

# ***Appendix 7***

Discussion paper on the influence of storm surges



## **Southern North Sea Sediment Transport Study, Phase 2 Sediment Transport Report**

### **Appendix 7 Discussion paper on the influence of storm surges**

#### **1. INTRODUCTION**

The regular tidal movements in the sea are continually subject to modification by the weather (Pugh, 1986). Meteorological disturbances are generated by the exchange of energy between the atmosphere and the sea surface. These disturbances are typically greatest during the winter months and are most evident in shallow seas. Atmospheric forcing may significantly increase the normal tide level causing widespread coastal flooding. These events are commonly known as tidal surges although the term is specifically applied to the excess sea level or the non-tidal residual generated during storm conditions (Pugh, 1986).

In particular, two main physical processes are responsible for the generation of storm surges.

##### **1.1 Atmospheric Pressure**

Changes in atmospheric pressure produce variations in the forces acting vertically on the sea surface, which are felt simultaneously at all depths. There is an inverse relationship between sea level and atmospheric pressure.

##### **1.2 Response to Wind Stress**

When two layers of moving fluid are in contact, energy and momentum are transferred from the more rapidly moving layer to the slower layer. The extent to which the influence of wind stress is felt below the surface is dependent upon the duration of the wind and the density stratification of the water column (Pugh, 1986). The effect of wind on sea levels increases inversely with water depth and hence, is most important when a strong wind blows over an extensive stretch of shallow water.

##### **1.3 Current Profiles**

Wind stress on the sea surface produces a variety of current speeds with depth. Current speeds decrease logarithmically with depth as the stress is transmitted from layer to layer (Pugh, 1986).

It is not usually possible to differentiate between the effect of wind stress and atmospheric pressure in a given storm. Surge events in the waters around Britain are caused by extratropical weather patterns, which produce a wide variety of dynamic responses. When considering tidal surges, attention is usually given to the extreme high water levels generated at the coast. However, fast flowing offshore currents are also generated during surge events that may have a significant impact on offshore structures as well as on sediment transport. Additionally, storms may generate extreme negative surges, which lower the sea surface by up to several metres (Burlace, 1986). Whilst these events do not carry the same risk of catastrophic flooding as their positive counterparts, negative surges can pose a significant threat to navigation and are also likely to have an influence on coastal sediment transport (Burlace, 1986).

The basic meteorological parameters that generate surge events are relatively uniform but the resultant dynamic response of the sea surface is influenced by local topographic variations. For this reason, surges along the west coast of Britain display different characteristics to those observed along the west coast of France (Pugh, 1986). Surge events in the North Sea are notorious, not only for their severity and the frequency with which extreme events take place but for their unique features that are not observed at other locations (Heaps, 1983).

A great deal of work has been carried out on North Sea surges but the majority has been aimed at predicting future events and devising warning procedures. Whilst the meteorological parameters that generate these events and the structure of the surge itself are now well understood, the influence of this phenomena on mass sediment movement has been largely neglected. In order to learn more about this influence and the result of interactions with coastal features, it is first necessary to understand why the North Sea is subject to such extensive surge activity. Attention should also be given to individual events so that the different physical responses to the forcing parameters may be used to predict the likely impact on seabed mobility

## **2. NORTH SEA SURGES**

The North Sea is open to the North Atlantic at its northern end but effectively constitutes a closed basin at the southern end. Surges are generated by pressure gradients travelling from the deep Atlantic waters onto the shallow continental shelf and by strong winds to the north of Scotland causing an increase in tidal levels (Pugh, 1986). As the resultant water movements propagate into the North Sea, they are affected by the earth's rotation and by the rapidly decreasing depth (The average depth of the North Sea is in the region of 40m). This effect is accentuated as the surge moves southwards down the east coast of Britain. These disturbances are commonly known as external surges, as the forcing mechanisms are generated outside the North Sea. Internal surges may also occur although they are much less frequent than external events (Pratt, 1995). As the name suggests, internal surges are generated within the North Sea basin. These events usually occur in response to north or north west winds produced by low pressure over the continent and areas of high pressure to the west of Ireland (Pratt, 1995). Although internal events occur less often than external ones, they generally produce more severe surges.

### **2.1 Historical Surge Events**

The earliest recorded surge event took place in 1218 when severe flooding of the Dutch coast claimed the lives of over 100,000 people (Van Malde, 1997). However, the first comparisons of surge levels were not made until after the 1530 and 1552 events. In November 1570, The Netherlands suffered the worst floods on record as surges caused water levels to rise almost 5m above Dutch ordnance datum. Other significant historical events took place in 1717 (+4.75m AOD), 1775 (+3.9m AOD), 1776 (+4.5m AOD) and 1825 (4.7m AOD) (Van Malde, 1997). Whilst these data refer specifically to the Dutch coast, the effects of these surges were almost certainly felt along much of the east coast of England.

A number of significant surge events have taken place during the 20<sup>th</sup> Century; notably, 1901, 1906, 1944, 1953, 1976, 1978, 1982 and 1993. Of these, the surges of 1953, 1982 and 1993 will be discussed in more detail as they provide typical examples of the different possible forcing mechanisms and the variety of physical responses that make North Sea surge events unique.

Perhaps the most intense North Sea surge took place between the 31<sup>st</sup> January and 2<sup>nd</sup> February 1953. The maximum residual reached 3m above the normal tide level and the resultant flooding claimed the lives of almost 2,000 people. Unlike most surges observed before or since, the 1953 event appears to have combined both internal and external components (Ishiguro, 1972). This undoubtedly explains the extreme water levels produced as the surge travelled down the east coast.

The origin of the external surge has not been recorded but once within the North Sea, it travelled in a clockwise direction around the basin at a similar speed to the diurnal tide. The height of the surge increased in a westwards direction, reaching a maximum at the entrance to the Wash by midnight on the 1<sup>st</sup> February (Ishiguro, 1972). This event alone would have been sufficient to increase the predicted water levels by 0.7m. However, between midnight on the 31<sup>st</sup> January and 9pm on the 31<sup>st</sup> January, two areas of high water appeared near the mouth of the Wash and off the Dutch coast. At the same time, irregular water level variations appeared offshore. During this storm, the wind direction was normal to the coast and speeds of over 20cms<sup>-1</sup> were maintained for almost 18 hours. This allowed the internal surge to develop

fully in the southern part of the North Sea. Maximum surge heights of 1.5m were attained between the Wash and the Straits of Dover (Ishiguro, 1972).

During the night of 31<sup>st</sup> January – 1<sup>st</sup> February predicted water levels were exceeded by more than 3m along much of the east coast of Britain and the Dutch coast. The extreme water levels resulted from the simultaneous arrival of the external and internal surges at the coast. Although the intensity of each component varied over space and time, the travelling external surge arrived in the southern part of the North Sea just as the internal surge reached its maximum height. Therefore, the combined effect of the two surges was to produce a single peak of double magnitude (Ishiguro, 1972).

By approximately 3pm on the 1<sup>st</sup> February, the wind speed began to drop causing the surge to decay gradually. The built up water mass was observed to dissipate in an anticlockwise direction round the coast. Shortly after this time, negative water levels were observed along the German coast.

As stated previously, certain combinations of atmospheric pressure and wind stress produce negative surges. These may occur as discrete events but are often observed either before or after large positive surges. Negative surges are less well documented as they are not associated with catastrophic flooding. However, these events pose a severe threat to the navigation of large vessels in shallow water and may have an effect on Sediment transport (Burlace, 1986).

On the 19<sup>th</sup> December 1982, the largest negative surge ever recorded occurred in the North Sea. The surge was caused by an area of unusually low pressure to the west of Scotland and strong southwesterly winds. The resultant set down of the sea surface caused water levels to fall more than 1m along much of the east coast and by over 2m at Southend and in the Thames Estuary (Burlace, 1986). The surge moved round the North Sea in an anticlockwise direction but did not propagate into the English Channel. The effects of the surge on the English coast were significantly stronger than on the Dutch and Belgian coasts. A time series profile of the 1992 negative surge event is shown in Figure 1.

Although no direct current measurements are available for this surge event, the relative residual current speeds have been extrapolated. During the morning of 19<sup>th</sup> December, northerly residual flows around the Anglian coast reached  $1.5\text{ms}^{-1}$ . By 10pm that night, the flow direction had reversed but the current velocity remained constant. Northerly flowing residual currents of  $1.5\text{ms}^{-1}$  were also observed along the Dutch coast at this time. Given that these figures refer only to the residual surge flows, and that the maximum negative surge coincided with high water; the total current speeds would have exceeded  $3\text{ms}^{-1}$  for much of the 19<sup>th</sup> December (Burlace, 1986).

Despite the fact that this surge coincided with high tide, water levels dropped sufficiently to pose a navigational hazard. The possible influence of this event on sediment transport will be discussed later.

The surge event of 21<sup>st</sup> February 1993 (Figure 2) was a classic example of an internal surge. It was generated by a combination of strong winds produced by low pressure over the continent and an area of high pressure to the west of Ireland (Pratt, 1995). The surge affected much of the east coast of England although North Norfolk experienced the highest water levels. A maximum residual of 2.6m was reached at Cromer (Pratt, 1995). In addition to the extreme water levels, the east coast was simultaneously battered by 5m waves. The effects of this surge were also significant in the Thames and Humber estuaries. The surge level exceeded 3m in the Thames resulting in the closure of the tidal barrage. Further north, the surge caused severe flooding in the Norfolk broads whilst the soft cliffs at Hemsby were undermined to the extent that houses were lost to the sea. The surge also penetrated into the English Channel where its effects were felt as far west as the Solent.

The three surge events described each caused the water level to fluctuate significantly above or below the predicted level. The consequences of these events were equally severe although each surge was generated by different forcing mechanisms. It is for this reason that surge activity in the North Sea is so frequent and so intense. Indeed, the North Sea has been described as ‘A splendid sea for storm surges’ (Heaps, 1983).

### 3. THE EFFECTS OF SURGES ON WIND WAVES AND ORBITAL VELOCITY

In the coastal zone, waves and tidal currents are responsible for mobilising and transporting sediment as bedload and in suspension. In general, the unsteadiness of tidal currents has a profound effect on wave-tide interactions in a shelf sea environment (Tolman, 1991). However, the relative importance of this unsteadiness varies over space and time. Tidal currents result in modulations of mean wave parameters with an oscillating character whereas surge induced currents produce more regular variations (Tolman, 1991).

During a surge event, the increased depth results in larger, longer period waves. This increase in wave height may be attributed to reduced bed shear stress. Conversely, wind induced currents generally reduce wave heights as they propagate in the same direction as the waves and decrease their fetch. Hence, the two separate surge parameters would appear to cancel each other out resulting in a negligible effect on wave action. However, when considering a typical North Sea storm, other complex interactions must be taken into account, which may accentuate the influence of surge events on wave action. It is possible to conclude therefore that during moderate conditions, wave-current interactions are tidally dominated whilst in extreme conditions, an accumulation of effects means that relatively small surge currents might have a significant impact on mean wave parameters (Tolman, 1991).

The impact of storm surges on wave orbital velocity will have a profound effect on sediment transport. Given that the orbital velocity is governed by wave height and water depth, one would expect the orbital velocity to decrease during a positive surge event, provided that the wave height remains constant. However, it is important to consider at what point of the tidal cycle the maximum residual occurs. If, as is often the case, a large surge event coincides with high water on a spring tide, the overall depth would increase significantly causing the near bed orbital velocity to decrease. Conversely, if the maximum residual happens to coincide with low water, the overall increase in water level would not be sufficient to reduce wave action at the seabed; rather, this parameter would simply not increase as expected as the tidal level fell. This view is somewhat oversimplified in that other dynamic interactions are ignored. For example, Figure 3 shows the orbital velocity profile during the surge event of 21<sup>st</sup> February 1993. Both before and after the event, orbital velocities are low, indicating calm conditions. The maximum orbital velocity occurs sometime during the morning of the 22<sup>nd</sup> February and corresponds to the first low water after the surge. During the event itself, the orbital velocity fluctuates slightly and then increases towards the maximum. However, during the initial phase of the surge, the near-bed orbital velocities are small. This may be explained by the lag effect between the onset of the gale force winds and the maximum wave heights as well as by the increased water levels.

The orbital velocity profile for the 19<sup>th</sup> December 1982 negative surge (Figure 4) shows a clear increase during the event. A combination of the negative surge and the accompanying storm waves caused the orbital velocity to increase more than 10 fold. Had the maximum residual not occurred at high water, this impact would have been even greater.

In order to properly assess the influence of surge events on wave parameters and sediment transport, it is necessary to consider the complex interactions between waves and currents. Indeed, the currents produced by the 1982 surge reached  $1.5\text{ms}^{-1}$ , which would exceed the threshold of motion along much of the East Coast. These velocities were almost doubled when combined with the tidal currents. Observations of tidal currents during storm surges are comparatively rare; particularly for the North Sea although a study was carried out on surge currents in the Bristol Channel during 1977 (Heathershaw, 1982). Current meter recordings showed that during the surge event of 11<sup>th</sup> November 1977, and for almost 20 days afterwards the normal, near-bed current directions were reversed. Nearer the surface, the flow quickly regained its typical orientation. This phenomenon may have resulted from the interaction between atmospheric pressure and wind set-down, which combined to generate strong shoreward flowing currents (Heathershaw, 1982). The currents measured during the 11<sup>th</sup> November surge event were a factor of five

times larger than those recorded under normal tidal conditions. Strong winds blowing offshore drive water away from the coast, which ultimately sets up a compensating flow at the seabed (Heathershaw, 1982). Whilst it is possible to identify sediment movements, due to surge events, further analysis of the dynamic relationship between waves, tides and surges is clearly required.

#### **4. THE INFLUENCE OF SURGES ON SEDIMENT TRANSPORT**

In the nearshore region, the direction and magnitude of sediment transport results from the combined action of unidirectional tidal currents and oscillatory wave motion in the bottom boundary layer (Hequette et al, 1995). Consequently, combined flows induce sediment mobility at lower current velocities than wave orbital velocities alone. Storm surges generated by wind set up against the coast produce an onshore water movement at the surface. As water piles up against the coast, downwelling occurs and offshore flowing bottom currents are generated (Hequette et al, 1995). Seaward directed horizontal pressure gradients that are a by-product of tidal surges also serve to drive crossshore near bed currents. Whilst these offshore currents have been found to vary in duration between specific events, the majority persist for a time after the surge has subsided. These flows, combined with high-energy wave orbital velocities significantly increase the potential for sediment transport. Indeed, once the waves have supplied the power to mobilise the sediment, the direction and magnitude of the resultant transport will be strongly influenced by the residual surge currents (Hequette et al, 1995). It is therefore likely that considerable offshore sediment transport takes place during surge events although factors such as shoreline configuration and seabed topography will also partially control this process.

Evidence of offshore sediment transport during surge events has been recorded in the Canadian Beaufort Sea (Hequette and Hill, 1995). Sidescan sonar tracks taken the day after a storm revealed narrow bands of shore parallel ripples, intersected by flat sand patches. Whilst the ripple beds are indicative of near bed orbital motion associated with surface gravity waves, the sand patches were almost certainly formed by offshore directed currents (Hequette and Hill, 1995). In shallow seas, extensive reworking of sediments under wave action gives rise to offshore mass transport during storm conditions.

Cores taken at the site contained thick graded sand layers interbedded with mud. These are thought to represent rapid deposition associated with the decaying phase of a surge event (Nelson, 1982). A surface sand layer present in many of the cores was thought to represent the most recent storm deposit. Further evidence that significant offshore transport is driven by surge currents is provided by the distribution of the surface sand layer. The thickness of the deposit decreases linearly with distance offshore, which is indicative of decreasing current speeds with time and depth (Nelson, 1982).

During a typical 1m surge, normal current speeds are at least doubled whilst suspended sediment transport rates increase up to 10 fold. In addition to the resuspension and advection of significant quantities of suspended sediments, surge currents are also responsible for prograding large volumes of sediment as bedload over distances of up to 100km offshore. There is also evidence to suggest that surge driven currents can instigate liquefaction of fine-grained sediments (Nelson, 1982).

In effect, the graded sand beds produced by decaying surge currents seem to mimic those of Bouma turbidites and provide an excellent example of shallow water sedimentation that is similar to the deep water sequences formed by turbidity currents (Nelson, 1982).

#### **5. THE EFFECTS OF SURGES IN ESTUARIES**

The influence of meteorological forcing in the North Sea also penetrates into the major estuarine systems; notably the Thames and the Humber. Studies carried out on surge activity in these estuaries have identified a number of interesting characteristics and interactions that are brought about by the nature of each different estuarine environment.

An investigation into the physical processes of the Humber estuary found that surge activity is highest in Autumn and Winter (Begum, 1999). Surges are typically diurnal in character but sometimes display semidiurnal oscillations that result from the configuration of the estuary. Surge maxima were found to coincide with minimum atmospheric pressure and maximum weighted wind speed. Reductions in air temperature also tend to induce large surge events when combined with other contributory factors. Perhaps more importantly, significant increases in river discharge were observed during surge events (Begum, 1999) and SPM concentrations were almost doubled. Hardisty (2002) found an association between with surge events moving along the open coast and into the outer Humber estuary with high SPM concentrations.

Observations of storm surges in the Thames reveal an interaction effect between tides and surges (Rossiter, 1961). In general, surges are amplified on the rising tide and maximum levels are propagated upstream. Tides in the Thames estuary propagate as a progressive wave oscillation rather than as standing wave. This may partially explain the amplification of the surge as it travels up the estuary. Whilst positive surge events increase the speed of tidal propagation up the estuary, negative surges have the opposite effect (Rossiter, 1961). Negative surge events retard tidal propagation as the resultant reduction in depth and increase in bed friction inhibit the progression of the free wave. Modelling tests carried out on a theoretical 'Thames Estuary' reveal that the amplification of the surge is probably a function of the water level at the mouth of the estuary. The model output also suggests that surge-tide interactions are likely to occur when the surge and tide have been travelling together for a considerable distance in shallow water (Rossiter, 1961). This indicates that similar interactions may be observed in the Humber and the Wash estuaries.

## **6. NUMERICAL MODELLING OF SURGES**

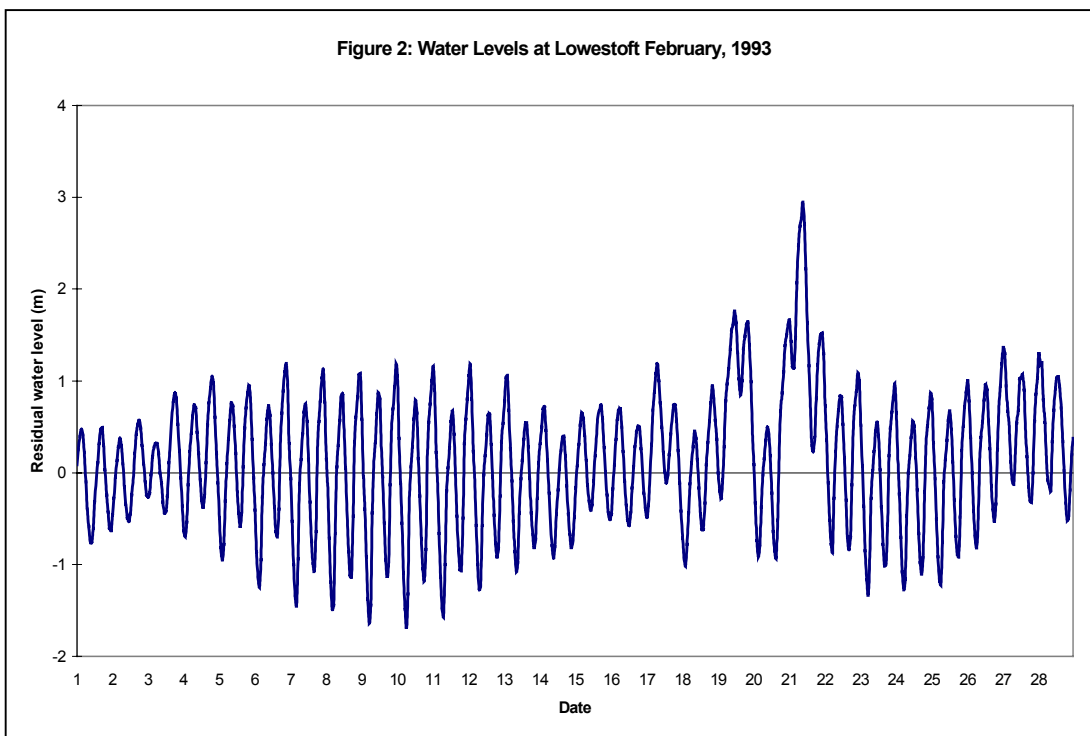
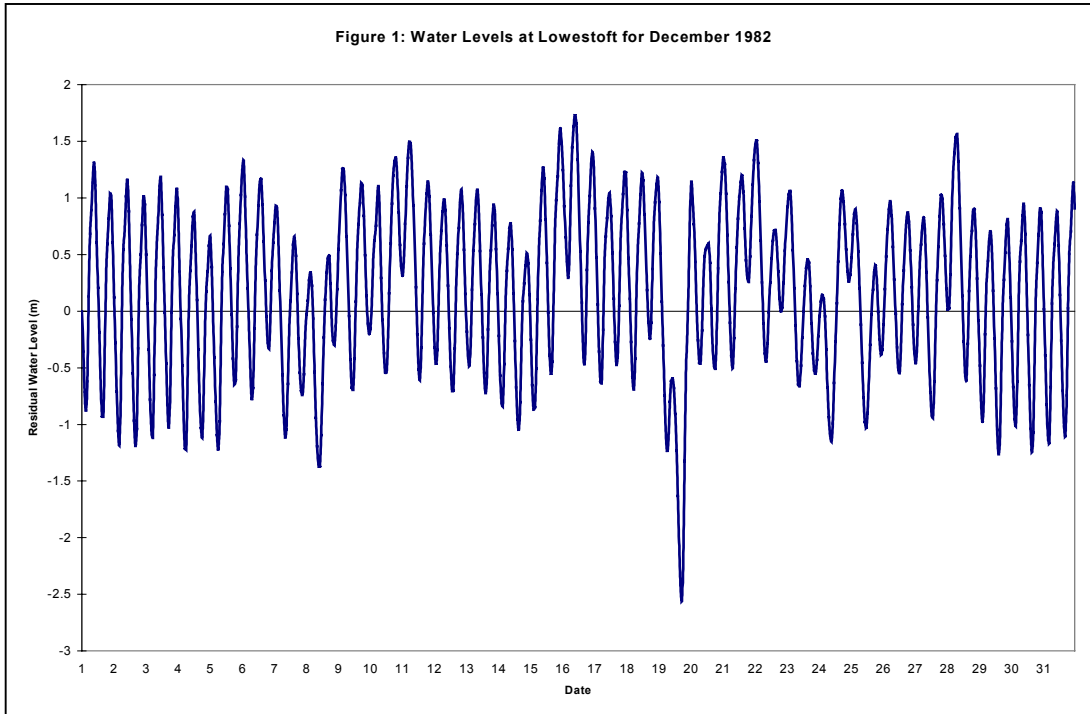
Whilst it is possible to theoretically describe the basic response of the sea to meteorological forcing, the actual response of a real sea to a real set of atmospheric conditions is far more complicated. The prediction and forecasting of future surge events is particularly important in the light of past coastal flooding. The need for an adequate surge warning system has led to the development of several numerical models, which facilitate the prediction of future water levels based on real hydrodynamic parameters. For further information on tidal surge models, the reader is referred to the works of Flather and Davies (1978), Flather, (1987), Pugh, (1982), Prandle, (1975) and Ishiguro, (1965)

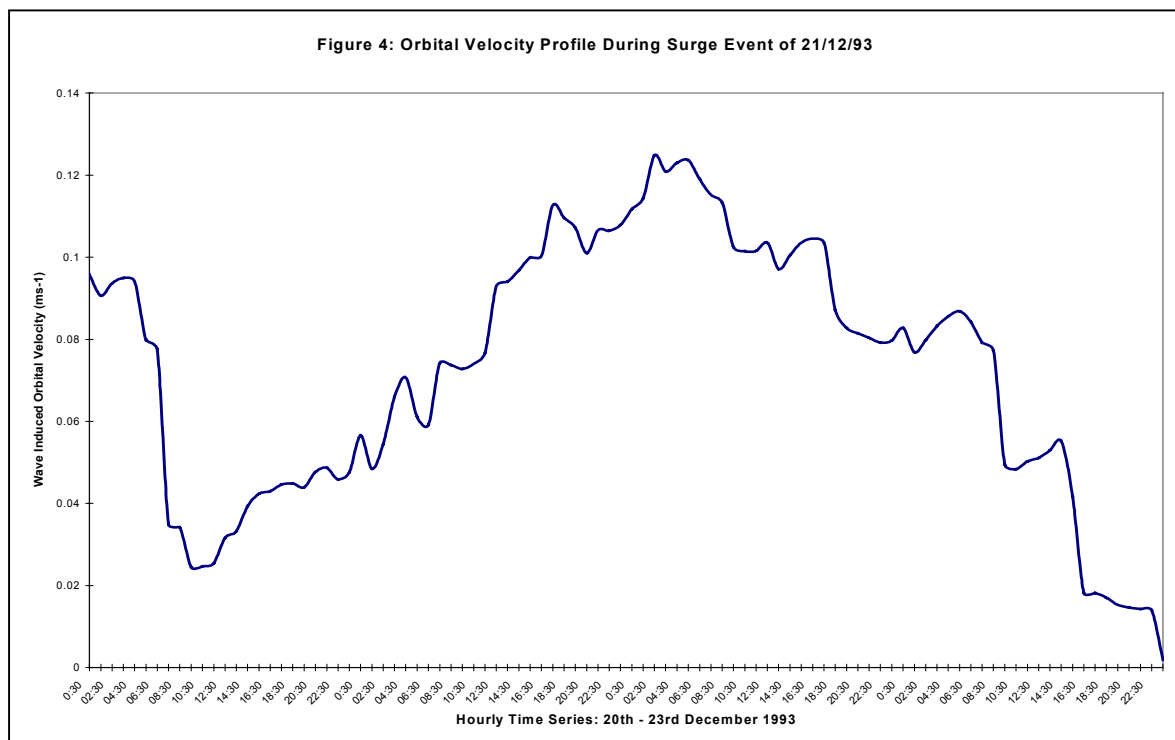
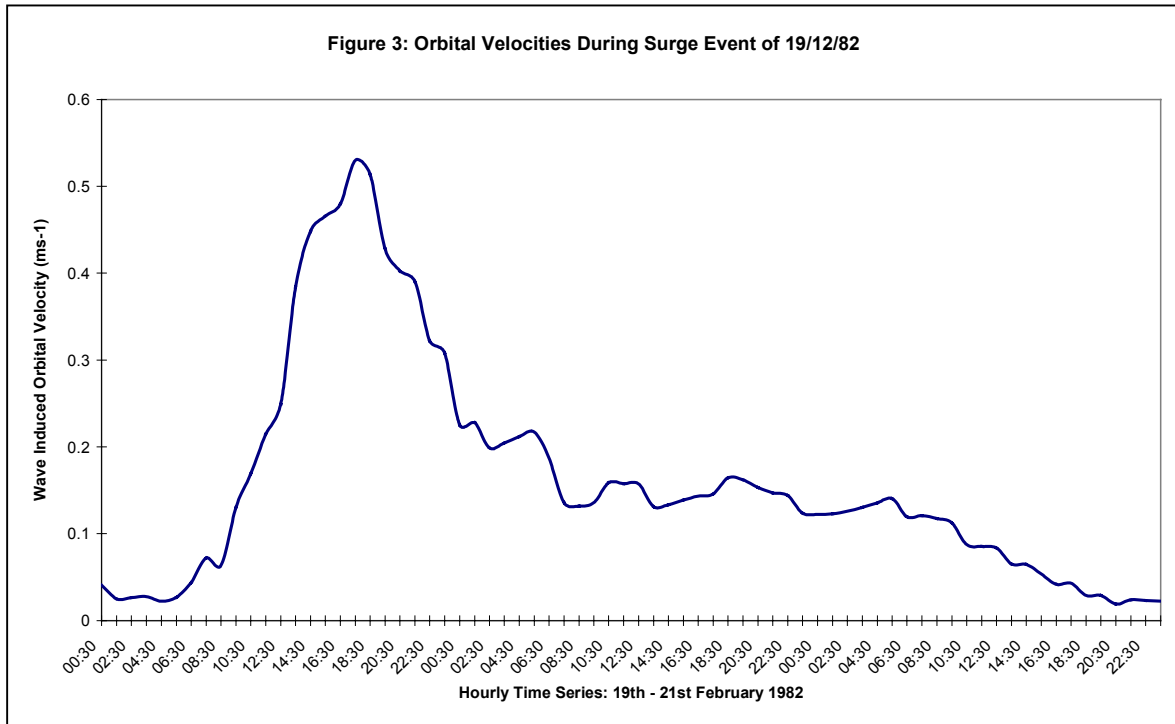
## **7. CONCLUSIONS**

Surge activity in response to atmospheric forcing is well documented, particularly for the North Sea. However, much of the literature focuses on surge heights and the potential for coastal flooding. This is mainly due to the catastrophic events that have occurred in the past and the need for an adequate surge warning system. The effects of surge activity on wave action and coastal sediment transport have been neglected but, by observing the physical characteristics of a given surge event, it is possible to highlight potential impacts. Studies undertaken elsewhere in the world have provided evidence that surge activity had a profound effect on sediment transport in the nearshore zone. At present, it is unclear whether this influence is site specific, and since there is no such information available for the North Sea, it is not possible to predict the extent of sediment transport under surge driven currents for the East Coast. Given the frequency and severity of surges within the North Sea, further research into the interaction between waves and surge currents is necessary if the mechanisms of sediment transport are to be completely understood.



FIGURES





## **BIBLIOGRAPHY**

Begum, D.A. 1999: Analysis of surge phenomena in the Humber estuary, North Sea coast of eastern England. *Indian Journal of Marine Sciences* 28 (1): p17-23

Burlace, M.I. 1986: The negative North Sea surge of the 19<sup>th</sup> December 1982. *Hydrographic Journal* 39: p11-15.

Davies, A.M. and Flather, R.A. 1978, Application of numerical models of the north west European continental shelf and the North Sea to the computation of the storm surges of November to December, 1973. *Deutsche Hydrographische Zeitschrift, Ergänzungsheft, A.14*: 72pp.

Flather, R.A. 1984: A numerical model investigation of the storm surge of 31 January and 1 February 1953 in the North Sea. *Quarterly Journal of the Royal Meteorological Society*, 110: p 591-612.

Hardisty, J. 2002. Physical processes in the Humber Estuary: Modelling and in situ measurement of sediment flux in the Lower Humber with particular reference to freshwater controls, tidal and storm forcing. NERC/LOIS Special Topic 56 –6ST/02/747 report prepared for the Environment Agency by University of Hull/North Sea Software Systems.

Heathershaw, A.D. 1982: Some observations of currents in shallow water during a storm surge. *Estuarine, Coastal and Shelf Science* 14: p635-648.

Heaps, N.A. 1983: North Sea modelling real time predictive models. Canadian Technical Report of Hydrology and Ocean Science 28: p27.

Hequette, A. Derosiers, M. and Forbes, D.L. 1995: The role of shoreline configuration and coastal morphology on nearshore sediment transport under storm combined flows, Canadian Beaufort Sea. BORDOMER, 95 – Coastal Change Vol II. (Proceedings of International Conference organised by BORDOMER and COI/IOC UNESCO, 6-10 Feb 1995, Bordeaux France): p563-570.

Hequette, A. and Hill, P.R. 1995: Response of the seabed to storm generated combined flows on a sandy Arctic shoreface, Canadian Beaufort Sea. *Journal of Sedimentary Research*, 65(3): p461-471.

Ishiguro, S. 1976: Highest Surge in the North Sea. Institute of Oceanographic Sciences, Report No 36: 31pp.

Ishiguro, S. 1965: Detailed structure of a storm surge in the North Sea. Communication No110 in, *La Petrole de la Mer*, (1st Congres International, Monte Carlo, 1965) Vol. 2.

Prandle, D. 1975: Storm surges in the southern North Sea and the River Thames. *Proc. Royal Society of London, A*, 344: p509-539.

Pratt, I. 1995: The storm surge of 21February, 1993. *Weather* 50(2): p42-48.

Pugh, D.T. 1987: Tides, surges and mean sea level: a handbook for engineers and scientists. J. Wiley & Sons, 472pp.

Rossiter, J.R. 1961: Interaction between tide and surge in the Thames. *Geophysical Journal of the Royal Astronomical Society* 6: p29-53.

Tolman, H.L. 1991: Effects of tides and storm surges on North Sea wind waves. *Journal of Physical Oceanography* 21(6): p766-781.

Van Malde, J. 1997: Historical extraordinary water movements in the North Sea area. Hydrographic Journal 86: p17-24.