Seven days a week, 24 hours a day, sands and muds are being carried around the world’s coastlines through the actions of tides, winds and waves. The erosion, transport and deposition of these sediments continually modify the boundary between the land and the sea, changing and reshaping its form. Sometimes the changes evolve slowly over long stretches of time, at other times rapidly, due to natural episodic events or the introduction of man-made structures into the shoreline. For over half a century we have been trying to understand the physics of sediment transport processes and formulate predictive models. Although progress has been made, our capability to forecast the evolution of the shape and form of coastlines from basic principles is still relatively poor. However, innovative techniques for studying the fundamentals of sediment movement are now providing new insights, and it is expected that such observations, coupled with developing theoretical work, will allow us to take further steps towards the elusive goal of predicting the evolution of coastlines and coastal bathymetry.

The importance of sediment studies
The mobility of sea-bed sediments, and hence of navigation channels, has been of concern to mariners over millennia. In more recent times, the appearance of supertankers and large container vessels in shallow coastal waters has brought the issue of channel mobility and predictability into even sharper focus, on account of the increasing environmental hazards posed by navigational accidents. The unpredictability of sand bars in shallow water was of vital concern during the Second World War, in connection with the use of landing craft on beaches. The laying of offshore gas and oil pipelines has raised further issues of strategic and economic importance linked to the stability of the sea-bed. Nowadays, climate change and sea-level rise are forcing us to think hard about strategies, ‘green’ or otherwise, for the defence of the coastline itself. All of these issues come back to the same underlying question: can we understand and then predict the movement of sea-bed sediments?

A prerequisite for the successful modelling of sediment transport is the representation of the flow itself and, in particular, the modelling of currents and waves. The nature of turbulent mixing in steady ‘boundary layer’ flows has been understood since the 1930s. At this time, when most interest was on river flows, key concepts such as the ‘threshold’ of sediment motion, and the shape of the suspended sediment concentration profile, were linked to the bed shear stress and its prediction, usually using measured logarithmic velocity profiles. The subsequent detailed measurement of turbulence became possible from the 1970s onwards. Observations of turbulence made in steady channel flows and tidal streams led to a much more detailed understanding of mixing processes, and also provided the rationale for the use of (numerical) turbulence models of increasing complexity for the prediction of sediment transport rates. The role of waves in stirring and transporting sediment in coastal waters was studied from the 1950s, and initially this research was undertaken rather separately by coastal engineers. Much work was carried out at this time in the USA in relation to the longshore drift of sediment by currents induced within the surf zone by the breaking waves themselves.

Only during the late 1970s and the 1980s were serious attempts made for the first time to bring the two strands of sediment transport research, involving currents and waves, together. Models were developed of the interaction between waves and currents in the sea-bed boundary layer, together with new formulations for predicting the shapes of the resulting bedforms (ripples etc.), in order to quantify sediment transport rates in combined wave and current flows. These transport rates can be one or two orders of magnitude greater than the transport by currents alone because of the ability of waves to stir up the bottom sediments, making this topic one of fundamental importance for coastal scientists and engineers.

Major advances followed in the 1990s, involving the enhancement of our observational capabilities with regard to sediments, both in the field and in small- and large-scale laboratory facilities. The challenges posed to existing models by these new data have led to a new generation of sophisticated, well validated modelling methods. These new models are now believed to have at least the
Coastal development can have unexpected effects on local and adjacent coastlines.

**Figure 1** Aerial view of a coastal resort in the Algarve, Portugal. This shows the impact of coastal erosion on the local coastline and the large unsightly boulders dumped onto the beach to reduce further land and beach loss.

Correct general behaviour over the wide range of wave, current and sediment conditions found in typical coastal areas. This is an important prerequisite for successful ‘morphological modelling’ whereby the evolution of the sea-bed can now be predicted on medium time-scales of months, and possibly for longer, with reasonable accuracy, based on a climate of waves superimposed on tidal currents. Although this new generation of morphological models is still in its infancy, and is still constrained by computer run-times for long-term simulations, it represents the key link between local sediment process studies and larger coastal area studies, and it provides critical tests of our ability to represent detailed sediment transport processes realistically.

Figure 1 shows an example of what can happen when developments occur without a full understanding of their ramifications on the local coastal environment. It can readily be seen that the construction has impacted on the local coastline, causing the need for a significant shoreline barrier of boulders; such structures are in no way aesthetically pleasing and may in the long term generate as many problems as they try to solve.

**Figure 2** The sediment interaction triad.

Sediment, bedforms and flow all affect one another, so if we are to understand sediment transport, we need to measure all three simultaneously.

Such failures to predict the consequence of developments are not atypical. Our capability to predict the impact that man-made structures may have on the coastal environment is relatively limited, and in particular the influences that such structures have on sediment transport pathways is surprisingly difficult to forecast. On the larger scale, if modifications occur in sediment transport pathways or the wave climate changes, due for example to increased sea-level and storminess, the impact on this vital boundary between the land and the sea could be profound. Here we reflect on the problem of understanding sediment movement, its measurement in one of the world’s largest man-made facilities for studying sediments, and how sound is helping to provide a clearer picture of some of the physics of sediment transport.

**Sounding out sediment movement**

Suspended sediment transport can be thought of as arising from three interacting components, namely the mobile sediment itself, the bedforms and the forcing hydrodynamics (currents, waves). This triad is illustrated in Figure 2.

For example, vortex generation due to flow over ripples on the sea-bed can have a significant influence on the suspension of sediment. Further, the shape of the ripples contributes to the overall flow resistance, and hence to the flow structure in the boundary layer. Yet the ripples themselves are a product of the local sediment transport. This triad of interactions and feedbacks has to be measured simultaneously, both temporally and spatially, in order to understand the fundamental processes of sediment transport. Sound can help in the making of such measurements.

As with acoustic imagery in medical ultrasound, acoustics can be used to visualise how sediments are moved around by waves and tides. The concept of using acoustics for underwater sediments transport studies is attractive and straightforward, as illustrated by the diagram in Figure 3. A pulse of high frequency sound, typically in the range 0.5–5.0 MHz and centimetric in length, is transmitted from a downward-pointing directional sound source, usually mounted at 1–2 m above the bed. As the sound pulse travels towards the bed, sediments in suspension backscatter a proportion of the sound and the bed itself generally
returns a strong echo. The backscattered signal is normally sampled at about 1.0 cm range intervals. The signal backscattered from the suspended sediments can provide information on profiles of suspended sediment concentration, particle size, and the three components of flow velocity, while the bed echo provides the time history of the bed and hence, if the bed features (e.g. ripples) are moving, its form. Acoustics can therefore measure all three components of the triad, and can do this with sufficient spatial and temporal resolution to allow the fundamental intra-wave and turbulent processes to be probed non-intrusively.

A case study: vortices over a rippled bed
Over large areas of the continental shelf outside the surf zone, sandy sea-beds are covered with wave-formed ripples. If the ripples are steep, the entrainment of sediments into the water column as a result of waves is mainly associated with the generation of vortices. This process is illustrated in Figure 4. A spinning parcel of sediment-laden water, \( v_1 \), is formed on the lee side of the ripple at the peak positive (onshore) velocity in the wave cycle, as shown in Figure 4(a) and (b). This sediment-rich vortex is then thrown up into the water column at flow reversal (Figure 4(c) and (d)), carrying sediment well away from the bed and allowing it to be transported (offshore) by the flow. At the same time, another sediment-rich vortex, \( v_2 \), is being formed on the opposite side of the ripple due to the reversed flow. As shown in Figure 4, \( v_2 \) grows, entrains sediment, becomes detached and moves over the crest at the next flow reversal, carrying sediments into suspension. The main feature of the vortex mechanism is that sediment is carried up into the water column twice per wave cycle at flow reversal. Under steep surface waves, vortex \( v_1 \) becomes stronger than vortex \( v_2 \), giving rise to an offshore ‘pumping’ of the suspended sediment.

To study this fundamental process of sediment entrainment, experiments were conducted in one of the world’s largest man-made channels, specifically constructed for such sediment transport studies – the ‘Delta flume’ at the De Voorst Laboratory of Delft Hydraulics in the Netherlands. The flume (Figure 5(a), overleaf) is 230 m in length, 5 m in width and 7 m deep and it allows waves and sediment transport to be studied at full scale. A huge paddle at one end of the flume generates waves which propagate along the flume over a sandy bed and dissipate on a beach at the opposite end. The bed in the present experiments comprised coarse sand which was located approximately halfway along the flume in a layer of thickness 0.5 m and length 30 m. In order to

**Figure 3** Diagram summarizing the use of acoustics for sediment transport studies (\( u, v \) and \( w \) are the components of the flow velocity as obtained by reflections from particles in suspension).

**Figure 4** Schematic representation of vortex entrainment of sediment over a rippled sandy bed. In each panel, the horizontal arrow represents the near-bed velocity resulting from the passage of the wave.
make the acoustic and other auxiliary measurements an instrumented tripod platform was developed; this is shown in Figure 5(b). The tripod STABLE II (Sediment Transport And Boundary Layer Equipment) used an acoustic backscatter system (ABS) to measure profiles of particle size and concentration, a pencil beam acoustic ripple profiler (ARP) to measure the bedforms, and electromagnetic current meters (ECMs) to measure the horizontal and vertical flow components. Figure 5(c) shows a wave propagating along the flume with STABLE II submerged in water of depth 4.5m, typical of coastal zone conditions.

The bed, the suspended sediments and the model
To investigate and then model the vortex entrainment process it was necessary to establish at the outset whether or not the surface waves were generating ripples on the bed in the Delta flume. Using the acoustic ripple profiler, the profile of a 3m transect of the bed was recorded over a period of time. The results of the observations over a 90-minute recording period are shown in Figure 6. Clearly, ripples were formed on the bed and the ripples were mobile. To obtain the formation of vortices requires a ripple steepness (ripple height/ripple wavelength) of the order of 0.1 or greater. An analysis of the observations showed this was indeed the case.

Using the acoustic backscatter system, some of the most detailed measurements of sediment transport ever recorded over a rippled bed at full scale were captured simultaneously. These measurements from the Delta flume were used to generate the images shown in Figure 7. The changing concentrations of suspended sediment over the ripple during the course of the wave cycle were constructed over a 20 minute period as a ripple passed in the onshore direction beneath the ABS. Comparison of Figure 7 with Figure 4 shows substantial similarities. In Figure 7(a) there can be observed the development of a high concentration event at high (onshore) flow velocity above the lee slope of the ripple ($v_l$). In Figure 7(b), as the forward flow reduces in strength, the near-bed sediment-laden parcel of fluid travels up the lee side of the ripple towards the crest. As the flow reverses, this sediment-laden fluid parcel ($v_l$) travels over the crest and expands. As the reverse (offshore) flow increases in strength, Figure 7(d), the parcel $v_l$ begins to lift away from the bed and a new sediment-laden lee vortex ($v_l$) is initiated on the offshore-facing slope of the ripple.

In order to capture the essential features of these data within a relatively simple (and hence practical) one-dimensional in the vertical (1 DV) model, the data have been horizontally averaged over the ripple wavelength to give the ripple-averaged variation in the concentration of suspended sediment over the wave cycle. The resulting pattern of sediment suspension contours is shown in the bottom
Figure 6  Observations of the sand ripples on the bed in the Delta flume during a 90-minute observation period, obtained using the acoustic ripple profiler. The observations were used to assess if the ripples present fell into the vortex regime, which proved to be the case for the present work.

Figure 7  Composite sound image of suspended sediment concentration above a rippled sand bed in the Delta flume, at four different times in the wave cycle. In each panel, the length and direction of the arrow represents the near-bed velocity due to passage of a wave. The vortices generated are indicated by $v_1$ and $v_2$. The grey scale represents sediment concentration, with black being the highest concentration.

At maximum flow, a parcel of water spins up on the leeside of the ripple; this rotating water parcel scoops up sediment and then carries it away from the bed when the flow reverses.
The measured concentration contours presented in Figure 8 show two high-concentration peaks near the bed, which propagate rapidly upwards through a layer with a thickness corresponding to several ripple heights. The first (and strongest) of these peaks occurs slightly ahead of flow reversal, while the second peak (which is weaker and more dispersed) is centred on flow reversal. The difference in the concentrations of the two peaks reflects the fact that the positive onshore velocity beneath the wave crest (time = 0s) is greater than the negative offshore velocity beneath the wave trough (2.5s). Between the two concentration peaks the sediment settles rapidly to the bed. Maybe rather unexpectedly, this settling effect occurs at the times of strong forward and backward velocity at measurement levels well above the bed. The underlying mechanism of sediment entrainment by vortices shed at or near flow reversal is clearly evident in the spatially-averaged measurements shown in Figure 8.

Any conventional model that treats the bed as flat, but with enhanced roughness to account for the ripples, and attempts to represent the above sequence of events in the suspension layer, runs into immediate and severe difficulties, since such models predict maximum near-bed concentration at about the time of maximum flow velocity and not at flow reversal. Therefore, for the first time in a 1DV model, we tried to capture these effects realistically through the use of a strongly time-varying eddy viscosity that represents the timing and strength of the upward mixing events due to vortex shedding. The model initially predicts the size of the wave-induced ripples and the size of the grains found in suspension, and then goes on to solve numerically the equations governing the upward diffusion and downward settling of the suspended sediment.

The essential two-peak structure of the eddy shedding process can be seen to be represented rather well in the bottom panel of Figure 8, with the initial concentration peak being dominant. The rate of decay of the concentration peaks as they go upwards is also represented quite well, though a phase lag develops with height, which is not seen to the same extent in the data. Despite some discrepancies, the model and experiment are well matched, allowing the model to go on to be used for practical prediction purposes in the rippled regime, which is the bed form regime of most importance over wide offshore areas in coastal seas.

Reflections
Long gone are the days when coastal sediment transport predictions were commonly in error by orders of magnitude. Although this is not appreciated by some casual observers of the field of sediment transport prediction, progress has come on by leaps and bounds in the last 10 to 20 years, particularly for non-cohesive sediments (sands). The key to successful transport prediction remains our ability to estimate the ‘roughness’ of the sea-bed which depends, in turn, upon the heights and wavelengths of the ripples formed by waves and currents. Although many uncertainties still remain, particularly for natural mixtures of...
sediment sizes, we are now much more confident about predicting both the roughness of the bed and the associated and often complex mixing processes above the bed, than was the case 20 years ago.

Our understanding of the complete sediment ‘triad’ (Figure 2) can now be considered to be quite well advanced. In practice, net sediment transport predictions in ‘blind’ field tests can now, through careful work, make predictions within about a factor of two or so of the observations; this represents an enormous improvement on past uncertainties. Of course, many challenges remain for the future. What happens to our ‘clean sand’ predictions when a small ‘cohesive fraction’ is present on site? Can we successfully implement our improved understanding of the local small-scale sediment transport processes within morphological models of coastal areas? Can we provide a robust physics-based approach to predict the future of these coastal areas, and of the position of the coastline itself, as the sea-level rises inexorably around us? These are now some of the challenges that coastal marine scientists face, and that need to be answered on behalf of the 50% of the world’s population that now lives within 60 km of the shoreline.

Further reading

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Alan Davies is is Professor of Physical Oceanography at the University of Wales Bangor† and a visiting research scientist at POL. He is a modeller of detailed hydrodynamic processes and sediment transport in the sea-bed boundary layer beneath waves and currents, and is applying this knowledge to the modelling of morphological change of the sea-bed in the coastal zone.

Terra firma is not always as permanent as you might like it to be, especially near the coast

Interested in the application of geophysics to oceanography and Earth sciences?
Issue 23 of the British Geological Survey publication Earthwise contains a number of short articles on this topic, including the use of sonar to map habitats in the Bristol Channel and determine the complex shapes of Scottish fjords, and the production of digital maps of the British continental margin. Ostracods (the subject of another article in this issue) also make an appearance!