y—X.
2. The second hypothesis stated that calm conditions will lead to a build up of the upper beach or will maintain a linear profile of increased volume; this is partly confirmed by the observations made here but requires refinement. Some low energy conditions gave rise to a build up of the upper beach (M—N, N—O), but also coincided with periods when the beach remained stable (N—N, M—M, P—P, R—R etc.). The latter was usually observed during calm conditions when the waves possessed insufficient energy to move sediment to build up even the most depleted profile (e.g. P—P).

When the waves between the extremes were considered (0.5-1.0 m) things were more complicated. The beach was more mobile, in terms of the number of types which it exhibited, than with lower waves but the direction of sediment transfer induced by these waves was not constant - it may be either onshore or offshore. These observations were particularly marked in winter when a wider range of heights was recorded. In summer when no waves over 1.0 m high were encountered, the full range of transitions was not observed. This may explain why the, often hypothetical, extreme beach states put forward by Sonu (1973), Sonu and James (1973) and Wright and Short (1983) were never achieved. Great care must be taken if their models are applied to coasts with a limited wave climate.

All the comments which have been made about variations in beach transitions with respect to wave conditions have been qualitative, the general trends being extracted from the data. It would be more satisfactory to test the statistical significance of the relationship between beach transitions and wave height. However, apart from those for winter, the available data did not cover a sufficiently wide range of wave heights for statistical tests to be carried out.

An exploratory chi-squared (χ^2) test was performed on the winter data: the contingency table of observed and expected values used to determine the general trends reported above, provided the data necessary to calculate the χ^2 statistic. At first each transition was considered separately and wave heights grouped into four categories, 0-0.5 m, 0.51-1.0 m, 1.01-1.50 m and over 2.0 m (no waves between 1.5 and 2.0 m were recorded). The χ^2 value of 180 was statistically significant at the 95% level and the contingency coefficient, a measure of the extent of association between the two sets of attributes, was 0.803 (Siegel, 1956). However, the use of such a detailed contingency table meant that the requirements of the Chi-squared test were not met; many of the cells in the table had expected values under 1, and most were under 5. To fulfil the requirements another test was attempted with aggregated data. The transitions were grouped into four categories comprising:

a. unchanging profiles

b. seaward movement of sand

c. landward movement of sand

d. both upper and lower beach build up or depletion.

Again, a significant difference was observed (χ^2 = 17.45, table value at 95% level = 16.919). There is a danger here that so much aggregation is taking place that different transitions which actually occur under different wave conditions are being considered together.

It is thought that in this part of the work, owing to the necessary limitations of the data, the best indications of the links between beach evolution and wave height are obtained by examining the departure of the "raw" observed and expected data as summarised in Table 4.4.

Summary

The general results obtained on Holderness confirm those of other workers and allow the tentative hypotheses put forward earlier to be upheld. Waves up to 0.33-0.50 m high result in relatively static beaches, those from 0.50-1.0 m produce more active and variable beach profiles, while waves over 1.0 m lead to a seawards transfer of material from the upper beach, and the beach being "combed down". Though beach behaviour is strongly influenced by wave height this is not the only control, future beach behaviour also depends upon the present nature of the beach, as indicated by the probability model.

The main limitation of this work was that, owing to the limited range of wave heights during much of the year, a statistically significant relationship between beach transitions and wave height could not be established.

This section has linked the deterministic models described in the literature and the probabilistic model advanced in the present study. The patterns involved in the latter model reflect wave conditions but the response of the beach in terms of the future states it may exhibit is limited by its present state.

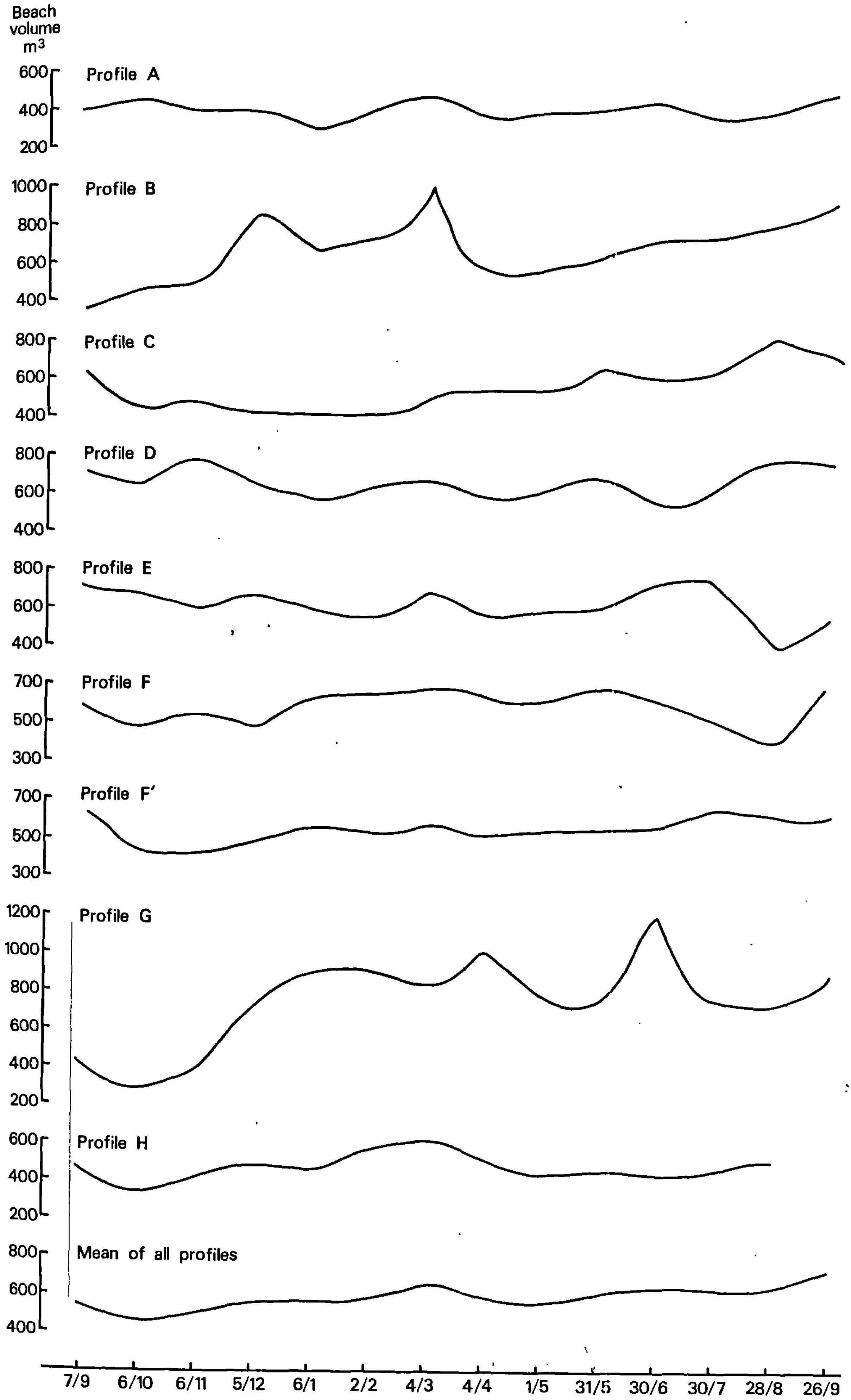
The next section is a short discussion of some more general aspects of beach morphology which were not specifically included in the profile model.

4.2 a (iv) General Beach Behaviour

The beach profiles surveyed between October 1983 and Sepetember 1984 provide an indication of the temporal and spatial variability exhibited by the beach. Examples of the forms produced were shown in Figure 2.8, together with the maximum and minimum beach profiles recorded over this period. Although the envelope describing these extremes does not represent the annual total volume of sediment moved (both extremes may occur in one month), the plots yield the net changes over a year. It is therefore possible to calculate a sediment budget. Generally speaking, the minimum beach conditions, particularly on the upper beach, were observed during and after high energy storms. The maximum beach conditions tended to follow moderate energy wave conditions. The nature of the wave conditions, rather than the season, determines beach variability; however, since high energy waves are more common in winter, the beach is more variable then. This is also confirmed by the results of the Markov model. Profiles show a vertical variation of up to 2.5 m, although this figure may be slightly greater at profiles E and F. At all locations the variability of beach height was greater on the lower beach sections than on the upper beach at the cliff foot. This may reflect the greater energy required to move the coarse upper beach material and, more importantly, the boundary influence of the till platform beneath the beach. The difference between the maximum and minimum beach elevations 150 m from the cliff may be over three times that at the beach crest.

Although the profiles surveyed in September 1983 and September 1984 give the annual net change in sediment volume under the beach, and allow a sediment budget to be calculated, they give no indication of what occurred throughout the year. Similarly, the envelopes of

Figure 4.1 (i) Spatial and Temporal Variation in Beach Volumes on Holderness: September 1983 to September 1984.
(Measured for a 1 m wide strip of beach to an arbitrary datum).



Beach volume m3
Profile A
600
400
200
Profile B
1000
800
600
400
Profile C
800
600
400
Profile D
800
600
400
Profile E
800
600
400
Profile F
700
500
300
Profile F′
700
500
300
Profile G
1200
1000
800
600
400
200
Profile H
600
400
200
Mean of all profiles
800
600
400
7/9
6/10
6/11
5/12
6/1
2/2
4/3
4/4
1/5
31/5
30/6
30/7
28/8
26/9

beach extremes (Figure 2.8) do not reflect the month to month changes. Figure 4.1 (i) shows the volume under each beach profile from September 1983 to September 1984 (measured to an arbitrary basal datum). This allows certain observations about spatial and temporal variations in beach volume to be made. Spatial variations such as the occurrence of ords, are covered in Chapter 3 and again later.

Figure 4.1 (i) emphasises the highly variable nature of the beach. Though "seasonal" trends may be observed they are variable and there is no single common pattern. Beach volume may increase in both spring and autumn (e.g. Profiles A, C, D) but equally reductions may be observed in late summer (Profiles E and F). While some profiles exhibit a steady change in volumes (Profiles A, C and D), others exhibit more rapid fluctuations, e.g. Profile E, and more particularly profiles G and B. Profile G coincides with what may be the transition zone where the sheltering influence of Flamborough Head diminishes.

The difference between the maximum and minimum beach volume varies from profile to profile, from around 200-300 m^3 at Profiles A and D to 500 m^3 or more at B, F and G (for a 1 m wide strip of beach).

As far as temporal variation is concerned, profiles A to E (cell v)) exhibit a fairly steady increase in volume, which is reflected in the sediment budget. Generally, the volume is greater in summer (May to July) than around December, January and February. Over much of the beach (Profiles C to H), the volume decreases from September 1983 to October, November and December. Profiles E, F and G exhibit a greater degree of temporal variation. At profile E, on the boundary of the two cells, though the volume fluctuates it does so around the same value (= 650 m^3); profile F behaves in a similar manner. Within cell (iv), in the north of the field site, the lowest values are generally observed around October, November and December 1983, possibly as a result of storm waves stripping material from the beach; this is followed by a rapid increase in volume in the first four months of 1984. It must be remembered that this figure gives only a guide to changes in beach volume; possible survey errors must be taken into account, as well as the fact that the beaches were not always of a comparable length.

When the mean volume of all beach profiles is plotted, not surprisingly, the fluctuations are dampened. A general increase in beach volume during the year is revealed with, in common with most of the individual profiles, minimum beach profiles from October to January.

On the whole variations in beach volume are great and overshadow any consistent seasonal changes. At first the absence of any systematic seasonal/temporal change all along the beach may seem surprising. However, on reflection, the more significant seasonal beach variations are in the <u>distribution</u> of the sediment over the profile, i.e. the exchange of material between the upper and lower beach. These major changes are discussed in the preceding section on Markov models. What Figure 4.1 (i) helps to show are net transfers between the intertidal (upper and lower) beach and the cliff and offshore zones on a monthly basis.

observed once. The presence of an inter-tidal nearshore sand bar is reported as being characteristic of an ord, but low amplitude oblique bars are frequently observed along the coast, especially following a seaward movement of sediment during higher energy conditions.

Pattern of Till Exposure - Spatial and Seasonal Variations

Figure 4.2 shows the fortnightly sequence of bare till patches on the study beach from April 1983 to September 1984, indicating their size and position on the profile. Plate 3.1 shows an example of the till exposure. The maximum width was 52 m and the patches were generally observed from profile F northwards but occasionally at profile E. Their length alongshore may from time to time be indicated by the number of profiles which they cover; sometimes only one profile was bare and the length of the exposure was often less than 100 m, while at other times the length may have been much greater, e.g. almost 2 km in May 1983. Usually between surveyed profiles some areas of the upper beach had a veneer of sand. The patches exhibited no particular form - they were just a uniformly sloping section of till platform. On a small scale the till was often ripple-marked with pebble armouring.

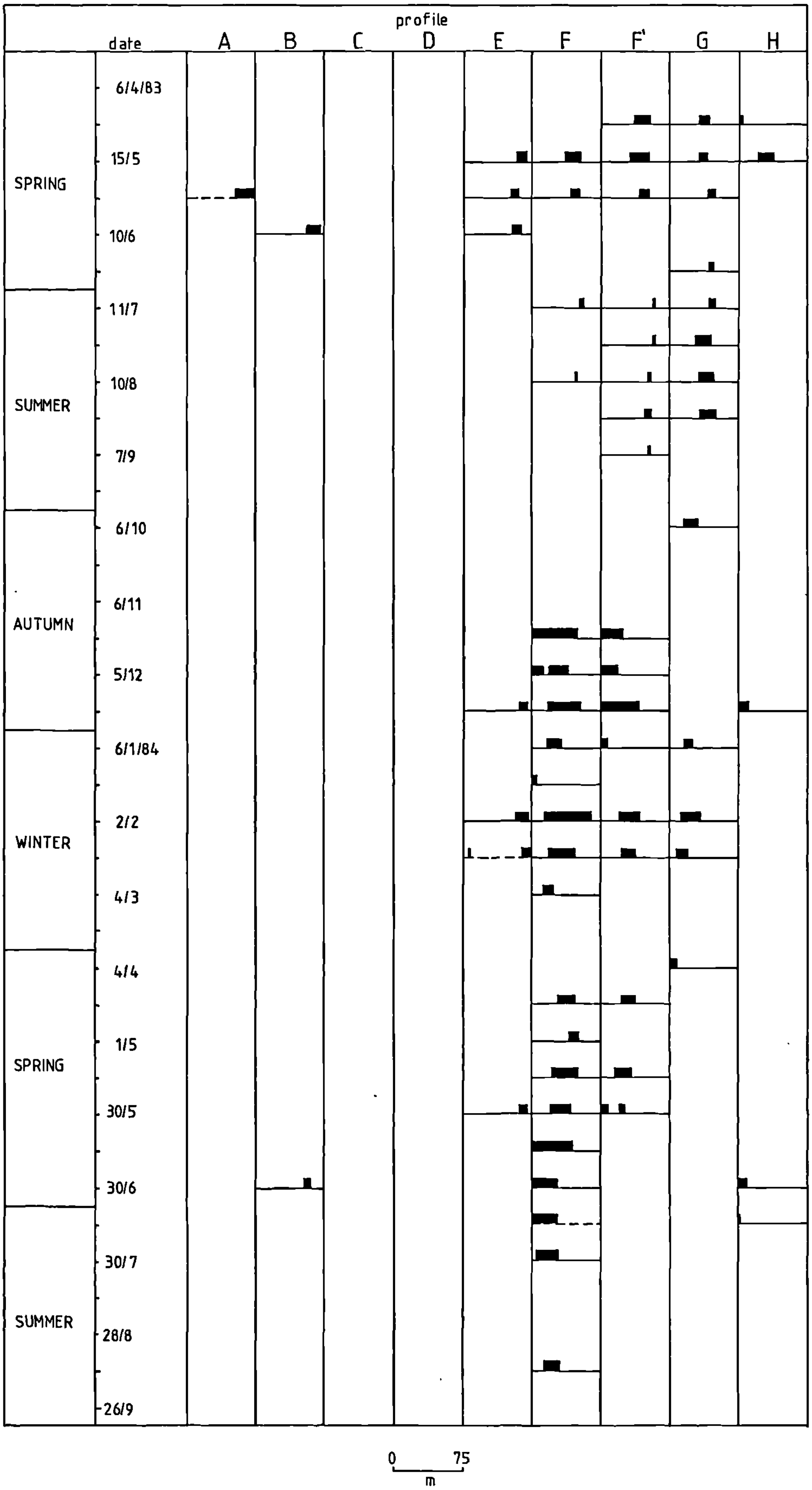
On the field site the lower beach was always "full" seawards of the till exposure, a feature noted by Phillips/Pringle and is the normal beach response when high energy waves are able to remove material from the upper beach. Low amplitude bars were also observed (Plate 3.2). Armoured mud balls, another feature of the coast recognised in previous studies, were frequently present on low sections of beach, though not exclusively associated with till patches; Plate 3.1 also shows these mud balls, which are lumps of cliff or platform till with shingle or pebbles embedded in their surface, and are gradually abraded on the beach.

Figure 4.2 Till Platform Exposure on Field Site Beach Profiles, April 1983 to September 1984.

—■— : location and extent of till exposure along profile measured from the cliff foot.

- - - - till covered by very thin sand veneer (< 0.005 m).

n.b. No till exposures at Profiles C or D, or on the lower beach


profile
date
A
B
C
D
E
F
F'
G
H
SPRING
SUMMER
AUTUMN
WINTER
SPRING
SUMMER
6/4/83
15/5
10/6
11/7
10/8
7/9
6/10
6/11
5/12
6/1/84
2/2
4/3
4/4
1/5
30/5
30/6
30/7
28/8
26/9
0
75
m

During the 18-month study period the centre of distribution of the exposed till sections appeared to have moved southwards (see Figure 4.2), reflected by fewer exposures at G and H and smaller exposures at F', and more, larger exposures at F as time passed. An estimated migration, assuming that the centre of the depleted section was around profile G in April 1983 and by July/September 1984 had reached profile F, is 700 m in 15 to 18 months. This is similar to Pringle's (1985) value of 0.5 km/yr but assumes, of course, that the many small sand-free areas are really part of one much larger form; this is probably not the case. The till disappeared under a mantle of sand in summer. The presence and distribution of these "mini-ords" varied throughout the study period, and if they are part of one large ord, which seems doubtful, then its size is extremely variable (Figure 4.2). They were fewer and less extensive from June to November, i.e. in summer, and during calm offshore conditions, e.g. March and April 1984, though they persisted at one location (profile F) until July 1984; this may have been the centre of the "ord".

As well as alongshore and seasonal variations, they exhibited considerable variation across the beach profile. Over the 18 months, the exposed till on some profiles moved towards the cliff which would suggest a southwards migration according to Pringle's (1985) morphological observations. Unless conditions changed dramatically their extent remained the same.

Phillips (1964) and Pringle (1985) suggested that these sediment-free areas originate on this northern section of the field site where the shelter of Flamborough Head diminishes. The coast is suddenly exposed to more energetic waves which can remove large quantities of sediment and leave a depleted beach, but evidence for subsequent southwards migration is sketchy. The <u>extent</u> of the till exposure depends on the amount of wave energy available.

Till Exposures and Wave Height

From June 1983 to mid-November 1983 low energy waves ($H_0 \leqslant 0.5$ m) prevailed and any till patches were narrow (< 10 m). This fits in with general theory of beach build-up during periods of relatively low waves. In mid-November larger till patches reappeared at profiles F and F' following a spell of higher waves ($H_0 \leqslant 1.5$ m), which had obviously stripped the sand and shingle veneer away. In December, following waves of 2.5 m, the till exposures had extended to profiles E and H, and by early January to G as well. This too is consistent with traditional beach theory. Slight recovery was observed in late January, but waves over 2 m high at the end of the month led to long, wide till exposures in early and mid-February, while low waves in March and April 1984 meant that all of the till was covered. High waves in early May 1984 estabished the exposure at profile F which persisted until the end of July 1984. The extent of till exposures depends therefore on the amount of wave energy available on the beach.

A number of conclusions can be drawn from the observations made in the present study, with reference to previous work. The till exposures on the field site were relatively small and poorly defined in comparison to Pringle's (1985) ords, and there was no evidence for their being filled with more mobile sediments which would be re-excavated repeatedly. Their occurrence is probably a natural response to the limited sediment reservoir of the upper beach veneer, and the highly variable and limited supply of material from the cliffs. Any depleted beach is susceptible to high energy waves which, in transporting large quantities of sediment seawards, will innevitably expose the upper beach till platform. Such forms would not be self-perpetuating or permanent as a depleted section of beach will allow increased cliff erosion which in supplying material to the beach will aid its recovery. Material will also be supplied from alongshore and, upon the return of lower energy conditions, from the lower beach. This is indicated on Figure 4.2 where during the summer till exposures are non-existent or very small. In other words, the till patches at specific locations may be transient because the inter-relationships in the coastal system cause a readjustment, in an attempt to establish or re-establish equilibrium.

As far as the suggested southward migration of ords is conderned (Pringle, 1985), it is likely that rather than the form moving "as a whole", what is observed is merely a change in position of the most depleted beach sections. After all, field observations in the present study recorded relatively short exposures of till not one large form; the centres of depletion probably "oscillate" slightly, reflecting local variations in wave energy and sediment supply. It is difficult to see how "ords" could, in the face of variable beach profiles and sediment supply alongshore, migrate as a discrete form. Once again, their total disappearance in summer is inconsistent with Pringle's findings. If there is no significant and sustained migration then ords cannot all form at one specific location north of Skipsea. If they exist in a characteristic form at all they must form at any point along the coast where sediment supply is limited, and/or its removal is rapid. In the north of Holderness at least, it seems that the importance and characteristics of these "ord" forms have been overemphasised. From observations in the present study there are no permanently exposed till featues,and when they do exist, usually in winter, do not represent a unique phenomenon but simply the natural response of a veneer beach to variations in wave energy and sediment supply.

Some other patterns of beach surface variability are observed which do not result in till platform exposure. From both field work and the results of sediment transport and beach morphology models, the beach is seen to be much more variable in winter than in summer. In winter the trend is for the upper beach to supply sediment to the lower beach which becomes full, whilst in summer a reverse sediment movement allows the upper beach to build up. Though these general trends can be picked out easily, the changes between profiles from survey to survey are more subtle, and their response cannot always be directly linked to certain conditions, hence the need to classify profiles before a (Markov) model of beach evolution covering more quiescent periods could be produced. Occasionally certain prolonged or extreme events or conditions may produce distinct beach changes, e.g. an elevation of the beach surface following a spell of low waves or a depression accompanying higher waves. Figure 4.3 shows examples of this.

This section has established that:

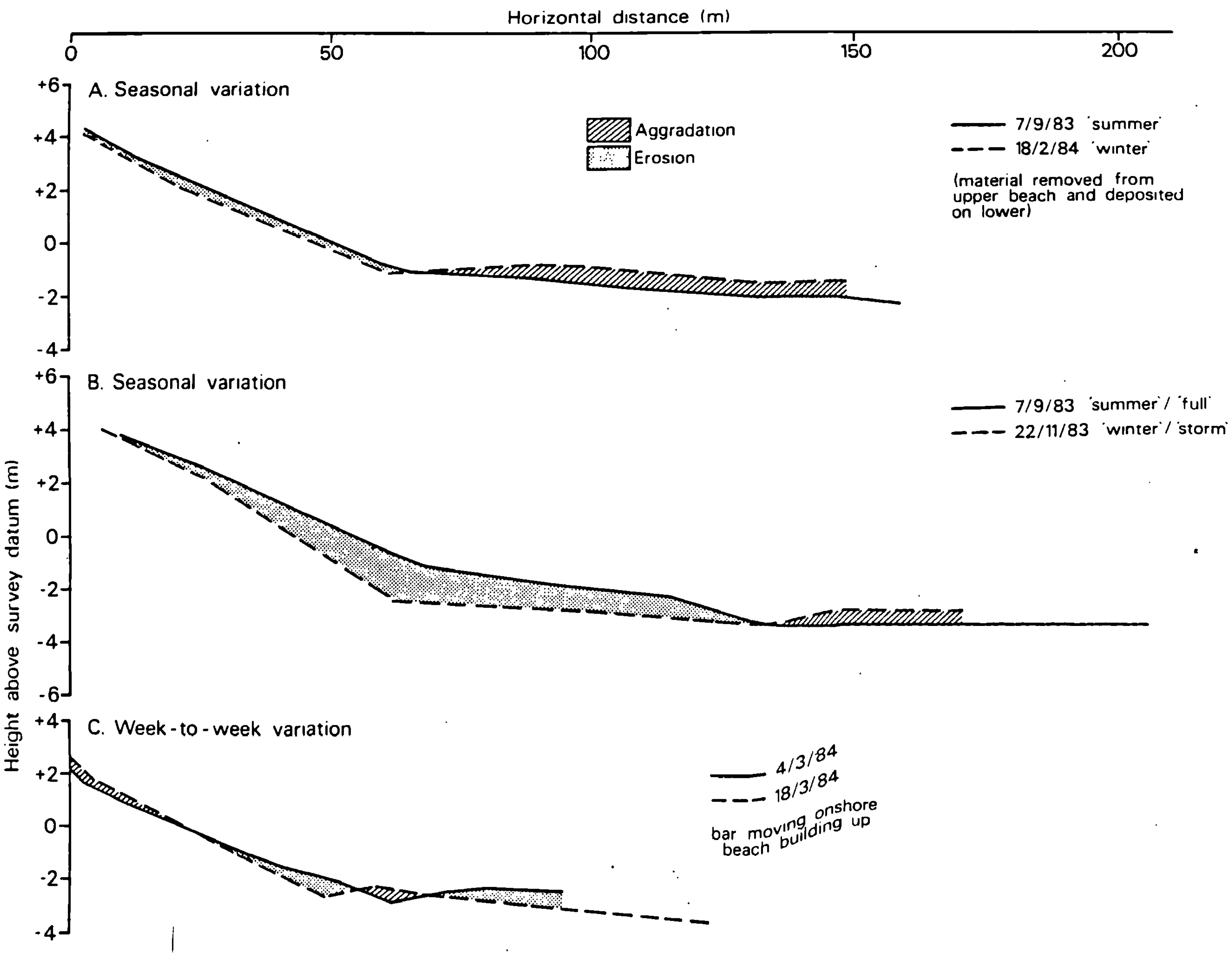
1. The study beach exhibits featureless till exposures of variable size and position associated with the response of a beach with limited sediment supply to higher energy conditions, and on the field site the presence of Flamborough Head.
2. These patches are ephemeral and are largest during the winter when high waves can strip sediment from the beach. In summer the beach is built up and the patches disappear.
3. The centre of distribution of these sediment-free areas moves, and while this might reflect a southwards migration it is more likely to reflect beach processes seeking to achieve some equilibrium form.

Figure 4.3 Beach Profiles Responding to Wave Conditions.

A Higher energy winter waves cause erosion.

B Higher energy winter waves cause erosion.

C Waves between 0.5 and 1.0 m result in an onshore movement of sediment.


Horizontal distance (m)
0
50
100
150
200
Height above survey datum (m)
A. Seasonal variation
Aggradation
Erosion
7/9/83 'summer'
18/2/84 'winter'
(material removed from upper beach and deposited on lower)
B. Seasonal variation
7/9/83 'summer' / 'full'
22/11/83 'winter' / 'storm'
C. Week-to-week variation
4/3/84
18/3/84
bar moving onshore
beach building up
+6
+4
+2
0
-2
-4
-6

4. These till exposures may be similar to Pringle's ords but do not exhibit their characteristic morphology, behaviour and permanence.

Summary

This section on beach morphology has traced the development of beach evolution models, discussed the results of the Holderness Markov model and interpreted them with reference to the previous studies. The improvements incorporated in the present study were summarised. Section 4.2 a (iii) confirmed that, though beach evolution could be modelled without reference to wave records, there is a relationship between the types of transitions and the coincident wave conditions. The final section is a more general interpretation of morphological field observations, comparing the findings of the present study with others carried out on Holderness.

The next section of work in the beach sub-system considers its sediment composition. This is important because as beach morphology changes so may its composition, reflecting wave conditions. The trends were established in Chapter 3, and will be interpreted in 4.2 b with reference to wave conditions.

4.2 b BEACH COMPOSITION

This section is an interpretation of the results of monitoring beach sediments which were presented in Section 3.2 b.

The aim of this work was to establish the temporal and spatial variations in beach sediments, and the relationships between sediment characteristics and offshore conditions. Beach composition is intrinsically linked to beach forms, and wave action on a particular grade of sediment will create a specific range of forms. The nature of beach sediment therefore influences the important relationship between offshore conditions and both sediment movement and beach morphology.

The beach sediment characteristics considered were mean particle size and sorting, the former because it determines the wave energy required to move beach sediments and the latter because it shows the range of different particle sizes which make up the beach sediment, and hence reflects the depositional environment. The records of each of these variables were presented in Chapter 3 and will be compared with the wave data for the same period in an attempt to establish the relationships between wave height and sediment characteristics. The interpretation of the mean particle size results will be presented first as it is regarded as the more important variable.

Mean Particle Size

The results in Figure 4.4 show the upper and lower beach mean particle size from May 1983 to September 1984, and a record of wave heights. In common with other beaches world-wide the upper beach material was considerably coarser and of more variable calibre than that of the lower beach. At profile A the upper beach coarsened during winter, then fluctuated widely during the spring and early summer. Similar behaviour of the lower beach was observed at profile D, but the upper beach was more variable with finer sediments dominating from mid-July 1984 onwards. At profile F' the lower beach begins to exhibit seasonal changes, being coarser in November and February. The size of upper and lower beach sediments are much closer on this profile and at one point the curves cross. The upper and lower beaches are thus less sedimentologically distinct (Figure 3.2), a feature which has been noticed in respect of other beach variables, e.g. a less distinct break of slope between the upper and lower beaches. This distinction is also poor at profile H, where the lower beach is

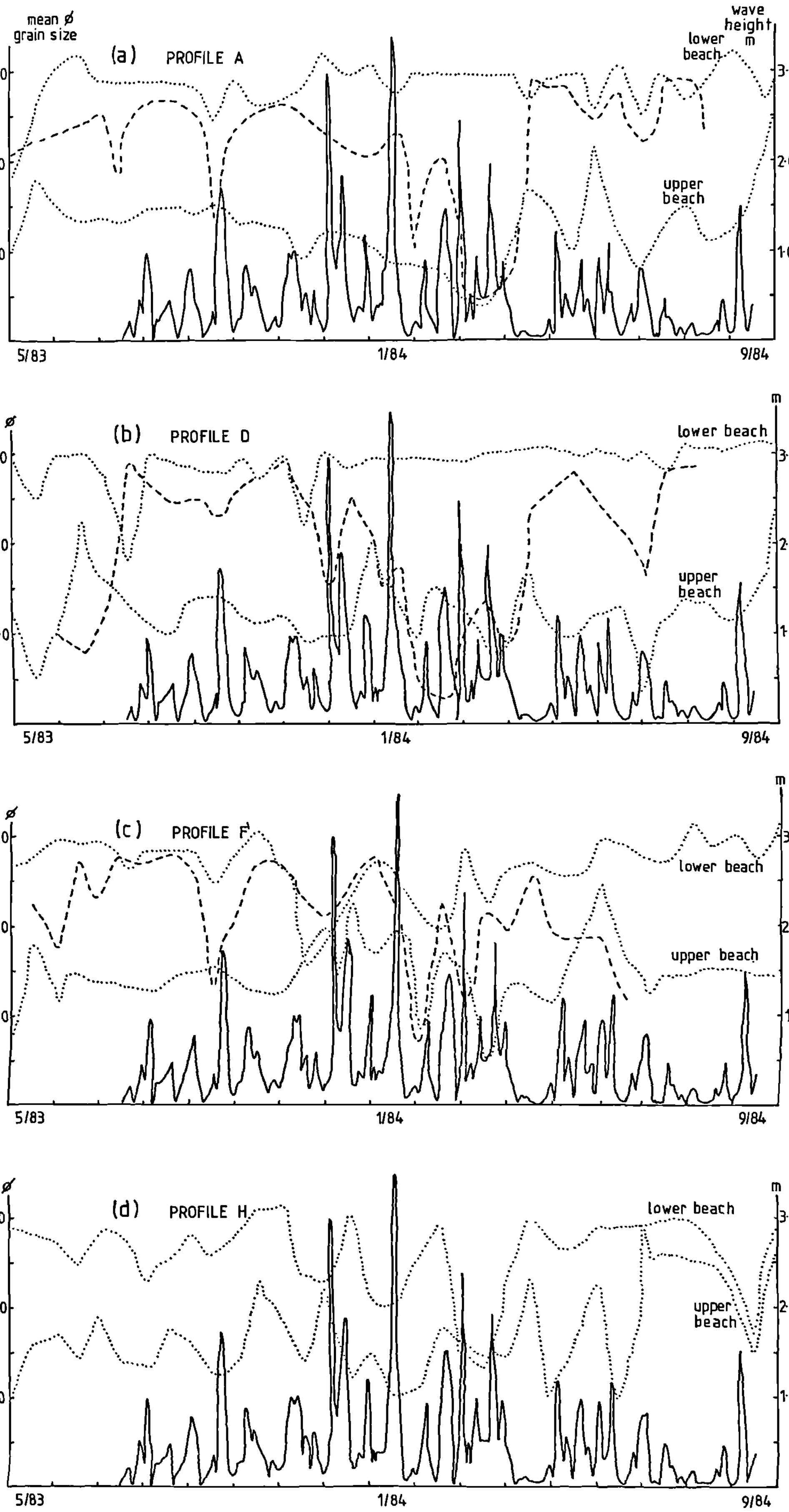
Figure 4.4 Mean Particle Size of upper and lower beach (dotted lines) and beach crest (broken line), and wave height (solid line), May 1983 to September 1984.

a Profile A

b Profile D

c Profile F'

d Profile H


mean ø
grain size
(a) PROFILE A
wave
height
m
lower
beach
upper
beach
2·0
0
-2·0
3·0
2·0
1·0
5/83
1/84
9/84
ø
(b) PROFILE D
m
lower beach
upper
beach
2·0
0
-2·0
3·0
2·0
1·0
5/83
1/84
9/84
ø
(c) PROFILE F
m
lower beach
upper beach
2·0
0
-2·0
3·0
2·0
1·0
5/83
1/84
9/84
ø
(d) PROFILE H
m
lower beach
upper
beach
2·0
0
-2·0
3·0
2·0
1·0
5/83
1/84
9/84

coarser than at A and D and exhibits a greater range in size throughout the year. The upper beach at profile H is coarser in winter.

Mean Particle Size and Wave Height (see Figure 4.4 a-d)

From Figure 4.4 (a) it can be seen that at profile A the increase in sediment size of the upper beach coincides with increased wave heights from September 1983 to mid-March 1984 when waves are capable of moving coarser material and of winnowing fines. The same trend can be seen on profile D but, as before, the relationship is less clear. From F' northwards the lower beach too depends on wave height as the upper and lower beach system breaks down, but the relationship between wave height and sediment particle size becomes more obscure towards the north. It appears, however, that the increase in mean particle size on the upper beach associated with higher wave conditions reflects;

1. The ability of higher waves to strip fine material from the beach, leaving the underlying coarser material exposed.
2. That under very high energy conditions the coarse material may be moved and redeposited on, or near, the beach surface.

A lag may exist between a change in the wave conditions and the beach sediment response, which could not be identified in the present study. Beaches are often coarser after a period of high waves, e.g. in January, February and March 1983 at profile F' (Figure 4.4 (c)).

Wave height (as a surrogate for wave energy) is more important in influencing the particle size distribution in the south of the field area than in the north. The sheltering effect of Flamborough Head may modify the wave climate at the northern end of the field site, dampening the extremes and leading to a more uniform wave climate than has been attributed to the site. Hence its less distinct "seasonal" behaviour of beach sediments and the breakdown of the upper beach/lower beach pattern, confirmed by morphological evidence.

In the south of the field area there is a good relationship between sediments and waves, and it may be significant that the wave recorder producing the data used in the study is opposite profile C. Between these two sections is a variable stretch of coast at the edge of the sheltered zone where the two distinct beaches may be present at one time, but at another the profile is more uniform. It is at this point that offshore bars begin to weld onto the shore (Plate 3.2).

Beach crest material: The changes in composition of the beach crest reflect the removal of fines from the top of the beach during high energy (winter) conditions, corresponding to berm destruction on other beaches. Very coarse material may actually be thrown up to the top of the beach under such conditions, although in the north of the area, where the overall trend of winter coarsening is the same, the picture is less clear. This again indicates both the seasonal and longshore variations in the beach.

Direct plots of wave height against upper beach particle size (Figure 4.5 a-d) were compiled in an attempt to determine a more precise relationship between the two variables but showed poor correlations. However, a general exponential relationship may be proposed, best observed at Profiles A, D and H. It is suggested that at these locations the beach sediment is in equilibrium with the wave conditions, H in the lee of Flamborough Head, and A and D outside its influence. F' may be in the transition zone between them.

Only the overall trends can be gleaned from these graphs, and certainly nothing can be deduced about the speed with which the beach sediments respond to changes in wave height. Any relationships might be revealed more satisfactorily if the appropriate lag between wave height and sediment response could be established. Then a specific

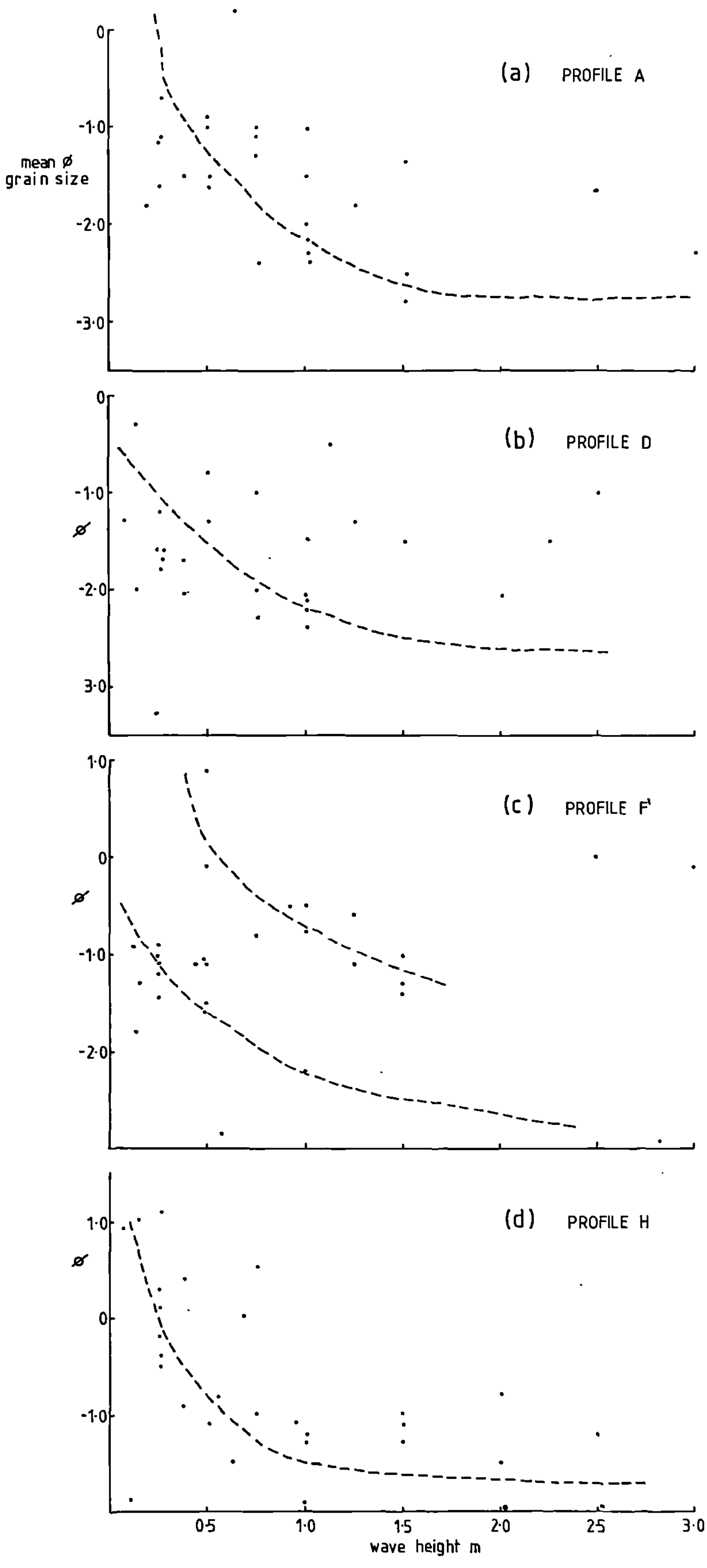
Figure 4.5 Wave Height against Mean Particle Size.

a Profile A

b Profile D

c Profile F'

d Profile H



(a) PROFILE A
mean ø
grain size
0
-1·0
-2·0
-3·0
(b) PROFILE D
ø
0
-1·0
-2·0
3·0
(c) PROFILE F¹
ø
1·0
0
-1·0
-2·0
(d) PROFILE H
ø
1·0
0
-1·0
0·5
1·0
1·5
2·0
2·5
3·0
wave height m

wave height could be associated with the sediment conditions with greater confidence. Spatial and temporal variations in the response of mean particle size to wave conditions will be masked as a result of the more or less uniform supply of material from the cliff. With a steady, though temporally variable, supply from the cliff and platform it is innevitable that the beach will never reach an equilibrium in which sediments reflect purely wave influences.

Variation in lower beach material was generally very low, suggesting that this grade of sediment could be transported under most prevailing wave conditions and was the most dynamic material on the beach, i.e. in winter some of it would have been removed from the beach crest and deposited on the lower beach.

Sorting

As expected upper beach material was less well sorted than that on the lower beach (Folk and Ward, 1957). However, the plots in Figure 4.6 a-d were too variable to draw any firm conclusions about the relationships between sorting and wave height, though better sorting tended to coincide with periods of higher waves (e.g. at H from December to March). This is explained by the higher waves being able to winnow finer material from between coarser particles and deposit it, when it can no longer be held in suspension, among material of a similar grade. This response may be masked by high waves having the opposite effect, i.e. they would allow increased cliff erosion and hence the introduction of material of a wide size range to the beach. Not all of the material can be evacuated immediately and so the beach is, for a time at least, more poorly sorted. On the whole, sorting results are therefore qualitative and the interpretations tentative. The distinction between the sorting of the upper and lower beach declines from south to north

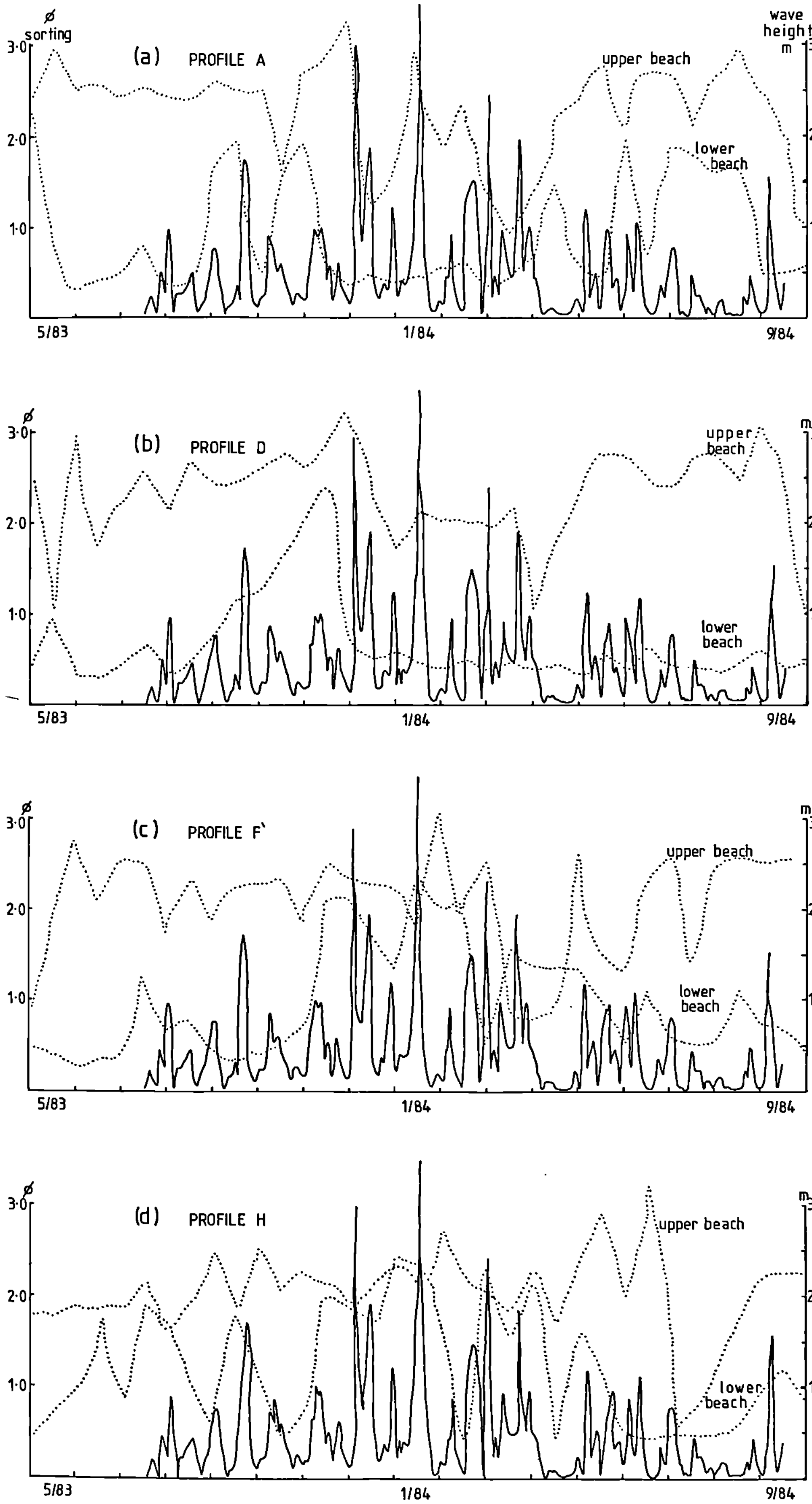
Figure 4.6 Sorting of upper and lower beach sediments (dotted lines), and wave heights (solid line), May 1983 to September 1984.

a Profile A

b Profile D

c Profile F'

d Profile H



ø sorting
wave height m
(a) PROFILE A
upper beach
lower beach
(b) PROFILE D
(c) PROFILE F`
(d) PROFILE H
3·0
2·0
1·0
5/83
1/84
9/84

(Figure 3.26), again reflecting the breakdown of this system. The convergence is brought about by the lower beach becoming more poorly sorted towards the north, while on the upper beach the value remains much the same. This pattern would be expected bearing in mind the increase in grain size of the lower beach from south to north.

Although the nature of the beach sediment supply meant that few specific relationships between sediments and wave conditions could be established, a number of conclusions concerning beach sediments in general can be drawn from the present work:

1. An increase in wave height coincides with an increase in the mean particle size of the upper beach, while that on the lower beach remains unaffected; the upper beach relationship may be exponential.
2. There is a decrease in the correlation between particle size and wave height from south to north.
3. Sediment particle size reflects the seasonal build-up of a fine-grained beach crest during summer and its destruction in winter.
4. Sediment characteristics reflect the breakdown in the upper beach/lower beach system towards the north of the field site. The indices of particle size and sorting describing the two populations converge.
5. Sorting appears to be less dependent on wave height than is mean particle size.
6. The breakdown of the upper and lower beach pattern reflects a major change brought about by the sheltering of Flamborough Head.

Summary

This section has drawn a number of conclusions regarding the nature of sediments on the Holderness coast; it was apparent that the sedimentary characteristics of the beach were correlated with the wave record, though it was difficult on this coast to establish the precise relationships involved. Sediment characteristics vary with both offshore conditions and bulk beach morphology.

Although the beach sediment results did not contribute as much to the understanding of the beach as morphological and tracer work, they are important in establishing some responses of the beach to offshore conditions, and as such help in the understanding of the relationships involved in the coastal system, one of the main aims of this research. It has helped to emphasise that critical beach zones or areas of unusual behaviour may be revealed by a wide range of ultimately interlinked variables, e.g. sediment transport, beach morphology, sediment movement and cliff retreat rates.

The final section interpreting beach results considers those obtained from field tracer experiments.

4.2 c SEDIMENT TRANSPORT FROM TRACER EXPERIMENTS AND A COMPARISON WITH MODELLED RATES

In Chapter 3 (Section 3.2 c) sediment transport rates measured in the field were presented. The aim of this tracer work was to establish the direction and rates of sediment movement under differing offshore conditions, and to compare them with sediment transport rates obtained from a refraction model. If necessary the modelled transport rates could be calibrated against the measured results. Should the modelled results prove to be realistic, it is satisfactory to base a sediment budget on them. The interpretation of the tracer methods and results also aims to compare the Holderness techniques and sediment transport rates with those of previous studies, to assess the effectiveness of the present study and to determine whether Holderness is similar to coasts elsewhere.

In some respects it is difficult to know whether these results should be presented with work concerned with morphological evolution and sedimentary characteristics, or with work concentrating on the offshore system. Even though the offshore work led to the production of potential sediment transport rates it was decided to include the measured sediment transport rates with beach work, and compare the two in this section. In fact the tracer experiments form a link between the offshore zone and beach behaviour.

This section begins with a résumé of the techniques used in, and results obtained from, previous relevant sediment transport studies. A summary of the Holderness results is then presented and a comparison made with both modelled results and results obtained elsewhere. This will enable the sediment transport processes on the Holderness coast to be considered in context, and may help to establish relationships between offshore conditions and sediment transport processes. Finally, the conclusions drawn from this work will be presented and suggestions for any improvements made.

4.2 c (i) Previous Work

Numerous studies have sought to produce rates for sediment transport on a variety of coasts by using mathematical and computer models, often calibrated or tested against the results of limited field studies. Several studies which involve computer modelling fail to give details of results measured in the field, merely stating that the model's predictions were "confirmed" by fieldwork, or that "similar" (but undefined) rates were obtained (Komar and Inman, 1970; Cambers, 1973; Cambers *et al.*, 1978).

Two main techniques are used to establish field sediment transport rates;

1. Those which involve marking a certain quantity of beach material and then tracing its progress along the beach.
2. Those which trap and retain the sediment moving within a certain area of beach.

Some studies (Brunn and Purpura, 1964) combined these techniques - traps being used as a means of obtaining sediment samples containing some tracer grains. The present study used tracers since these are more suitable for examining alongshore transport, and have been widely used. Numerous papers have described basic tracer techniques and subsequent improvements (Zenkovitch, 1960; Newman, 1964; Yasso, 1966; Teleki, 1966,1967; Price, 1968; Knoth and Nummedal, 1978; Weatherill, 1978), but very few quantitative results have been presented. There seems to have been a general problem in achieving good "returns" of tracer material, possibly because of burial and an underestimation of the depth of disturbance. Pebble experiments seem to have been particularly prone to poor returns since their detection relies upon scanning the beach surface, rather than taking discrete depth volume samples. Burial therefore prevents recovery. It has been particularly difficult to obtain good results under high energy conditions, often the very time for which information is required. During such conditions transport rates are so rapid that most "practical" quantities of tracer would be flushed out of the area altogether. Kidson et al. (1956), using radioactive techniques, established that pebbles could be moved along the sea floor, e.g. at Scolt Head in Norfolk pebbles moved southwards up to 200 ft in three days, though some movement to the north was recorded. This work was mainly in the inshore zone and it was concluded that currents alone (presumably tidal) were insufficient to transport pebbles. Storm conditions were required when wave action would move small quantities at all times.

Fluorescent tracer experiments have been more common recently although Fox (1978) pointed out that they may give misleading indications of sediment movement, and Knoth and Nummedal (1978) found that tracer movement only occurred on the upper beach. Frequently, tracer experiments have been used to establish the direction of sediment movement, and sometimes a general sense of speed (Lavelle et al., 1976). Indeed, it is in establishing transport directions that many studies seem to have had most success. Many of the earliest studies investigated movement of sediment around man-made objects and defence works (Ingle, 1966). At most study sites movement of sediment has rarely been found to be in only one direction. When experiments cover a range of conditions the relative strength of movement in opposite directions depends on wave approach direction and the energy available. On the Russian Black Sea coast, Zenkovitch (1960) found that occasionally sand grains moved at speeds of up to 3 km an hour when a strong swell was running.

Ingle (1966) carried out numerous tracer experiments on the Pacific coast of Califormia where breaker heights between 0.3 m and 3.0 m were recorded. His experiments involved injecting 1.2-25.5 kg of tracer into the breaker zone and sampling with sticky cards very soon afterwards. Initial high speeds of 0.018 to 0.114 ms^{-1} were recorded, (more respresentative results may have been obtained if displacement had been investigated many tidal cycles after injection). Ingle found transport rates of 56-2059 m^3/day. Short term transport rates appear to have been multiplied to produce daily rates and so may be overestimates.

On the East Anglian coast, Cambers et al. (1978) attempted to confirm the modelled annual sediment transport rates of 30 000 to 100000 m^3 but the tracer results proved to be "inaccurate".

Wilkinson (1980), using sand tracers in Swansea Bay, found that the centroid of tracer concentration moved alongshore between 0 and 27 m per tide, and between 0 and 34 m per tide across the beach. In this study too the rate declined markedly after the first sampling interval. 150 tonnes (110 m^3) of sediment were transported per half tide (440 m^3/day) under 1 m high waves. When waves were 0.2 m the figure was 10 tonnes per half tide (less than 10 m^3), equivalent to 36 m^3/day. Blackley (1980), again working in Swansea Bay, recorded a sand tracer movement of 50 m in the first two tides for a wave height of 1 m. Contour diagrams of fluorescent grain concentration were rather complicated, with "limbs" extending across the beach away from the longshore plume.

4.2 c (ii) Holderness Tracer Experiments

The results of the fluorescent sediment tracer experiments of the present study have already been presented (3.2 c) and are summarised in Table 4.5 The centroid positions and isolines can be seen in Figures 3.27 A-J and in Figure 3.28. The two sand experiments revealed sediment transport in opposing directions. Experiment one coincided with waves from the north-east, resulting in sediment movement towards the south. Wave heights of 0.6-0.7 m were recorded during the first couple of days, falling to 0.3-0.4 m by the fourth day. Transport rates of between 13 and 54 m^3/day were recorded, the largest value coinciding with the highest waves. By the last day the wave direction had swung round to the south-east and the centroid moved northwards at a similar rate to the previous southwards movement. The second experiment took place during calm conditions with very small breakers; it coincided with a wave approach from the south-east, resulting in a movement of sand to the north. Rates on the lower

Table 4.5 Sediment Transport Rates on Holderness

Sand, Experiment 1

Dates	Q (m^3)
1/7-2/7	-54.44
2/7-3/7	-21.16
3/7-4/7	-13.11
4/7-5/7	+14.12

Sand, Experiment 2

Dates	Q (m^3)
7/7-8/7	+15.12
8/7-9/7	+3.42
9/7-10/7	-18.15
10/7-11/7	+3.52
11/7-12/7	+26.72
12/7-13/7	+18.15

-ve movement to the south +ve movement to the north.

Pebbles

Dates	Velocity m/day
1/7	63.0
2/7	15.8
3/7	26.9
4/7	16.8
5/7	30.2
6/7	30.6

beach varied from 3 m^3/day to 26.72 m^3/day, lower than for experiment one when waves had been higher. Thus the drift on this coast may be in both a northwards and southwards direction.

These results indicate that the direction of sediment transport depends upon the direction of wave approach, and that the higher the waves, i.e. the greater the amount of energy arriving at the beach, the greater the drift will be. The rates would be higher (by approximately 50%) if the values on the lower beach were assumed to prevail on the upper beach.

The pebble experiment on the upper beach produced unsatisfactory results, and for this reason they were presented as displacement velocities (Table 4.5). Rates of movement are similar to those found by Kidson et al. (1956) with pebbles travelling 61 m in three days. The Holderness range of velocities (16-63 m/day) would be equivalent to 45-189 m^3/day, assuming a depth of disturbance of 5 cm and an upper beach width of 60 m.

The calm conditions during the second experiment were not particularly unusual on Holderness; from October 1983 to September 1984 they prevailed for 17.88% of the time. The conditions during the first experiment were calmer than a yearly mean value, representing the types of waves often observed during spring, summer and autumn, e.g. the percentage of waved under 0.5 m was 72%.

Comparison of Modelled and Measured Sediment Transport Rates

At this point is it useful to compare the values for modelled and measured sediment transport. Table 4.6 summarises the two sets of results.

Table 4.6 Modelled and Measured Sediment Transport Rates

	Model		Tracer		
	$\bar{H}_o$ (m)	Q m^3/day	Q m^3/day	$\bar{H}_o$ (m)	
summer	0.25	0-58	3-26 (LB) 6-52 (T)	0.01	Expt 2
spring	0.30	75-124	13-55 (LB)	0.3-0.6	Expt 1
autumn	0.46	19-151	26-110 (T)		

LB - lower beach only T - total

The tracer results for the second experiment fall well within the values of modelled rates for summer; as expected the results are low as a result of the almost calm wave conditions from 7 to 12 July. The first experiment produced rates which were somewhere between the predicted summer and spring/autumn rates. This again shows a good agreement between modelled and actual field rates. Though taking place in July, the first experiment coincided with wave energy conditions somewhat in excess of the summer mean of 0.25 m so would be expected to give results more like those modelled for spring and autumn.

The sediment transport model is therefore satisfactory for calculating the general range of sediment transport rates, and can be used to cover much larger areas.

Comparison of Holderness and Other Tracer Results

In comparison with the studies mentioned earlier the sediment transport rates presented for Holderness are low, but, in common with some, movement was observed in opposing directions, with drift in one direction dominating (see Table 4.7). This variation in direction does not accord with pebble tracer experiments further south on Holderness (Phillips, 1962), and probably reflects the conditions prevailing during both experiments. A common failing of most tracer experiments is that they are relatively short-term, infrequently carried out, and thus the chances of recording unrepresentative conditions is high. Indeed, most studies do not mention whether conditions were typical of the prevailing conditions for the location. According to the sediment transport model the amount of sediment moved in winter may be four times higher than summer rates!

Bruun and Purpura's (1964) 300000 m^3/yr sediment transport is huge in comparison with a maximum yearly value (from experiment one) of about 36000-40000 m^3/yr on Holderness, even allowing for movement on the upper beach. The difference may reflect the relatively calm conditions on Holderness at the time of the experiments, and also that sediment traps are notoriously inaccurate (Komar, 1976a). It is not satisfactory, however, merely to multiply summer results by four to cover the entire year. To take account of more energetic conditions in winter a gross rate on Holderness of nearer 90000 m^3/yr (maximum) or 42600 m^3/yr (mean) would be more likely. Gross rates do not take into account movement in opposing directions.

Ingle's (1966) grain displacements of 60 m/hr-360 m/hr are high in comparison with a Holderness mean drift of .25 m/hr (over one day), but were observed during the passage of the first few waves after injection when tracers had not been incorporated into the native beach material and would be particularly vulnerable to wave attack.

Table 4.7 Measured Sediment Transport Rates

Source	location	method	Transport	Waves
Bruun and Purpura (1964)	Florida, Atlantic coast	sand traps	300000 m^3/yr (= 820 m^3/day	$H = 0.6$ m
Ingle (1966)	Californian Pacific coast	sand tracers	56-2000 m^3/day	$H_o = 0.3$-3.0 m
Wilkinson (1980)	Swansea Bay	sand tracers	440 m^3/day 36 m^3/day	$H_o = 1$ m $H_o = 0.2$ m
Present study	Holderness	sand tracers	13-54 m^3/day 3-27 m^3/day	$H_o = 0.4$-0.6 m $H_o = 0$-0.1 m

His values of 56-2000 m^3/day appear high, but the wave height coinciding withthe lower value was the same as that during experiment one on Holderness when the maximum field value (54 m^3/day) was recorded.

Wilkinson's (1980) Swansea Bay transport results of 36 m^3/day under 0.2 m waves compare very well with the results on Holderness. Under similar conditions the Swansea Bay longshore centroid velocity was 0-27 m/tide compared with 3.5-55 m/2 tides in the present study. Blackley, also in Swansea Bay, recorded speeds of 50 m/2 tides. Wilkinson observed a centroid movement across the beach (at right angles to the shore) of 0-34 m/tide. This is in stark contrast to the findings on Holderness where the maximum cross-beach drift was 2-3 m/day, often much less. The concentration plots for the study area were much simpler than those presented in the literature, e.g. Blackley (1980) recorded not only a plume of sediment extending down drift, but also "outliers" of higher concentration seawards, landwards and updrift of the main plume. The present study revealed a simple plume of tracer-bearing sand in the downdrift direction with only a weak reverse drift.

Centroid movement across the beach indicated a very slight shorewards movement in the first experiment, coinciding with waves of around 0.5 m and less; the second experiment showed no such movement. This suggests that upper beach build-up at the expense of the lower beach does not normally occur under calm conditions. The best conditions for this build up would occur with slight to moderate waves like the pulse of energy described by Bowman and Goldsmith (1983). Under high energy conditions large amounts of sediment would be put into suspension and moved offshore. Thus most constructive conditions probably exist with 0.5 m waves; this is supported by the results obtained when beach evolution is compared with wave conditions (4.2 a (iii)).

Results indicate that longshore sand transport dominates on Holderness and that in ignoring transverse movements the sediment model does not grossly distort reality.

If the observed conditions are representative of overall conditions, then it can be concluded that:

1. Sediment movement takes place in both directions along the coast with the southwards drift being the greater and suggests that previous studies may have overestimated this southwards transport.
2. Rates are lower than those on very exposed coasts in Britain and abroad but are similar to those obtained in partly sheltered locations elsewhere in the UK, e.g. Swansea Bay.
3. Rates of movement on the upper beach may be higher than those on the lower beach.
4. The results from the tracer experiments confirm those produced by the sediment transport model;
    a. sediment movement may take place in either direction along-shore but that the net drift is southwards.
    b. the rates obtained with each method were similar for similar offshore conditions.

This internal consistency is most encouraging; however, for any firm conclusion about the sediment budget or erosion/deposition on the beach surface to be made, tracer experiments would have to be conducted repeatedly and at several locations alongshore, so that the volume of material entering a stretch of beach could be compared with that leaving it.

It was apparent from examining the beach profiles during the experiments that, although over 100 m^3 of material was being moved, they changed very little. The beach appeared to be in equilibrium, with the sediment supply from the north in the first experiment, and from the south in the second, being adequate to replace that being removed.

Summary

This section has established the relationships between wave conditions and sediment transport rates and directions for the Holderness coast. It also confirmed the accuracy of the sediment transport model advanced in an earlier section (3.2 a and 4.2 a), and by comparing the Holderness tracer results with those obtained elsewhere, similarities to other partly sheltered coasts were observed.

Summary of Beach Work in Section 4.2

The results of work carried out in the beach sub-system have helped to fulfil the main aims of this research. They have enabled a proability model of beach evolution to be presented, and a comparison to be made between beach transitions and offshore conditions. A discussion of the behaviour of the beach in more general terms, e.g. the presence of "ords", suggested that till exposures on the beach are a normal response to limited sediment supply and to prevailing offshore conditions. The nature, and spatial and temporal variations of beach sediments, and the way in which they were related to offshore conditions were established. Finally, "real" sediment transport rates were measured in the field, which allowed a comparison to be made with offshore conditions and with the potential rates produced by the sediment model used in the offshore work.

This work revealed that in some respects the field site was similar to other coasts, e.g. in terms of sediment movement rates, while in others it exhibited different behaviour, as a result of local influences. Results repeatedly implied that there was a critical beach zone in the northern half of the field site where the distinction between the characteristics of the upper and lower beach broke down, and the beach was depleted. This zone has been associated with sheltering in the lee of Flamborough Head.

4.3 THE CLIFF

4.3 a COASTAL EROSION AND CLIFF RETREAT

Research on the cliff aimed to establish the temporal and spatial variations of retreat rates on Holderness, and to relate these variations to the state of both the beach and the prevailing conditions of the area. The main causes of cliff erosion are also investigated. In order to do this the retreat rates were measured (section 3.3) and later used in a sediment budget for the area. The place of Holderness in a world-wide context will be assessed by comparing the causes and rates of erosion there with those on other coasts, particularly where the cliffs are of a similar composition; any unique features of the field site will be identified.

This section is in two main parts; the first considers erosion rates obtained world-wide from both "hard" and "soft" cliffs, and is followed by a comparison of Holderness erosion rates and those from other coasts. The processes of cliff retreat on Holderness will be considered and the reasons for their variation explained.

4.3 a (i) World-wide Cliff Erosion

In considering rates of coastal erosion world-wide, attention will be confined to irreversible erosion, i.e. cliff retreat, rather than short term erosion of the beach face which has the potential for restoration to its former state. Studies of erosion on sand nesses, spits and barrier islands etc. have been discussed elsewhere (Bruun, 1954; Hubbard et al., 1977; Porter et al., 1979; Allen, 1980; Dolan and Hayden, 1981; Tye, 1983; Wright and Short, 1983).

Coastal erosion has given increasing cause for concern during the past few decades, particularly where its effects are felt directly by man. Indeed, man himself has induced erosion in some places, and has accelerated its progress in others. These pressures on the coast have provided extra stimulus for applied research to assess the best ways of preventing or reducing land loss. Even in Britain, where erosion control projects have received little government support, coastal defence works are much more widespread than they were earlier in the century, with over 60% of the eroding East Anglian coast being protected. Research is consequently progressing on a much wider scale, both geographically (studies are reported from India, Japan, North America, Europe and Russia) and methodologically. No longer is it sufficient to describe patterns of erosion, its causes too are being investigated. Influences as diverse as wave height, water level, beach elevation, man's intervention, cliff composition and mechanical properties are studied, and physical and mathematical models have been produced (Sunamura, 1977, 1981, 1982, 1983a). Despite this research Hails, quoted in Hands (1983), pointed out that

> "... the biggest problem is simply the collection of data for a sufficiently long period to gain a representative picture of the changes taking place".

For relatively "soft" coasts in Britain, fairly reliable records show losses over almost 1000 years but on "hard" rock coasts the time for which reliable records are available is often insufficient for much land loss to have occurred. Indeed the inactivity of these coasts and the fact that retreat does not greatly affect man's activities, has led to the existence of fewer reports. Retreat is often almost imperceptible over a generation, far less during the time of a normal research grant! Consequently the processes involved are poorly understood.

Numerous examples of retreat rates have been obtained on a variety of cliff coasts throughout the world. By far the most common methods of determining mean rates of cliff retreat have been by studying old maps and photographs, and by consulting historical records, including tax and rate assessments. For rapidly eroding areas, newspaper cuttings and local reminiscences may be useful (Fulton, 1981). Occasionally, rates on soft rocks have been deduced from the present state of inscriptions or grafitti (Emery, 1941), or from micro-erosion meters (Trudgill, 1983).

On a short-time scale retreat of rapidly eroding soft cliffs can be measured in the field by time-series survey. This can identify the intermittent catastrophic collapses which go to make up the overall mean rates. Sunamura (1983b) cites an example on Long Island (New York) where 12 m of cliff disappeared during one day, the equivalent of an annual retreat of 4380 m!!, while the average over 80 years is 0.5 m/yr.

Erosion of Soft Cliffs

The major factors which affect erosion, particularly on soft till coasts such as Holderness, were considered in section 1.3. Sunamura (1983b) summarises the influences in two categories - the force of the waves, and the resistance of the cliffs (e.g. mechanical strength and geological structure); it is the relative size of these two variables that determines the rate of erosion. Man's influence has sometimes been marked on soft till coasts, often following the construction of inappropriate shore protection schemes. For instance, if cliffs which supply a significant amount of material to the beach are protected, the beach, starved of its main source of sediment, dwindles, and eventually may disappear, leaving the protective works vulnerable to undermining (Clayton, 1980). It is not only intervention on the beach which may cause problems. Farming practices on cliff tops often have disastrous consequences as a result of altering the water-table and/or drainage patterns. Erosion is often rapid adjacent to drains and this "Canyon Head Erosion" may remove up to 30000 m^3 within a few days (Kuhn and Shepard, 1983). Building on prime cliff-top sites may also alter the level of the water-table, and on clay this, and the weight of the building, may induce liquifaction of the cliff material and mudflow formation. Water from gardens, septic tanks and cess pools all help to raise the water-table (Kuhn and Shepard, 1983).

Numerous reports exist giving retreat rates of soft unconsolidated cliffs throughout the world, and because of the rapidity of their erosion there is a relative abundance of data for glacial till cliffs in particular. Some examples of rates achieved without the intervention of man can be seen in Table 4.8. These are all average rates, although extreme storm events may remove more than ten metres of material overnight. In Britain the southern section of the North Sea coast is largely composed of glacial till, which retreats at mean rates of 0.3-3.5 m/yr (Table 4.8).

A more detailed account of published work on the Holderness coast was presented in section 1.4. Various rates of retreat have been reported from 0.8 m to over 3.0 m/yr for different locations alongshore. Sheppard(1912) based his calculations of coastal losses on a retreat of 1.78 m/yr (Figure 1.4, Table 1.2).

Erosion of "Hard" Cliffs

World-wide there are fewer erosion data for hard cliff coasts but they are nevertheless important. Sunamura (1983b) gives the order of retreat rates for a range of cliff lithologies averaged over

Table 4.8 Rates of Cliff Erosion: "Soft" Coasts

Source	Location	Lithology	Retreat rate m/yr*
Sunamura 1983b	Iceland	Volcanic ejecta	100 m/4 mths
	Japan	" "	120 m/2 mths
	Mexico	lava	18 m/5 mths
	Japan	"	80
	Iceland	"	25-37
	Krakatoa (Sicilly)	"	33
Quigley and Nardo 1980	L. Erie, Canada	till	2
Bryan and Price 1980	L. Ontario, Canada	"	.76
Davidson-Arnott and Amin 1983	L. Ontario, Canada	"	1.0
Sunamura 1983b	German Baltic	till	0.6-0.8
	Massachusetts, U.S.A.	"	0.1-0.3
	Michegan, U.S.A.	"	3.0
	Laptev Sea, U.S.S.R.	"	4.0
		* unless otherwise stated	
Britain			
Robinson 1979	Suffolk	till	1.45
	Hunstanton, Norfolk	"	0.30
	Sof Lowestoft, Norfolk	"	2.95
	Sussex	sand and clay	0.04-0.36
	Kent	" " "	0.29-0.89
Sunamura 1983b	N. Ireland	till	0.21-0.84
HMSO 1907	Holderness	"	1.80-3.66
Sheppard 1912	"	"	1.78
De Boer 1964	"	"	2.75
Phillips 1964	"	"	1.20

periods of one to a hundred years:	granitic rocks	10^{-3} m/yr
	limestone	10^{-2}m/yr
	flysh and shale	10^{-2} m/yr
	chalk, tertiary rocks	10^{-1}-10^{0} m/yr

Although lithology controls erosion, it is wave action that often induces it. More specific rates for various "hard" coasts (here regarded as including limestones, sandstones, shales, conglomerates, etc.) throughout the world are presented in Table 4.9. Overall, British coasts which have been eroded most rapidly are those with clayey cliffs but the chalk coasts of Kent, Sussex, the Isle of Wight and Dorset also suffer significant retreat (Table 4.9).

The data presented illustrate the wide variety of cliff retreat rates observed throughout the world; the rates differ not only among rock types but within a single type. Limestones and sandstones differ in strength depending upon the cementing matrix and the conditions under which they were originally deposited. Till retreat may vary depending upon its moisture content and composition. Even if two rocks are identical, the rate of erosion will vary from place to place according to the general exposure of the location and the energy available at the coast. Relative wave heights, water level, storminess, beach level and intervention by man may help to produce significantly different responses.

Summary

Before concluding this section on world-wide erosion it is useful to put it into perspective; in most countries deposition is taking place at many locations. In fact, total deposition is frequently greater than the total amount of erosion but the location of the two is important. In Britain deposition occurs in sheltered inland estuarine locations, and erosion on the more exposed open coasts

Table 4.9 Rates of Cliff Erosion: "Hard" Coasts

Source	Location	Lithology	Rate m/yr
Sunamura 1983b	U.S.S.R.: Baltic and Barents Sea	granite	0.001-0.002
	California	cretaceous sandstone	0.006-0.012
	"	limestones	0.005-0.051
	Aldabra Atoll	limestones	0.001-0.0013
	Barbados	corals	0.0005-0.002
	New Zealand	mudstones	0.06-0.24
	Sweden	limestones, marls	0.018-0.023
	California	mudstone, shale	0.20-0.40
	"	siltstone, mudstone	0.40-1.00
	Germany	sandstone	1.0
	"	chalk	3.0-4.0
	U.S.S.R. Baltic	sandstone	3.0
	U.S.S.R. Black Sea	limestone and loess	3.0
	" " "	conglomerate	12.0
Britain			
Bird and May 1976	Isle of Wight	chalk	0.36-0.63
	Kent	"	0.42
	Sussex	"	0.07-0.22
	Flamborough Head, Yorks.	"	0.30
Brunsden and Jones 1980	Dorset	limestone	0.34-1.40*
	"	"	0.13-0.53**
Bird and May 1976	"	marl	0.4-0.5
	Yorkshire	shale	0.023-0.036
	Wales	limestone, shale	0.008-0.43

* including major land slips ** smaller scale continuous degredation

(Bird and May, 1976). The Royal Commission on Coastal Erosion (HMSO, 1907, 1911) obtained results for net gains and losses for both the foreshore and for land. In Great Britain between 1879 and 1904, 19426 ha of land were gained and 2687 ha lost, a net accretion of 16738 ha. In Yorkshire 313 ha were lost and 881 gained between 1848 and 1893. The foreshore (i.e. open coasts only) experienced net losses. In Britain the deficit was 19050 ha, comprising a loss of 28372 ha and a gain of 9322 ha. Thus erosion affects larger stretches of open coast where the foreshore is steepening.

4.3 a (ii) Coastal Erosion and Cliff Retreat on Holderness

Figures 3.30 and 3.31 show the progressive retreat of the Holderness coast during the last four centuries and illustrate the reduced erosion along protected stretches of coast, e.g. at Bridlington, Hornsea and Withernsea. The rates from graphs, diagrams and surveys are summarised in Table 4.10 (details in section 3.3 a), which also includes figures published by Valentin (1971) for comparison.

Retreat from maps: These results illustrate the variability of cliff retreat rates both along the shore and during different time periods, and also the greater range of rates obtained when the averaging period is smaller (this is in accord with the findings of virtually all previous cliff retreat work). The rates obtained here are similar to those obtained on glacial till coasts throughout the world (Table 4.8), e.g. S.E. Ireland, the Great Lakes and the eastern United States, though the 6 m value obtained for the period 1850 to 1912 does seem high. Long-term rates are generally within the same range as those further south on the east coast of England, 0-2.75 m/yr. In detail the rate of erosion increases from Bridlington to Spurn Head. Valentin (1971) produced a map of retreat from 1852

Table 4.10 Retreat Rates from Holderness Experiments and Valentin (1971)

Location	Retreat (m/yr) Source: Maps (1850-1912)	Maps (1912-1968)	Aerial Photos 1968-1984	Field Measurements	Valentin (1971)
Bridlington					0.29
Fraisthorpe					
Ulrome		1.75-2.0			
Skipsea	0.5-1.75				
Southfield Ho		1.0-1.25	2.0-4.0	1.0-3.0	1.10
Low/High Skirlington			2.0	0-1.0	
Atwick					
Hornsea	v. slow	2.0-2.5			
	v. slow				1.12
Aldbrough		1.0-1.5			
Withernsea	3.5-6.0				
Holmpton					
Easington	2.2-2.9				1.75
Kilnsea					
Mean	1.34		2.5		

to 1952, which illustrates the same pattern as a similar diagram prepared in the present study (see Figure 3.35). His results for separate sections of the coast are shown in Table 4.10. The lowest rates are found near Flamborough where the coast is sheltered from north-easterly waves. Around Skipsea, the full effects of the waves begin to be felt as the sheltering diminishes and maximum exposure occurs around Kilnsea and Easington, where refraction also helps to concentrate energy.

Retreat from aerial photographs: Again these results are highly variable and are somewhat higher than those obtained from maps and in the literature. This is partly a reflection of the relatively short time over which an average was obtained and also reflects errors in aerial photograph scale and in taking measurements, which were inevitably large at the 1:50000 scale. The high but decreasing retreat values from Southfield House to High Skirlington coincide with an area of lower beach profiles (profiles E to H) where the upper and lower beaches are less distinct, and consequently where wave attack on the cliffs occurs more frequently. Further south rates rarely rise above 3 m/yr and are often around 2 m/yr; here the beach profiles are much fuller, inhibiting wave attack on the cliff for much of the time. The mean retreat rate of 2.5 m/yr is again somewhat higher than Valentin's long term mean and that obtained from maps in the present study: this may indicate a period of particularly stormy weather and / or unusually low beaches. The 1970s also saw a change in land use in part of the area from arable agriculture to recreation (caravan sites), involving the introduction of new drains and other "pressures" near the cliff edge.

Retreat from field measurements: Not suprisingly the greatest variation in cliff retreat rates was obtained from field measurements covering 16-18 months. In the same area, but between monitored locations, losses of up to 10 m occurred, while some other places remained static. The retreat rates in the northern half of the field area were sometimes three or four times greater than those in the south. In the north (profiles E-H) the height of the top of the beach was generally lower than further south. It is possible that in the future profiles A to F may become lower and the position will be reversed; however, unless there is a significant alteration in the prevailing wave climate, it is likely that profiles F-H will be depleted, and the cliff will experience rapid erosion for some time to come. The sheltering effect of Flamborough Head is also associated with the break-down of the characteristic upper and lower beach system.

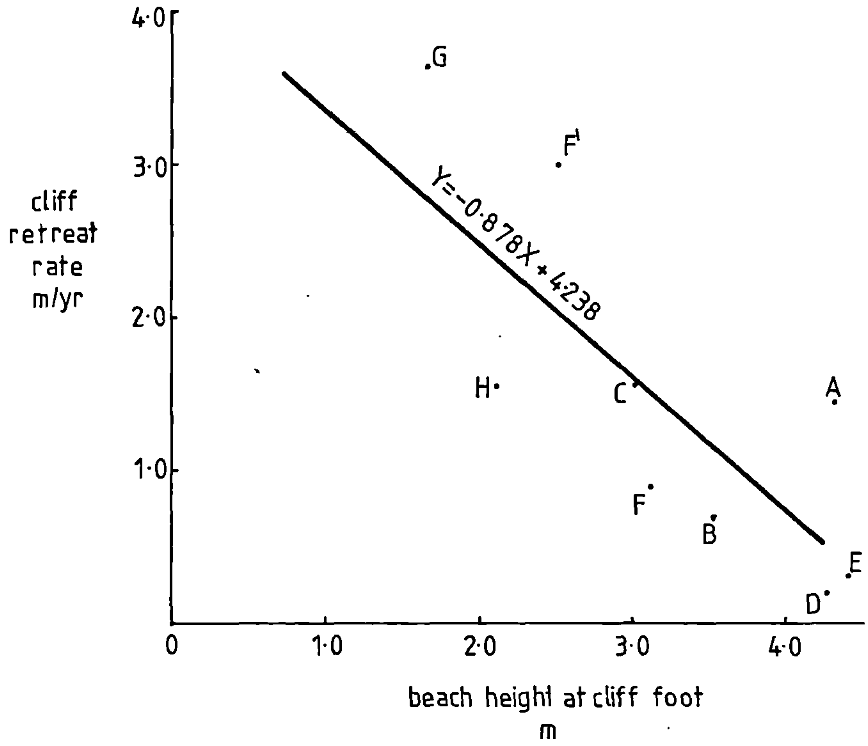
Figure 4.7 shows a plot of mean beach height at the foot of the cliff against the mean annual retreat rate (both measured from June 1983 to September 1984). The graph indicates an inverse relationship between beach height and cliff retreat. The correlation coefficient was calculated ($r = -0.827$) and indicated a significant relationsip between the two variables at the 95% level. The equation describing this relationship is:

$$Y = 0.878\ X + 4.238 \qquad Y = \text{annual retreat}$$

$$X = \text{beach level}$$

The departure of the data from the regression line indicates that beach height at the cliff foot is not the sole determinant of cliff retreat; other things such as cliff composition, cliff moisture, rainfall and the frequency of long dry periods will come into play. On a smaller time scale, e.g. three to four months, the correlation

Figure 4.7 Cliff Foot Beach Height against Cliff Retreat Rate (from field measurements).
correlation coefficient = -0.837 (significant at 95% level).



•A beach profile

was poorer owing to the influences of these variables.

The methods used to obtain retreat rates in the present research are the same as those used in other studies and are, therefore, directly comparable. In previous studies maps and aerial photographs of a variety of ages have been used in conjunction with regular field measurements. However, field measurements over relatively long periods are comparatively rare.

Temporal Variations in Cliff Retreat

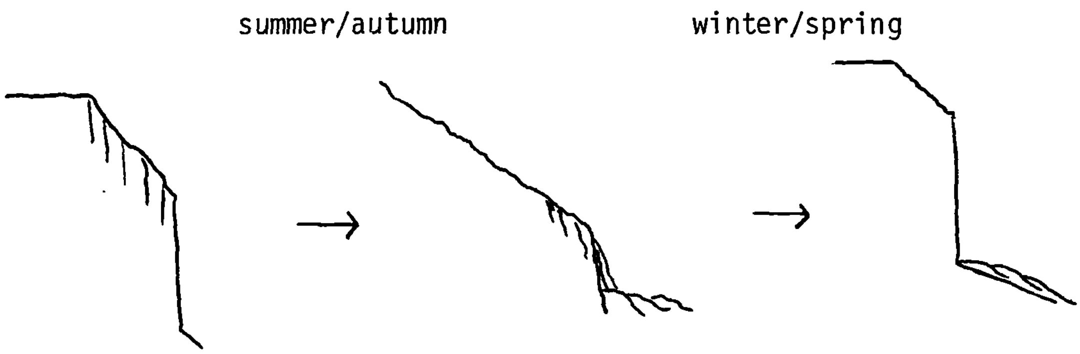
Erosion takes place on the Holderness coast because waves are able to reach the cliff and remove material, and because weakening of the cliff enables portions of it to break off. Between Skipsea and Atwick a number of factors determine the extent to which this takes place, i.e. they cause temporal variations in cliff retreat. Most of those revealed in the present field study were seasonal, a result of the time scale of the project. As maps revealed there is considerable long term temporal variation. The important factors are described below:

1. Beach level appeared to be an important influence on this coast with lower beaches fronting areas of rapidly retreating cliffs (Figure 4.7). It can explain increased erosion in winter when the beach is lower, and will cause a long-term variation if a beach becomes fuller over a number of years.
2. Wave conditions influence temporal variations in that a period of storm waves may remove considerable portions of the cliff.
3. The sedimentary composition of the till cliffs is an important factor in rapid retreat rates. Temporal variation may occur if there is a change in composition, e.g. if the cliff-edge coincides with a more resistant lithology the retreat rate may be reduced for a time. The same is observed if coastal defences are constructed.

4. The effect of moisture on the cliff is very important, particularly the pattern of periods of wet and dry weather. The consequences of a prolonged dry spell followed by heavy rain can be quite dramatic, resulting in large losses of cliff material.

The effects of desiccation on the cliff were observed during the dry summer of 1984 when the till dried out and cracks formed which gradually become enlarged. Heavy rain entered the cracks and washed supporting material away before small-scale individual failures could occur. As a result portions of cliff up to 8 m wide were removed within a very short period of time.

Despite collapses in summer, the cliff as a whole was more active during winter for the reasons mentioned in 1-3 above. A sequence for cliff collapse may be put forward. Till falls at the cliff top in summer and autumn produce a less steep cliff face, which in winter is steepened by attack from the foot, producing high



till buttresses (Plate 1.4) with a very steep or vertical face at the top of the beach and a less steep upper cliff. It is important to remember that for erosion to proceed cliff collapse must be accompanied by removal of the debris from the cliff foot. On this coast, owing to the nature of the cliff material and the beach height, such material is removed rapidly from the upper beach surface, at least within a fortnight when spring tides can reach the cliff.

Spatial Variations in Cliff Retreat

There are a number of small scale spatial variations in erosion on Holderness, such as those caused by field drain outlets, and, though there is a general increase in erosion towards Spurn Head, one major spatial variation is exhibited on the field site. It is the increase in erosion between profiles E and H. Many other beach variables change at the same position where the beach becomes depleted, and there is a morphological and sedimentological break-down in the characteristic upper beach/lower beach pattern. Some of the same influences affect spatial variation as affect temporal variation.

1. Beach level: the most rapidly eroding cliff sections are from profile E to profile H where the beach is depleted.
2. Wave conditions are important in determining the spatial distribution of depleted beach sections and hence cliff erosion (see below).
3. The sedimentary composition of the cliffs, while enabling erosion to take place, is spatially uniform on the field site and does not contribute to the overall spatial variation of erosion. The effects of meteorological and atmospheric conditions should also be uniform within the field site.
4. Man's intervention has led to reduced erosion rates at Bridlington, Hornsea, Withernsea and Aldbrough following the construction of coastal protection works but this has exacerbated flank erosion.

The major spatial variation in erosion within the field site is also reflected by other beach characteristics. In the north, erosion increases behind a depleted beach, a result of a variation in the wave climate. This is caused by the sheltering of, and refraction around, Flamborough Head, and by refraction and shoaling over the sand banks of Bridlington Bay which results in the proportion of north-easterly waves on this stretch of coast being reduced, i.e. the waves which have the longest fetch and potentially possess the highest energy. The area of depleted beach occurs where the effect of Flamborough Head diminishes and the coast becomes exposed to the higher north-easterly waves which remove material rapidly to the south. Owing to the net southwards drift on the coast (reflecting the overall lower energy from south-easterly waves) the return drift from the south will not be sufficient to compensate for this loss. At the same time little material is arriving from the sheltered beach to the north, and this results in high net losses from this northern section of the field site. Consequently it becomes depleted, sometimes to such an extent that the sand and shingle veneer is stripped off completely. From approximately profile E southwards, where the beach is receiving a supply of sand from the north, the profiles are fuller and the upper and lower beaches are once again quite distinct. The present pattern of cliff erosion at one location being over three times that at adjacent sites cannot of course continue indefinitely, some response will take place to reduce it. However, the causes of this spatial variation, e.g. the sheltering of Flamborough Head are more permanent than many, and any beach changes will be slower. While Flamborough Head does exert a strong influence on the coast here to cause a beach depletion, there is no evidence of similar permanent influences further south.

Pringle (1985) associated ord formation with sheltering by Flamborough Head, and then attributed their migration southward to the net drift on this coast. However, at this point on the coast if migration does occur it is just as likely to be northwards. The beach is variable and has a constant sediment supply at an ord so that it is unlikely that discrete beach forms will persist for any length of time. This suggests that there is no systematic migration of ord forms and associated increases in erosion alongshore but that it is merely a reflection of local conditions. A more detailed study of beach profiles and erosion all along the Holderness coast might help to clarify this variation.

Thus, sheltering in the lee of Flamborough Head and shoaling of waves over the banks of Bridlington Bay have a considerable impact on the field site which results in the formation of a critical beach transition zone between a fully sheltered area in the north, and a fully exposed and readjusted area to the south. This transition zone exhibits:

1. A depleted beach where till is frequently exposed on the upper beach.
2. An increase in wave attack on cliffs and therefore an increase in the rate of cliff retreat. This supply of material is not yet sufficient to build up a full beach so increased erosion and the depleted beach persist.
3. A breakdown in the upper beach/lower beach morphology: the slope is more uniform.
4. A reduced distinction between the sediment characteristics of the upper and lower beaches.
5. A form which may be similar to the ords described further south, but the migration of such forms is questioned, and is discussed in section 4.2 a (iv).

Summary

Cliff retreat investigations have established the following:

1. Rates of long-term (over 400 yrs) cliff retreat on the Holderness coast, and more detailed short-term retreat rates for small stretches of the coast.
2. That cliff retreat on Holderness is variable, both spatially and temporally.

3. That these variations reflect differing wave climates and beach and cliff conditions.
4. That variability of mean retreat rates increases with a decrease in the length of the sampling period.
5. That mean rates of retreat are similar to rates for similar coasts elsewhere.
6. That an important influence on temporal variations in cliff retreat is the moisture content of the cliff.
7. That the most important influences on erosion are beach level and wave energy, both of which vary spatially and temporally, and depend upon the degree of shelter from Flamborough Head.

Having established and discussed both the rates of cliff retreat and hence sediment supply to the beach, and the alongshore sediment transport rates on the field site, this interpretation will consider the sediment budget which was calculated from such data.

4.4 SEDIMENT BUDGET

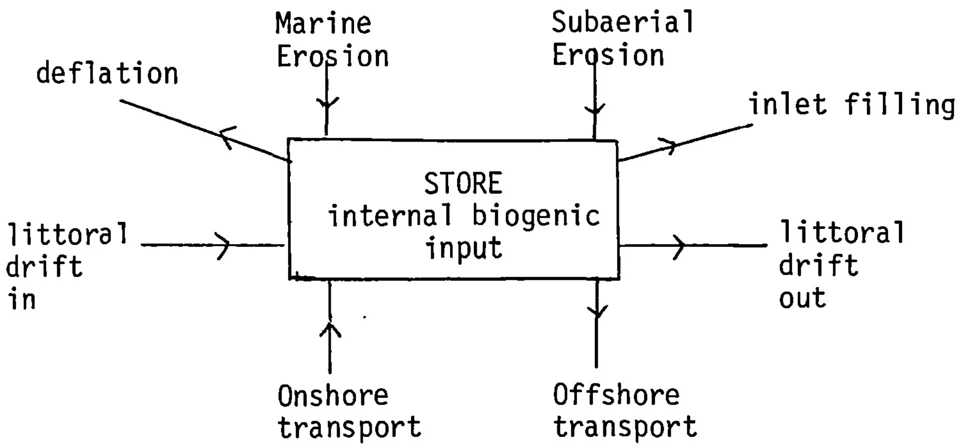
Data from all the coastal sub-systems can be incorporated into a sediment budget for this stretch of the Holderness coast (section 3.4); here it will be interpreted. Firstly a brief comment will be made about previous applications of the concept of sediment budget, followed by a summary of the Holderness budget and its implications for beach behaviour. The long-term implications of a sediment budget will also be considered before the conclusions for Holderness are presented.

4.4 (i) Previous Applications of Sediment Budgets

Numerous beach studies have used the concept of sediment budget to describe beach behaviour, and to predict certain unknown elements of it (e.g. Komar, 1976a; Kureth, 1978; Shuisky and Schwartz, 1983).

The complexity of the sediment budget depends upon the complexity of the coast in terms of the numbers of its sources and sinks. However, as Komar (1983a) pointed out, it is sometimes impossible to attach quantities to many of the gains and losses, and so the more elements that are involved, the less reliable the budget figures become. In many cases the best known element is the net change itself, obtained by monitoring erosion of, and depositon on, the beach over a number of years. It is simpler to calculate a budget for a closed system such as a bay, where there is no longshore supply or loss of material at the boundaries.

Davies (1974) presented a model which summarised some of the "inputs" and "outputs" of a littoral system, and which he regarded as being the key to quantification of coastal geomorphology.



Sunamura and Horikawa (1977) produced a sediment budget for an area in Japan which had no fewer than seven major sources - two receding cliffs, three eroding beaches and two rivers. Jarrett (1977) used sediment budget analysis to correlate the volume changes in the beach with energy flux distribution, while Allen (1980) applied the technique on the New Jersey coast to identify the causes of erosion on a spit. Budgets have commonly been used to assess man's impact on the shore (Komar, 1983b) and to assess the rate of shoreline change.

Figure 4.8 Annual Sediment Exchanges

Cell	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	average error on N. Holderness (m^3)
alongshore supply (m^3)	x 6440	28605	0	35830 28250	3155 21400	y	±15000
alongshore removal (m^3)	-28605	-6440	-28250	-3155	-35830	-21400	
cliff supply (m^3)	9640	10883.8	24987.6	11374.8	17931.4	16273.1	±3937
net change ΔV	x-12525	+33048.8	-3262.4	+72299.8	+6656.4	y-5126.9	±18937
equivalent beach level change (m)							
beach 150 m	$\frac{x-12525}{281250}$	+0.118	-0.012	+0.257	+0.024	$\frac{y-5126.9}{281250}$	±0.067
width 200 m	$\frac{x-12525}{375000}$	+0.088	-0.008	+0.193	+0.018	$\frac{y-51269}{375000}$	

Few studies have considered the general effectiveness of sediment budgets, and have tended to consider the implications for particular field sites. As sedimdnt budgets are empirical it is difficult to interpret the results of the present study in the light of what others have found.

4.4 (ii) The Holderness Sediment Budget

Calculation of the sediment exchanges and budget on Holderness appears to be relatively simple, involving fewer sources and sinks than on many coasts. There are no rivers or significant biogenic sources and no man-made structures which seriously interupt sediment transport.

Implications for the field site beach: Figure 4.8, repeated from Chapter 3, summarises the gains and losses in each cell on Holderness, apart from transfers in an onshore/offshore direction. The final column estimates the maximum possible errors which may be present (Section 5.3 e); in fact it is likely that the errors were very much smaller. The validity of the assumption that onshore/offshore movements are insignificant can be tested against field observations, i.e. is the pattern observed in the field the same as that modelled under the assumption of minimal onshore/ offshore transfers? The maximum build-up occurs in cell (v) (see Figure 4.9) which coincides with the southern half of the field site. Although the value is well within the limits of beach level fluctuations over periods as short as a month it may not be sustained year after year. The only area of predicted beach depletion is cell (iv) which corresponds to the northern half of the field site. For cells (iv) and (v), the "predicted" change in beach elevation under these conditions was similar to that observed in the field. These results suggest that if the potential sediment transport is an adequate estimate of real rates, then indeed the transfer of sediment transverse to the shore is very small. Much also depends on the cliff retreat rates used; if the values for this stretch of coast given by Valentin (1971) were used (1.1 m/yr) the supply of material would not keep pace with beach removal in many places, and much more bare shore platform would be exposed.

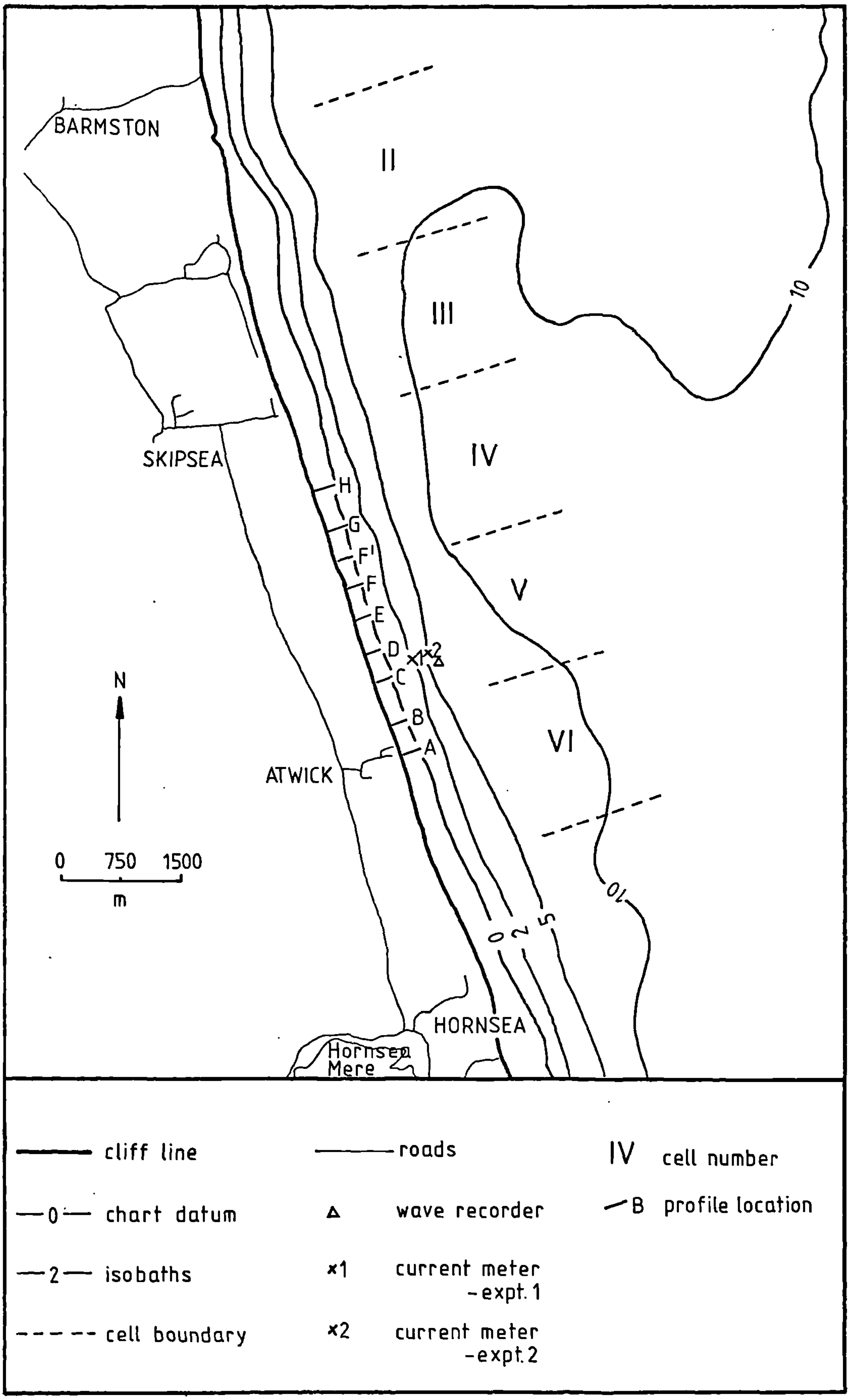
For beach cells (iv) and (v) (Figure 4.9), the difference in elevation between beach profiles (Figure 4.10) allows offshore sediment movement to be calculated and a full sediment budget to be presented for these cells (discussed in Chapter 3). It is important to remember that although the profiles were plotted at a one year interval, it is unlikely that the conditions at each time were exactly the same and a full year "beach cycle" had been executed in between. This is why for calculating the budget, an average August/September volume was taken for each year to avoid extreme effects. The highly variable nature of the coast is reflected by the sediment transport rates and hence the sediment budget. Figure 2.8 shows envelopes delimiting the range of beach elevations, representing a greater volume of sediment movement than shown in Figure 4.10, though still not necessarily the total transport; some material is deposited and re-transported within the extreme profiles. The temporal variation in beach volume was discussed in greater detail in Section 4.2 a (iv). The budget shown in Table 4.11 incorporates data from Tables 3.32, 3.33 a and 3.33 b.

Table 4.11 Sediment Budget

Cell	(ii)	(iii)	(iv)	(v)	(vi)	(vii)
alongshore supply (m^3)	x 6440	28605	0	35830 28250	3155 21400	y
alongshore removal (m^3)	-28605	-6440	-28250	-3155	-35830	-21400
cliff supply (m^3)	9640	10884	24988	11375	17931	16273
onshore/offshore transfer (m^3)	A	B	-91613	-16312	C	D
Δ volume	x-12525 ±A	33049 ±B	-94875	+55987	6656 ±C	y-5127 ±D
Δ beach elevation (150 m wide beach)	* $\frac{x-12525}{281250}$	* +0.118	-0.337	+0.199	* +0.024	* $\frac{y-5127}{281250}$

* modelled assuming negligible offshore sediment movement

Figure 4.9 Holderness Coast showing Beach Cells.



BARMSTON
SKIPSEA
ATWICK
HORNSEA
Hornsea Mere
II
III
IV
V
VI
10
0
2
5
H
G
F'
F
E
D
C
B
A
×1
×2
N
0 750 1500
m
cliff line
0 chart datum
2 isobaths
cell boundary
roads
wave recorder
×1 current meter -expt. 1
×2 current meter -expt. 2
IV cell number
B profile location

The sediment exchanges in cells (ii), (iii), (vi) and (vii) were dealt with in Chapter 3 and in the preceding section. The rest of this discussion will be confined to the complete budget for cells (iv) and (v), for which the onshore/offshore sediment transfer is known.

A net offshore sediment movement was observed, equivalent to an average removal of 22.4 m^3 per tide in cell (v) and 125.8 m^3 per tide in cell (iv); this is still a very small layer of material over a 150 m wide beach and 1875 m long cell (0.08 mm in the south and 0.45 mm in the north), bearing in mind that field observations may reveal changes of tens of centimetres over one tide. The fact that a net offshore movement is revealed does not imply that onshore movement never occurs, just that it is the minor component. Storm waves can move vast quantities of material, a metre or more thick, and beach recovery inevitably involves a compensating onshore movement. However, the size of the offshore transfer is sensitive to errors in modelling, and surveying.

The onshore/offshore movements considered here are not the transfers between the upper and lower beach, discussed in the sections on beach evolution, but those between the inter-tidal beach and the nearshore/offshore zone. Although the sea bed immediately offshore is virtually free of sediment, material may be dispersed to sandbanks well offshore, or may be intercepted in suspension and transported towards Spurn Head.

The sudden exposure of the coast outside the influence of Flamborough Head helps to explain the high offshore removal in the north of the field site (it is over 5 times greater than in the south). In the short term the offshore sediment movement will be encouraged because of the low level of the beach at this location. It is likely that much of the material lost as a result of rapid cliff retreat is lost directly offshore by wave action - the residence time on the beach will be very short.

The changes in beach volume and elevation which represent the net result of the budget are a function of the relative sizes of the sediment sources and sinks on the coast. The considerable depletion in cell (iv) - over 30 cm in a year, is largely a result of the high offshore transfer; it also reflects the lack of supply to the cell and the large loss to cell (v). The only supply to this cell is from the cliff which, not surprisingly, fails to compensate for the removal along- and offshore.

The smaller removal offshore from cell (v), together with the large supply of sediment from the cells on either side, more than compensates for the reduced cliff supply and the relatively small southwards removal of sediment. The result is an average beach build up of almost 20 cm (assuming the beach is 150 m wide).

Comparing the changes in the beach elevation in cells (iv) and (v) with those modelled for other cells (for which offshore sediment movement was ignored), it is apparent that this ommission does make a significant difference. The estimated increases in beach elevation elsewhere has probably been over-estimated; this highlights the need for a wave refraction/sediment transport program which is capable of modelling onshore and offshore transfers.

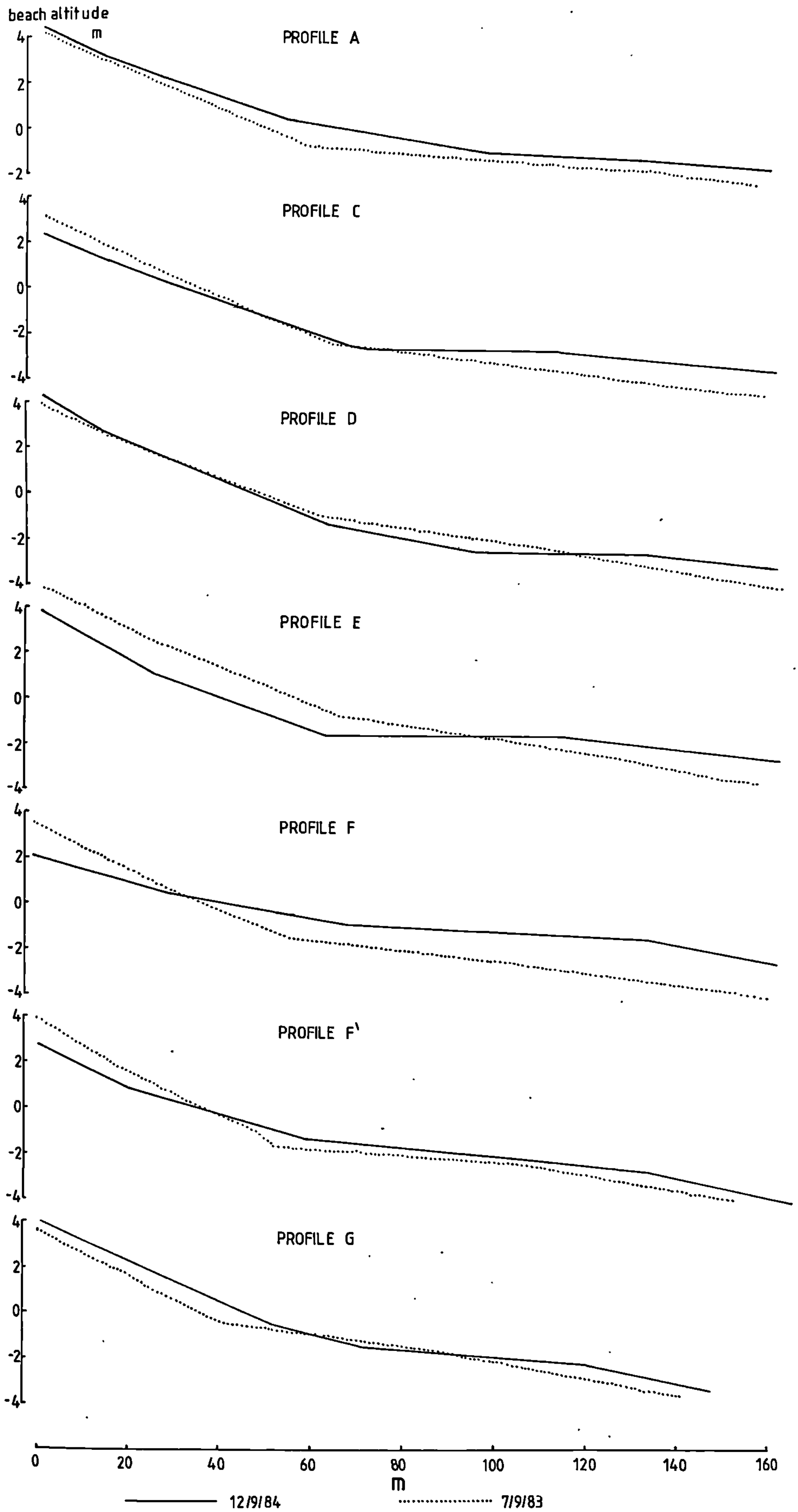
The sediment budget summarises the way in which sediment transport patterns influence beach behaviour; this is what most engineering schemes aim to predict. In this example the difference in longshore sediment transport seems to have been particularly influential on beach behaviour in general. However in some beach cells offshore movement curtails the critical balance between cliff and longshore supply in determining beach behaviour. Where onshore/offshore movement is unknown, many valuable predictions and observations may still be made from longshore sediment movement. The most satisfactory way of establishing onshore/offshore movement would be to extend the profile surveys alongshore to cover all beach cells and any future project would have to consider this seriously. It appears that such is the variability from cell to cell of on/off transport, that it cannot be overlooked. Certainly the negligible on/off transport suggested by the tracer experiments are misleading and point to either the bulk of offshore movement occurring in a short (storm) time undetected by tracer studies here or that beach-only tracer studies do not reflect interchange between the beach and nearshore.

Sediment budget and field observations: The pattern of sediment build up and erosion observed in cells (v) and (iv) is confirmed by general field observations of beach heights and profile shapes. Depleted cell (iv) coincides with an area where the beach top is lower, the profile gentler and more dissipative, and has a poor distinction between the upper and lower beach. Here the till platform is frequently exposed (cf. Pringle's ords). In the field, accreted cell (v) exhibits higher beach tops, profiles having a distinct upper beach/lower beach junction and a more reflective upper beach (Table 4.12)

Table 4.12 Beach top elevation - profiles A-H

	cell (v)				cell (iv)				
Profile	A	B	C	D	E	F	F'	G	H
Mean beach elevation (m) at cliff foot	4.3	3.5	3.0	4.25	3.9	3.1	2.85	1.65	2.12

Figure 4.10 Change in Beach Elevation between September 1983 and September 1984.


beach altitude
m
PROFILE A
PROFILE C
PROFILE D
PROFILE E
PROFILE F
PROFILE F'
PROFILE G
4
2
0
-2
-4
0
20
40
60
80
100
120
140
160
m
12/9/84
7/9/83

If a greater length of coast had been surveyed, it would have been possible to estimate the onshore/offshore movement of sediment in all cells. More accurate yearly surveys would enable a much more reliable estimate of transverse sediment movement than has been possible here. The errors inherent in these calculations will be dealt with in Chapter 5.

Assuming that the conditions prevailing during the year September 1983 to September 1984 were representative of the general conditions on this coast, as it seems they were, then the offshore movements are likely to be similar from year to year. A number of long-term implications arise from the sediment budget and follow on from those of a short term nature described above.

Offshore sediment transfers, greater in the north of the field site, are again confirmed by field observations of the beach height at the foot of the cliff; where the removal offshore is greater the beach top is lower.

This section has demonstrated the production of a full sediment budget from sediment exchanges. There is scope for development of such work in the future.

Long-term implications of the sediment budget: The changes in beach level described in the sediment budget, and observed in the field, could not be sustained indefinitely, over centuries or even decades; changes in beach height will eventually act to reduce sediment build-up by protecting the cliff from attack and starving itself of a primary sediment source, i.e.

over a long time the beach seeks to remain in equilibrium. The system may reduce the depletion of a section of beach by increasing the supply of material from the cliffs. If this exceeded the volume of sediment which could be moved into the next beach cell, the depletion would be halted. On the other hand, an accreting section of beach may become so high that supply from the back of the beach may be cut off; some beach material will continue to be removed and gradually the beach elevation will be reduced. If potential sediment removal exceeds the amount of material on the beach the excess energy will be "wasted" and the sediment budget will not achieve its potential, i.e. the predicted supply to an adjacent area will not be realised.

The protection afforded to the coast by Flamborough Head assumed to be primarily responsible for the depletion of cell (iv), will remain. Unless there is an increase in the frequency of higher energy waves from the south-east, then it is unlikely that there will be any significant increase in supply of sediment to this cell. A more likely alteration in prevailing conditions is a temporary slight change in weather conditions, which might lead to an increase or decrease in cliff retreat rate.

An alternative method of reducing depletion and hence cliff retreat would be if the increased erosion eventually built up a sufficiently large beach into the nearshore so that the north-easterly waves which begin to affect the coast, shoal and lose a considerable amount of energy before they reach the upper beach and cliff. The upper beach may then accumulate and erosion will decrease. On Holderness this may take some considerable time but there must be some response if the overall plan of the coast is to remain the same, i.e. in dynamic equilibrium.

This discussion of the long-term implications of sediment budgets suggests that it is unsatisfactory to present a sediment budget over too long a time period for one coast; the coastal system is so variable that the elements in the sediment budget should be reviewed every few years, and the beach behaviour checked.

The main limitations of the sediment budget were a result of the scale of the research project, both in terms of the length of coast covered and the length of time during which measurements were made. To obtain a comprehensive sediment budget for Holderness, the study would have had to cover the coast from Bridlington to Spurn Head. This was impractical with the limits of this study and the time available. Inevitably errors may be made in estimating various sediment supply and removal rates which range from the inaccurate determination of, and use of unrepresentative, cliff retreat rates, to the use of a sediment transport model which incorporates many simplifying assumptions. It is worth re-iterating that this is only a potential budget which may take little account of the transport of coarser grades of material. In the future, it may be possible to establish the concentration of finer grades of sediment suspended offshore, against which the sediment budget could be tested.

4.4 (iii) Suspended Sediment off Holderness

More than half of the till material lost by the cliff is transported offshore and if accurate estimates of suspended sediment concentration could be established, the supply of material from the cliff remaining on the beach could be calculated. It might also give an indication of the fate of sands which have been suspended temporarily and removed offshore, since in the sediment budget they are assumed to be moved only alongshore. This will help to explain why in some places the beach may be more depleted than the sediment budget would suggest.

Considerable concentrations of suspended sediment may be seen off the Holderness coast (Plates 4.1 and 3.5). The material is predominantly silt and clay from the till cliffs and platform, which is removed when the material reaches the beach, and represents 66% of the cliff composition. Along the entire eroding coast the supply of fines is approximately 906 000 m^3/yr. Sediment plumes are seen offshore even under the calmest wave conditions, and indeed it is often during the calmest conditions that the most intricate patterns can be observed, e.g. semicircular plumes with alongshore periodicities of 300-500 m (Plate 3.5). Field data analysis and processing of multi-spectral scanner images has allowed a classification of concentration to be derived which is then used to plot concentrations offshore (Plate 4.2) (Curran et al., 1986).

The precise causes of this rhythmic pattern of suspended sediment are not known, though a number of suggestions can be made:

1. Following fresh water seepage through the beach until the water-table intersects the beach or until the till platform is exposed, suspended material is removed easily, preserving any alongshore patterns inherited from seepage routes.
2. Variations alongshore may arise from changes in the composition of the cliff or till platform. The wavelength of variation is too small to be associated with ords (Pringle, 1985).

In slight turbulence subtle patterns tend to break down, and under still rougher conditions coarser material from the beach face and nearshore would also be thrown into suspension. Further work will reveal whether the pattern is observed alongshore towards Bridlington and Spurn Head.

Plate 4.1 Suspended Sediment Plume.

Plate 4.2 Density-Sliced Classification of Suspended Sediment Concentrations Offshore from the Field Site.

Once detailed local work has established a classification of suspended sediment concentrations, it can be used further afield and over wider areas. In the future this will be important for two reasons.

1. It provides information on concentrations and dispersion patterns of nearshore sediments, and
2. It provides an independent check on the accuracy of sediment budget calculations based on the behaviour of different material to that incorporated into the beach.

Previous studies have found most results of sediment budget analysis to be rather unreliable and notoriously difficult to produce satisfactorily (e.g. Carr, 1981).

Despite the limitations mentioned earlier, the sediment budget proposed in the present study seems reasonably satisfactory.

Summary

The present study was particularly useful in assessing the practicality of sediment budgets. In thoery, of course, the balance should account for all gains and losses. In this study all the elements of the budget were obtained for one stretch of coast and the results of the budget calculations reflected general field observations.

The budget correctly predicted the generally depleted beach in cell (iv) and the fuller beach in cell (v), and was reasonably successful in that the onshore/offshore transfer was confirmed by morphological evidence. In this respect it seems to have been more successful than many of the sediment budgets presented in the literature. As before, the spatial pattern underlying the sediment budget was attributed to the sheltering effects of Flamborough Head.

Sediment budgets have thus proved to be a valuable way of assessing beach evolution and change, provided that the weaknesses of the constituents are not forgotten. They are especially useful in ensuring that all possible sources and sinks have been taken into account. If cliff retreat rates alter in the future, the nearshore bathymetry changes, or there is a significant change in wave climate, affecting sediment transport, then the budget balance can be re-calculated for the new set of prevailing conditions. The response of the beach can be predicted, and, if necessary, suitable action taken. Alternatively, for changed conditions the new cliff erosion rate may be calculated if the beach budget is known.

Summary of Chapter 4

The interpretation presented in this chapter has enabled the aims of the research to be fulfilled. It was found that potential modelled sediment transport rates were adequate for inclusion in a sediment budget, and that the modelling methods used on Holderness could be used elsewhere if sufficient high quality data could be obtained. Flamborough Head was identified as having considerable effects on sediment movement but the results were similar to those on other partly sheltered coasts. It was concluded that the tidal current velocities off Holderness would have a negligible effect on beach sediment transport, and therefore that it is reasonable to omit these effects from the model.

Previous beach evolution models were mainly deterministic, and a number of possible improvements were identified which the new Holderness model was able to incorporate, notably the lack of dependence on wave conditions, the rigorous classification of beach types, the concentration on transitions among beach types, and the inclusion of a temporal framework for these transitions. Tests confirmed that the beach exhibited Markov properties, and the probability matrices were capable of describing and predicting beach evolution throughout the year. A comparison of beach transitions and coincident wave conditions allowed the hypotheses put forward in Chapter 3 regarding their relationships to be upheld, and thus a link between the present probabilistic model and previous deterministic models to be made. Low energy waves were found to produce static beaches, waves around 0.5 m resulted in a build-up of the upper beach, and higher energy waves (over 1 m) caused depletion of the upper beach. General morphological observations identified transient till exposures on the beach, which seemed to be a natural response to a limited sediment supply and higher energy offshore conditions; this led to the conclusion that the importance of "ords" on the Holderness coast has been overestimated. A general decrease in the distinction between the upper and lower beach morphology was observed towards the north of the field area, a trend also exhibited by variations in sediment characteristics. The relationships between sediment characteristics and offshore conditions were not clear,though there may be an exponential relationship between mean particle size and wave height. The internal consistency of modelled and measured sediment transport rates in this study was confirmed by the tracer experiments, results which again were similar to those obtained from tracer studies on other partly sheltered coasts.

The rates and variation of cliff retreat were determined, the values proving to be similar to those for till cliff coasts elsewhere. The important influences on erosion were found to be beach elevation, wave energy, water level and the moisture content of the till.

The sediment budget was confirmed by field observations; areas of predicted deficit coincided with depleted beaches, while areas of sediment surplus exhibited fuller beaches. Again this internal consistency is encouraging, and suggests that the sediment transport model was realistic. The main limitation of the budget was its scale, but the unquantifiable removal of suspended sediment, and onshore/offshore transport was discussed: the importance of regular recalculation of budgets was stressed, thus acknowledging the long-term changes that inevitably take place.

Repeated comparisons with other work enabled the present study to be placed in context, and the implications for the Holderness coast of various findings were discussed. A number of improvements to both the research design and experimental method were made.

The final chapter will present the detailed conclusions of the Holderness research, summarise its limitations and suggest a number of improvements. Finally the scope of the research will be assessed.

CHAPTER 5 CONCLUSIONS

The main objective of this study as put forward in Chapter 1 was to explain the processes governing beach variability and its interaction with till cliff erosion. In order to fulfil this aim four more specific aims were set out, i.e.:

1. To establish the relationships between beach morphology and sediment transport processes.
2. To establish the relationships between these processes and inter-tidal and nearshore marine conditions.
3. To establish the relationships of beach morphology and wave conditions to the erosion of till cliff sediments, and
4. To produce a probabilistic model for beach evolution.

The work also enabled the identification of similarities and differences between the Holderness study area and coasts elsewhere.

By definition the fulfilment of these aims involved work in all three coastal sub-systems, i.e. the offshore zone, the beach and the cliff, in order to determine the amount of sediment from different sources passing through the Holderness beach, and its interaction with beach morphology and cliff erosion.

The conclusions are summarised below; firstly the most important ones are drawn from each specific section of work, to allow decisions to be made about whether the aims of the research have been fulfilled and whether the hypotheses advanced in Chapter 1 should be upheld. A second set of broader conclusions will be presented with reference to these aims and hypotheses.

This research also revealed a number of important points regarding the limitations of, and improvements which could be made to, a number of standard techniques. These will be presented before the wider implications of this study are considered and suggestions for further work are made. Finally the general contribution of the present study to coastal geomorphology is assessed.

5.1 SPECIFIC CONCLUSIONS

The specific conclusions drawn from various experiments will be presented in four sections, dealing with work offshore, on the beach, on the cliff and in producing a sediment budget; they will be presented in point form.

5.1 a THE OFFSHORE ZONE

1. Data gathered at Dowsing Light Vessel and from a wave-recorder 1 km offshore form the field site enabled seasonal sediment transport rates to be modelled and a net annual value to be calculated. Modelling with wave-recorder data was more satisfactory, producing resultant seasonal sediment transport rates ranging from 0.005 x $10^3 m^3$ to 19 x $10^3 m^3$, with a net southwards sediment movement in all seasons except winter. The annual rates in various beach cells varied from 28.6 x $10^3 m^3$ towards the south to 35.8 x $10^3 m^3$ towards the north, the net mean being 2.8 x $10^3 m^3$ southwards. Rates were similar to those on partly sheltered coasts elsewhere.
2. Offshore conditions affected the rates and direction of movement Waves from the east and south-east produce a northwards drift, and those from the north-east and east-north-east, a drift towards the south. Sediment transport rates were highest under high winter waves.
3. The relatively high component of northwards drift was explained by the sheltering effect of Flamborough Head which protects this stretch of coast from the highest north-easterly waves.
4. A small net residual southwards tidal current was measured 1 km off the Holderness field site; maximum currents of approximately 0.45 ms^{-1} were recorded, with a mean in either direction of 0.15-0.21 ms^{-1}. It is unlikely that substantial net transfer of sediment is produced by such currents.

5.1 b THE BEACH

A large part of this research concentrated on the extremely variable morphological behaviour of the beach.

1. The beach comprises a mobile sand veneer on a till platform; at times the upper beach is removed altogether leaving the till exposed. The presence or absence of these till exposures at a particular location on the beach depended upon wave conditions and the state of the beach. During the summer ($H_0 \leq 0.5$ m) till exposures were limited in size and number; higher energy waves ($H_0 > 0.7$ m), more common during winter, enabled the thin sand layer to be stripped from the till in many places.
2. On the field site beach the till patches do not exhibit any characteristic morphology (unlike "ords" (Phillips, 1962, 1963, 1964; Pringle, 1981, 1984, 1985)) and seem to represent the normal response of a beach to limited sediment supply and the prevailing offshore conditions.
3. In the north of the field site the distinct upper and lower beach pattern broke down; the upper beach became gentler and the lower beach steeper.
4. The existence of a depleted area in the north of the field site was linked to reduced longshore sediment supply from the north.

These general observations formed only part of the work on beach profiles; much comprised a more quantitative approach to beach evolution in which the profiles were classified and evolutionary cycles between these classes were examined.

5. A probability transition matrix model possessing first order Markov properties was produced which was capable of describing

and predicting beach transitions among seven profile classes during a number of time periods and all along the beach section.

6. To increase the accuracy of prediction two models, both independent of wave conditions, were produced, one for use in summer and the other, with nine profile classes, for winter when the transitions were more variable. Though these models had been produced without recourse to wave records later work revealed that during periods of low waves the beach profiles tended to change their "types" less frequently. As wave heights increased transitions became more variable.
7. The winter model included more transitions which involved a net movement of material from the upper to the lower beach (e.g. M-N, Q-P); during summer, transitions which involved no net transfer or an off-shore transfer of material were more common (e.g. N-N, M-O). Again, a comparison with detailed field site wave records revealed that with low energy fewer transitions involving beach depletion occurred, while with waves over 1.0 m high beach depletion was more common.

A number of conclusions were derived from monitoring beach sediments.

8. Upper beach sediments were considerably coarser and less well sorted than those on the lower beach.
9. When the wave and sediment records were compared, a predominance of the largest sediments coincided with periods of higher waves, especially in the south of the field site.
10. The nature of the beach crest seems to depend upon wave conditions (especially in the south of the field site); in summer it is built up with fine material whereas in winter it is much coarser and lower. In the north the beach crest is, if present at all,

poorly developed.

11. The relationship between sediment sorting and wave height is weaker than between wave height and particle size.
12. Generally the relationship between sediment characteristics and wave conditions was poor in the north and may be associated with the influence of Flamborough Head on beach morphology.

Tracer experiments established real sediment transport rates in the field:

13. Daily transport rates on the lower beach coinciding with deep water wave heights of 0.3-0.7 m varied from 13 to 54 m^3, and for calm conditions from 3 to 27 m^3; tentative results for pebble movement on the upper beach were 81-89 m^3/day (waves 0.7-0.8 m high).
14. Movement was observed in both directions alongshore, depending upon wave approach.
15. An estimate of maximum annual sediment transfer might be 90 x 10^3 m^3 (ignoring net effects of movement in opposing directions); this is similar to other partly sheltered locations.

Comparisons of tracer results and modelled transport rates revealed that:

16. Both allowed for northwards and southwards drifts but each indicated a net southwards drift.
17. The modelled rates for specific seasons agreed with those measured in the field under similar wave conditions.
18. It was concluded that the beach sediment transport model is suitable for use on this coast.

5.1 c THE CLIFF

1. Coastal erosion on Holderness is extremely variable, both spatially and temporally. A mean annual retreat of 1.34 m was similar

to rates on other rapidly eroding till cliff coasts.

2. Within the field site retreat rates were much higher in the north than in the south; some northerly locations outside the monitored network experienced retreats of over 8 m in a fortnight.
3. There is a strong correlation between mean cliff retreat and beach elevation; where the upper beach is depleted, the waves attack the cliff for longer and can remove more material.
4. Beach level is influenced in turn by the presence of Flamborough Head. At the north end of the field site, just outside its influence, material may be moved south more rapidly, but is replaced by little or no sediment from the more sheltered areas to the north. The beach becomes depleted and cliff erosion proceeds.
5. The main mechanism of retreat on this coast is the removal of material by direct wave action, leaving the cliff above susceptible to collapse. The moisture content of the cliff is also an important influence.

5.1 d SEDIMENT BUDGET

Though the sediment budget prepared in the present study was simple, it seemed to reflect general beach behaviour well.

1. The observed and modelled changes in beach volume allowed the onshore/offshore sediment movement, which could not be measured in the field, to be calculated. Both cells (iv) and (v) experienced a net offshore sediment movement, that in cell (iv) being significantly greater.
2. The budget, based on modelled sediment transport rates, indicated the highly variable movements of material alongshore.

3. Only about one third of material supplied to the beach from the cliff is sufficiently coarse to be retained on the beach; the fine silts and clays are removed offshore.
4. The sediment budget predicted a deficit in the north of the field site, i.e. a depleted beach, and an accreted beach in the southern half of the area; this pattern was observed in the field.
5. The sediment budget suggested that the area may include a critical beach transition zone where the beach is depleted. Beyond the field site in the north, in the shelter of Flamborough Head, the beach seems reasonably stable; in the northern half of the field site, however, where the shelter is reduced and the most energetic waves can reach the coast, the beach is depleted. In the southern half of the field site, where sediment supply is possible from the north or south, the beach is fuller and dynamic equilibrium is restored.

These are the findings and conclusions of the present study. They will now be considered with reference to the original aims of the research and the hypotheses put forward in section 1.1.

5.2 GENERAL CONCLUSIONS

The first broad hypothesis, that a number of specific relationships exist among beach morphology, sediment transport processes and till cliff erosion, is evidently true, though the specific inter-relationships are very complicated and some may not have been understood fully. The results and conclusions for a number of comprehensive experiments allowed the aims of the research to be fulfilled and the more detailed hypotheses advanced in section 1.1 to be upheld or rejected.

The first aim of establishing the relationships between beach morphology and sediment transport processes was fulfilled in the sediment budget work, where the beach level was related to the amount of sediment entering and leaving a beach cell. The hypothesis that "beach morphology is determined by sediment transport processes" could therefore be upheld. The hypothesis that "theoretical models of sediment transport produce results which agree with field results" was also accepted. Modelled results from experimental work in the offshore zone were similar to the results of beach tracer experiments, provided of course that wave conditions were approximately the same. The size and occurrence of till exposures on the shore must also depend upon sediment movement.

In practice the first aim overlaps the second which was to establish the relationship between sediment transport and marine conditions. The morphology of the beach and its sedimentary characteristics were linked directly to offshore conditions, with sediment transport being the agent bringing about change. High waves promoted a movement of sediment from the upper to the lower beach, a general combing down of the beach: lower waves induced a movement in the opposite direction, while calm conditions were incapable of producing any change. Higher waves could strip the sand off depleted sections of beach, and at the same time produce a beach which was coarser, particularly on its upper slope. Thus, the hypothesis that "the rates and directions of sediment transport vary as a result of variations in marine conditions" is upheld.

However, the relationships are not as simple as this summary might suggest; many relationships observed in the south of the field site broke down towards the north. There is an external influence which led to the beach morphology at the northern end of the field site being significantly different from that at the southern end.

This "external influence" is Flamborough Head, which shelters the coast north of Skipsea from the most energetic north-easterly waves. South of Skipsea, the influence decreases rapidly and the coast is progressively exposed to a greater proportion of these waves.

The third aim, establishing the relationship between both beach morphology and wave conditions, and cliff erosion, was partly fulfilled. A strong, negative correlation was established between beach height and cliff retreat; in turn the level of the beach was determined by the amount of wave energy available as well as the long-term morphology of the beach. This enabled the hypothesis "rates of till cliff erosion are influenced by the morphology of the beach in front of it" to be upheld. Beach morphology and wave energy are not the only influences, however; cliff erosion also depends on the unmeasured independent variable of cliff moisture.

As a result of modelling beach evolution and comparing the results with wave conditions, the hypothesis that "beach evolution (among a number of beach types) reflects offshore marine conditions" was accepted. General observations of beach morphology in relation to wave conditions indicated that in winter higher waves may cause already depleted sections of beach to be stripped of sand, leaving the till platform exposed.

The final aim, that of producing a probabilistic model of beach evolution, was fulfilled as a result of monitoring beach profiles for over a year. It was found that the beach state throughout the year could be described by a set of beach types, allowing the relevant hypothesis to be upheld; it was possible to classify well over 90% of the beach profiles into a limited number of classes. A first order Markov model described beach development, in which the beach profile state depended upon the state which immediately preceded it but not upon any before that: in other words there is no long-term memory in the system. This allows the hypothesis that "cycles of beach geometry change can be interpreted as belonging to a Markov chain, with evolutionary cycles being expressed as a probability function based on previous beach states" to be upheld. The introduction of a second model meant that "winter" and "summer" transitions could be predicted equally well, both spatially and temporally. These models allowed an objective investigation of beach transitions and wave conditions to be made. High energy waves were associated with a combing down of the beach, lower waves, with accretion on the upper beach at the expense of the lower, and calm conditions with low sediment transport rates and a fairly static beach. Thus the hypothesis that "beach evolution among a number of beach types reflects offshore marine conditions" is also upheld.

The initial aims of the research put forward in section 1.1 have thus been fulfilled, the broad hypothesis regarding the coastal system confirmed and each of the seven more detailed hypotheses have been upheld.

5.3 LIMITATIONS OF THE PRESENT RESEARCH AND POSSIBLE IMPROVEMENTS

The limitations of the experimental methods, and their influence on results have already been dealt with in the results and interpretation sections. They will now be summarised and improvements suggested; many limitations are functions of the errors involved in some experiments. Once again, this section will consider each sub-system in turn.

5.3 a THE OFFSHORE ZONE

Sediment Transport Model

Most offshore work has concentrated on modelling sediment transport; it is in this area that the limitations are greatest, and in which the greatest approximations and assumptions had to be made. The limitations may be considered in three sections, firstly the fundamental limitations associated with the method, particularly the wave refraction program, secondly the limitations involved in the application of the model in the present study, and finally those involving the quality of the available data.

The first category of limitation applies to all users of sediment transport programs; the programs assume that Airy wave theory is applicable, but even more importantly they cannot predict onshore and offshore movement of sediment. Overcoming the latter limitation must be an important priority in coastal geomorphology. Hardisty (1984) proposed a method of assessing this type of movement, and the next stage should be to incorporate such a model into some of the existing wave refraction and sediment transport computer programs. A common limitation is imposed by the program errors, e.g. the crossing of wave rays, which makes subsequent calculations unsatisfactory; such errors were negligible in the present study. Some errors may result from the application of empirical formulae to convert P_l to sediment transport rates.

Problems more specific to this coast include the errors which arise as a result of the orientation of the coast relative to the x-axis of the grid, and the directions of wave approach; they resulted in a slight overestimate of sediment transfer towards the north. A way of overcoming this would be to consider wave directions perpendicular to the shore, and to consider narrower classes of wave approach, e.g. 45^{o} or even 20^{o}. The depth grid too involved certain limitations in its representation of reality; it comprised a set of sample points over the sea bed, representing the bed as a series of intersecting planes with the sample points of the apices; errors arose when waves had insufficient time before breaking to adapt fully to the new slope of the bed. It is doubtful whether closer sample spacing would help to eliminate this.

Wave data were only measured at one position and there is a limit to how far along the coast these heights represent true conditions. The limitations of this type of study would be reduced greatly if more wave recorders were available along a greater length of coast, and if more directional data were recorded. On this coast in particular a slight change in wave direction may reverse the longshore sediment transport and therefore have important implications for the sediment budget. It is important therefore to obtain accurate records.

Currents

When considering sediment movement induced by tidal currents the limitations imposed by the data were minimal; sampling was frequent and any errors which arose would have been a result of instrument inaccuracy. The limitations are methodological; it was assumed that current velocities measured 500 m and 1 km from the shore also operated further inshore. If this assumption is false, the installation of current meters, both closer to, and further away from, the shore, would provide a more detailed impression of nearshore conditions and would enable the physical limits of the study to be extended.

Current velocities were used to predict only the type of material likely to be moved, not the quantities. From the percentage time exceedence of various entrainment velocities it should be possible to calculate the volume of material moved on each tide, and hence identify the amount and direction of any net drift.

5.3 b THE BEACH

On the beach the limitations depended variously upon the available data, field measurement errors and the techniques used.

Surveying of Profiles

Field work errors and the quality of beach profile data could be improved by using more accurate survey techniques but this would require many surveyors. A more useful estimate of beach volume could have been obtained if a horizontal "cut-off point" for profiles had been defined, as well as an arbitrary basal datum.

The biggest limitation of the profile studies was the scale of the project; a more comprehensive data set could be obtained by surveying more often, over a longer time period, at shorter intervals along shore and along a much longer stretch of coast, but again this would involve a large number of people.

Modelling of Beach Development

Real data were used to model beach evolution, and not the artificially generated data used in previous studies. The tests involved in the modelling were adequate although in the chi-squared test some data were aggregated so that the requirements of the test were fulfilled.

The biggest limitation of the Markov model only applies if the scope of the study is extended, as it was necessarily derived specifically for this northern section of the Holderness coast. Although it proved that beach behaviour can be described by this type of model, if the method were to be applied to another coast, or even to a different stretch of the same coast, it may not be realistic and would require verification.

There are no particular limitations imposed by the probabilistic nature of the model; in fact it is more comprehensive than many deterministic models which have been proposed. Such models are inaccurate and can only predict beaches to be one of perhaps three types, little better than a simple winter or summer "classification". The probability model can also distinguish among profile shapes which are much more similar than the extremes used in many beach studies. Perhaps the most important way in which it is less limited than other models is that it depends solely on beach profile information and not upon wave data. Models of this type could therefore be derived for areas where no wave recorders are installed.

The analysis of beach transitions with respect to wave conditions was limited to general observations of trends of the two variables. Testing of statistical significance was a minor part since there was not a sufficiently large wave range to use suitable tests. The results do, however, give a good indication of the relationships involved. An improvement would be to obtain many more months of transition data thus allowing the frequency of the transitions of each type to fulfil the test requirements.

There were no significant limitations in the methods used to investigate beach particle size and sorting. The only limitations were in the scale of sampling; one sample was taken to represent each beach zone, i.e. the beach crest, upper beach and lower beach. The comparisons of beach characteristics and wave conditions were purely qualitative; for a more rigorous test of the relationships between wave height and particle size to be made, the lag between the two would have to be established accurately.

Finally, tracer studies had few limitations involving data quality. However, the main limitations involved the scale of the experiments as the main object was simply to obtain an indication of actual sediment transport rates for comparison with modelled rates. If a sediment budget was to be prepared from measured values then sand dying would have to be carried out on a vast scale, and many more experiments would have to be carried out all along the coast under a wide range of conditions. Pebble studies in particular would require much larger quantities of material. In practice there will always be limitations imposed by the scale of tracer experiments; the planning, execution and data analysis are so time-consuming that it would be difficult to cover a large stretch of coast.

5.3 c THE CLIFF

Most of the limitations of the cliff work were, once again, not imposed by the methodology but by the scale of the experiments; most of the errors which arose could theoretically be removed. The same methodology could be applied anywhere provided that data were available. The experiments based on map data were limited by the scales of the maps, their time span and accuracy. The same applied to the aerial photographs; they should be most valuable in the future when a longer record has accumulated , particularly if they are rectified to remove internal scale irregularities. Field data are limited by the length of record and the size of area which can be monitored conveniently. Reducing the limitations means acquiring many more high quality data.

5.3 d SEDIMENT BUDGET

Most of the limitations of the sediment budget are a function of the limitations of experiments which provided the results from which the budget was calculated. The one big drawback is that owing to the nature of the sediment transport model there is no estimate of onshore or offshore sediment movement is limited. Theoretically this could be overcome by using real sediment transport values instead of modelled potential rates, but this would involve tracer experiments being carried out on a huge scale, requiring many field workers over a longer period of time. Though the sediment budget presented here is limited - the figures are only complete for cells III to VI - it could be extended, provided that potential sediment rates could be produced for the whole coast.

The major limitations of the methods used in this study are a function of the scale of operation and the density of data collection. This is a result of the length of the research period and the man-power avilable. The biggest improvements would probably be achieved if the data were gathered more frequently over a denser sampling network, but the time required for analysis would be great. Generally, however, the methods could be extended to larger coastal areas in most parts of the world.

5.3 e ESTIMATION OF ERRORS

The previous sections, while discussing the limitations of the project, did not make an attempt to quantify any errors which may have arisen. Although every effort was made to minimise errors, in such a dynamic environment as the coast, it is inevitable that they will occur and it is useful if an estimate of their contribution can be made.

1. The survey methods used were as accurate as possible bearing in mind various practical constraints. However, an estimate of the error in determining the volume under a beach section should be made. This is particularly important in calculating a full sediment budget; for the Markov beach model the error in gradient is unlikely to make a significant difference to

the beach type. For an average error of $\pm 1^o$ over a beach section 150 m long, sloping at 5^o, 2^o and 1^o over appropriate stretches, the difference in area under the profile might be approximately $\pm$ 49.6 m^2 which for a beach cell 1875 m long is $\pm$ 93000 m^3; this would be equivalent to an average beach elevation or depletion of 33.1 cm.

2. Errors in the modelled sediment budget depend on the errors associated with its constituents. The importance of the errors in the area/volume under the beach profile in influencing the production of a full sediment budget, including the onshore or offshore sediment movement, was mentioned above. These potential errors should be borne in mind when the results are interpreted.

   a. It is difficult to quantify the errors involved in modelled longshore sediment transport - the causes of the errors have been mentioned already, It is possible that errors in P_l may be $\pm$ 20% (or even greater) which combined with errors from coefficients used to convert to sediment transport rates could mean variations in some cells (with a mean transfer of 28000 m^3) of $\pm$ 15000 m^3, equivalent to variations in beach elevation of 5.3 cm.

   A potentially large error in modelling sediment transport may arise from the very simple but vital step of converting the alongshore component of wave power into a volume longshore sediment transport. In this study, the equation was:

$$Q_1 = 2.57\ P_l$$

   This was a mean expression of two equations which had been used on sandy beach coasts similar to Holderness, i.e.

$S_1 = 1.77$ P   Allen (1981)

$Q = 3.37$ P   Vincent (1979)

If these, for example, represented the limits of the sediment transport then errors of $\pm$ 31.1%, or a volume of from $\pm$ 0.1 m^3/day to $\pm$ 65 m^3/day might occur throughout the year ($\pm$ 0.66 x $10^3 m^3$ to $\pm$ 11.14 x $10^3 m^3$ per year). This would obviously make an enormous difference to the sediment budget, and may consitute the largest error in it.

Despite choosing equations which seemed applicable to sand beaches like Holderness, if the equation used was unrealistic, then there is even greater scope for errors having been made. In fact very large errors are unlikely to occur, as measured sediment transport rates were similar to the modelled ones (see Section 4.2 c (ii)).

Appendix 1.1 contains a selection of sediment transport equations which incorporate different proportionality coefficients. If different constants had been used, e.g. that of 6.8 used by Komar (1983), then figures of $\pm$ 170% may have resulted, compared with the figures used in the present study.

b. There will also be errors in the values associated with cliff retreat. The long-term retreat rate will depend on the errors involved in making measurements on maps and photographs in the field. Other errors in long-term retreat are likely to be very small, but in one year there will be considerable spatial variation in the supply of material.

(i) Distances on maps were measured to $\pm$ 0.25 mm which meant an error of $\pm$ 121.0 m to $\pm$ 23.5 m on maps of scale 1:484000 and 1:94000 for determining the distance to the edge.

For Ordnance Survey maps this was ± 16 m. The error in the retreat measured from OS maps over a hundred years was probably around ± 32 m, equivalent to a cell volume of 840,000 m^3, or 8400 m^3/yr per cell. These errors are too small to put on Figure 3.32 which has a long time scale.

(ii) On Aerial Photographs distances were also measured to ± 0.25 mm, an error of ± 1.65 m and ± 12.5 m on photographs of 1:6600 and 1:50000. Determining retreat over 16 years would incorporate measuring errors of approximately 9.5 m - a volume of ± 249000 m^3 in one cell, or 15562 m^3/yr. Further unquantifiable errors are likely to have arison as a result of internal scale inconsistencies.

(iii) In the field, measurements were made to ± 5 cm; the errors from this source have been included in the sediment budget error section as, for the two cells for which a full budget could be presented, retreat values from field data were used. Errors would be approximately ± 10 cm over 18 months or, in a cell, 3937 m^3/yr.

The standard error curves and details for the aerial photograph plots in particular indicate the variations in cliff retreat rate. The error bars show the errors which may have arisen as a result of taking measurements from the photographs.

c. Within the field area, the errors in estimating the percentages of <u>sand in the till</u> are minimal; however, outside the field area, where the nature of the till changes much lower proportions of sand may be encountered. The proportion may be reduced by 25% to 50%, resulting in a contribution to the beach of half to three-quarters of that which has been assumed in the calculation of the sediment budget, e.g. 4820-7230 m^3, and 12500-18750 m^3 per cell at the extremes. These figures would be equivalent to a beach depletion of 1.71-2.6 cm and 4.44-6.67 cm for a 150 m wide profile.

d. If this method of obtaining a supply of till material were extended to other areas, there may be an error in the contribution extended to other areas, there may be an error in the contribution from the till platform under the veneer beach. In the field area, when the beach was stripped of sediment, the till platform was observed to slope almost uniformly at 3^o on the upper beach section; reports suggest that outside the field side the platform slopes steeply on its upper section, and more gently on lower stretches. South of the field area therefore, the contribution, assuming a 6^o slope for 40 m and 2^o for 60 m, is 12.5 m^2 a year for an annual retreat of 2 m (i.e. 6.28 x retreat), a figure approximately twice that in the north but still less than that supplied by the cliff. This is a volume of 23550 m^3 per cell, again for an annual retreat of 2 m. Assuming 30% sand content this would be an additional supply of sand to the beach of 7065 m^3, equivalent to a beach elevation of approximately 2.5 cm, compared with approximately 1.2 cm in the north, i.e. an error of 3656 m^3 (+ 1.3 cm) (150 m wide beach in a 1875 m long cell). This error is small compared with some of those mentioned above.

The approximate maximum error terms, are summarised below, for the field site and for the coast further south (Table 5.1).

Table 5.1 Error Assessment

Error Source	Field Site		Southern Holderness	
	volume (m^3)	Δh (cm)	volume (m^3)	Δh (cm)
Till platform contribution	-	-	+3656	+1.3
Cliff retreat	±3937	±1.4	±8400	±3.0
Till composition	-	-	-9844	-3.5
Longshore sediment transport	±15000	±5.3	±15000	+5.3
Total	+18937	+6.7	+26890 -33244	+9.6 -11.8

Δh = equivalent change on a 150 m-wide beach.

Taking errors from the above sources into account, modelling errors may be equivalent to beach level changes of +9.6/-11.8 cm in the south and +6.7 in the north, and possible field errors of ±33.1 cm may occur. These figures must be borne in mind when the sediment budget figures are considered. However, there errors compare favourably with those produced in many studies. It is also important to stress that the figures used in Chapter 3 realistically represent the supply of material to the field site.

5.4 FURTHER WORK

It has been recognised that the general research procedure and experimental techniques of this study could be applied more widely on Holderness and on other coasts. The first priority, given the concern about erosion on Holderness, is to produce a sediment budget, which will require an expansion of present work in all three subsystems. This is required so that the various sources and sinks can be recognised and areas of critical importance alongshore identified. Although Pringle (1985) suggests ords as critical areas, it is likely that they are not unique forms; a number of other places may be vulnerable to depletion and respond to a limited sediment supply and offshore conditions. The role of "ords" may be clarified if, in the future, more than one is monitored at a more frequent survey interval than that used by Pringle (1985).

If a sediment budget were prepared for the whole coast it should be possible to understand the sediment exchanges, and if necessary plan some suitable coastal protection. The rôle of Spurn Head in the sediment budget could then be assessed. Further work on suspended sediment from multi-spectral scanner data may enable the destination of much of the fine material to be identified.

The most important task in the offshore zone, with important implications for beach studies,is to apply and improve the available techniques for determining onshore/offshore sediment movement (e.g. Hardisty, 1984), and to accumulate the data which will be required. This would increase the accuracy of the sediment budget greatly. Further work to establish sediment transport rates in the nearshore zone would be most helpful in determining movement of material away from or towards the intertidal beach. Such work would require more difficult offshore tracer experiments. Sediment budgets could be produced for a range of theoretical conditions, to predict what might happen as a result of the introduction of a number of proposed schemes.

On the beach, larger scale sediment tracer experiments would help to establish accurate sediment budgets. Results could be used to check, and if necessary calibrate, modelled sediment transport rates. Further tests of the Markov model should be carried out on other stretches of the Holderness coast to check its applicability over a greater area.

Elsewhere, provided that suitable data were available,sediment transport could be modelled and comparisons made with the Holderness Coast. Purely theoretical studies could be undertaken to determine effects of extreme events. Markov models of beach development could also be produced for coasts which exhibit a different range of beach types. The observed transitions on the "new" coasts could be compared with wave conditions to check whether the relationships were similar to those on Holderness.

Additional work on cliff retreat may help in establishing more accurate sediment budgets and might include more accurate estimates of the erosion rates being obtained. However, having established areas of erosion, greater attention should be paid to the mechanisms of cliff retreat, and to the relationship between rates of cliff retreat and the state of the beach in front of it. It is doubtful whether many deterministic relationships could be established. Future work could then identify the main influences on erosion and concentrate on devising schemes to reduce their impact. In the United States this is already the primary aim of much research and is becoming more important in Europe (e.g. The Holderness Coast Protection Project).

The present research has provided the first necessary steps in the process of achieving a more comprehensive understanding of the Holderness coast. The Joint Advisory Committee of the Holderness Coast Protection Project has produced a list of "study topics" which should be investigated in order to understand and explain the behaviour of the coast. In identifying the forms and development of beach morphology, modelling and measuring longshore sediment transport rates, producing a sediment budget for a limited section of coast, accumulating comprehensive wave and current records and presenting patterns of wave refraction, the present work has covered a number of the "study topics". Future work which is essential if erosion is to be reduced will build on the present work.

5.5 THE SCOPE OF THE PRESENT RESEARCH

The present research has fulfilled the aims set out in section 1.1 and has enabled a number of hypotheses to be tested. The relationships among a number of variables, and their influence on the beach in particular, have been investigated (sections 5.1 and 5.2).

The scope of this study was wide; it considered elements of all three sub-systems of the coastal zone, though the nearshore work was rather limited. Within the scope of this study, perhaps its comprehensive nature and the new Markov model work will have made the greatest contribution to coastal geomorphology generally. The work, while demonstrating the great variability of the system, and the inter-relationships within it, has established the nature of some of these inter-relationships, and has identified and sought to overcome some problems in the techniques used in previous studies.

For the Holderness coast more specifically, where there is considerable interest in reducing coastal erosion, the work has been important for a number of reasons. Firstly, its comprehensive nature allowed many coastal relationships to be investigated and secondly the work was concentrated on a site which had been the subject of little previous research. Finally, the location of the field site made the results particularly valuable; it included a stretch of coast which was behaving "normally" and a stretch which lay in the transition zone where the sheltering effect of Flamborough Head was beginning to be felt. The influence of this headland varies depending upon the direction of wave approach, and therefore complicates beach behaviour. Within this critical field site many processes operate which may influence the entire coast from Bridlington to Spurn Head.

The data collected in the present study will be useful in the continuing work on erosion along this coast: indeed, many of the results obtained and interpretations made will also be valuable in this respect, for example in understanding the processes which must be overcome or moderated if erosion is to be halted or substantially reduced.

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Appendix 1.1 Sediment Transport: Equations for calculating sediment transport rates

1. $S = \frac{0.026}{\gamma_b} \rho g H_b^2 \, Cg \sin \alpha_b$ — Willis (1977) from CERC (1975)

   S = sediment transport
   ρ = density of water
   g = acceleration due to gravity
   H_b = breaker wave height
   Cg = group wave velocity
   α_b = breaker angle
   γ_b = depends on breaker type

2. $Q = 4.1 \times 10^5 P_\ell$ — Cambers *et al.* (1978)

   Q = sediment movement $m^3 s^{-1}$
   P_ℓ = longshore wave power $Jm^{-1}s^{-1}$

3. $Q = 2 \times 10^5 H_b^2$ — CERC (1975)

   Q = sediment movement yd^3/yr
   H_b = breaker height ft

4. $Q = (7.5 \times 10^3)P_\ell$ — CERC (1975), Armon and McCann (1977), Madsen (1978)

   P_ℓ = longshore wave power ft-lb/ms
   Q = sediment movement yd^3/yr
   ($Q' = 1.29 \times 10^3 P_\ell$ where Q' is in m^3/yr and P_ℓ in $J\ m^{-1}s^{-1}$)

5. $Q = 135Ea$ — Fairchild (1966)

   Q = sediment transport yd^3/day
   Ea = intensity of net alongshore wave energy ($x10^6$ ft-lb/ft/day)

6. $Q = \frac{P_\ell}{H_s} (f\ (H_s/d))$ — Thornton (1968)

   Q = sediment transport (g/min/m)
   H_s = significant wave height (m)
   P_ℓ = longshore component of wave energy flux ($g\text{-}m^2/s/m^2$)
   d = water depth
   f = dimensionless proportionality constant

7. $S = 210\ (P \sin \alpha \cos\alpha)^{0.8}$ — Bagnold (1963)

   $= 210\ P_\ell^{0.8}$

   S = longshore volume sediment movement
   P_ℓ = longshore component of wave energy flux

Appendix 1.1 continued

8. $I_\ell = 0.048\ (\rho g H_b^{\,2})\ \sqrt{g2H_b}\ \sin 2\alpha$ Allen (1980)

I_ℓ = immersed weight of sediment transport
S_ℓ = volumetric sediment movement

$$S_\ell = \frac{I_\ell}{5.88\ (\rho s - \rho)}$$

ρs = density of sediment
ρ = density of water

9. $S_\ell = 2.05 \times 10^{-5} P_{\ell R}$ from Allen (1981)

$P_{\ell R}$ = Resultant longshore wave power (Js^{-1}) (per m length of beach)
S_ℓ = volumetric sediment movement (m^3/s)

10. $Q = 3.9 \times 10^{-5} P_{\ell R}$ from Vincent (1979)

Q = volumetric sediment movement $m^3 s^{-1}$
$P_{\ell R}$ = resultant longshore wave power Js^{-1}

Appendix 2.1 Wave Refraction using WAVEJB.F77

Input to program: equations used in program: output of program

A Input

Grid Data: for each (x,y) coordinate on the grid covering the nearshore area, the corresponding depth was extracted from Admiralty charts (Nos. 121 and 129), and used to produce a matrix of depth values.
Wave approach direction was measured anti-clockwise from the positive x-axis. Because of the orientation of the coast an approach direction from the north-east was represented in the present study by 115°, east by 70°, and south-east by 25°.
Wave ray origins were specified; each had to be at least three grid units inside the grid margins to avoid edge effects.

The program read a data matrix which comprised the x-coordinate, y-coordinate and angle of approach.

Wave conditions

The following parameters are read from a data file as a string of numbers. The notation is that used in the program.

1. TT Wave period (s)
2. NOR Number of wave rays (maximum is 50)
3. MM Number or grid points on the x-axis (including the origin)
4. NN Number of grid points on the y-axis (including the origin)
   n.b. NN must be less than or equal to MM
5. GRID Length of one grid unit (m)
6. DCON Depth conversion (= 1 when SI units are used)
7. NXD Depth matrix selection (=0 when depth grid is included in input)
8. HD Deep water wave height
9. IP Default = 5
10. PR Default = 0
11. PUN Default = 0
12. NSH Default = 0
13. TIDE Default = 0
14. CF Coefficient of bottom friction = 0.030

parameters 9-13 were redundant in this executuion of the program and the default values used.

B Formulae used in program

In sub-routine RAYN, a number of intermediate parameters are constantly recalculated according to the following formulae. Later, many form the output from the program. The notation is that used in the program.

1. Wave Power POW = $1256\times HI^2 \times CXY \times XN$
2. Longshore component PL = POW × DSIN (2×BETA/57.2958)/2
3. Mean longshore current V = (2.7 × 3.1416 × HI × DSIN(BETA/57.2958))/(TT x SKH)
4. Average of computed group and wave speeds WAVSP = (CXY + (CXY×XN))/2
5. Breaker wave height using average speed HII = 0.78 × DB
6. Wave angle at breaking BETAB = $((ASIN(PL/HI^{2.5})/2223.6)\times 57.2958)/2.0$
7. Wave length at breaking WVLNG = $((9.80\times DBB)^{0.5})\times TT$
8. Incident wave power POZ = $1256 \times (HB)^2 \times (9.8 \times DBB)^{0.5}$
9. Longshore component of wave power POY = POZ × DSIN (2.0×BETA/57.2958)/2

Appendix 2.1 continued

10. Longshore current speed VAVE = $0.50 \times 45.275\ HB^{0.5} \times SLOPEI \times DSIN (2 \times BETA/57.2958)$

HI	= wave length	XDEP	= depth at x
CXY	= wave velocity	TT	= wave period
XN	= ratio of group to phase velocity	L	= wavelength at time of calculation
BETA	= angle of wave crest with shore	DB	= $(0.31944 \times WAVSP)^2$
SKH	= Sinh (KH)	DBB	= 12.8 × HB
KH	= 6.2832 × XDEP/L	HB	= (HI + HII)/2.0
SLOPEI	= 0.019		

D refers to double precision variables
division by 57.2958 converts radians to degrees

C <u>Output</u>

For each wave ray the following data are produced at intervals along its path to the shore; the notation is that which appears in the output print-out.

MAX - sequential number of the iteration which has been reached along the ray
X - X - coordinate of the point on the ray
RFX - X - coordinate of the time equivalent point on the reference ray (i.e. where no refraction occurs)
Y - Y - coordinate of the point on the ray
RFY - Y - coordinate of the time equivalent point on the reference ray
ANGLE - Angle (anti-clockwise) from the positive x-axis to the wave ray vector and the point
TIME - elapsed time since the start of the ray
RFT - equivalent elapsed time on the reference ray
DEPTH - water depth at the point on ray
WL - wavelength at the same point
DIST - incremental distance from preceding point
HT - wave height
DE/DR - energy loss gradient
BETA - angle between ray and the normal to the isobath
CR - coefficient of refraction
UMAX - maximum horizontal wave orbital velocity at the bottom

Appendix 2.1 continued

Following this breaker parameters are listed for each ray.

1. Total breaker power
2. Effective shore-parallel component of breaker power
3. Mean longshore current velocity
4. Group velocity to phase velocity ratio
5. Average of computed group and phase speeds
6. Computed wave height at breaking.
7. Breaker height using average speed
8. Average breaker height
9. Wave angle at breaking
10. Wavelength at breaking
11. Different calculation of wave power, longshore wave power and longshore current speed.

Appendix 2.2 Angular variations of grid x-axis and shore

General Grid 1		Detailed Grid 2	
x	α^o	x	α^o
0.0-1.0	21.80	0-7.8	12.77
1.0-8.9	14.886	7.8-30.0	2.06
8.9-23.9	12.77	30.0-43.8	-4.97
23.9-35.0	2.06	43.8-49.8	-7.59
35.0-41.9	-4.97	49.8-60.0	-21.413
41.9-44.9	-7.59		
44.9-50.0	-21.413		
50.0-52.2	-56.310		
52.2-55.0	-76.068		

x - x-coordinate of coastal section

α - angle between shore and x-axis

Appendix 2.4: Sediment Tracer Experiment
Suppliers and details of materials.

Paint Supplier: Paint Services (Godalming) Ltd.
Weydown Road
Haslemere
Surrey
GU27 1BT

Manufacturer: Dane and Co. Ltd.
1, Sugar House Lane
London
E1S 2QN

Day-Glo Brushing Paint System: DG 1690 Fire Orange
DG 1691 Saturn Yellow
DG 1695 Rocket Red
DG 1696 Blaze
DG 1698 Flash Green

Resin Manufacturer and Supplier: (British Industrial Plastics)
BIP Chemicals Ltd.
Popes Lane
Oldbury
Warley
West Midlands
B69 4PD

Appendix 2.5 Sediment Tracer Experiments.

Procedure for Producing dye and coating sand.

The following quantities of materials were mixed in a covered vessel in a fume cupboard:

18.75 ml resin
106.25 ml solvent   sufficient to dye 12.5 kg of sand.
156.00 ml paint

12.5 kg of dry sand* were placed in the drum of the "Throtnungler" and a hollow made into which the paint mixture was poured; this was to avoid it coming into contact with the sides of the drum. The drum was then rotated for 15 minutes without the air heater being switched

Appendix 2.5 continued

on until the dye was distributed; this ensured that the dye was not ignited. The hot air was then switched on and run for an hour or so until the sand was dry. The drum was then left open for a few hours to allow the fumes to disperse properly. The tracer was removed and stored in bags until required. This procedure was repeated until sufficient sand of one colour had been produced. When a different colour is required clean glassware must be used for mixing the dye, and the inside of the drum must be cleaned thoroughly with a wire brush to remove the remnants of the old colour.

* Weatherill (1978) dried collected sand in the throtnungler, but this was found to be inconvenient and time-consuming. It was decided to dry the sand on trays in a large oven which was being used to dry other samples.

Appendix 3.1 Modelled Sediment Transport Rates: General Holderness Refraction; Equations for calculating resultant power

Winter

Standard allocation of low/medium and medium/high energy (65% 35% allocation)

$P_{\ell R} = 25\% \, (65\% \, P_{\ell\ell m,NE} + 35\% \, P_{\ell mh,NE}) + 15\% \, (65\% \, P_{\ell\ell m,E} + 35\% \, P_{\ell mh,E}) + 20.56\% \, (65\% \, P_{\ell\ell m,SE} + 35\% \, P_{\ell mh,SE})$

Proportions of low/medium and medium/high energy from Ocean Wave Statistics (OWS allocation)

$P_{\ell R} = 25\% \, (66.44\% \, P_{\ell\ell m,NE} + 28.86\% \, P_{\ell mh,NE}) + 15\% \, (78.08\% \, P_{\ell\ell m,E} + 21.92 \, P_{\ell mh,E}) + 20.56\% \, (71.51\% \, P_{\ell\ell m,SE} + 28.49\% \, P_{\ell mh,SE})$

Spring

Standard allocation

$P_{\ell R} = 39.56\% \, (65\% \, P_{\ell\ell m,NE} + 35\% \, P_{\ell mh,NE}) + 22.53\% \, (65\% \, P_{\ell\ell m,E} + 35\% \, P_{\ell mh,E}) + 12.64\% \, (65\% \, P_{\ell\ell m,SE} + 35\% \, P_{\ell mh,SE})$

OWS allocation

$P_{\ell R} = 39.56\% \, (72.49\% \, P_{\ell\ell m,NE} + 27.51\% \, P_{\ell.m,NE}) + 22.53\% \, (65.55\% \, P_{\ell\ell m,E} + 34.45\% \, P_{\ell mh,E}) + 12.64\% \, (70.16\% \, P_{\ell\ell m,SE} + 29.84\% \, P_{\ell mh,SE})$

Summer

Standard allocation

$P_{\ell R} = 16.85\% \, (65\% \, P_{\ell\ell m,NE} + 35\% \, P_{\ell mh,NE}) + 9.78 \, (65\% \, P_{\ell\ell m,E} + 35\% \, P_{\ell mh,E}) + 23.37\% \, (65\% \, P_{\ell\ell m,SE} + 35\% \, P_{\ell mh,SE})$

OWS allocation

$P_{\ell R} = 16.85\% \, (80.10\% \, P_{\ell\ell m,NE} + 19.90\% \, P_{\ell mh,NE}) + 9.78\% \, (75.73\% \, P_{\ell\ell m,E} + 24.27\% \, P_{\ell mh,E}) + 23.37\% \, (73.15\% \, P_{\ell\ell m,SE} + 26.85\% \, P_{\ell mh,SE})$

Autumn

Standard allocation

$P_{\ell R} = 16.30\% \, (65\% \, P_{\ell\ell m,NE} + 35\% \, P_{\ell mh,NE}) + 14.13\% \, (65\% \, P_{\ell\ell m,E} + 35\% \, P_{\ell mh,E}) + 16.85\% \, (65\% \, P_{\ell\ell m,SE} + 35\% \, P_{\ell mh,SE})$

OWS allocation

$P_{\ell R} = 16.30\% \, (83.56\% \, P_{\ell\ell m,NE} + 16.44\% \, P_{\ell mh,NE}) + 14.13\% \, (82.52\% \, P_{\ell\ell m,E} + 17.48\% \, P_{\ell mh,E}) + 16.85\% \, (75.38\% \, P_{\ell\ell m,SE} + 24.62\% \, P_{\ell mh,SE})$

$P_{\ell R}$, = resultant longshore wave power.

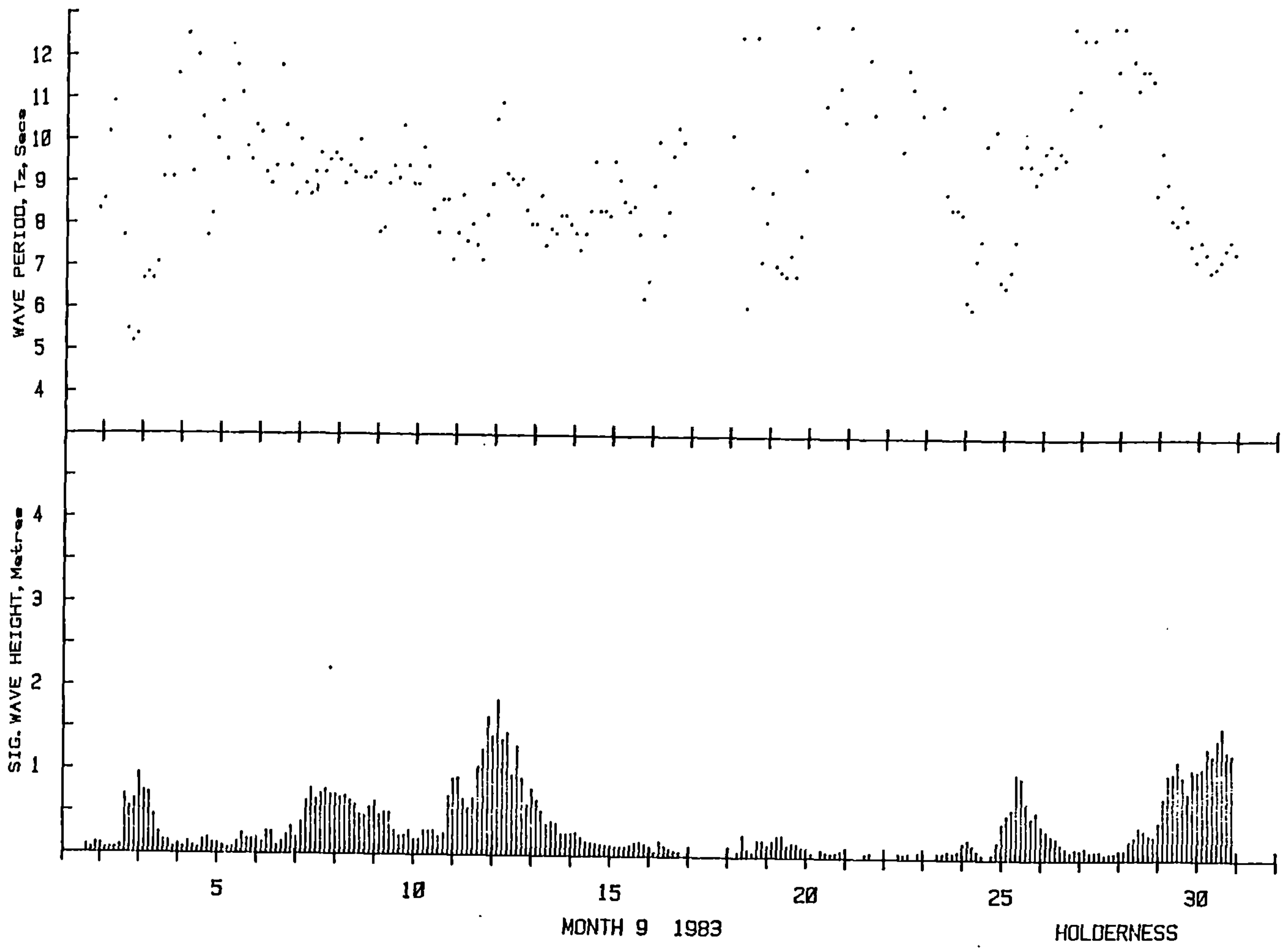
$P_{\ell \ell m_{NE}}$ = longshore component of power for low/medium energy waves from the north east.

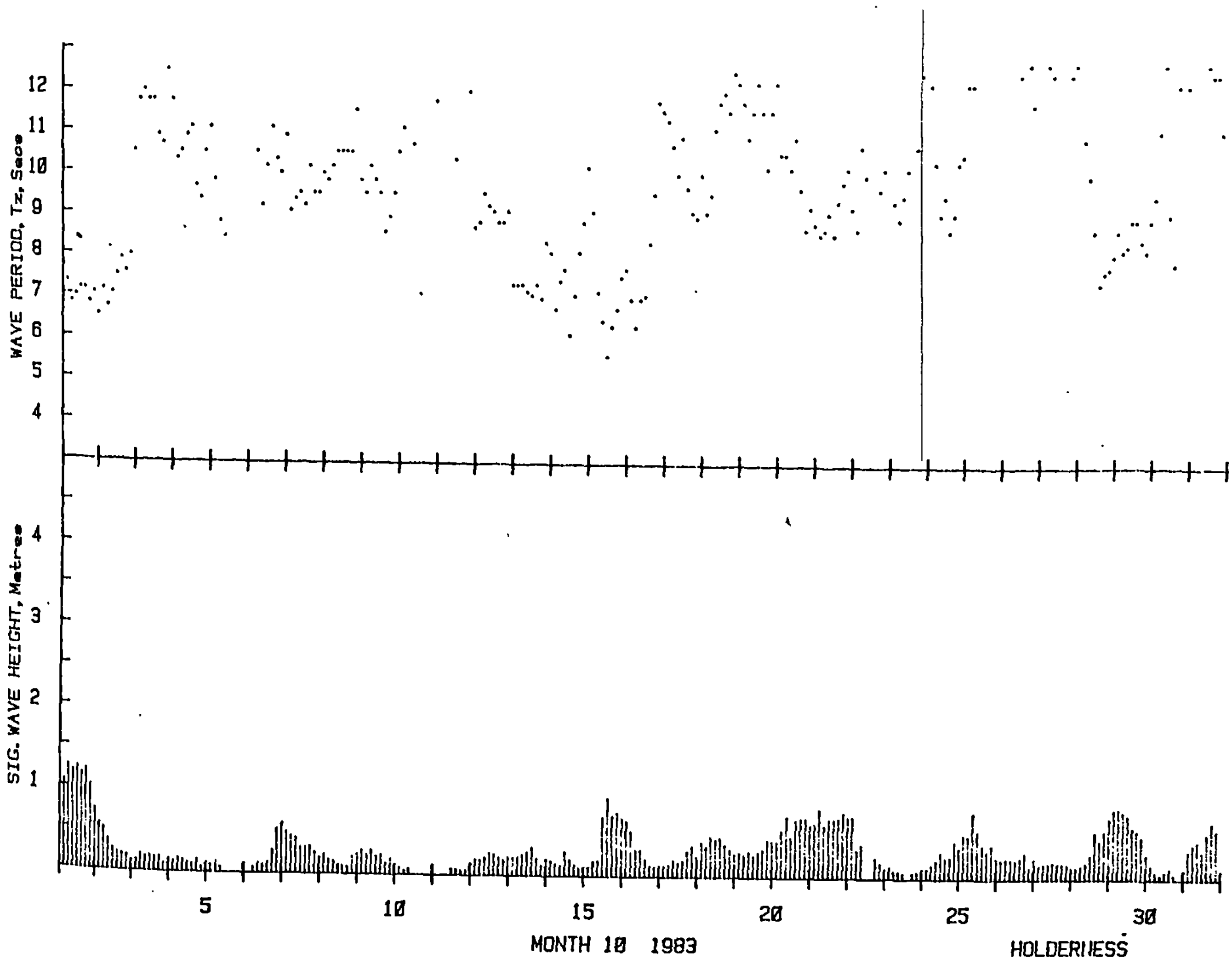
$P_{\ell mh_{E}}$ = longshore component of power for medium/high energy waves from the east.

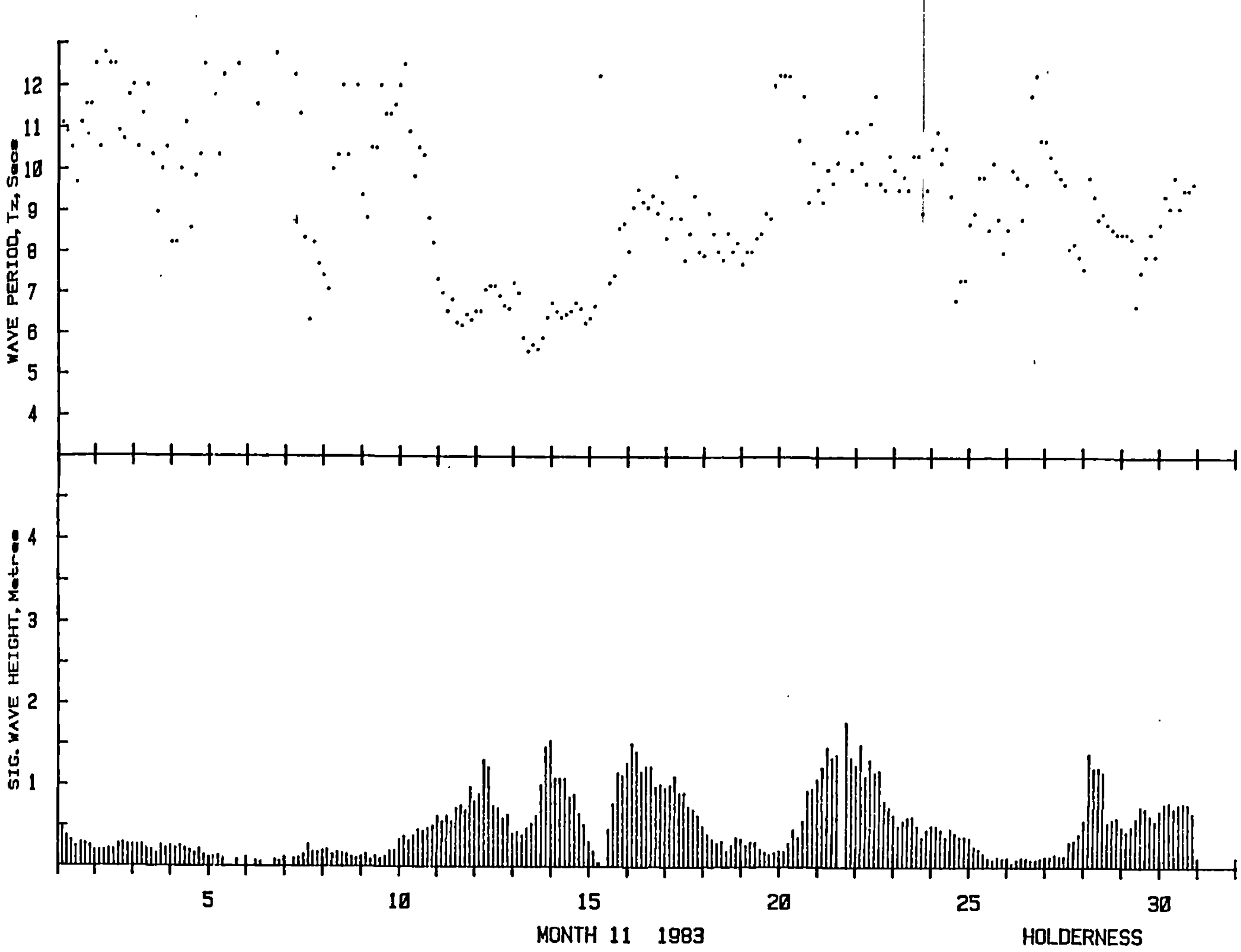
Appendix 3.2 Modelled Sediment Transport: Field Site Refraction Wave Recorder data from September 1983 to September 1984

Wave data were collected as part of a joint project at Sheffield University and consequently the data collection and analysis comprise part of the thesis. The following pages contain the complete wave height record for the year for which sediment transport rates and sediment budget were calculated. Wave directions are shown in Appendix 4.1.

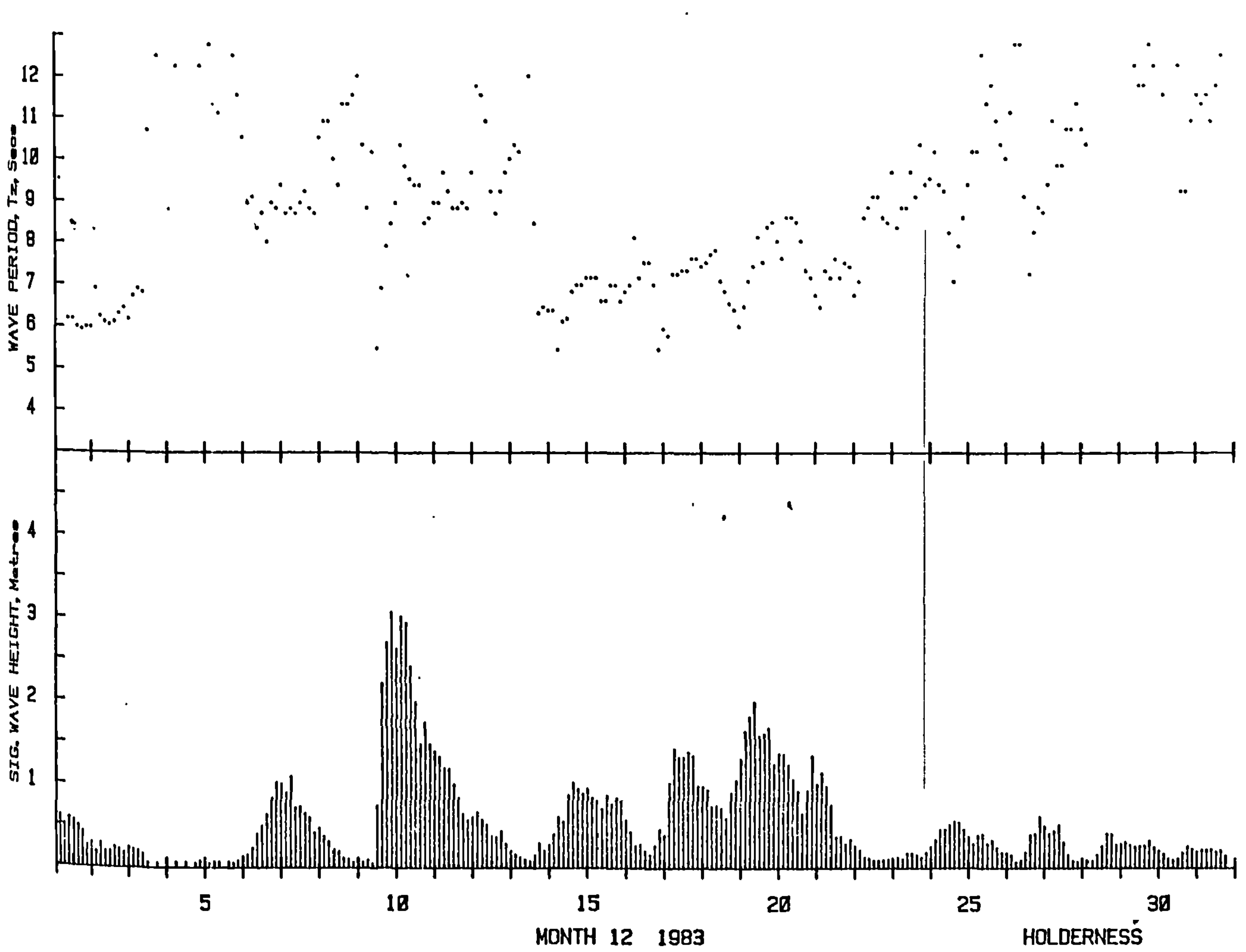
For each day the dominant, representative wave height for 0-12 hours and 12-24 hours was extracted. These and the wave directions recorded for the same periods by the coastguards at Hornsea and Flamborough Head were analysed to produce figures like Figure 3.2 for each month. Thus the proportion of waves of different heights from different directions were known. These data were used to model sediment transport rates as described in Section 3.1.a.


WAVE PERIOD, Tz, Secs
SIG. WAVE HEIGHT, Metres
5
10
15
20
25
30
MONTH 9 1983
HOLDERNESS

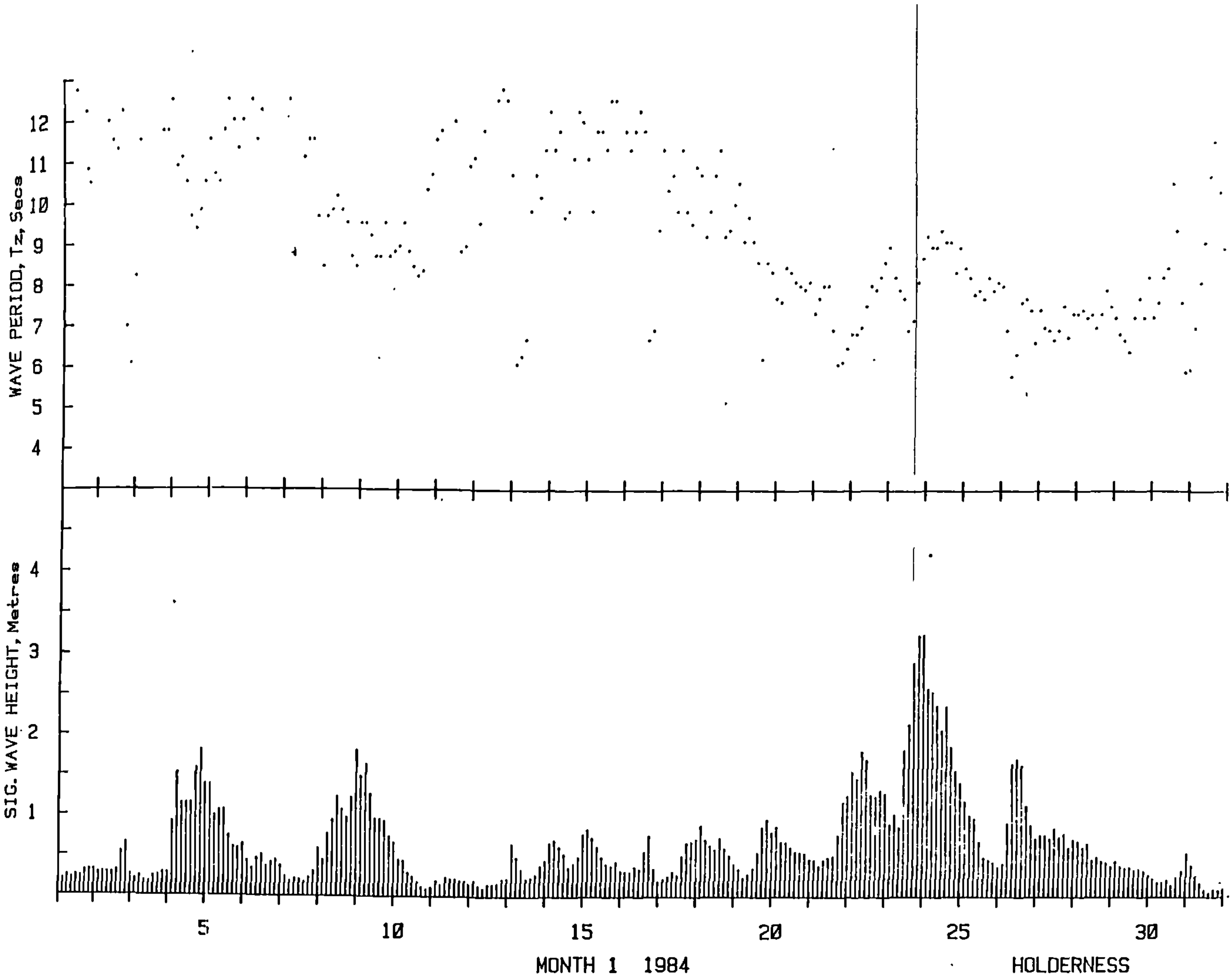

WAVE PERIOD, Tz, Secs
SIG. WAVE HEIGHT, Metres
5
10
15
20
25
30
MONTH 10 1983
HOLDERNESS



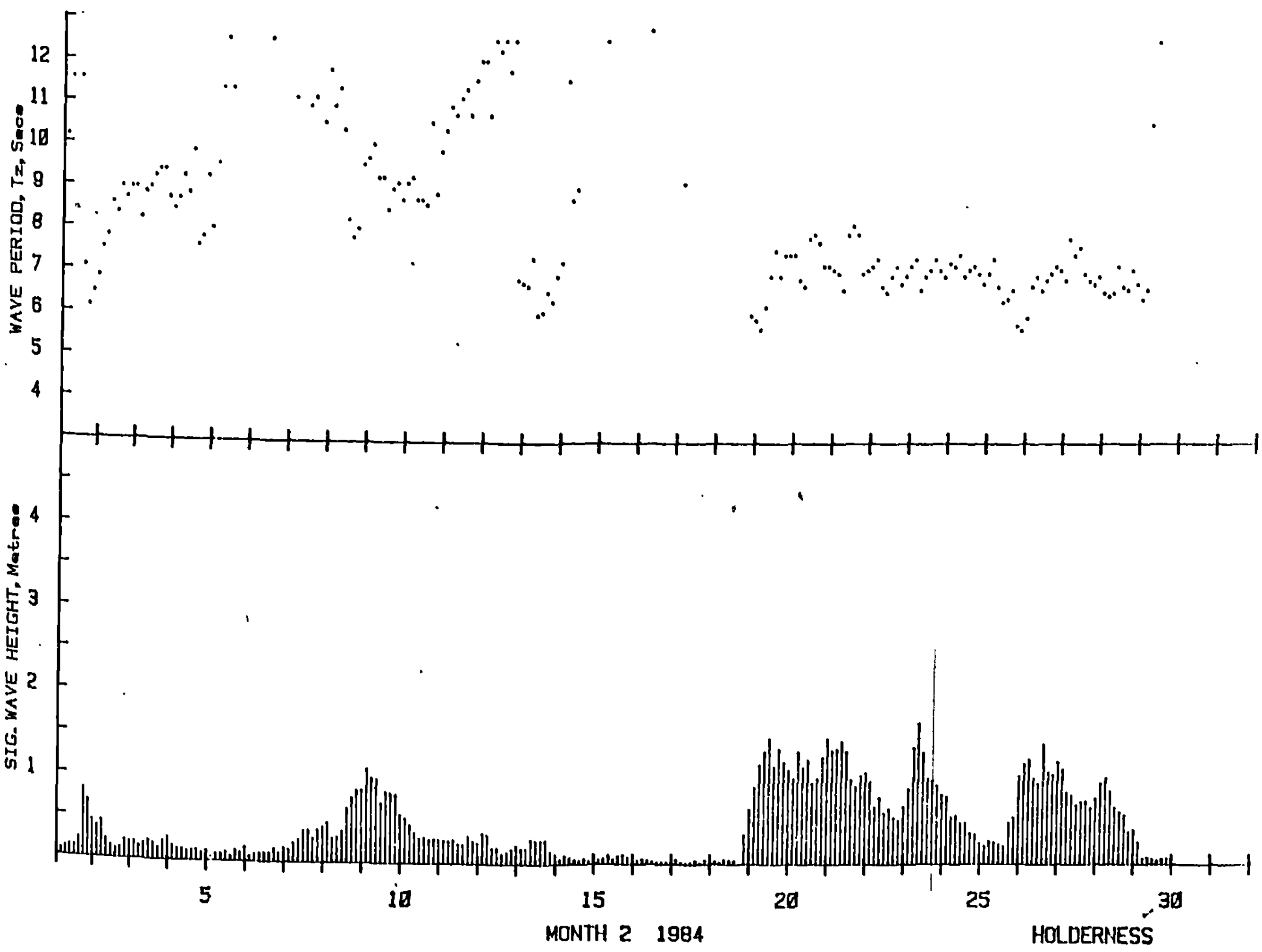
WAVE PERIOD, Tz, Secs
12
11
10
9
8
7
6
5
4
SIG. WAVE HEIGHT, Metres
4
3
2
1
5
10
15
20
25
30
MONTH 11 1983
HOLDERNESS



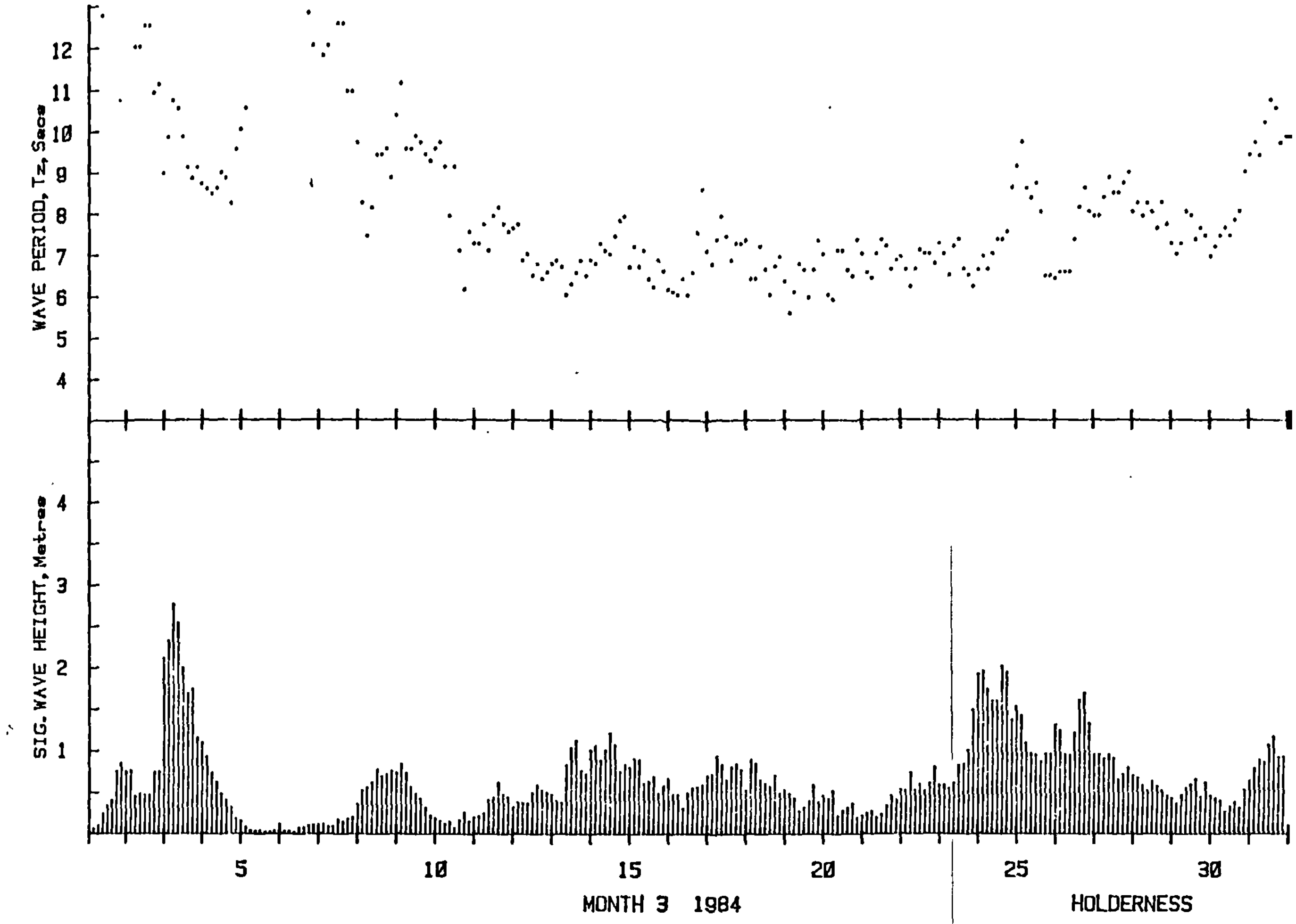
WAVE PERIOD, Tz, Secs
12
11
10
9
8
7
6
5
4
SIG. WAVE HEIGHT, Metres
4
3
2
1
5
10
15
20
25
30
MONTH 12 1983
HOLDERNESS



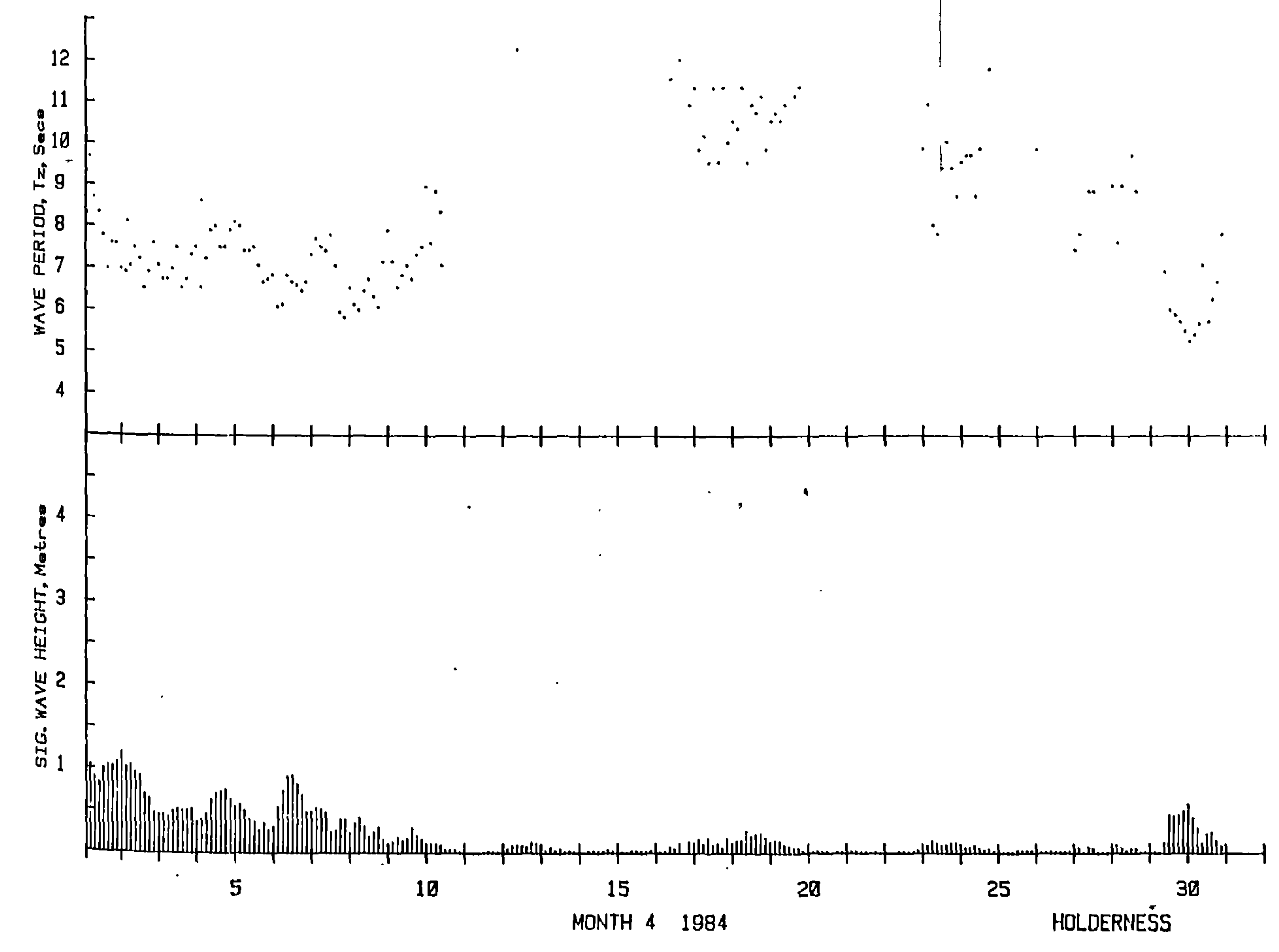
WAVE PERIOD, Tz, Secs
SIG. WAVE HEIGHT, Metres
MONTH 1 1984
HOLDERNESS



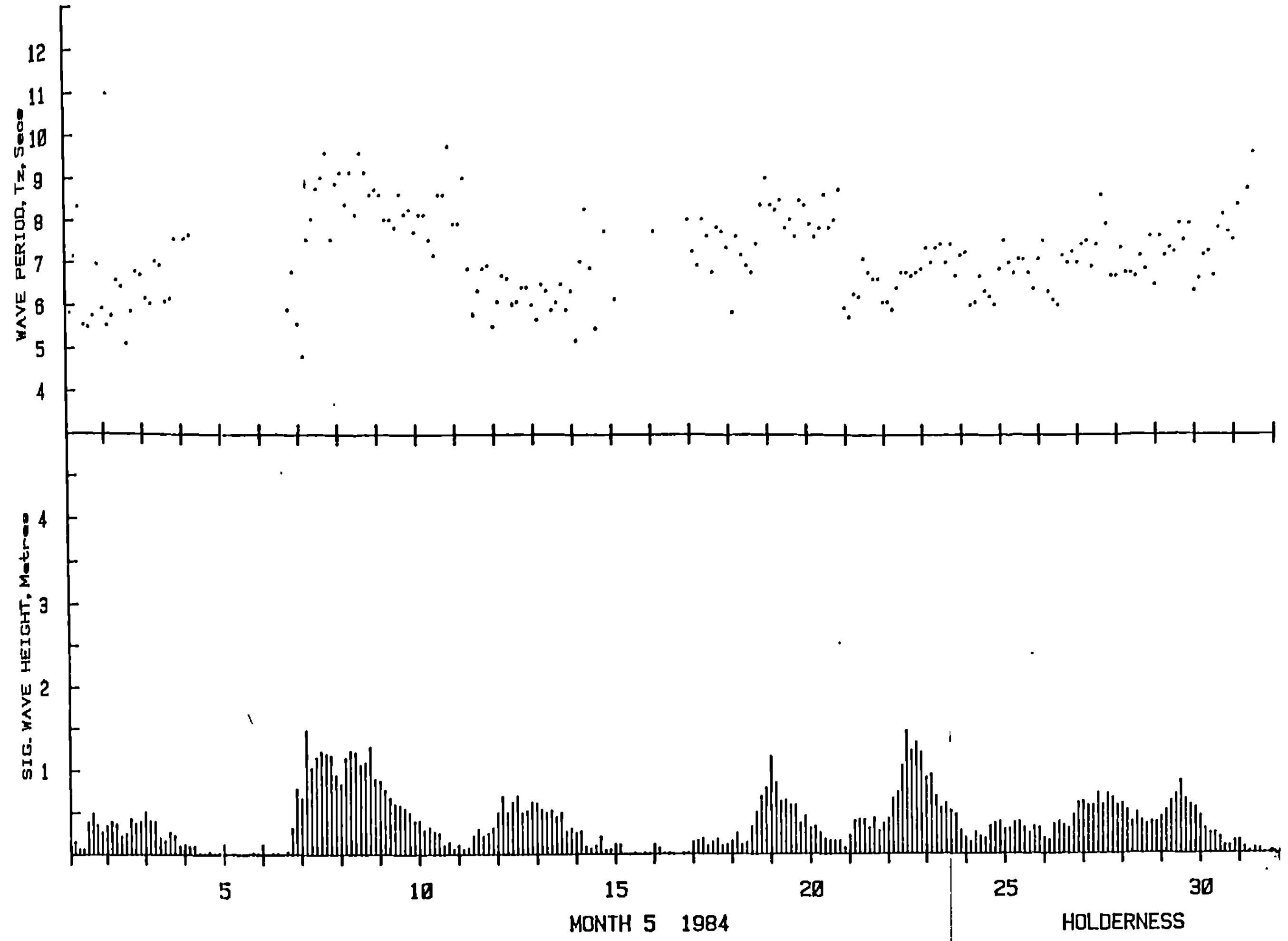
WAVE PERIOD, Tz, Secs
SIG. WAVE HEIGHT, Metres
MONTH 2 1984
HOLDERNESS

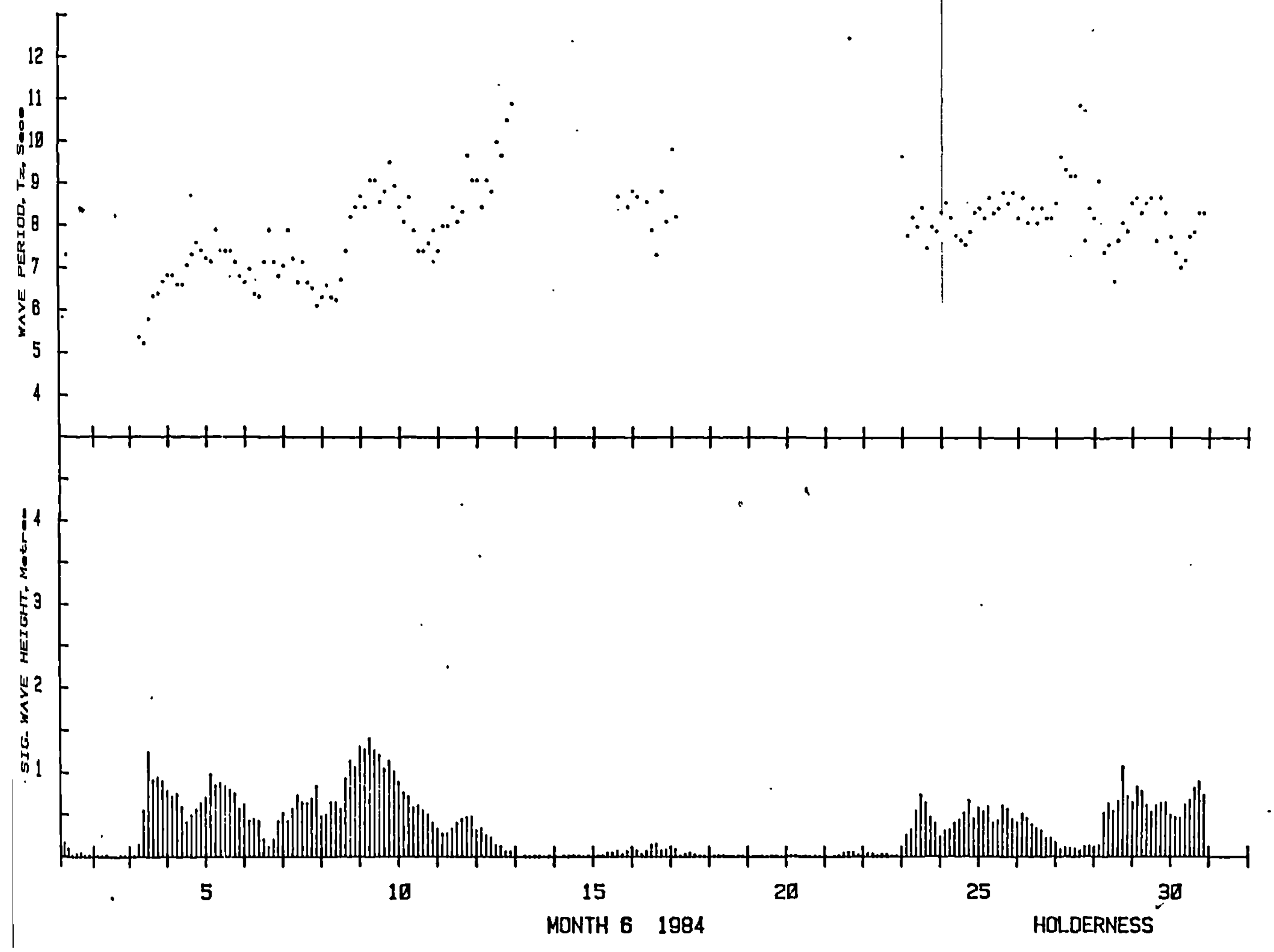


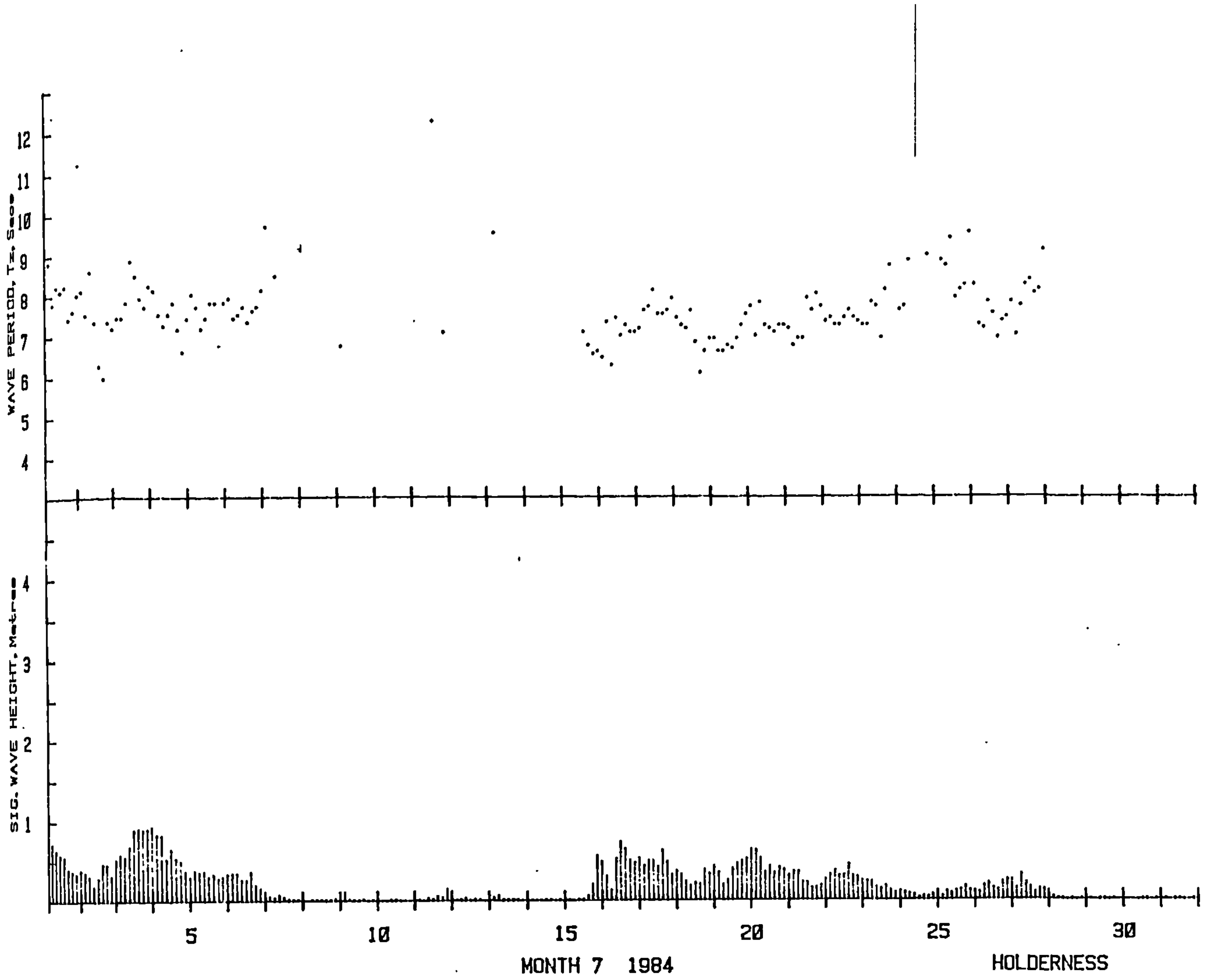
WAVE PERIOD, Tz, Secs
SIG. WAVE HEIGHT, Metres
MONTH 3 1984
HOLDERNESS

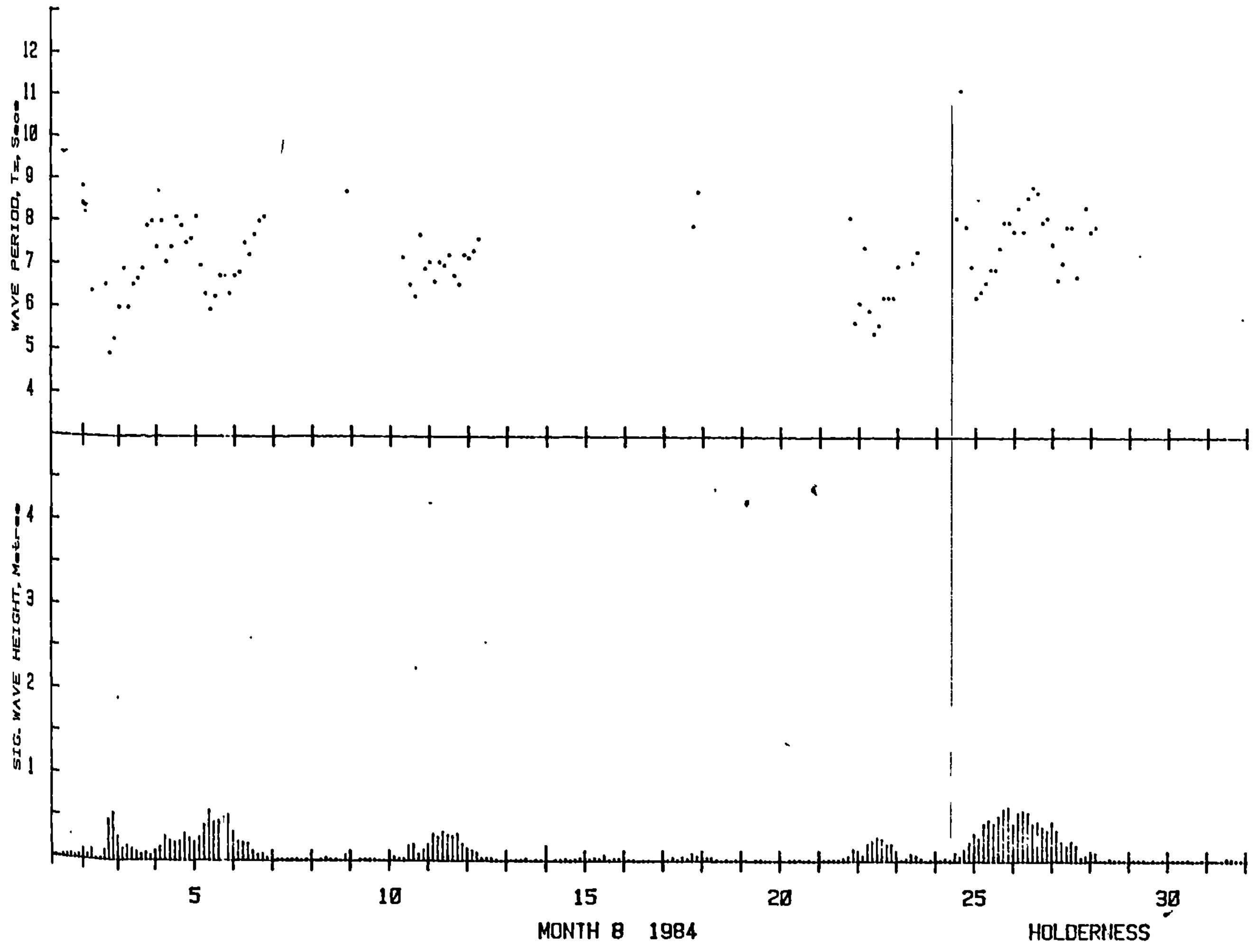


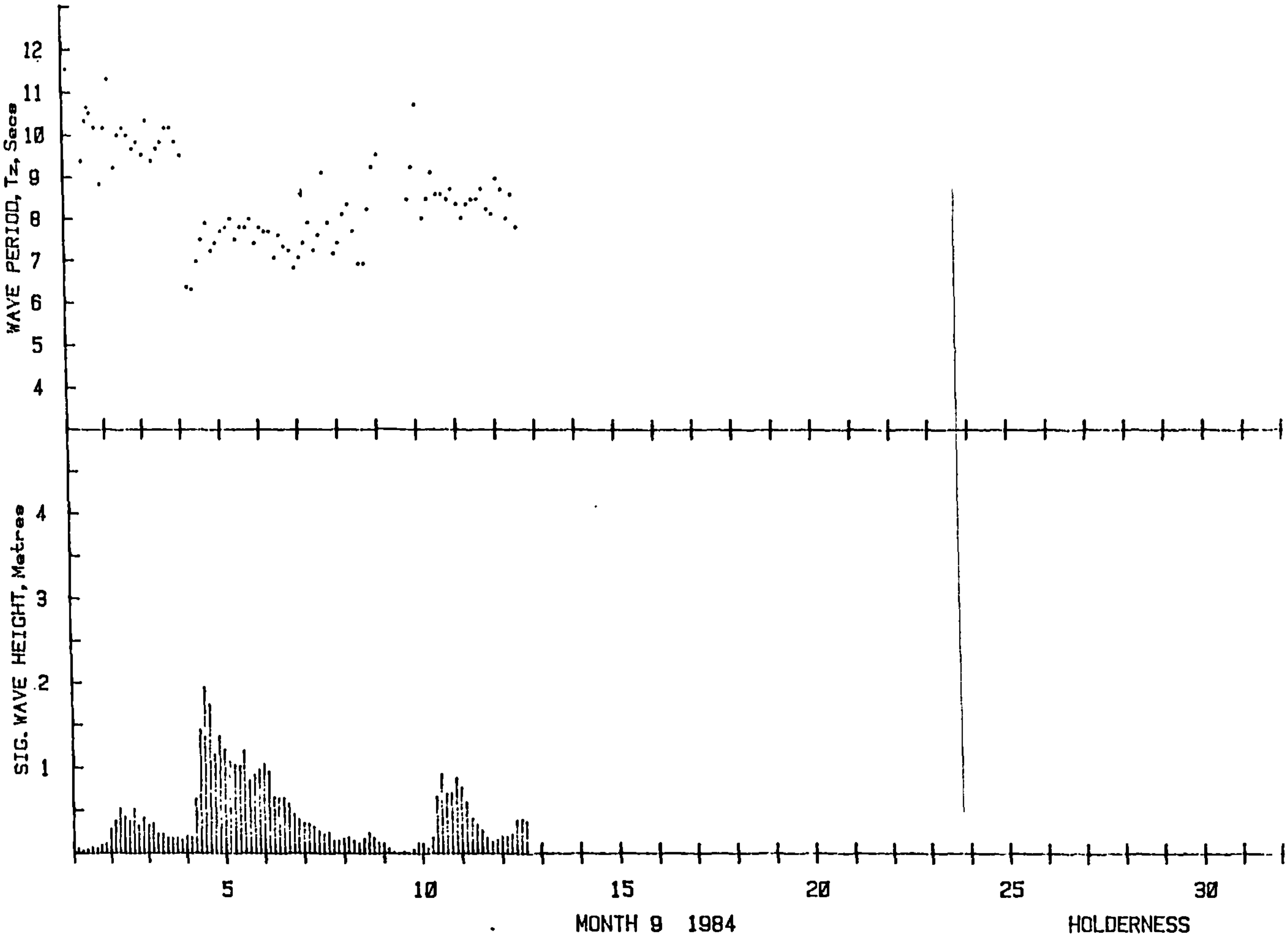
WAVE PERIOD, Tz, Secs
SIG. WAVE HEIGHT, Metres
MONTH 4 1984
HOLDERNESS


WAVE PERIOD, Tz, Secs
SIG. WAVE HEIGHT, Metres
MONTH 5 1984
HOLDERNESS


WAVE PERIOD, Tz, Secs
SIG. WAVE HEIGHT, Metres
MONTH 6 1984
HOLDERNESS


WAVE PERIOD, Tz, Secs
SIG. WAVE HEIGHT, Metres
MONTH 7 1984
HOLDERNESS


WAVE PERIOD, Tz, Secs
SIG. WAVE HEIGHT, Metres
MONTH 8 1984
HOLDERNESS



WAVE PERIOD, Tz, Secs
12
11
10
9
8
7
6
5
4
SIG. WAVE HEIGHT, Metres
4
3
2
1
5
10
15
20
25
30
MONTH 9 1984
HOLDERNESS

Appendix 3.3 Modelled sediment Transport: Field Site Refraction.
Tally tables showing asymmetry of wave heights.

Spring wave height (m)	northeasterly waves frequency		easterly waves frequency		southeasterly waves frequency	
0.0-0.25	7	total = 45	24	total = 61	6	total = 10
0.26-0.50	16	% < 0.5 m	22	% < 0.5 m	2	% < 0.5 m
0.51-0.75	14	= 51	11	= 75	1	= 80
0.76-1.00	8		4		1	
1.01-1.25	5	total = 6	1	total = 1		
1.26-1.50	1	% < 1.5 m		% < 1.5 m		
1.51-1.75		= 100		= 100		

Summer wave height (m)	northeasterly waves frequency		easterly waves frequency		southeasterly waves frequency	
0.0-0.25	13	total = 42	40	total = 61	4	total = 5
0.26-0.50	16	% < 0.5 m	14	% < 0.5 m	1	% < 0.5 m
0.51-0.75	10	= 69	6	= 88.52		= 100
0.76-1.00	3		1			
1.01-1.25		total = 2	4	total = 4		
1.26-1.50	1	% < 1.5 m		% < 1.5 m		
1.51-1.75	1	= 50		= 100		
1.76-2.00						

Autumn wave height (m)	northeasterly waves frequency		easterly waves frequency		southeasterly waves frequency	
0.0-0.25	16	total = 51	43	total = 77	14	total = 24
0.26-0.50	17	% < 0.5 m	23	% < 0.5 m	5	% < 0.5 m
0.51-0.75	14	= 65	8	= 86	1	= 76
0.76-1.00	4		3		4	
1.01-1.25	6	total = 10	2	total = 5	1	total = 1
1.26-1.50	3	% < 1.5 m	2	% < 1.5 m		% < 1.5 m
1.51-1.75	1	= 90		= 80		= 100
1.76-2.00						
2.01-2.25				total = 1		
2.26-2.50				% < 2.5 m		
2.51-2.75			1	= 0		
2.76.300						

Appendix 3.4 Modelled Sediment Transport: Field Site Refraction.

Weightings incorporated into $P_{\ell R}$ formulae to compensate for asymmetry of wave height distribution.

Winter Weightings

	energy	H.E.	M.E.	L.E.
direction	NE	1.0	0.9	1.05
	E	-	0.625	0.225
	SE	1.5	-	0.875

formulae become

$P_{\ell NE} = 4.11\%\ P_{\ell HN} + 9.9\%\ P_{\ell MN} + 89.13\%\ P_{\ell LN}$

$P_{\ell E} = 8.66\%\ P_{\ell ME} + 19.38\%\ P_{\ell LE}$

$P_{\ell SE} = 8.25\%\ P_{\ell HS} + 82.64\%\ P_{\ell LS}$

Spring Weightings

	energy	H.E.	M.E.	L.E.
direction	NE	-	0.5	1.0
	E	-	0.75	0.5
	SE	-	-	0.7

formulae become

$P_{\ell NE} = 5.88\%\ P_{\ell MN} + 88.24\%\ P_{\ell LN}$

$P_{\ell E} = 1.25\%\ P_{\ell ME} + 49.16\%\ P_{\ell LE}$

$P_{\ell SE} = 70\%\ P_{\ell LS}$

Summer Weightings

	energy	H.E.	M.E.	L.E.
direction	NE	-	1.0	0.81
	E	-	0.5	0.62
	SE	-	-	0.5

formulae become

$P_{\ell NE} = 3.17\%\ P_{\ell MN} + 78.43\%\ P_{\ell LN}$

$P_{\ell E} = 2.22\%\ P_{\ell ME} + 59.25\%\ P_{\ell LE}$

$P_{\ell SE} = 50\%\ P_{\ell LS}$

Autumn Weightings

	energy	H.E.	M.E.	L.E.
direction	NE	0.5	0.6	0.85
	E	1.5	0.7	0.63
	SE	-	0.5	0.75

formulae become

$P_{\ell NE} = 0.835\%\ P_{\ell HN} + 10\%\ P_{\ell MN} + 69.42\%\ P_{\ell LN}$

$P_{\ell E} = 1.8\%\ P_{\ell HE} + 4.21\%\ P_{\ell ME} + 58.44\%\ P_{\ell LE}$

$P_{\ell SE} = 3.84\%\ P_{\ell MS} + 69.23\%\ P_{\ell LS}$

P_{lNE} = longshore wave power of waves from NE

P_{lMN} = longshore wave power of medium energy waves from the NE

Appendix 3.5 Current Meter Experiments.

Description of steps in CMMANIT.F77 to convert current data into real figures and to calculate the desired current chrarcteristics.

1. The current meter had the capacity to record six variables, and as only two were required, the remaining four "blank" channels which had been copies into the data file were deleted.
2. The first and last hundred or so readings of the record which comprised the record for the the time between switching on and launching the meter, and between retrieval and switching off, were deleted.
3. The first step in the manipulation proper was to obtain a mean direction associated with the average velocity recorded over the ten-minute sample period. The mean velocity is assigned to the half-way point in the sample interval. The mean of the direction recorded at the beginning and at the end of the interval was calculated and assigned to the mid-point time.
4. The next step was to convert the mean direction value in the form recorded on the 9-channel tape to a true direction. The maximum possible value of the recorded direction on the computer record was 1023, representing 360^{o}. A conversion factor of x 0.3519062 was applied to each value to give the bearing from magnetic north. The result of this was then converted to a reading relative to grid north by subtracting 7.5^{o}.
5. At this stage the digital bit values for current velocity were converted to true values. The maximum 1023 value of the computer data represented a pre-determined maximum current of 125 cm/s. Each recorded velocity value was divided by 8.184 to give the current velocity in cm/s.
   These procedures resulted in a series of velocity measurements and the associated direction of that current.
6. The next step was to resolve the current velocity into its components in a north-south (V) and east-west (U) direction. in the conventional manner.

$$V = S \cos (GD)$$
$$U = S \sin (GD)$$

where GD = direction relative to grid north
S = velocity

Appendix 3.5 continued

7. The frequencies of currents flowing in various directions were counted, providing data for a histogram (Appendix 3.6 (i)). A similar count was carried out for the unresolved current speed for intervals of 5 cm/s (Appendix 3.6 (ii)).
8. The next count carried out was that of the frequency of north-south component velocities. This direction component is of greater magnitude and hence more significant in moving sediment alongshore on this coast. (Appendix 3.6 (iii) shows a histogram of these data.)
9. One of the most useful results in analysing the effects of currents on sediments is the residual flow, usually measured over one day, i.e. two high/low tidal cycles. This was obtained by adding up the readings for a whole day, taking into account whether they are positive or negative (i.e. towards the north or south), then dividing the by the number of readings; 149 for 2 tidal cycles of 24 hours 50 minutes duration.

Appendix 3.6 Current Meter Experiments.

Summary of Current Data, Experiment 2

(total number of samples = 3847, i.e. 25.8 days)

(i) Histogram of current directions

D1 = direction 0^o-10^o

D2 = " 10.01^o-20^o

|

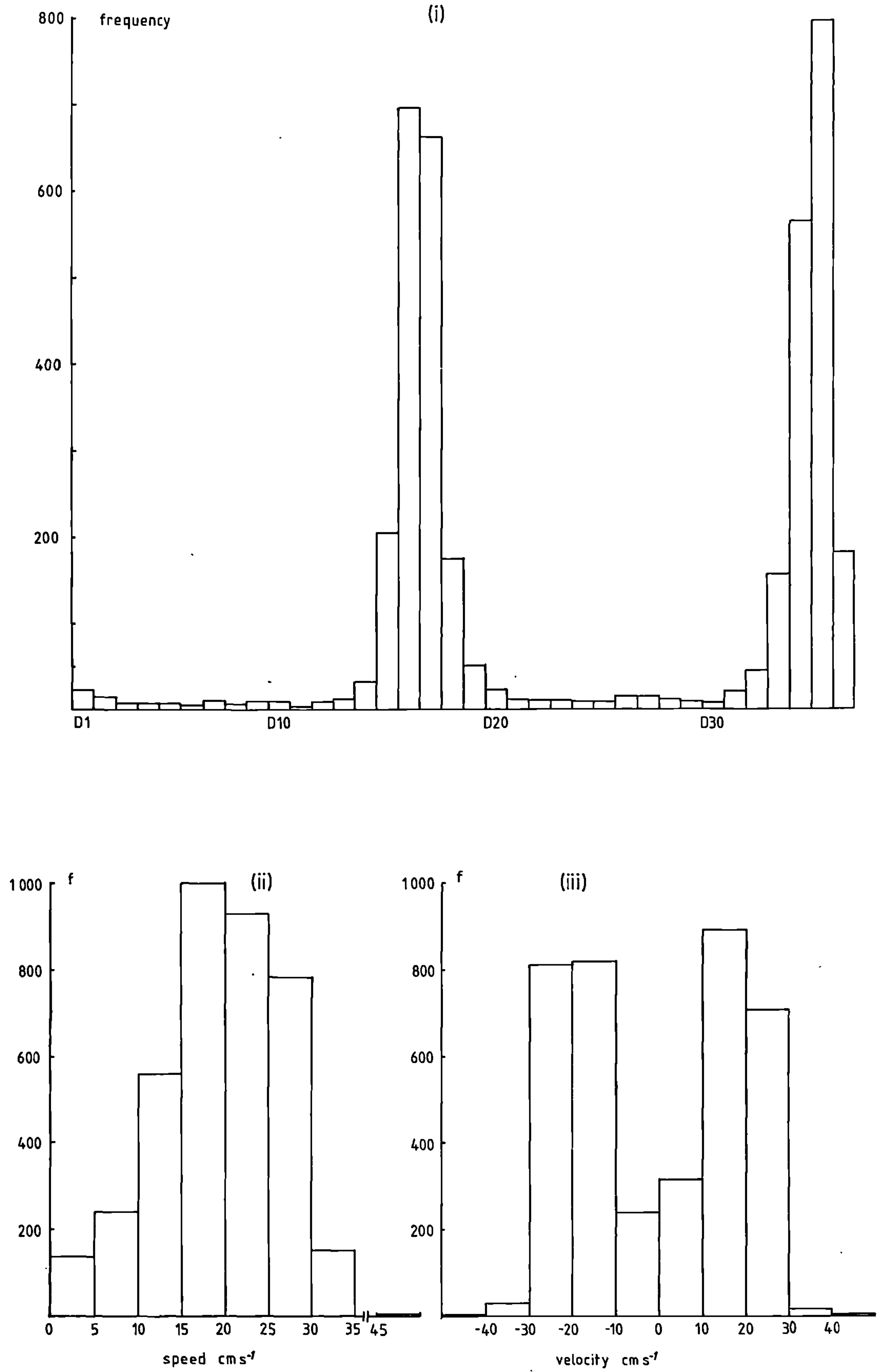
D36 = " 350.01-359.99^o

(ii) Histogram of current speeds

(iii) Histogram of current component velocity

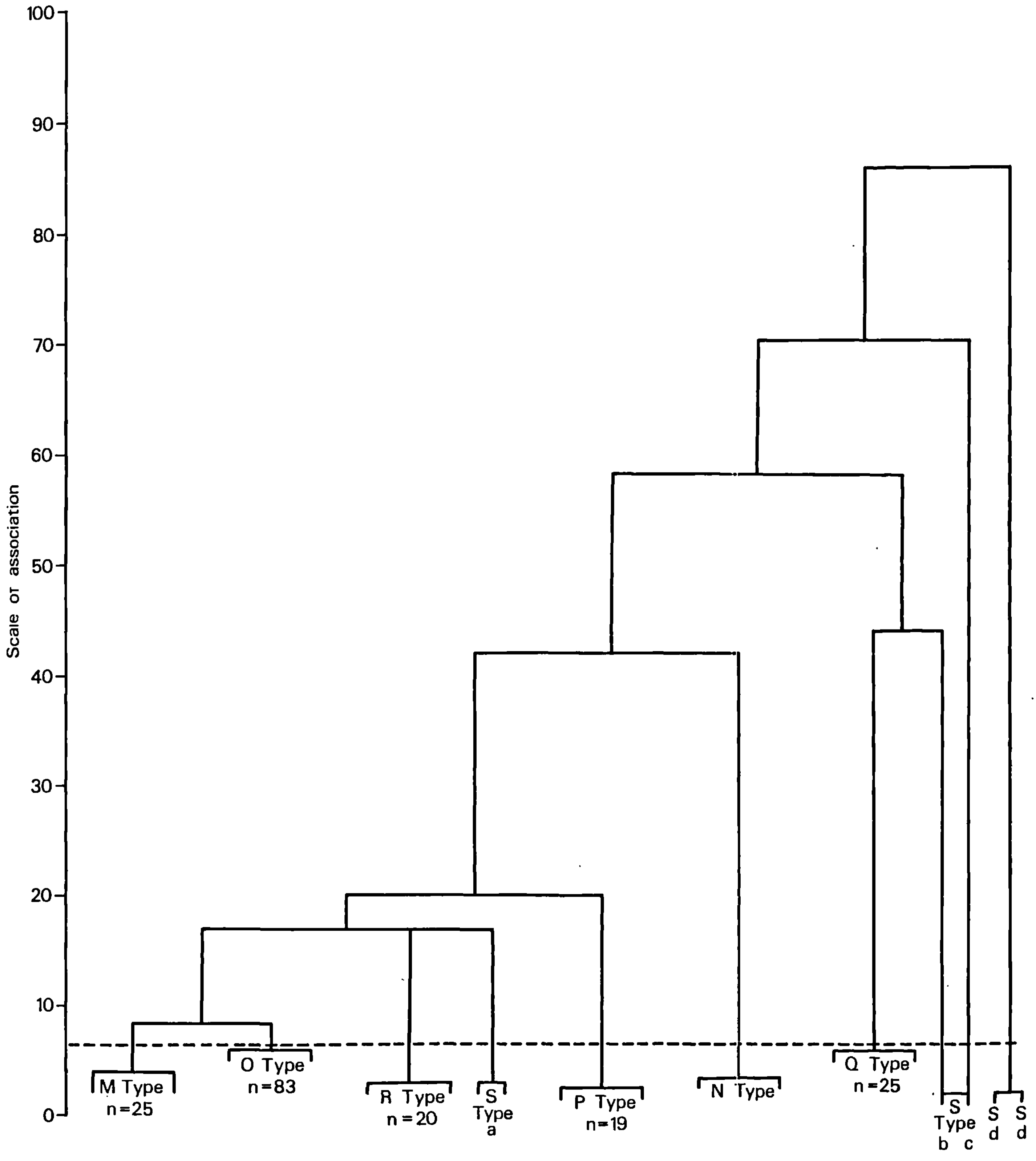
-ve = southwards current;

+ve = northwards current



800
frequency
(i)
600
400
200
D1
D10
D20
D30
1 000
f
(ii)
800
600
400
200
0
5
10
15
20
25
30
35
45
speed cm s-1
1000
f
(iii)
800
600
400
200
-40
-30
-20
-10
0
10
20
30
40
velocity cm s-1

Appendix 3.7 a Dendrogram of Beach Types



level at which final clustering into one type occurs

n = number of occurences

S Type a–d - miscellaneous categories

------ level of cut off to produce 10 clusters

Appendix 3.7b Beach Profile Work.

Sequence of beach profile transitions from April to Setpember 1984, profiles B-H.

Profiles monitored fortnightly except bracketed sections which represent daily surveys in July. Underlining indicates profiles which belong to both fortnightly and daily sequences.

Profile B

M - N - 0 - 0 - 0 - 0 - M̲
[M̲ - N - 0 - N - 0 - S - M -
- R - R - R - R - R - 0 - M̲]
M̲ - M - M - 0 - 0 - 0

Profile C

N - N - N - N - N - S - N̲
[N̲ - N - N - S - N - N - N -
- M - N - N - S - S - N - N̲]
N̲ - N - N - N - M - 0

Profile D

N - 0 - N - N - N - 0 - 0̲
[0̲ - M - 0 - M - M - M - M -
- M - M - M - M - M - 0 - S̲]
S̲ - 0 - 0 - 0 - N - M

Profile E

M - 0 - M - 0 - 0 - N - N̲
[N̲ - N - N - N - N - N - N -
- N - N - N - N - N - N - N̲]
N̲ - N - 0 - 0 - N - 0

Profile F

0 - 0 - 0 - 0 - 0 - 0 - 0̲
[0̲ - 0 - 0 - P - 0 - P - 0 -
- P - P - 0 - M - 0 - 0 - 0̲]
0̲ - 0 - 0 - R - 0 - 0

Profile F'

P - 0 - P - P - P - P - R̲
[R̲ - P - P - P - M - 0 - P -
- P - P - P - P - 0 - Q - P̲]
P̲ - R - R - 0 - 0 - 0

Profile G

Q - Q - Q - Q - R - R - 0̲
[0̲ - 0 - R - 0 - 0 - 0 - 0 -
- 0 - 0 - 0 - 0 - 0 - 0 - 0̲]
0̲ - 0 - R - 0 - 0 - 0

Profile H

Q - R - R - 0 - Q - Q - Q̲
[Q̲ - Q - Q - Q - S - Q - Q -
- Q - Q - Q - Q - Q - Q - Q̲]
Q̲ - Q - Q - Q - Q - 0

Appendix 3.8 Beach Profile Work.
The principles of Markov Properties.

A Markov chain can be defined as "a stochastic process in which the future development depends only on the present state, but not on the past history of the process, or the manner in which the present state was reached", Collins (1975). It should be noted that this is a first order chain, and is the kind used in this study. In a second order chain, in contrast, the state of the system at time T_2 depends not only on the state at T_1 but also the state at T_0.

Appendix 3.8 continued

Markov chains are particularly useful in studies concerned with problems of movement, either movement from one location to another, or as in this study, from one state to another. Markov chain models are conceptual devices for describing and analysing the nature of changes generated by a movement of variables (Collins, 1975). In some cases Markov models may be used to forecast changes in the future. It is the degree of dependency of the future state on the present which is the Markov property.

The concept of probability is inherrent in Markov chains; every event which occurs may have a probability assigned to it. For most events or courses of action the true fixed probabilities are not known so that they must be estimated or assumed. These estimates should, however, be as accurate or realistic as possible, so that suitable actions may be taken. Markov chains are based on trends in the past, e.g. the previous frequency of occurrence of certain events.

Information relating to past trends (e.g. six months of beach profiles) can be organised into a matrix which is the basic framework of a Markov Model. It is useful to consider an example concerning transitions among three beach types; T, U and V. The probabilities associated with these transitions might be.

	T	U	V	
T	0.6	0.3	0.1	
U	0.2	0.5	0.3	= P
V	0.4	0.1	0.5	

Each element represents the value of the probability of a change from one beach type to another. These are transition probabilities, the overall matrix is the probability transition matrix and each row is a probability vector. For example, of all T-type beaches at one time, 60% remained of that type, 30% became U-type and 10% V-type in a certain time interval. Thus rows, unlike columns, must add up to one.

Assuming a constant number of beach profiles, the redistribution of beach types over a certain time period can be calculated. The initial state of the system can be expressed in terms of a frequency vector (or if percentages are used a probability vector may be used - only frequency vectors were used in the present study).

e.g. $\begin{bmatrix}25 & 15 & 10\end{bmatrix}$

frequency vector

indicating 25 T-types
15 U-types
10 V-types

p(1) would refer to the state of the system after one set of transitions. To obtain the state p(1), then the initial vector or p(0) is multiplied by the Probability Matrix P.

For this example

$$\underset{p(0)}{\begin{bmatrix} 25 & 15 & 10 \end{bmatrix}} \times \underset{P}{\begin{bmatrix} .6 & .3 & .1 \\ .2 & .5 & .3 \\ .4 & .1 & .5 \end{bmatrix}}$$

$$\begin{bmatrix} 15 & 7.5 & 2.5 \\ 3 & 7.5 & 4.5 \\ 4 & 1 & 5 \end{bmatrix}$$

$p(1) = \begin{bmatrix} 22 & 16 & 12 \end{bmatrix}$ i.e. 22 T-type, 16 U-type, 12 V-type

Thus there will be a reduction in the number of T-type profiles and an increase in the numbers of both U-type and V-type profiles. If the probabilities of events remain the same and the total number of profiles is the same then the distribution of profiles after a further time period may be determined.

$$\underset{p(1)}{\begin{bmatrix} 22 & 16 & 12 \end{bmatrix}} \times \begin{bmatrix} .6 & .3 & .1 \\ .2 & .5 & .3 \\ .4 & .1 & .5 \end{bmatrix} = \begin{bmatrix} 21.2 & 15.8 & 13 \end{bmatrix} = p(2)$$

In general $p(n) = p(n - 1) \times P$

Alternatively, instead of multiplying each successive new state by the initial transition matrix, the same results are obtained by multiplying each successive power of the initial transition matrix by the initial state vector. Thus

$$\begin{aligned} p(1) &= p(0) \times P \\ p(2) &= p(0) \times P^2 \\ p(3) &= p(0) \times P^3 \\ p(n) &= p(0) \times P^n \end{aligned}$$

No more than one transition was carried out in this study but successive multiplications could be used to predict well into the future. P^2 would be calculated by following the same procedure as outlines for the vector-matrix multiplication. Each row in the first matrix is multiplied by each column in the second.

$$\begin{bmatrix} .6 & .3 & .1 \\ .2 & .5 & .3 \\ .4 & .1 & .5 \end{bmatrix} \times \begin{bmatrix} .6 & .3 & .1 \\ .2 & .5 & .3 \\ .4 & .1 & .5 \end{bmatrix} = \begin{bmatrix} .46 & .34 & .20 \\ .34 & .34 & .32 \\ .46 & .22 & .32 \end{bmatrix}$$

This method is used in most computer programs with geographical applications as further descriptive measures can be derived from successive powers of the transition matrix, whereas the first procedure reveals only the state of the sytem at the end of each time interval.

All this assumes that the system can in fact be described by a Markov model. The χ^2-test explained in Chapter 3 explains how the data may be tested for their possession of Markov properties.

Further information on Markov chain analysis and it uses can be found in the literature, e.g. approaches to equilibrium and limiting matrices (Krumbein, 1967; Sonu and James, 1973; Collins, 1975).

Appendix 3.9 Beach Profile Work.

Predicted and Observed Transition Matrices from Bulk Model. April to September 1984.

Profile A

$$[2\ \ 2\ \ 13\ \ 1\ \ -\ \ 5\ \ 1] \times P_{bulk} = [2.44\ \ 3.01\ \ 12.28\ \ 1.82\ .52\ \ 3.29\ \ .64]$$

$$\text{observed} = [1\ \ 2\ \ 14\ \ 1\ \ -\ \ 5\ \ 1]$$

transitions:

predicted

.84	.34	.66			.16	
.14	1.38	.36				.12
1.04	.91	8.32	1.04	.39	.91	.39
.05		.32			.10	
						.04
.25		2.5	.25		2.0	
.12	.38	.12		.13	.12	.13

observed

	1				1	
	1	1				
		9	1		2	1
		1				
1		3			1	
					1	

Profile B

$$[6\ \ 3\ \ 9\ \ -\ \ -\ \ 5\ \ 1] \times P_{bulk} = [3.82\ \ 4.1\ \ 10.9\ \ .97\ \ .4\ \ 3.23\ \ .58]$$

$$\text{observed} = [5\ \ 3\ \ 10\ \ -\ \ -\ \ 5\ \ 1]$$

transitions:

predicted

2.52	1.02	1.98			.48	
.21	2.07	.54				.18
.72	.63	5.76	.72	.27	.63	.27
.25		2.5	.25		2	
.12	.38	.12		.13	.12	.13

observed

2	2	1			1	
		3				
2	1	5				1
		1			4	
1						

Profile C

$$[2\ \ 18\ \ -\ \ -\ \ -\ \ -\ \ 4] \times P_{bulk} = [2.58\ \ 14.28\ \ 4.38\ \ -\ \ .52\ \ .64\ \ 1.6]$$

$$\text{observed} = [2\ \ 17\ \ 1\ \ -\ \ -\ \ -\ \ 4]$$

transitions:

predicted

.84	.34	.66			.16	
1.26	12.42	3.24				1.08
.48	1.52	.48		.52	.48	.52

observed

	1	1				
2	13					3
						1

Appendix 3.9 continued

Profile D

$$\begin{bmatrix}10 & 5 & 8 & - & - & - & 1\end{bmatrix} \times P_{bulk} = \begin{bmatrix}5.31 & 6.09 & 9.44 & .64 & .37 & 1.48 & .67\end{bmatrix}$$

$$\text{observed} = \begin{bmatrix}11 & 4 & 8 & - & - & - & 1\end{bmatrix}$$

transitions:
predicted

4.2	1.7	3.3			.8	
.35	3.45	.9				.3
.64	.56	5.12	.64	.24	.56	.24
.12	.38	.12		.13	.12	.13

observed

8		2				
1	2	2				
2	2	3				1
		1				

Profile E

$$\begin{bmatrix}2 & 17 & 5 & - & - & - & -\end{bmatrix} \times P_{bulk} = \begin{bmatrix}2.43 & 12.42 & 6.92 & .4 & .15 & .51 & 1.17\end{bmatrix}$$

$$\text{observed} = \begin{bmatrix}1 & 17 & 6 & - & - & - & -\end{bmatrix}$$

transitions:
predicted

.84	.34	.66				
1.19	11.73	3.06				
.40	.35	3.20				

observed

		2				
	15	2				
1	2	2				

Profile F

$$\begin{bmatrix}1 & - & 18 & 4 & - & 1 & -\end{bmatrix} \times P_{bulk} = \begin{bmatrix}2.11 & 1.43 & 13.63 & 3.61 & .54 & 2.14 & .54\end{bmatrix}$$

$$\text{observed} = \begin{bmatrix}1 & - & 18 & 4 & - & 1 & -\end{bmatrix}$$

transitions:
predicted

.42	.17	.33			.08	
1.44	1.26	11.52	1.44	.54	1.26	.54
.20		1.28	2.12		.40	
.05		.50	.05		.40	

observed

		1				
1		13	3		1	
		3				
		1				

Appendix 3.9 continued

Profile F'

[1 - 5 14 1 3 -] x P_{bulk} = [1.67 .52 9.55 8.01 .95 3.11 .19]

observed = [1 - 6 13 1 3 -]

transitions predicted

.42	.17	.33				
.40	.35	3.2	.40	.15	.35	.15
.7		4.48	7.42		1.4	
		.04	.04	.80	.08	.04
.15		1.5	.15		1.2	

observed

		1				
		2	2	1		
1		2	9		2	
			1			
		1	1		1	

Profile G

[- - 16 - 4 4 -] x P_{bulk} = [1.48 1.12 12.4 1.64 3.68 3.04 .64]

observed = [- - 17 - 3 4 -]

transitions: predicted

1.28	1.12	10.24	1.28	.48	1.12	.48
		.16	.16	3.2	.32	.16
.20		2.0	.20		1.6	

observed

		14			2	
				3	1	
		3			1	

Profile H

[- - 1 - 20 2 1] x P_{bulk} = [.3 .45 2.56 .98 16.16 2.59 .96]

observed = [- - 2 - 19 2 1]

transitions: predicted

.08	.07	.64	.08	.03	.07	.03
		.80	.80	.16	1.6	.80
.10		1.0	.10		.80	
.12	.38	.12		.13	.12	.13

observed

				1		
		1		17	1	1
		1			1	
				1		

Appendix 3.10 Beach Profile Work.

Poisson results for testing alongshore homogeneity of beach transitions:
Results for *bulk* transitions, April to September 1984.

	Transition	Expected	Observed	Probability	>.32	.1-.32	.05-1	<.05
Profile A	M-M	.84	0	≤0 = .4317	*			
	N-N	1.38	1	≤1 = .5986	*			
	O-M	1.04	0	≤0 = .3534	*			
	O-R	.91	2	≥2 = .2313		*		
	R-R	2.00	1	≤1 = .4059	*			
Profile B	M-N	1.02	2	≥2 = .2717		*		
	M-O	1.98	1	≤1 = .4113	*			
	N-O	.54	3	≥3 = .0178				*
	R-O	2.50	1	≤1 = .2872		*		
	O-M	.70	2	≥2 = .1629		*		
	R-R	2.00	4	≥4 = .1431		*		
Profile C	M-M	.84	0	≤0 = .4317	*			
	N-M	1.26	2	≥2 = .3590	*			
	N-R	1.08	3	≥3 = .0950			*	
	S-N	1.52	0	≤0 = .2187		*		
Pofile D	M-M	4.20	8	≥8 = .0644			*	
	N-N	3.45	2	≤2 = .3301	*			
	O-M	.64	2	≥2 = .1354		*		
	O-O	5.12	3	≤3 = .2483		*		
Profile E	N-N	11.73	15	≥15 = .205		*		
	O-N	.35	2	≥2 = .0488				*
	N-O	.66	2	≥2 = .1421		*		
Profile F	O-M	1.44	1	≤1 = .5780	*			
	O-N	1.26	0	≤0 = .2836		*		
	O-P	1.44	3	≥3 = .1764		*		
	P-O	1.28	3	≥3 = .1385		*		
	P-P	2.12	1	≤1 = .3744	*			
Profile F'	O-O	3.20	2	≤2 = .3798	*			
	O-P	.40	2	≥2 = .0620			*	
	P-R	1.40	2	≥2 = .4083	*			
	P-O	4.48	2	≤2 = .1757		*		
Profile G	O-M	1.28	0	≤0 = .2680		*		
	O-N	1.12	0	≤0 = .3262	*			
	R-O	2.00	3	≥3 = .3235	*			
	O-O	10.24	14	≥14 = .1544		*		
	O-R	1.12	2	≥2 = .3084		*		
Profile H	S-Q	.13	1	≥1 = .1220		*		
	O-Q	.03	1	≥1 = .0296				*

Appendix 4.1 A Comparison of the Wind and Wave Records for Holderness

Both wind and wave records were available for the Holderness field site. The wind record was obtained for a point about 1 km inland, and the waves are those for a point 1 km offshore from the field site.

The Figure Appendix 4.1 shows the wind speed, wave height, wind direction and wave direction for the 12-month period from October 1983 to September 1984. Records were available from July 1983 and exhibited the same patterns. The figures emphasise the disparity which may exist between wave and wind records, and very great care would have to be taken if wave data were to be deduced from the wind record. At this site winds blow offshore for the greater part of the year. A few general points can be drawn from these graphs.

When onshore winds blow they are rarely in exactly the same, or even within 20^0 of, the wave direction, but the general patterns of wave height and wind speed to tend to be similar, unless calm wave conditions prevail as they did in August 1984. A fairly good correlation can be seen for the duration of the onshore waves in December 1983, late January 1984 and late February 1984. The difference in wind and wave patterns when offshore winds blow can be seen in October 1983, early January 1984 and early and late July 1984.

There are exceptions to the general trends which have been described. In August 1984 there was no correlation between the onshore windspeed and wave height traces. During part of June 1984 the two records were similar against a background of offshore winds.

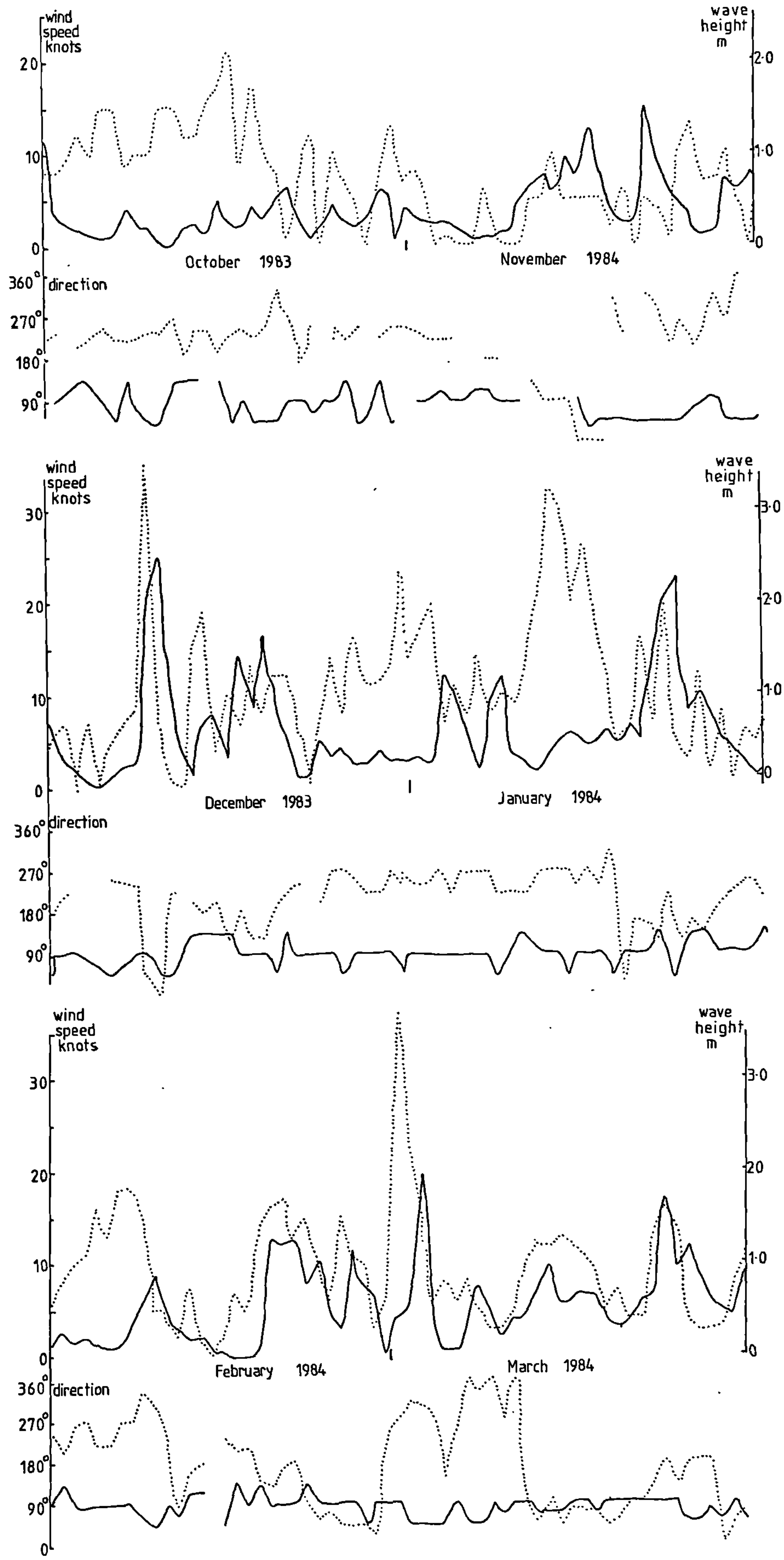
When there is a similarity in wind and wave patterns, a lag is often observed, for example in December 1983 the peaks in the wave height record lag behind the wind speed peaks by 24 hours. The nature of the data is such that it would be impossible to detect lags of less than a day. Similar lags can be seen in late February and early March 1984, and in mid-May 1984.

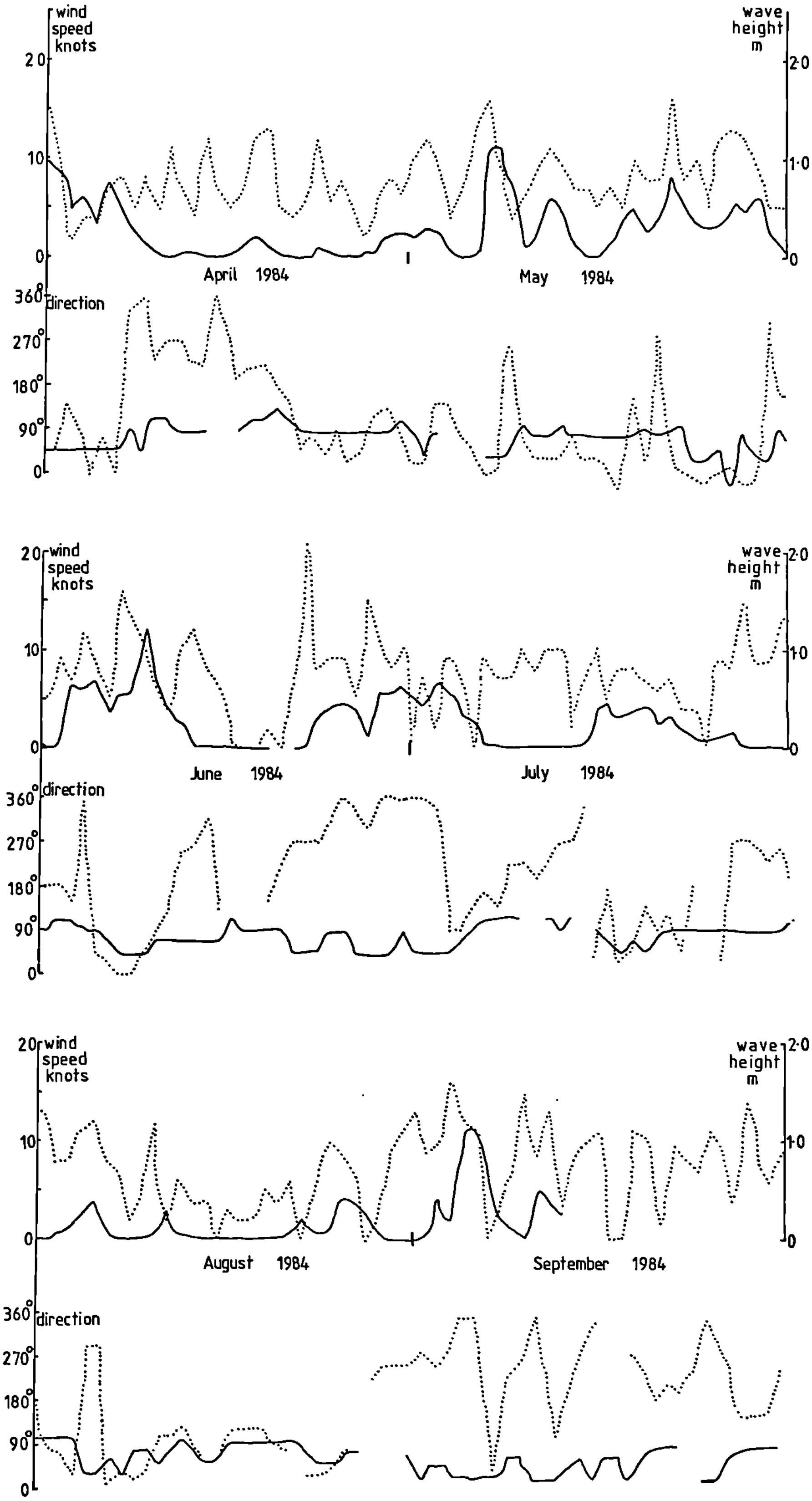
It would be difficult to make any quantitative correlations or predictions from these records. The derivation of wave data from winds must be very unreliable where offshore winds are significant, e.g. on the east coast of Britain and on the North American Great Lakes coast, where Davidson-Arnott and Pollard (1980) recorded onshore winds for only 37% of the time.

Figure Appendix 4.1 Wave and Wind Record for the Holderness, Field Site October 1983-December 1984.

Winds - dotted lines

Waves - solid lines.


wind speed knots
wave height m
20
10
0
2·0
1·0
0
October 1983
November 1984
360°
direction
270°
180°
90°
wind speed knots
wave height m
30
20
10
0
3·0
2·0
1·0
0
December 1983
January 1984
360°
direction
270°
180°
90°
wind speed knots
wave height m
30
20
10
0
3·0
2·0
1·0
0
February 1984
March 1984
360°
direction
270°
180°
90°
0



wind speed knots
wave height m
20
10
0
2·0
1·0
0
April 1984
May 1984
direction
360°
270°
180°
90°
0
wind speed knots
wave height m
20
10
0
2·0
1·0
0
June 1984
July 1984
direction
360°
270°
180°
90°
0
wind speed knots
wave height m
20
10
0
2·0
1·0
0
August 1984
September 1984
direction
360°
270°
180°
90°
0