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Sediment Input from the Norfolk Cliffs, Eastern England—A Century of Coast Protection and Its Effect

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ABSTRACT

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The 33 km of cliffs in northeastern Norfolk, average 25 m high and under natural conditions erosion supplies well over 5 x $10^5 m^3 yr^{-1}$ of sediment to the beach system, of which about two-thirds is sand and gravel. This provides a feed to beaches for a distance of over 60 km downdrift. Today 70% of the cliffs are defended, and the sediment supply has been reduced to 70-75% of its natural level. The reduction is less than was intended by the designers of the defences, but most of these are wooden revetments fronted by permeable groynes, which only succeed in reducing the rate of retreat to about two-thirds of its natural value. Considerable differences are found between the northern coast which is swash-aligned and has low rates of erosion, and the drift-aligned coast with its high rates of littoral drift where rates of erosion are high and defences are less effective.

ADDITIONAL INDEX WORDS: *East Anglia, North Sea coast, feeder bluffs, coastal protection, revetments, groynes, littoral drift, sediment supply.*

INTRODUCTION

The northeastern coast of Norfolk consists of an almost continuous length of cliffs cut into Quaternary sediments resting on Chalk. The Chalk lies above sea-level at the western end of the cliffs at Weybourne, and falls steadily eastwards to the end of the cliffs just south of Happisburgh, a distance of about 33 km, which brings its upper surface down to about 30 m below sea-level. The highest cliffs between Cromer and Mundesley reach 40 m, the average height (if we omit the 2.8 km at Walcott without any cliffs) is a little over 25 m (Figure 1). In plan the cliffs form a convex coast, with the section west of West Runton almost straight for 7.5 km and facing on average 4 degrees east of north, a gradually increasing curvature through to Overstrand (a distance of 6.5 km) and then a fairly straight alignment for another 19 km through to the end of the cliffs beyond Happisburgh. The direction faced by the first 7 km of this southern-most sector averages 31° (range 26–36°) and the remaining 12 km south of Marl Point, Mundesley averages 38° (range 30–47°).

These cliffs have been eroding since sea-level reached its current position about 5,000 years ago, and the average rate of retreat in the first half of this century came close to 1 $m.yr^{-1}$. Retreat rates were highest in the central curved section of coast (where the cliffs are also highest), lower towards the south, and appreciably lower west of West Runton (Figure 2). A sea wall was built at Cromer as early as 1845, but it is only since the end of the last war (1945), and especially since the storm surge of 1953, that defences have been erected along the major part of this cliffed coast. At the beginning of 1987, only 10.5 km (32%) remained undefended, and permission was then granted for a further 0.63 km of revetment and groynes south of Overstrand which were completed in 1988 to bring the defended length to 70% of the total. It seems possible that this may represent the final length of defences as it will be difficult to satisfy cost/benefit criteria for any more schemes: indeed, permission was recently refused for grant in aid of the repair and refurbishment of a length of revetment at Trimingham.

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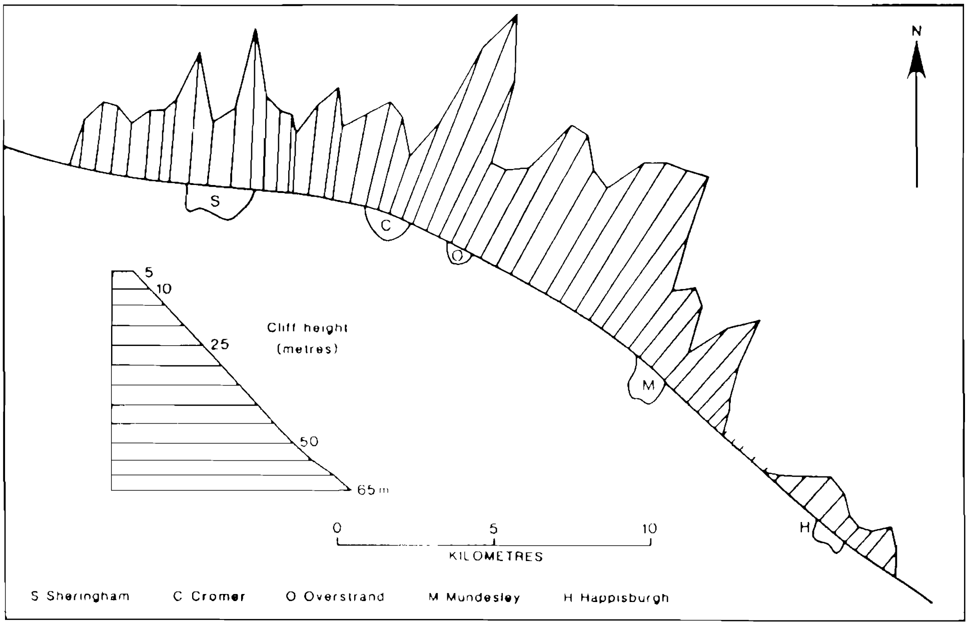

Figure 1. The cliffs of northeast Norfolk cut into Quaternary sediments. Heights are plotted for each of the 60 coastal cells used in the collection and analysis of data throughout this paper.

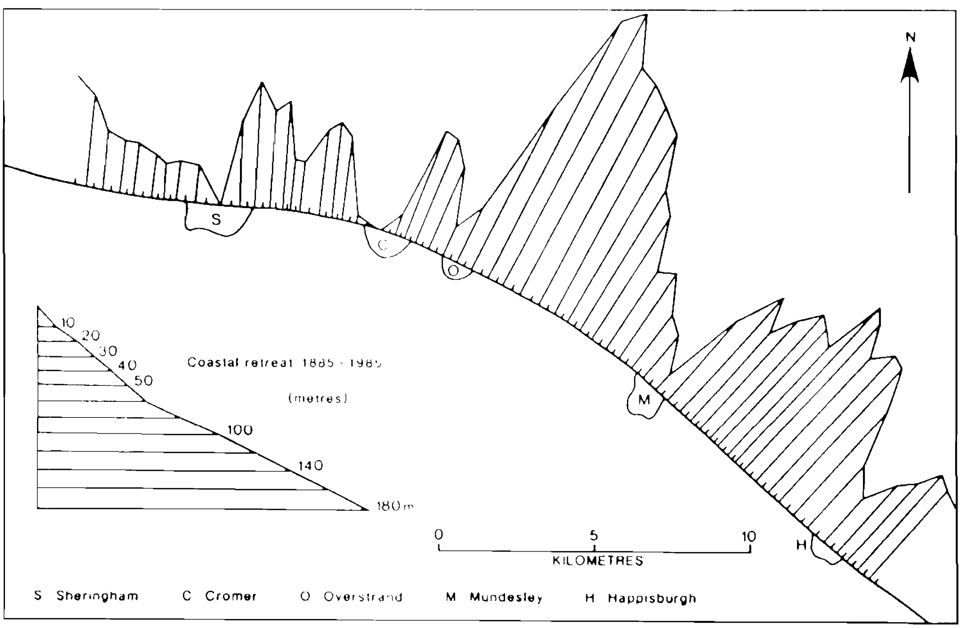

Figure 2. Total coastal retreat between 1885 and 1985. The 1885 coastal outline is taken from the first Ordnance Survey of this area at 1:10,560.

Members of the School of Environmental Sciences at East Anglia have been working on these cliffs for over 15 years. This included a period of particularly intense effort funded by the Department of the Environment when the beach profile monitoring stations were set up and a sediment budget was established. In the course of this work, CAMBERS (1976) has studied the retreat of the cliffs, while CLAYTON, MCCAVE and VINCENT 1983) have published a sediment budget. This paper summarises this work, which apart from these two papers, has mostly been recorded in locally published reports (a full list is appended to this paper). It then goes on to examine the effects of the intervention of man in this very active coastal system.

By taking measurements from published maps, Cambers confirmed that the average rate of retreat of the cliffs from 1880 to 1967 was 0.9 $m.yr^{-1}$, and records of former villages recorded in the *Domesday Book* (1086) and now missing through erosion, as well as other historical accounts, suggest that a similar average rate of erosion has persisted for at least the past 900 years. Indeed, since the waves incident on this coastline have succeeded in cutting back the cliffs 1-2 km over the past 900 years, they have necessarily also created the offshore ramp. The slope of this is such that a metre of retreat requires about 1.5 mm of reduction in ramp level. If this offshore deepening has been possible over a period when sea-level change was small, it is likely to have been a feature of the entire period since 5,000 BP when sea-level rose to within a metre or two of the position it has held ever since. It thus seems likely that these cliffs have been eroding at about the present rate for some 5000 years.

The measurements by Cambers established that the erosion of the Norfolk cliffs furnishes well over 500,000 m^3y^{-1} of sediment, and that up to two-thirds of this represents sand and gravel which may remain in the beach system. Littoral drift transports this sediment: a small part moves westwards along the North Norfolk coast, but most moves southwards Lowestoft (Figure 3) (CLAYTON, MCCAVE & VINCENT, 1983). Thus the beaches south of the cliffs for the 42 km to Lowestoft are largely, if not entirely, dependent on the cliffs for their throughput of sand. This sediment movement has been modelled and predicted by computer-based work on wave energies (supported by coastal observations by amateur wave observers) and confirmed by the tendency of the beach sediment to coarsen down the drift path through the preferential offshore loss of fines (MCCAVE, 1978).

The sediment which moves southwards is gradually lost to the offshore zone, where it is moved by tidal currents in a complex zone of submerged sandbanks. These banks provide a check on the concept that these cliffs have been eroding for several thousand years, for their volume is of the same order as the total volume of sand which is produced by extrapolating the current annual rate of sediment produced by cliff erosion, *i.e. c.* 2 x 10^9 m^3.

The various structures built along almost 70% of the cliffed coast have been designed to halt erosion, so we would expect the sediment output to have declined over the last few decades. However, it is also likely that the rate of erosion varies from one decade to another with climatic change, for this will influence the wave energy incident on the cliffs through variations in wind direction and the frequency of storms. Thus long-term changes in sediment output cannot simply be ascribed to the building of engineering structures, though where comparisons are made between defended and undefended coasts over the same time period this problem is avoided.

Recent work carried out by the author for the Nature Conservancy Council (CLAYTON & COVENTRY, 1986) was designed to examine the effectiveness of the revetments commonly found along this coast, and thus aimed to measure as accurately as possible the temporal and spatial pattern of erosion along the cliffed coast. This was achieved by measuring successive positions of the cliff top from published maps at 1:10,560 (and more recently 1:10,000) and converting these measurements into annual rates of retreat. As cliff height is also known, total sediment production could be calculated for any combination of coastal length and time period from 1880 to 1980. The error in determining cliff top position from the Ordnance Survey maps is about 0.1 mm, or 2.5 m. As the total retreat is on average 100 m, the overall error is less than 5%, though this rises to about 10% for the shorter periods of c. 30 years between successive measurements.

These data allowed us to determine the short-

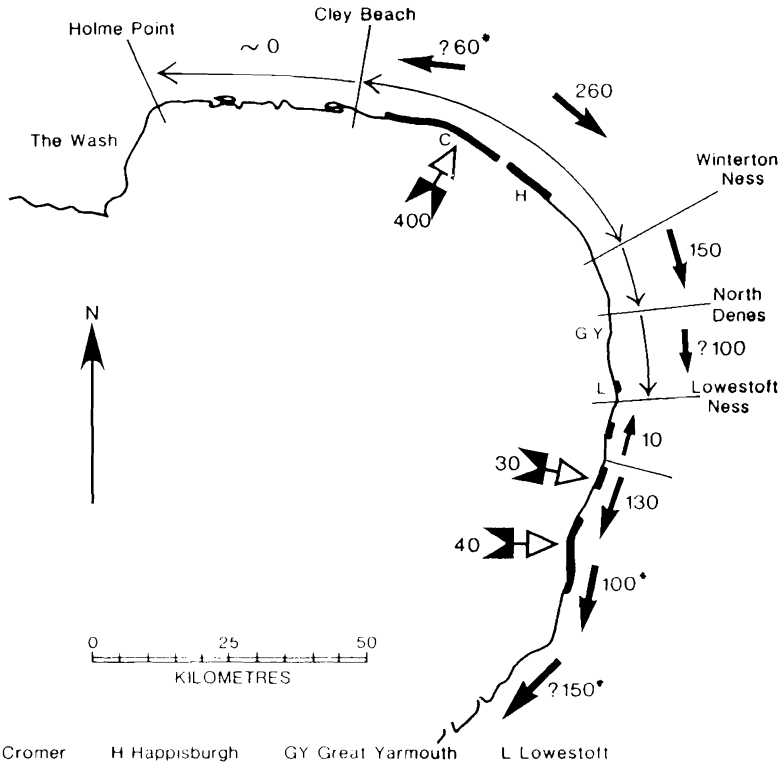

Figure 3. Sediment budget (sand) of the East Anglian coast showing the length of coast dependent on sediment derived from erosion of the northeast Norfolk cliffs between Weybourne and Happisburgh. Cliff input and (net) littoral drift values are in $10^3 m^3 yr^{-1}$. The queries apply to the annual totals, not to the direction of drift which is certain. The asterisks indicate theoretical values along shingle coasts where lack of sand precludes the transport capacity being reached.

and long-term effects of engineering structures, and also to investigate more detailed issues, such as the effect of omitting planks from revetments (Figure 4) in an attempt to allow some continued erosion at important geological sites. The detailed results for the different structures in different environments will be examined first, followed by a summary of the overall effect of coastal protection along these cliffs on the sediment input to the coastal system.

DATA COLLECTED

The coast was divided up into 60 cells; 57 averaging about 0.57 km length and three small lengths of wall (each about 100 m). The boundaries between cells were related to the structures found along the coast and all changes in type of defence coincided with cell boundaries (though not *vice versa*). Sixteen cells had seawalls or other hard structures, 27 had revetments (with various designs of groyne) and 17 were undefended (Figure 5). Using the various editions of the Ordnance Survey "Six Inch" map (1:10,560—now issued as a metric sheet at 1:10,000) from the first edition of 1880, supplemented by air photographs since 1960, the amount of retreat was determined for each cell by measurement at at least two or three identifiable points. This could only be done satisfactorily using the top edge of the cliff; it is not feasible to map the bottom of the cliff consistently from maps or air photographs. Mean cliff height was also determined for each cell. Finally, the date of installation of the first sea defences was determined for each cell. Thus over the years, an increasing number of the cells is protected by engineering structures

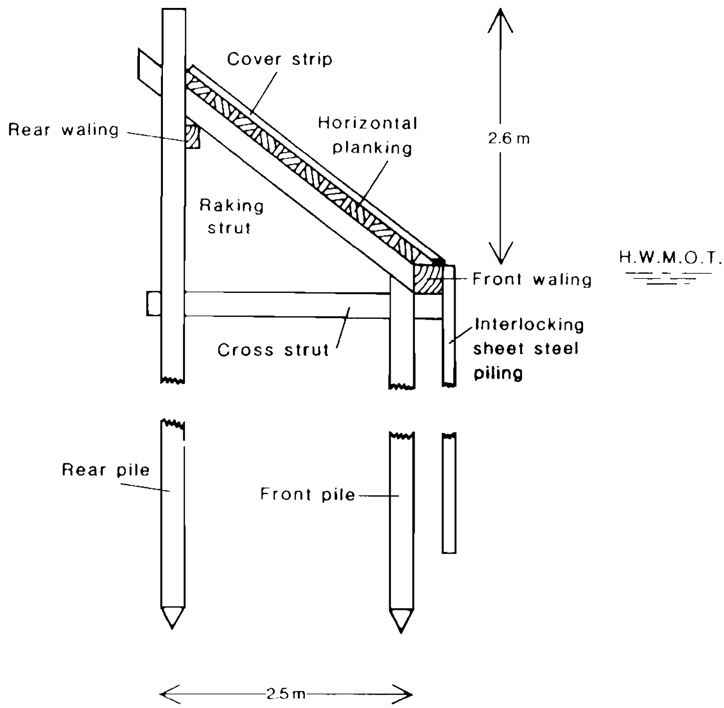

Figure 4. Cross section through a sloping timber revetment as commonly constructed below cliffs along the frontage of the North Norfolk District Council. Most lengths of revetments are fronted by permeable groynes.

(Table 1). The final line of Table 1 represents a length of 628 m immediately south of Overstrand which was being built in 1987; as already noted, it may well prove to be the last addition to this coastal system.

From the data, average rates of retreat can be determined on a number of bases and for varying time periods. Current rates of retreat can be compared with historical rates, and rates after the construction of defences can be compared with rates under natural conditions. The effectiveness of different types of structure can be compared and finally the total output of sediment from cliff erosion can be calculated over time.

THE RELATIVE EFFECTIVENESS OF DIFFERENT STRUCTURES

Table 2 shows the ranking of coastal retreat rates over the last ten years for various types of structure. It is remarkable that impermeable groynes (though these are uncommon along this coast) prove as effective as sea walls, and the average figure for all revetments is clearly influenced by those with impermeable groynes in front of them. The combination of revetments with permeable groynes gives an average retreat figure only 33% below that of the undefended coast. This is an unimpressive result when it is realised that these structures currently cost £1.6M.km^{-1}.

While the effectiveness of coastal protection structures is evident from the data, particularly in the years immediately after they are built, their limitations in reducing erosion are also apparent from consideration of beach levels. At 11 sites along this coast we have surveyed beach levels several times a year from 1974-1980 and occasionally since then. Comparison of sweep zones for these sites allows an estimate of the rate of beach lowering which may be represented (given the consistent beach slope over time) as an annual retreat value. Over several decades, both beach and cliff must attain the same retreat rates, but differ for

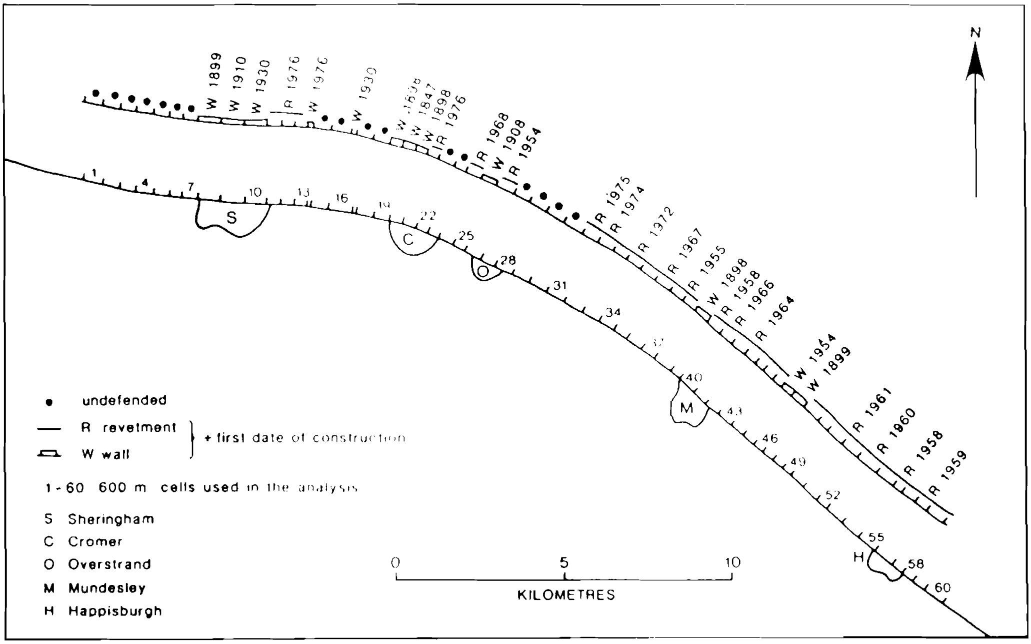

Figure 5. The date of first construction of coastal defences for each of the 60 coastal cells along the cliffed portion of the northeast Norfolk coast.

Table 1. *Stages in the extension of the coastal defence structures along the cliffed coastline of Norfolk.*

Year	No. cells defended	Length defended (km)	% defended
1885-1905	1	0.52	2
1946	6	3.39	10
1952	9	4.65	14
1954	15	8.01	24
1955	17	8.56	26
1958	18	9.06	27
1959	21	10.42	32
1960	23	11.46	35
1961	26	13.15	40
1964	28	14.77	45
1966	30	16.19	49
1967	32	17.32	52
1969	33	17.80	54
1972	36	19.42	59
1974	37	19.93	60
1975	39	20.96	64
1976	43	22.40	68
1987	44	23.03	70

Table 2 *Ranking of rate of retreat values, 1975-1985, for the entire 33 km of coast by type of structure.*

Structure	Rate of Retreat ($m.yr^{-1}$)
Walls	0.08
Effective (impermeable) groynes	0.085
Effective groynes excluding those fronting walls	0.110
All defended coast	0.209
Revetments	0.30
Ineffective (permeable) groynes	0.337
Average of all values	0.366
Revetments with permeable groynes	0.467
Undefended	0.699

shorter periods, and we might expect the cliff (but not the beach) to be protected by the revetments since this is their design and purpose. Broadly, this is the case (Table 3). At the one undefended site, the beach is retreating faster than the cliff in this seven-year period. At three sites of the five with walls, retreat is halted and the beach is stable; at the remaining two the beach is falling, very rapidly indeed in the case of Walcott. At two revetment sites both beach and the cliff are retreating at the same rate, while at the remaining three revetment sites, the beach is falling, though the cliffs are receiving some protection.

Table 3. *Rates of retreat measured at surveyed beach profile sites compared with the rates of cliff-top retreat at the same sites (1974-1980).*

Sector number (Fig 5)	Cliff-top Retreat (m. yr^{-1})	Sweep-zone Retreat (m. yr^{-1})	Type of Coastal Defence
01	0.33	2.00	none
08	0.00	0.00	wall
09	0.00	0.60	wall
10	0.10	0.00	wall
20	0.00	0.80	wall
26	0.22	0.20	revetment
37	0.00	0.40	revetment
41	0.00	0.00	wall
50	0.00	4.80	wall
57	0.31	0.30	revetment
60	0.27	1.80	revetment (replaced by wall in 1986)

Some additional information on the effect of revetments on the beach in front of them was gained from the measurements carried out at West Runton after the installation of the revetment and groynes there. At the request of the Nature Conservancy Council, two lengths of revetment were built in 1974 with fewer horizontal planks on them in the hope that this would maintain sufficient erosion on the cliffs to keep important geological exposures clean. This did not work, in part because large flints eroded from the coastal platform in this sector built a permeable berm behind the revetment. But monitoring also showed that the beach in front of the revetment was lowered far less rapidly where the planks were missing than in front of the unmodified sections. This suggests that the normal revetment design, despite its slope of about 45°, is reflective and so causes beach scour in front. In this case, the benefits from revetments will be short-lived, for there is little to be gained by protecting the cliff at the expense of more rapid lowering of the beach in front.

TOTAL SEDIMENT OUTPUT

Annual sediment output from these cliffs has been calculated for six periods (Table 4). This is the total volume eroded from the cliffs and includes mud (silt plus clay) which immediately moves offshore (MCCAVE, 1987). By systematically sampling the cliff, CAMBERS (1976) measured the proportion of mud as one-third by volume, and the totals in Table 4 should be abated by this amount to derive the volume of sand and gravel contributed to the beaches. It will be seen that the total fell to under 70% of the 1885-1905 level by 1975, but recovered to 74% by 1985. This recovery probably results from the resumption of erosion behind revetments following an initial reduction after they are constructed and while beach levels remain reasonably high. As time goes by, erosion resumes, despite the barrier represented by the revetment. However, interpretation should also allow for climatic change (wind direction and frequency of storms affecting the coast); thus the drop of 7% in 1905-1946 compared with 1885-1905 reflects changing climatic conditions rather than the effectiveness of the earliest lengths of coastal engineering structures. Support for this view comes from the shift of erosion from the north-facing coast from 1885-1905 (when it contributed 34% of the total volume) to 1906-46 when it contributed only 22% of the volume. Indeed, despite the overall decline between the two periods of 7%, the output from the SE sector rose by 10%.

Table 5 shows the proportion of material contributed from undefended cliffs (with the residual from defended cliffs) over the years and Table 1 shows the changing proportions of the coast with defences. It should be noted that some of the most rapidly eroding sections of coast remain undefended and that these are also the highest cliffs. Nevertheless, the cliffs protected by revetments still contribute appreciable volumes of sediment to the beach system. There is also some evidence that the protection of most of this coast has been at the cost of slightly more rapid erosion on the undefended sectors. These figures are given in Table 5, where the 1985 rates for the remaining undefended cells are compared with the earlier values for the same cells.

THE SWASH-ALIGNED, DRIFT-ALIGNED CONTRAST

A major contrast appears in all these data between the undefended cliffs which face north and the cliffs facing north-east. Those facing north are fronted by a swash-aligned beach (DAVIES, 1980, pp. 135-139) and suffer less erosion than the cliffs backing the drift-aligned

Table 4. *Annual volume of sediment delivered by cliff erosion (all volumes in $10^3m^3yr^{-1}$).*

	1885-1905	1906-1946	1947-1955	1965	1975	1985
Total	595	552	552	552	413	442
% of 1885-1905	100	93	93	93	69	74
From behind revetments	n/a	n/a	3	61	94	158

Table 5. *Comparison of volume of sediment produced by the 13 cells which remain undefended (all volumes in $10^3m^3yr^{-1}$)*

	1885-1905	1906-1946	1965	1975	1985
N-facing coast	27	15	15	27	27
W. Runton—Overstrand	59	41	54	7	7
Overstrand—Marl Point	234	224	192	245	245
Total from still undefended	321	280	261	280	280
Total from 33 km cliffs	595	552	552	413	442
% from these 13 cells	54	51	47	68	63

beaches southeast of Cromer. A complication is the existence of a chalk wave-cut platform in front of the north-facing cliffs which is missing east and southeast of West Runton, but it is not thought that this is the most important factor influencing the rate of retreat. Rather it is the retention of material (which includes many large flints) on the swash aligned coast and the rapid removal of material by longshore drift on the drift-aligned coast. Some support for this view is found in the effectiveness of impermeable groynes in reducing erosion, and also from the rates prior to the construction of defences; the mean rate of retreat either side of Sheringham, between 1885 and 1905 was 0.5 m/yr.

The sediment volumes from cliff erosion may be divided into material from the swash-aligned coast and that from the drift aligned sector. This shows that prior to the construction of defences, 33% of the sediment volume came from the swash-aligned coast, but that the figure is now under 19%. In other words, coastal protection structures have had far greater success on the swash-aligned coast than on the drift-aligned coast. By 1985 the swash-aligned coast was producing only 40% of the 1885-1905 volume (though 68% of the 1906–46 volume). The drift-aligned coast was producing 92% of the 1885-1905 volume and 83% of the 1906-46 volume. Thus without any more refined attempt to establish the most representative "natural" figure, the defences appeared to have reduced sediment output by about half on the north-facing coast, but only by about 10-15% on the southeast-facing coast. This difference applies to all types of coastal structure used in this area and Table 7 shows the contrast in each case.

One other significant observation from Table 6 is that while impermeable groynes appear to be the most effective structures on the drift-aligned coast, they are relatively ineffective on the swash-aligned coast where sediment is slow to drift into the groynes to improve the beach volume and orientation. This situation is aggravated by the fact that when groynes are constructed in Britain, normally they are left to accumulate sand through natural processes and the compartments are not filled after construction as is often the case in other countries. Indeed we may generalise and suggest that from this evidence, beach-parallel structures such as revetments and groynes are relatively ineffective on the drift-aligned coast, and structures normal to the beach are relatively ineffective on the swash-aligned coast.

THE IMPLICATIONS OF CLIFF PROTECTION

As has been shown in our earlier work, the Norfolk cliffs act as feeder bluffs for the sand beaches downdrift, especially southwards towards Yarmouth and even Lowestoft. This earlier work has also established that the rate of movement averages about 1.5 km.yr^{-1}. As this study shows, there was a natural reduction in the sediment output from the high value between 1885-1905, but that this was followed by a sharp dip in the earlier 1970's from which

Table 6. *Comparison of rate of retreat values* ($m.yr^{-1}$), 1975-1985, for the north-facing (swash-aligned) and north-east-facing (drift-aligned) coast by type of structure.

	$m.yr^{-1}$ N-facing	$m.yr^{-1}$ NE-facing	swash/drift %
Walls	0.01	0.13	8
Effective (impermeable) groynes	0.10	0.074	135
Effective groynes not fronting walls	0.18	0.08	225
All defended coast	0.09	0.26	35
Revetments	0.21	0.32	66
Average of all values	0.19	0.50	38
Revetments with permeable groynes	0.215	0.487	44
Undefended	0.26	2.13	12

there has been a partial recovery. If our estimates of the drift rate are of the right order, the lowest volume of output should by now have moved some 25 km downdrift from the midpoint of the supply—say Trimingham. This means that the beaches north of Winterton will have been affected, but not those to the south. Thus the low beaches currently to the south of Happisburgh and at Sea Palling (where the beach is now lower than at any time in the last 5,000 years) may well be linked with the defence of the cliffs, the recent fall in beach level at Hemsby (2 km south of Winterton Ness) is likely to have a different cause.

This lower sand volume will become increasingly difficult to identify as it moves south and its effects will be less significant. Nevertheless, along a coastline with no more protection than a single line of dunes resting on a post-1953 wall, and with relatively low ground towards the Broads drainage behind, any reduction in beach levels is unwelcome. For this reason alone, we may hope that current cost/benefit tests make further extension of the cliff defences impossible; indeed extension of cost/benefit assessment to include the downdrift beaches might make the case for the gradual abandonment of those revetments fronting agricultural land.

However that may be, it is to be hoped that cost/benefit assessments will not rest on the assumption that revetments will succeed in bringing erosion to an end; the record of their limited effectiveness portrayed in Tables 2 and 6 shows that a realistic assessment requires some allowance for continuing erosion. With the requirement to present cost/benefit appraisals of coast protection schemes, there has been a tendency to secure "good" figures by making high estimates of rates of erosion (often based on the few years of rapid erosion which have triggered the demand for a scheme) and by the assumption that the defences will completely halt erosion for periods up to 60 years. In the absence of readily-available long-term data for many coastal situations, these figures have often been accepted without challenge. The post-1953 record of limited success in coastal protection along this difficult coast is now long enough, and firm enough, for more rational decisions in the years ahead.

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