CHAPTER EIGHTY EIGHT

FLUCTUATIONS IN LITTORAL DRIFT

Richard Silvester[1]

ABSTRACT

The long assumed uniform movement of sand along the coast produced by wave action can be disputed when the interaction of storm sequences and swell is considered. Storm waves form a protective bar, which essentially puts material back into circulation for the oblique swell to work upon. The resulting longshore transport is swift whilst the bar exists but decreases to negligible proportions once it is denuded and the normal swell-built beach profile recurs. This impulsive drift has many implications for engineers and geomorphologists and to researchers attempting to predict annual rates of transport.

WAVE CLIMATE

In oceans a distinction can be made between storm waves and swell. The former are in the fetch, where winds are still generating them or maintaning a fully arisen sea. Swell is the term for waves that are dispersing across the sea outside the fetch. Since the energy concentrated in the relatively small storm zone is now spread over vast areas downwind of generation the wave heights must necessarily decrease (Silvester 1974). The characteristics of these two systems are specific in their influence on a mobile bed at the shoreline.

Storm waves are multi-directional from their mode of generation and due to the many fetches encompassed by a cyclone as it passes near or across the coast. They are continually breaking as the shorter waves steepen on the crests of longer waves, to pour down their front faces and so aid their growth. (Longuet-Higgins and Stewart 1960). Their optimum steepness implies that all waves contain much water above the SWL. Another characteristic of distinct importance is their short duration as on any coast a storm lasts for a few days only, with few repetitions annually.

Swell at any point in the dispersal area consists of waves propagating within a small fan of directions, encompassed by orthogonals to the side boundaries of the fetch. Thus swell waves arrive on a coast from persistent directions, certainly within the same quadrant, from the storm zones which are repetitive from month to month and year to year. In so spreading they take longer to arrive at a given shoreline, as recorded by Snodgrass et al (1966). On most western margins of continents swell arrives continually from the constant generation zones between 40° and 60° latitudes where cyclones travel from west to east. On eastern margins swell is more variable in direction throughout the year.

1. Department of Civil Eng., University of W.A. Nedlands, W.Aust.

Storm waves are variable in time until the fully arisen state is achieved and then vary at different points along the fetch. Swell, on the other hand, varies with distance from fetch and also continually with time. As components of the storm spectrum pass any point so the height and period change. The long low waves arrive first, followed by the high medium band of the spectral peak, after which the low period end of the spectrum arrives. It is therefore difficult for researchers to choose some mean wave condition for correlation with sediment transport over an annual period.

SHORELINE PROCESSES

If there is a sedimentation problem on a section of coast it is due to longshore transport which results in either siltation or erosion, or generally both. It is axiomatic that the persistent swell waves, which effect this movement, are arriving obliquely to the coast, in order that there is a longshore component of energy on breaking.

In crossing the continental shelf these waves are refracted and steepened as they travel into shallower water. The water particles at the bed oscillate and hence disturb the bed but they also suffer a net movement in the direction of wave motion, known as mass-transport. This varies throughout the water column, as seen in Figure 1, with the depth ratio, but for long period swell it is maximum at the bed. (Longuet-Higgins 1953). It may take weeks for this distribution to diffuse from the bed and sea surface for any wave train but is immediately

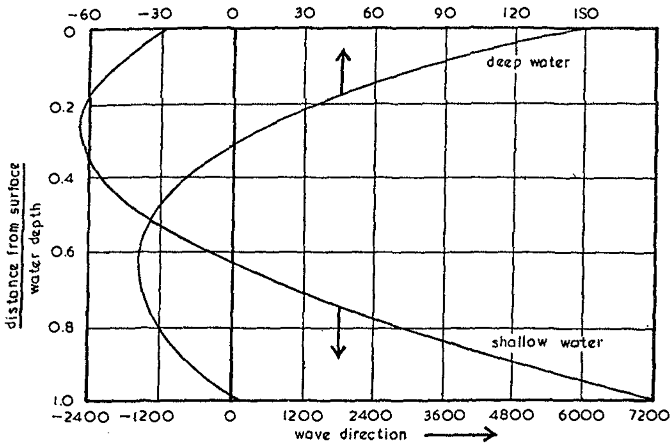


Fig 1. Mass transport due to waves, where X is net movement per wave period T for height H, and g is accelerative due to gravity assuming a flat bed and laminar boundary layer.

available at the bed. Thus a sweeping motion is exerted on the sedimentary particles towards the shore, and along it, beyond the breaker zone.

When these swell waves are steepened to an unstable steepness they break and then proceed as a bore towards the beach, thus forming the surf zone. Much sediment is suspended by the bore which then carries it up the face of the beach, as seen in Figure 2. The water carried in this uprush percolates through the berm down to a water table at about mean sea level. This is possible whilst there is a reasonable time between each wave, which is the case for swell.

This percolation reduces the volume of downwash so causing the sand carried up to be stranded on the beach, which results in accretion. Such build-up continues so long as their is sufficient material offshore to be fed to the breaking waves. Freshly deposited sand is loose which aids percolation. After persistent swashing by waves the beach face becomes well compacted.

When storm waves arrive to this swell-built profile a crest breaks almost every second, resulting in large volumes of water running up the beach face. This saturates the beach, as seen in Figure 2,

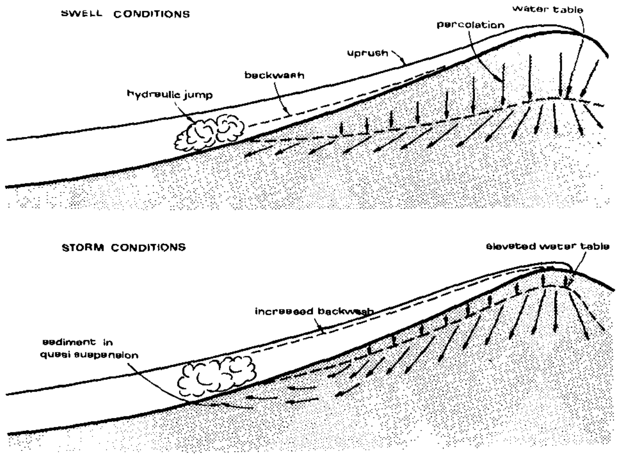


Fig 2. Beach processes for swell and storm conditions.

causing the water table to become almost coincident with the face. The downrush equals the uprush which drags sand down the slope, forming a larger than normal hydraulic jump at the toe. This occurs in the zone where ground water is rising almost vertically in returning to the sea. This sets up a liquefaction or "quick-sand" condition which results in swift erosion and consequent collapsing of the beach face. This creates a near vertical face against which waves reflect. It is little wonder that the beach is eroded metres in a matter of minutes.

The mass of water thrown onto the beach must return to the sea, in this case laden with sand. This runs as a density current hugging the bed, aided by the strong shoreward current at the surface due to the storm wind shear force. As deeper water is reached the velocity is reduced, so causing the sediment load to be dropped. A mound is formed some distance offshore which grows during the storm until the depth over it is sufficiently small for incoming waves to break over it. (See Figure 3). This breaking is also assisted by the seaward current from excess water returning to the sea. At this stage the major erosion ceases.

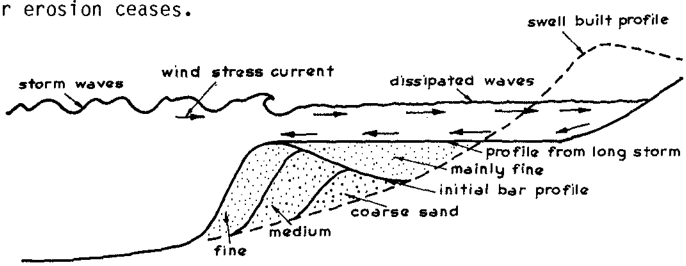


Fig 3. Offshore bar profiles during formation showing sediment sorting.

The first storm of the winter season exerts the greatest influence on the beach when the recession can be accepted as the maximum for the year. Only two situations can cause greater erosion. If a second storm is accompanied by a higher water level, due to a storm surge, or spring tide height, the bar must be elevated to break the waves. Also, if a subsequent storm is of longer duration the attenuated waves reaching the receded new vertical beach face can remove further material which fills the swale between bar and beach with the aid of the circulating current, as seen in Figure 3. An almost horizontal platform could result (Silvester 1979).

This natural sequence of forming a protective bar by storm waves is beautiful to behold. If it did not occur the previously accreted shoreline might be spread evenly over the seabed. It is a mechanism man cannot hope to emulate due to the large volume of material involved. Suggestions that a permanent bar be constructed by rubble-mounds is to no avail since the oblique swell waves would reflect from this submerged structure and scour the bed adjacent to it, so causing costly remedial measures. (Silvester 1977).

RETURN OF BAR

Part of this exciting phenomenon of coastal defense is the dismantling of the bar when it is no longer required. This is accomplished by the swell following the storm, either immediately or perhaps some weeks later. These break over the bar causing excessive suspension of sand which is redeposited on the beach. The berm is rebuilt up to the uprush of the waves. This is small initially as waves are well attenuated in traversing the bar and the wide surf zone. As the bar is lowered and the surf zone decreases in width so the run-up increases and hence the height of the berm. This is why the back berm can be lower than the seaward edge and shallow pools exist on it. The present discussion omits any influence of tides, which will have little effect until they exceed 2 m range.

The seaward slope of the offshore bar could be steeper than the swell built beach as it results from deposition by a seaward current and opposing mass-transport of waves. As swell waves traverse this face their ratio of breaking to deep-water wave height increases, which must result in a stronger littoral current, which is dependent on the square of the breaking wave height. This current is therefore magnified concurrently with enlarged suspension and so results in a great pulse of drift alongshore. This is aided by the larger surf zone width since the total transport is the summation of rates across this normal to the beach, even extending beyond the breaker line. (Andersen and Fredsøe 1983). As sand is pushed shorewards the surf zone becomes very flat.

This excessive littoral drift exists whilst the bar is being returned to the beach, which may take two to three weeks with reasonable swell input. Japanese engineers have concluded that 90% of this transport can take place over two weeks and 10% over the remainder of the year. As can be imagined, the rate is optimum directly after the storm but reduces as the bar recedes and the normal parabolic profile is approached. This is due to the diminishing effect of the bar slope on the waves and the decreasing width of the surf zone. The suggested distribution over time is depicted in Figure 4, which requires

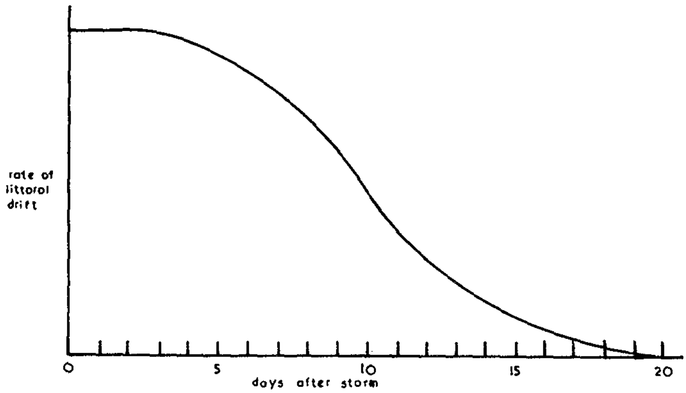


Fig 4. Suggested variation in littoral drift as bar material is replaced on beach.

verification from field measurements. To measure these peaks in drift it would be necessary to monitor accretion in sand spits or against some structures at daily intervals over the two or three weeks until the bar had disappeared, which would require profiling of the bar to ascertain its state.

FLUCTUATIONS IN LITTORAL DRIFT

The importance of this phenomenon of pulses in longshore transport warrants a little more discussion of the reasons for it. As stated earlier the seaward slope of the bar could be steeper than the bed approaching the swell built profile where the surf zone exists. Whilst this mound could be spread widely by the storm waves and outgoing current during the storm the swell waves could quickly steepen it by their mass-transport in these shoaling conditions. It may be inferred that water entering the valley between bar and beach will inhibit this steepening, but this seaward flow is generally accomplished by rip currents forming at weak spots in the bar. It is well known that these dangerous currents occur just after storms, and hence flow is minimal over most of the bar.

The ratio of breaker height to deep-water height (H_b/H_o) varies with deep-water wave steepness, but for any value of this ratio varies with the bed slope as in Figure 5 (Goda 1970). The ratio of crest height to deep-water wave height is decreased tending to make surging rather than plunging breakers. Another trend is for the wave front to become steeper (Adeyemo 1968) with increasing slope, again improving the ability to generate a littoral current through greater mass-transport. There is also the possibility of refraction lagging that from a midly sloped bed thus increasing the angle at breaking, but this phenomenon has not been reported to the author's knowledge.

Once the waves have broken at the apex of the bar they then traverse obliquely either a swale or even two or three such depressions before arriving at the beach. As noted already these valleys may be filled with sediment if the storm duration is long. In any case they could well be smoothed out by the transport of sediment from the peaks before material is finally replaced on the beach. The resultant bed within the surf zone therefore could be very mildly sloped. This causes the broken waves to reduce more slowly in height as they proceed to the beach face. This again creates better conditions for a strong littoral current.

Another factor to be taken into consideration is the partial reflection of the swell waves from this relatively steep slope of the bar. Battjes (1974) has shown that when the surf similarity parameter [$= \tan\alpha/\sqrt{H_b/L_o}$] has a value of 2.3 it "corresponds to a regime about half way between complete reflection and complete breaking." These reflected waves, which must necessarily be angled to the bar, interact with the incident waves to establish a short-crested system (Silvester 1974) whose orbital motions are conducive to sediment suspension with a large mass-transport alongshore. This action will cause an excessive drift on the face of the bar beyond the breaker line, which could exceed values estimated from the littoral current expanding from the surf zone.

To show the possibility of this parameter being of this order consider a storm system with a wind speed ($U_{19.5}$) of 30 knots in which case the component with most energy has a period of 10 seconds (Silvester 1974). The steepest bed slope as the swell arrives could be 1:6. If

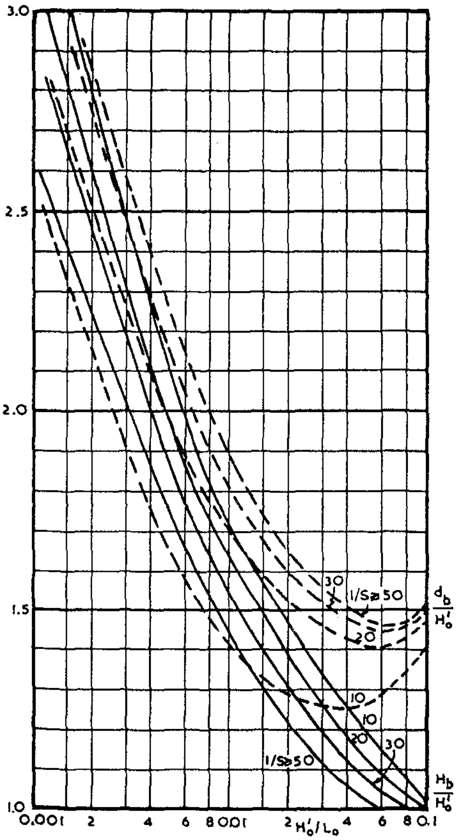


Fig 5. Parameters of breaking waves as presentd by Goda (1970).

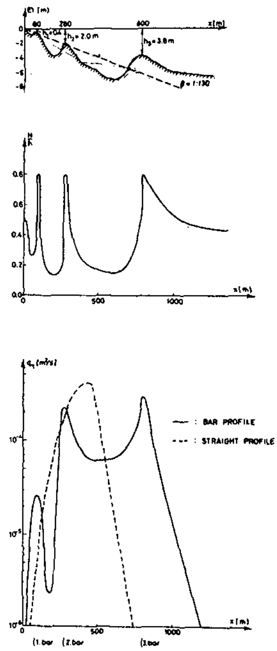
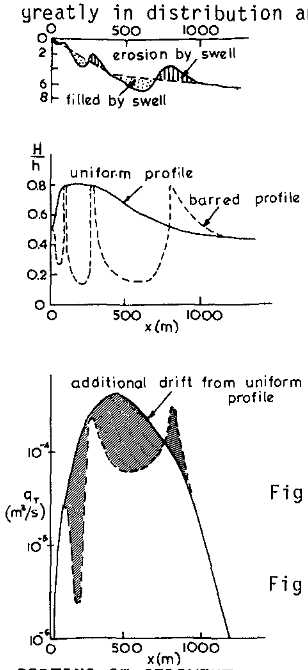


Fig 6. (a) Measured coast profile at the Danish west coast.
(b) Variation in wave height towards the coast.
(c) Computed sediment transport at the coast depicted in (a).
Taken from Anderson and Fredsøe (1983).

these waves arrive from a distant fetch their deep water height is of the order of 0.5 m, which near breaking could be doubled to 1.0 metre. Substitution in the above parameter gives a value of 2.07. If 12 seconds were used it becomes 2.5, so that the critical value of 2.3 could readily occur.

Andersen and Fredsøe (1983) have computed littoral drift along a barred beach and compared it to that on an equivalent uniformly sloped profile. Figure 6 is taken from this reference where it is seen that the three bars in (a) cause local increases in H/h as in (b), from which values of q have been derived as in (c). The distribution of transport for the equivalent uniform slope is doted in (c). Areas under these curves give the total rate of transport, which are essentially the same for barred and uniformly sloping beaches. An alternative progression is illustrated in Figure 7, where the swales are filled by bars seaward of them. This could result in two uniform slopes as shown in (a) which could result in the H/h curve as in (b). The q_T curve in (c) is based upon relationships indicated in Figure 6, which could result in greater overall transport. Taking in all the inaccuracies of these suppositions there is indicated the propensity for excessive drift whilst sand is being transported back to the beach.

Verification in models should be carried out on the littoral current generated on a barred beach, a uniform slope and the parabolic shape produced by swell waves. Realistic profiles could be formed in a fixed bed to confirm whether littoral current velocities differ greatly in distribution and overall discharge.



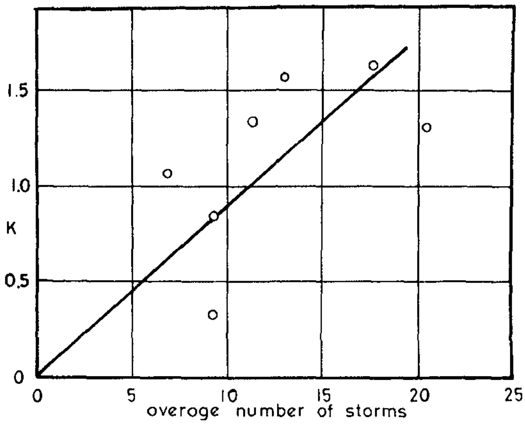


Fig 8. Values of k (Dean et al 1982) versus number of storms during periodic assessment of littoral drift.

Fig 7. Modified transport distribution for a saturated bar with equivalent uniformly sloped beach from Fig 6.

SORTING OF SEDIMENT

Another process worthy of consideration is the sorting that takes place of sand during the formation and ultimate replacement of Nature's protective bar. When the density current, at the initiation of erosion, slows down the first sand particles to be dropped are coarse, followed seawards by the median and fine components. As seen in Figure 3, the bar will comprise coarse sand at its landward base, median material in the middle, whilst the top and seaward face consist of the smallest grains.

When the swell commences to return the bar to the beach it is the finer material that is acted upon first. This is the stage when breakers are greatest, turbulence is optimum and the current is maximum. This small diameter sand is suspended more readily so that it is moved well downcoast from its original position by the time it is deposited on the back of the berm. Thus distribution aids the sorting in the next bar that is formed.

The median sand will be replaced somewhere in the centre of the berm with less longshore displacement. By the time the coarse material is shifted a short distance back to the outer berm the swell built profile almost exists with its reduced longshore transport capacity. Thus the coarse grains move very little downcoast. This is why measurements of fineness along the coast are taken as indicative of drift direction.

LITTORAL DRIFT CALCULATIONS

It is salutary to look at what variables are included in formulae for longshore drift and compare the assumptions with the conditions discussed above. It is normal to correlate volumes of accretion taken over a year with some average swell condition for the same period. As noted already, swell waves vary in height and period from hour to hour and hence the selection of some meaningful average, including direction of approach, is in the realms of fantacy.

As seen above the fluctuations in littoral drift are severe, the bulk of this transport taking place two or three weeks after each storm. If three storms occur during a year instead of one the drift can be trippled. No account appears to be taken of these events even though measured accretions vary tremendously for little apparent reason. Take, for example, the data gathered by Dean et al (1982) at Santa Barbara which recorded the filling of a dredged hole over a period of 380 days. Eight surveys were analysed which resulted in data as listed in Table I. The longshore wave energy was computed two different ways giving P and S. These were then divided into the immersed transport rate to give correlation constants K and K_*. The ratio of these was computed and listed to illustrate the sensitivity of the mode of deriving this input energy. They give factors varying from 1.78 to 2.94.

But accepting perhaps the usual constant K it is seen that this ranges from 0.32 to 1.63. The authors commented: "However the smallest value which exhibits the greatest deviation from the norm is associated with the fourth intersurvey period which is characterized by a very small value of I. If this one point is not included, the ratio of the largest to the smallest of the remaining K values is less than two, which appears reasonable for this type of measurement." (author's underlining). No mention is made in the article of storm sequences during these surveys but the extra high storm waves would have been included in the energy calculation without reference to the changing directions of these locally generated waves. But averaging of such coefficients, which in this case was 1.23, as distinct from the previously accepted value of 0.77 (U.S. Army Coastal Eng. Res.

Centre 1977) reduces confidence in such formulae.

Inspection of the U.S. Navy Marine Climate Atlas (1977) for the North Pacific Ocean shows the average number of storms for each month for the 10° square adjacent to the California coast near Santa Barbara. These were interpolated for the survey periods in Table I as used by Dean et al (1982) and this is graphed against K as in Figure 8. Inspite the scatter a relationship is indicated of K increasing with the number of storms. It would have been preferable to use the actual number of storms during the 1970-80 period of drift measurement but this was not possible from the wave data available. However, it would appear that this variable should be included in any future assessments of littoral drift.

Table I Field results from Santa Barbara (Dean et al 1982)

No. of days	Total Vol. Change $(m)^3$ Rate I(N/S)	Immersed wt Transport Rate I(N/S)	Component Wave Energy Flux at breaking P (N/S)	K=I/P	Component of mmtm S(N/m)	K_*=I/S (m/s)	K_*/K
48	32,820	85.3	52.2	1.63	27.8	3.06	1.90
51	65,070	159.1	101.4	1.57	45.4	3.50	2.13
35	82,810	295.0	352.4	0.84	119.5	2.47	2.94
53	10,290	24.2	76.6	0.32	37.9	0.64	2.0
82	22,220	33.8	31.7	1.07	17.6	1.91	1.78
57	38,760	84.8	63.8	1.33	32.6	2.60	1.95
54	35,640	84.6	64.4	1.31	34.2	2.47	1.89

Another example is given of variations in computed drift, model verification, and actual measurements in a sand trap. (Pratte et al 1982). Two previous estimates were 120,000 and 205,000 m^3/yr. whilst the model suggested 30,000 m^3/yr. The actual accumulation to date of publication averaged 110,000 m^3/yr., indicating the need for "a permanent dredging plant." Even though waves from the most severe annual storms were used in the model it is doubtful that a proper bar profile would have formed in the model. These large discrepancies point to some missing link in the chain of events, which is herein suggested as the impulsive movement after each storm. It is stated in this reference that "it took approximately 12 hours to fill in the entrance during storms", which could be taken to mean just after such sequences.

If it is accepted that the bulk of transport occurs during the removal of the bar the greatest concern is the difference in profile used in computations (a uniform slope) from the changing bed structure of this active period. Another important aspect is the assumption of uniform sand size. As noted above the fine sediment on the bar is moved first when turbulence and longshore current is optimum. As the swell-built profile is approached it is the coarse material being returned a short distance to and along the shore.

GEOMORPHOLOGICAL CONSEQUENCES

The author has wondered for many years why sand spits are formed across deep embayments of the coast or why lagoons are enclosed parallel to the shoreline. Why, for example, should such indentations not be silted up completely by the slow uniform supply from littoral drift? The reason now seems to be available, of pulsational supply of sediment by waves that can only deposit it at the tip of the spit. In essence, too much material is fed for them to handle.

At the extremity of a spit, as seen in Figure 9, the waves refract sharply and lose their longshore transporting capacity. Deposition results at this point so that the spit is enlarged parallel to the shoaled wave crests. Sudden spit formation after storms has been observed by many but not monitored scientifically with simultaneous profiling of the disappearing bar associated with it. Such daily records over 2 to 3 weeks would require a large team of workers on stand-by, to go into action immediately after a storm event.

A model verification could be made by having a beach end abruptly as seen in Figure 10. Initially oblique monochromatic waves could break on a profile comprising a bar. Once this has been returned to the beach the bar could be reformed with the aid of wire templates shaped as a mound. A spit should emerge from this condition and could then be compared to the form of accretion when a swell profile is maintained along the upcoast beach. The templates should be extended as the spit elongates.

In natural conditions there could be periods of the year with little drift, in which case the tip of the spit could be rounded off, as indicated in Figure 10. But after the next storm and another pulse the spit will suddently enlarge and the process continued. Aerial photographs of newly formed spits should exhibit such variations in width, with perhaps semi-circular beaches on the leeward side.

These spits, or barrier beaches as they are termed, occur the world over and vary greatly in magnitude. If conditions permit the shoreline can accrete extensively in front of an initially narrow spit. In this context it should be remembered that sediment transport in past geologic ages could have been much greater than today, because many rivers are now harnessd for water supply or to prevent flooding, thus diminishing the supply of material to the coast. Such barrier beaches will not form unless there is significant oblique swell energy for transport plus a good supply of sediment from rivers debouching upcoast. In some cases spits have formed from either side of an indentation due to swell energy arriving from two quadrants during different seasons of the year. This must be accompanied by storm cycles for impulsive drift to occur, which is a basic requirement for spit formation.

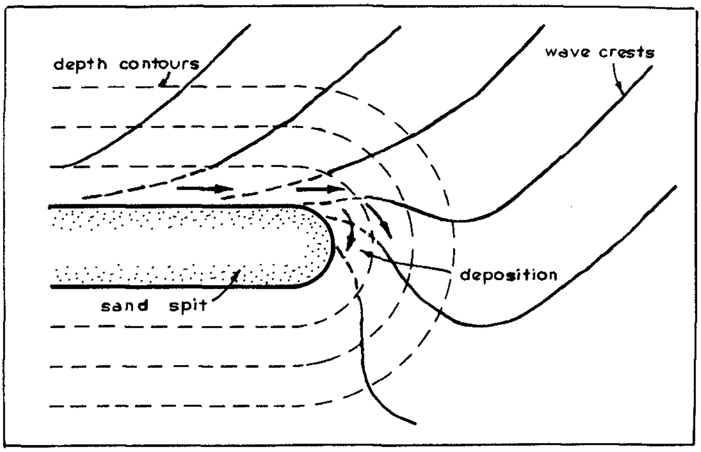


Fig 9. Accretion at the end of a spit during a pulse of littoral drift.

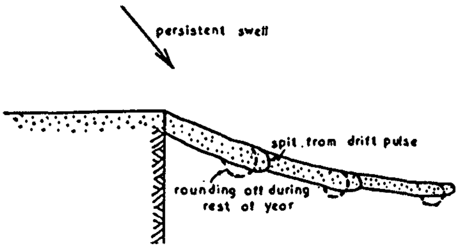


Fig 10. Spit construction at the extremity of a beach with pulsative drift.

Examples of barrier beaches are illustrated in Figure 11, being respectively from the Australian and Atlantic coasts. (Melville 1984). It can be seen that they run for tens of kilometres. These features are ubiquitous and very important commercially. Because of changed supply conditions many of these areas are now being eroded as Nature sculptures them to balance the existing wave climate (Converse 1982). Kaufman and Pilkey (1971) blame solely mans' actions on these adverse developments, but his influence is very modest and local compared to natural trends in longshore sediment distribution.

ENGINEERING IMPLICATIONS

Coastal engineers' for some decades have been trying to analyse why littoral drift and concomitant shoreline changes occur so continually and so swiftly. They certainly do not fit into the concept of a nice uniform process. This view of "A river of sand" has distracted research into this mammoth transporting mechanism resulting from severe meteorological fluctuations experienced over millions of years.

These spectacular changes are not only due to the processes described above but also result from other natural and man-made influences. Fluctuating sediment input from rivers, the predominant supply of material to the coast, can effect long-term fluctuations. Concentration of storm wave energy on specific lengths of shoreline can produce larger than normal bars and hence humps of sand traverse

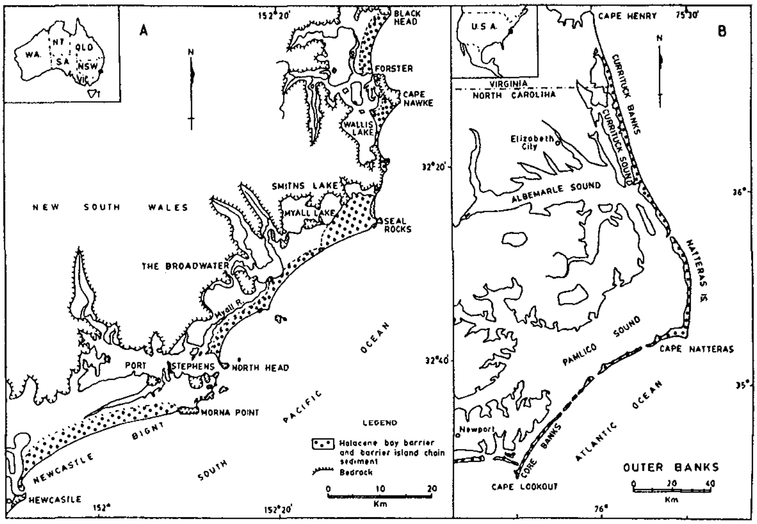


Fig 11. Barrier beaches formed on A: the NSW coast of Australia and B: the east coast of the USA (From Melville 1984).

the coast. Whilst the construction of breakwaters and groin fields can provide a transient interuption to longshore drift a much greater influence is exerted by channels dredged across the continental shelf to a port. This can cause cessation of sediment movement across this line as effectively as if a structure were built along the length of the channel. Material deposited in this trench is dredged and deposited well out to sea. Thus the offshore region downcoast is scoured. The bed is deepened and the profile to the beach steepened which then demands more sand for construction of the protective bar. Some of this will remain offshore to make up the deficiency there and hence the beach recedes. The rate of filling of the channel will vary with distance from shore but will fluctuate more near the surf zone, with peaks just after each storm. This knowledge should help in the surveying and planning of remedial dredging. The formation of shoals and even spits at river and harbour mouths will also be swift after a storm sequence. This affects navigation through these areas and hence recognition of the times of peak supply and perhaps verification of rates during these critical periods can assist by-passing operations. The action of weir-type jetties to accumulate drift for later disposal downcoast could be put in jeopardy by sudden silting of the structure to the outer full height segment.

The engineers' role should be to observe Nature on this precious margin of land and sea, accept these prodigious forces but not try to work against them. Nature achieves an admirable result in protecting the shorelines by her construction of the offshore bar. In this she can be helped by providing the volume of material required for this task. It is possible that this placement of material back into circulation need not be accompanied by longshore movement, if headlands are installed for Nature to sculpture bays of equilibrium shape. (Silvester and Ho 1972). In this case the persistent swell arrives normal to the beach around the complete periphery of the bay and hence places the bar material back from whence it came ready for the next storm.

CONCLUSIONS

1. Storm waves and swell have denuding and accreting effects respectively on beaches, the former placing beach material in the sea for the latter to transport.
2. The action of storm waves in constructing an offshore bar is Nature's way of protecting the coastlines, which should be used and aided by man.
3. Whilst swell waves return the bar to the beach, over a very short period, the excessive littoral current and suspension of material causes a pulse of littoral drift far greater than on the swell built profile.
4. The reasons for this optimum drift are the increase in breaker height, enlargement of surf zone width, maintenance of broken wave height in this zone, perhaps greater obliquity of breakers, and partial wave reflection on the seaward face of the bar.
5. Sediment sorting during bar formation causes fine particles to be moved more readily alongshore than median sizes, with coarse material being least affected.
6. Formulae for littoral drift vary drastically in their predictions due to their non-recognition of the part played by storm sequences, as instanced in many reports.
7. Impulsive littoral drift can explain why sand spits have formed naturally across deep indentations of the coast to form barrier beaches.
8. Besides the transient peaks of drift from bar formation other longer term influences can vary sediment supply on any coast, the understanding of which should aid the coastal engineer in planning by-passing measures and coping with siltation.
9. Littoral drift can be minimised by headland control which entails sculpturing of equilibrium shaped bays between them, around which the persistent swell arrives normally and hence lacks a longshore component to generate a littoral current.

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