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The Use of Morphological Models as a Tool for Assessing The Long-term Impact of Structures in Estuaries

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A systematic study has been undertaken to assess the suitability of using a morphological model in assessing the longer-term impact of placing structures in an estuary. The approach adopted uses a real estuary. In the area chosen to place the structure the bathymetry has been flattened continuing upstream to the tidal limit whilst maintaining the bed slope. The model has then been forced using different forcing drivers and parameter settings and different combinations of drivers and parameters the results compared to test the response of the model in both the short- (daily) and longer-term (yearly). An assessment of the channel formation with and without the structures in place has then been undertaken to determine the level of impact that the structures have on the system.

I. INTRODUCTION

The form an estuary takes is influenced by a range of physical processes that operate over varying temporal and spatial scales. In terms of the morphology of an estuary, and in particular the sediment transport, the principal hydrodynamic forcing mechanisms are tidal flow, fluvial flow, waves and density driven circulation. In order to implement works within these systems it is necessary to understand the impact any such scheme will have on that system and how it will interact with the physical processes driving that system. Even with the technology and understanding at our disposal today this is still no mean feat.

The objective of this study was to assess the extent to which a process-based morphological model can be used to investigate the longer-term impact of placing structures within an estuary. In the current study the structures are representative of bridge piers. The approach adopted makes use of the 'online' morphological model, which is part of the Delft3D suite of modelling tools. A real estuary has been chosen as the location for the investigation, specifically the Mersey Estuary.

The Mersey Estuary, Figure 1, is located on the west coast of England. The outer estuary forms Liverpool Bay, a generally shallow region containing large areas of sandbanks that are exposed at low water. Liverpool Bay is bounded to the east by the Lancashire coast, from Seaforth to Formby Point; and to the south by the Wirral Peninsula, from Hilbre Point at the mouth of the Dee Estuary, to New Brighton at the mouth of the River Mersey. At New Brighton the width of the Mersey is 1.5km, approximately, and at Pier Head the river narrows to about half this width (hence its name the Narrows). Beyond this point the river opens up to a large tidal basin, generally termed the 'inner estuary', which widens to a maximum width of about 5.5km. Beyond this is the upper estuary, which extends for a distance of about 42km from the Dingle to Howley Weir. At low water almost all of the tidal basin dries out leaving three channels, Garston, Middle Deep and Eastham. In the upper estuary, the low water channels meander through large areas of sand and mud banks. The primary sources of freshwater into the Mersey are at the tidal limit at Howley weir and over the sluices of the Weaver navigation

II. MODELLING APPROACH

In current study a fully calibrated and validated hydrodynamic model has been set up using the Delft3D suite of modelling tools, developed by WL | Delft Hydraulics. The numerical model is based on the Delft3D 'online' module, which solves the shallow water and transport equations using a finite difference scheme applied over a curvilinear grid. The software simulates hydrodynamic and sediment transport conditions simultaneously. At selected time-steps the bed is updated morphologically. A scaling factor (MORFAC) can be applied to the simulation to allow the model run to be predict change over longer periods of time. However, in particularly dynamic systems it is questionable if a scaling parameter can be applied due to the rapidly changing morphology.

Two models grids have been used in the study, the first covers the extents of the Mersey out into part of Liverpool Bay (Figure 2). The second grid starts at Gladstone Dock and extends to the tidal limits at Howley Weir (Figure 3). In the first grid the model's offshore boundary was driven with astronomic tidal constituents derived from a high-resolution model of the Irish Sea. In the second model, the seaward boundary was driven with either astronomic tidal constituents derived from real tidal records at Gladstone Docks or a real times series of water levels, again from Gladstone Docks.

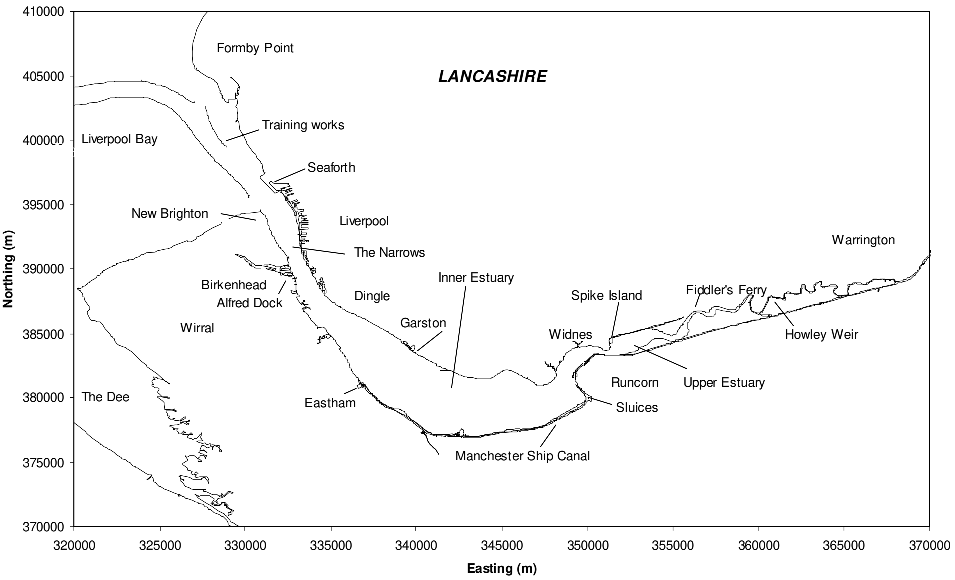

Figure 1: Plan of the Mersey Estuary.

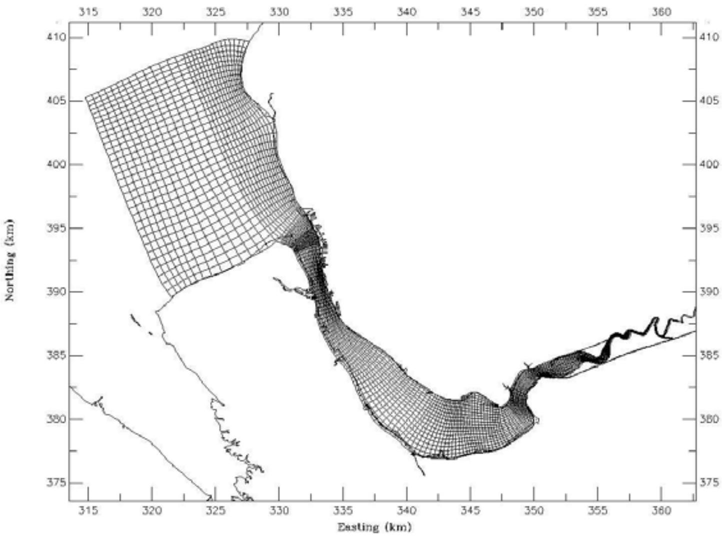

Figure 2: First curvilinear grid extending into Liverpool Bay.

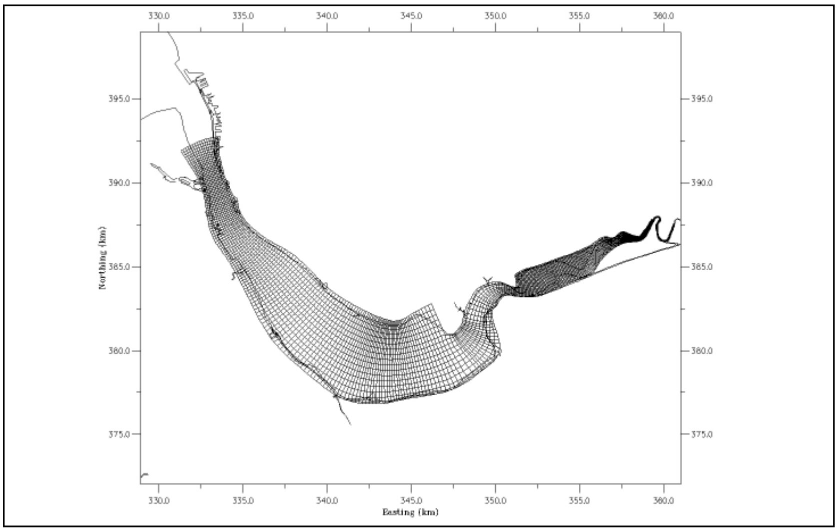

Figure 3: Second curvilinear grid starting at Gladstone Dock.

III. PHYSICAL AND NUMERICAL MODELS

Historically, modelling the interaction of the sediments with structures has always been carried out using physical models. Provided the measured parameters in the model are related to their corresponding prototype quantities by scaling laws that satisfy the rules of similitude then this approach is valid (Yalin, 1971). Physical models have been in use for a considerable time. In fact, in 1890 Professor Vernon-Harcourt read a paper to the Royal Society, London, entitled "Effects of Training Walls in an Estuary". In this paper he described a series of physical modelling experiments undertaken to investigate the impact of various engineering schemes would have on the Mersey Estuary. Around the same period Professor Osborne Reynolds, working at the University of Manchester was also undertaking experiments of a similar nature. Both of these engineers were pioneers in the use of models to aid the understanding of the physics of estuaries and the use of models as tools to investigate the impact of engineering schemes if placed within such environments.

More recently it has become possible to apply numerical processed based morphological models to look at the impact of engineering works in estuaries. However, as Hibma (2004) has recognized, understanding and predicting the morphodynamic evolution of estuaries is still limited by their complexity both spatially and temporally. However, it is possible to demonstrate that these processed based models have evolved sufficiently to reproduce similar behaviour to their physical counterparts.

Figures 4 and 5 show sketches of the bathymetric survey of the Mersey Estuary of 1881 and the results of Vernon-Harcourt's physical model simulation, respectively. The model used for the investigations represented the Mersey estuary from a little below Warrington out into Liverpool Bay beyond the bar, made to a horizontal scale of 1:30000 and a vertical scale of 1:500. The tidal period was calculated to be about 32.66 seconds with the maximum tidal rise of 9.45m at Liverpool amounting to 1.89cm in the model. Fine Bagshot sand was used to represent the bed of the estuary in the model (for further details see Vernon-Harcourt, 1890). A comparison of Vernon-Harcourt's results with the 1881 bathymetric survey shows that the general features of the estuary are fairly reproduced. An exact correspondence would not be expected due to the constantly shifting channels particularly in the upper reaches. In addition, a hydrographic survey of the whole estuary could not be taken rapidly enough to obtain the exact condition of the estuary at any given time.

Figure 3 shows the results of a numerical simulation using the 'online' morphological module within Delft3D modelling suite. The simulation starts from an initial flat bed condition (no initial slope applied) and assumes a uniform distribution of sand (median grain size diameter of 150μm). Typically, sand fractions within the estuary vary from between 700μm - 125μm, but the majority of deposits range between about 125μm and 250μm. Within the model set up the initial sediment thickness was set at 30m and the bed level was set at 8m below OD(Newlyn). The offshore boundary conditions used in the model were described by the use of astronomic tidal constituents. The model was set up to run in depth-average mode. Freshwater flow was applied at the tidal limit at Howley Weir ($30m^3/s$) and over the Weaver sluices ($10m^3/s$). Salinity was set at 27ppt along the offshore boundary and 0.01ppt at the points of fluvial input into the model.

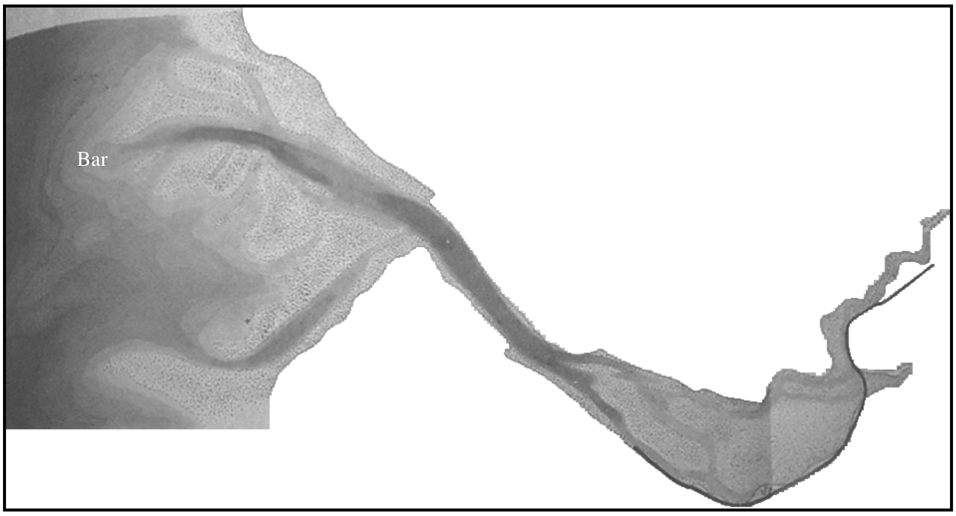

Figure 4: 1881 bathymetric survey of the Mersey Estuary (After Vernon-Harcourt, 1890).

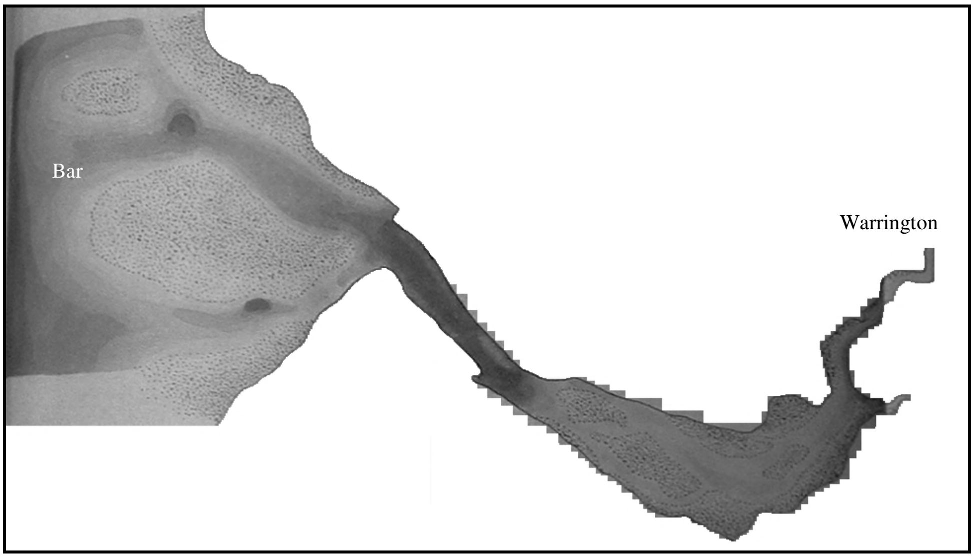

Figure 5: Results of physical model simulation of the Mersey Estuary (After Vernon-Harcourt, 1890).

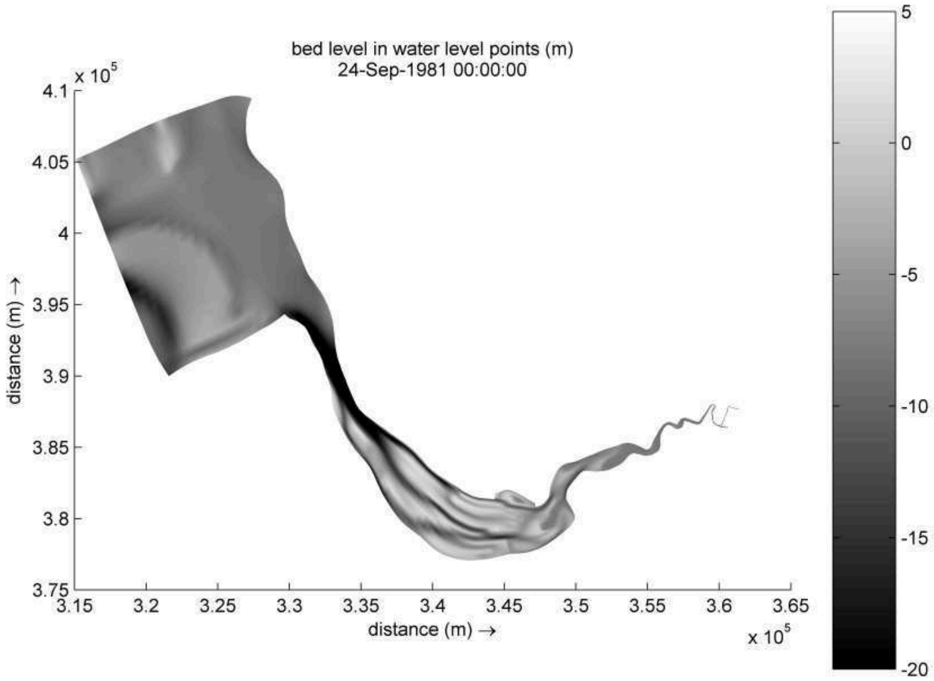

Figure 6: Numerical simulation of morphological evolution of the Mersey Estuary from a flat bed

From Figure 6 it can be see be seen that the numerical model is capable of reproducing the general features of the estuary: the development of channels within the estuary; a channel along the Wirral foreshore and the start of bank formation within Liverpool Bay. The model was run in real time with no morphological scaling applied and the figure represents the morphological evolution of the estuary after about 21 months. The system has still not reached equilibrium, and based on the results of a ‘single element’ model it will take about 41years (real time) for equilibrium to be reached (Townend, 2006). However, a comparison of the results from the physical and numerical models against the actual bathymetric survey of 1881 show reasonable agreement in respect of the main features.

Therefore, based on these results the morphological model is deemed suitable for exploring the impact of placing structures into the system.

IV. MODEL SIMULATIONS

The Mersey Estuary has again been used for the second part of this study. Within the estuary the area chosen for placing the bridge crossing is in the upper estuary (above Runcorn) and consists of low-water channels that meander through large areas of sand and mud banks and is characterized by a highly mobile and active riverbed. The tidal action in this part of the estuary creates strong currents (>2m/s on spring tides), which are an important part of this process. In addition, historically the position of the low water channel in the estuary has shown considerable movement over the period of existing records.

The principal aim of these tests is to simulate channel formation in the upper estuary without and with the bridge piers in place and to observe the differences in predicted channel formation. The grid used for these investigations is shown in Figure 3 and is relatively coarse with a grid cell size of about 80m x 80m in the area of interest. The grid resolution has been adopted primarily to allow longer time-scale simulations to be undertaken within a reasonable time-frame.

The starting point for the study was a bathymetric and LIDAR survey undertaken of the estuary in 2002. Upstream of Runcorn (see Figure 1) the bathymetry was flattened (excluding hard points such as quay walls) whilst maintaining the general channel slope along the length of this portion of the model. A series of model runs were undertaken for the ‘baseline’ case, that is, with no bridge piers in place but with the flattened bathymetry. The model was run for a period of a year and the morphology allowed to develop over that period. No morphological scaling factor was applied so all the simulations were run in model real time. The model was driven with different conditions and combination of conditions together with different parameter settings in the morphological set up such as grain size and initial sediment thickness. Table 1 shows the various model settings applied for each run for the baseline case.

TABLE I.
MODEL SETTINGS FOR BASELINE CASE

Run number	Sediment type	Tidal boundary	Fluvial flow	Wind	Initial sediment depth (m)
1	Sand - 150μm	Harmonic constituents	Constant mean annual	None	1
2	Sand - 150μm	Harmonic constituents	Mean daily	None	1
3	Sand - 150μm	Real time-series	Constant mean annual	None	1
4	Sand - 150μm	Real time-series	Mean daily	None	1
5	Sand - 100μm	Real time-series	Constant mean annual	None	1
6	Sand – 64μm	Real time-series	Constant mean annual	None	1
7	Sand - 300μm	Real time-series	Constant mean annual	None	1
8	Sand - 300μm	Real time-series	Constant mean annual	None	4
9	Sand - 300μm	Real time-series	Constant mean annual	Real (hourly)	4

For the bridge pier scenario two tests were undertaken (Table II). The first test (run 1s) represented the bridge piers as solid structures, whilst the second test (run 2s) represented the piers as added friction terms. The additional friction is applied as a loss term in the model equations. In both scenarios three bridge piers were placed within the upper estuary. The initial run represents an extreme scenario as the piers each occupy a single model cell making them of the order of 80m in diameter. The second run represents the piers as 10m diameter structures.

TABLE II.
MODEL SETTINGS FOR BRIDGE PIER SCENARIOS

Run number	Sediment type	Tidal boundary	Fluvial flow	Wind	Initial sediment depth (m)
1s	Sand - 150μm	Real time-series	Constant mean annual	None	1
2s	Sand - 150μm	Real time-series	Constant mean annual	None	1

V. RESULTS

The morphological model proved to be unstable for different model forcing conditions and combination of forcings. This made comparison difficult for some of the scenarios tested. Figures 7 to 10 shows the variation in channel formation over several months for 64μm, 100μm, 150μm and 300μm median sands (runs 6, 5, 3 and 7, respectively). In all four tests the freshwater flow was kept constant, whilst the seaward boundary was forced using a real water level time-series. Overall, the difference in sediment size has little effect on the formation and position of the channels, only in the time required to form them. There are subtle differences in between the morphology formed using the various grain sizes, however, in general the patterns of channel formation are identical. This would suggest that sediment size is not a primary driver in the formation of the channels.

Figure 11 shows the variation in channel formation over a 6 months period for 150μm sand using astronomical tidal constituents to force the model on the offshore boundary and a constant annual mean freshwater flow (run 1). Initially, a channel is formed in the location of an existing channel along the north bank. However, this channel does not develop and is eventually cut off. There is no significant difference between the channel formed under these boundary forcing conditions and those formed using a real time-series and shown in Figure 9.

Figure 12 shows the results for the baseline case were the model boundaries have been forced using astronomical tidal constituents at the seaward end and a varying real mean daily flow has been applied at the tidal limit (run 2). The results represent the morphological change over a four months period. The model proved to be unstable as a result of applying the varying daily mean discharge. As previously, over the duration of the simulation the model results show the development of a single main channel and there appears to be no significant difference between the channel formed under these forcing conditions and that observed in the previous scenarios presented (Figures 7 to 11).

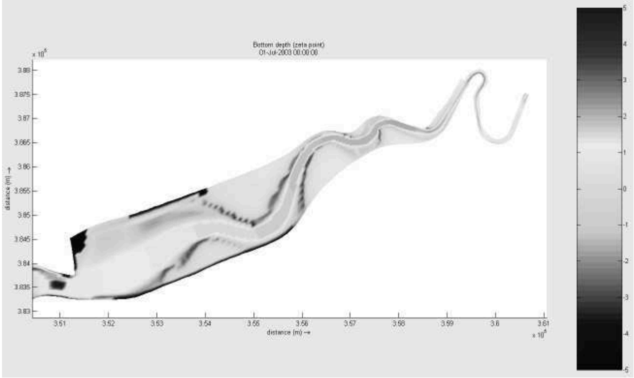

Figure 7: Bathymetric change after 6 months for 64μm sediment, using a real tidal time-series driver and a constant mean annual fluvial flow.

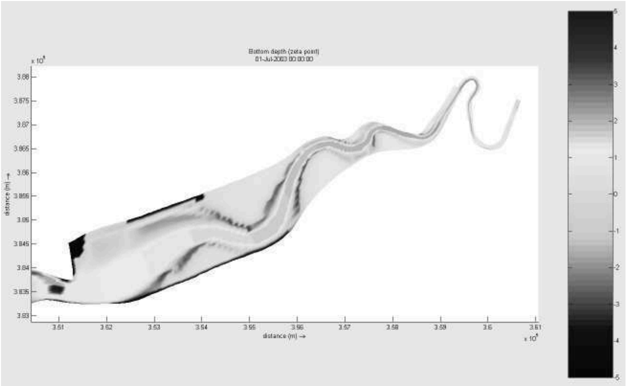

Figure 8: Bathymetric change after 6 months for 100μm sediment, using a real tidal time-series driver and a constant mean annual fluvial flow.

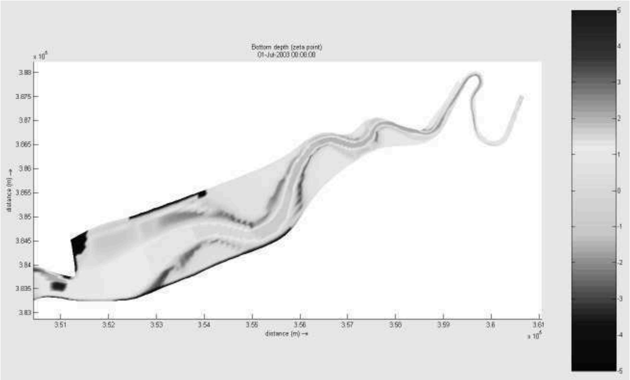

Figure 9: Bathymetric change after 6 months for 150μm sediment, using a real tidal time-series driver and a constant mean annual fluvial flow.

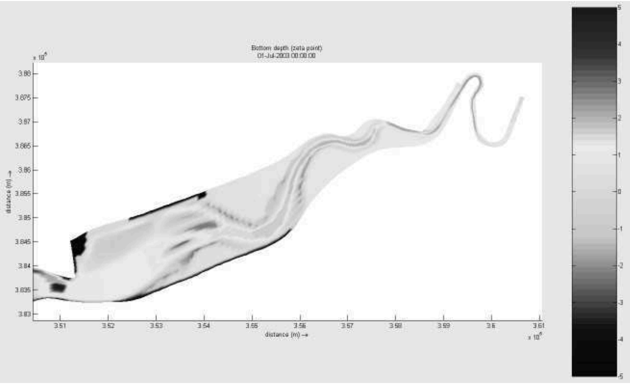

Figure 10: Bathymetric change after 6 months for 300μm sediment, using a real tidal time-series driver and a constant mean annual fluvial flow.

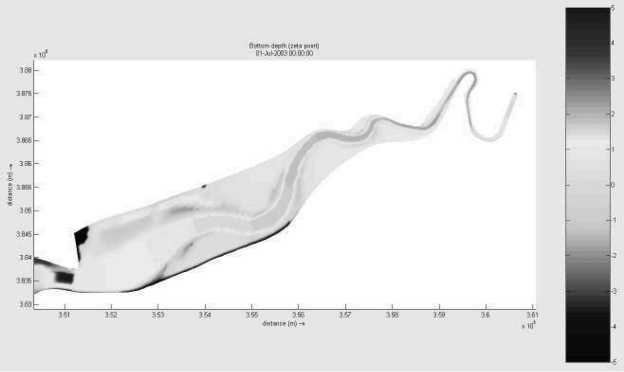

Figure 11: Bathymetric change after 6 months for 150mm sediment, using harmonic tidal constituents and a constant mean annual fluvial flow.

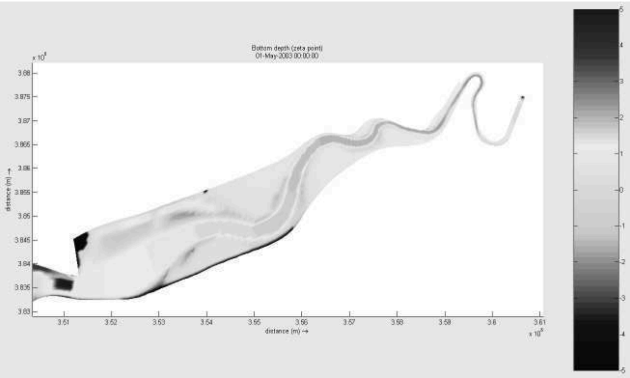

Figure 12: Bathymetric change after 4 months for 150mm sediment, using harmonic tidal constituents and a daily mean fluvial flow.

Running the same scenario but replacing the seaward boundary condition with a real time-series of water levels instead of the using astronomical tidal constituents led to instabilities developing after a month (run 4). Therefore, the results for this simulation have not been presented.

Figure 13 shows the results of a simulation using 300μm sand using a real time-series of water levels along the seaward boundary and a constant mean annual discharge at the tidal limit. In addition, the initial depth of sediment was set at 4m (run 8) rather than the 1m initial depth used in all the previous results reported earlier. From the figure it is evident that the initial depth of sediment applied in the model leads to a different morphological outcome than that observed in the series of tests presented up to this point. Whilst there is still a principal channel formed there are also channels formed, initially, along both the south and north sides of the estuary. Towards Runcorn (refer to Figure 1) the main channel is deeper and narrower than that formed previously. Interestingly, the formation of the channels towards the sides of the estuary show some similarity to the existing situation.

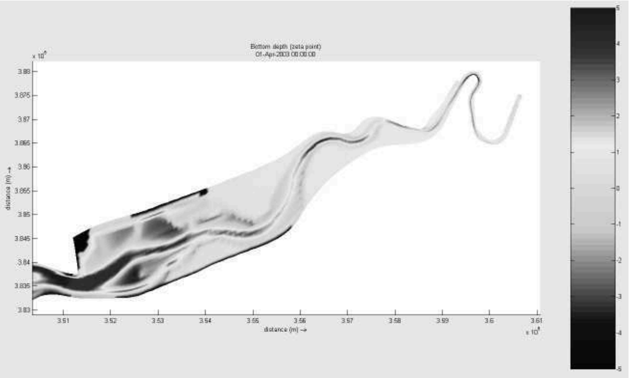

Figure 13: Bathymetric change after 3 months for 300mm sediment, using a real tidal time-series driver, a constant mean annual fluvial flow and an initial 4m depth of sediment.

The final test carried out with the baseline case used the same set up as for run 8 except with the addition of a wind stress over the model, which varied hourly in both speed and direction. The data applied was recorded at the seaward boundary of the model. Figure 14 shows the results from this simulation. The imposition of a wind stress over the model has no major impact on the model results.

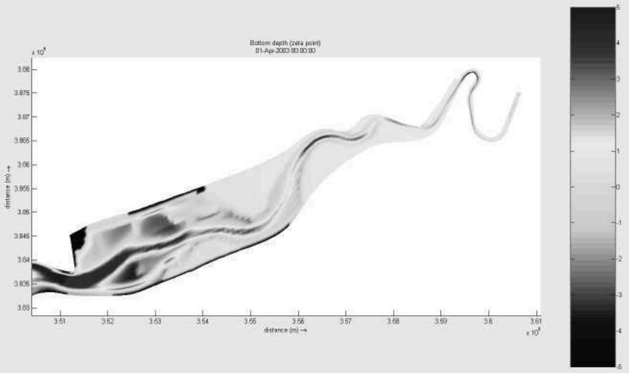

Figure 14: Bathymetric change after 3 months for 300mm sediment, using a real tidal time-series driver, a constant mean annual fluvial flow an initial 4m depth of sediment and an hourly wind speed and direction.

The final series of model runs were undertaken for the two bridge pier scenarios. Figure 15 shows the results of the simulation of three 80m diameter structures. There is an evident response of the system to having these structures within the estuary. Initially, the model shows a series of channels formed next to the piers (Figure 15a). However, over time these sperate channels become less marked (Figure 15b).

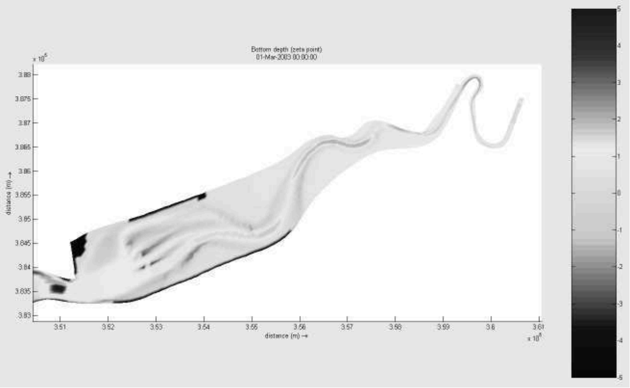

Figure 15a: Bathymetric change after 2 months with three 80m x 80m structures in place for 150mm sediment, using a real tidal time-series driver and a constant mean annual fluvial flow.

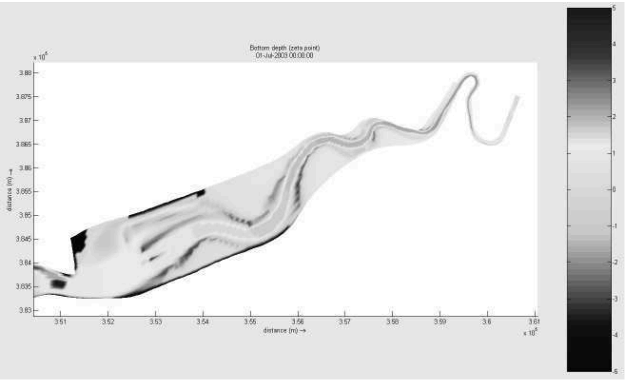

Figure 15b: Bathymetric change after 6 months with three 80m x 80m structures in place for 150mm sediment, using a real tidal time-series driver and a constant mean annual fluvial flow.

Figure 16 shows the response of the upper estuary to having three 10m diameter structures placed across the channel section. The results from this scenario show a very similar morphological pattern to that obtain with no structures in place (compare Figure 16 with Figure 9).

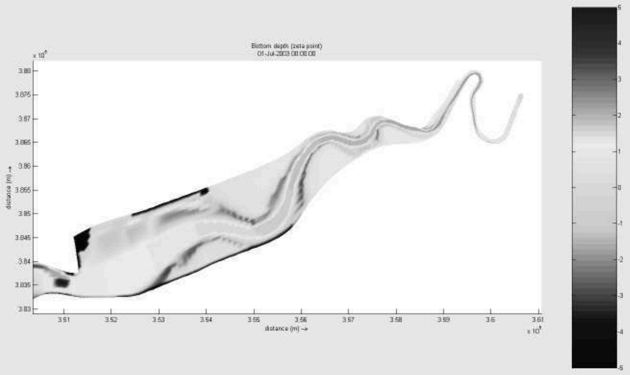

Figure 16: Bathymetric change after 6 months with three 10m diameter structures in place (represented using added friction terms) for 150mm sediment, using a real tidal time-series driver and a constant mean annual fluvial flow.

Over a longer time-scale the morphological changes in response to the piers may be reduced. However, the initial results from these last series of simulations demonstrates that the size of the structures placed within the cross-section of the estuary and thus the blockage effect that they represent in respect to the cross-sectional area is very important in respect to the effect of morphological development.

VI. DISCUSSION

The initial morphological modelling exercise to 'mimic' the behaviour of a physical model has demonstrated the ability of such models to reproduce realistic channel–shoal systems. This would suggest that the numerical model possesses the requisite processes necessary to allow these estuarine channel-shoal systems to evolve. These results have supported the application of such models to the investigation of practical engineering issues such as the long-term impact of placing a structure, in this case a bridge, within an estuary system. There are limitations though, primarily the time required to simulate such problems is prohibitive, particularly if the model grid is particularly refined and if the model is run in 3D mode. The introduction of multiple sediment fractions will also have an impact on model run times. For estuary systems where the morphology is slow in adjusting then this may not be too limiting as the use of a scaling factor in the morphological simulations (MORFAC) may allow longer time-frames to be simulated. However, in estuary systems that are particularly dynamic then the use of such factors is highly questionable.

The results from the sensitivity tests have demonstrated that the model, when run in 'real time' (i.e. no morphological updating is applied) is generally insensitive to most model parameter settings. Changing the parameters such as grain size (within a reasonable range) do not appear to influence the eventual morphological pattern obtained only the time-scale taken for the pattern to form or the length-scale of the pattern formed. The exception to this is the initial depth of sediment, which has a much greater influence on the channel-shoal formation. This would suggest that this is a key parameter if the model is to have any chance of reproducing real morphological change. Therefore, the imposition of the Holocene surface as the initial depth of sediment may be important. However, this still neglects any change in sediment composition with depth.

The differences in water depth and the corresponding changes in the velocity distribution in response to the morphological updating in the model lead to the development of small perturbations in the morphology. These perturbations can become unstable and grow exponentially and cause the model to 'blow-up'.

More surprising is the effect of various boundary forcings applied to the morphological model such as tide-surge conditions, wind and varying freshwater flows. From the model tests undertaken the results suggest that the model is insensitive to such conditions, at least in a time-scale corresponding to the morphological change imposed when running the model with no applied scaling. Based on the results obtained the greatest limitation of the model is an apparent inability to create any form of dynamic equilibrium even when applying a varying wind speed and direction. The model results all show the development of a static equilibrium.

With respect to the simulations undertaken with bridge structures in place within the estuary, the model results enable limited conclusions to be drawn as to the longer-term effects. The model provides insight into the effects any significant loss in flow cross-section may have on morphological development. In addition, some inference can be made, based on the results, that if the simulation with the structures in place shows the same result as that with no structures present then the impact will be not be significant on the estuary system as a whole. However, the model currently appears incapable of reproducing any form of dynamic equilibrium and, therefore, has implications for longer-term impacts. For example, what would be the long-term outcome should a channel locate itself through the position of one or more of the bridge piers. Will the channel remain 'locked on' to the pier or will it be free to carry on meandering? In an estuary system like the Mersey where the sandbanks can be eroded by more than 1m in a single day such questions are important to the long-term evolution of the system. Early studies of the estuary by Cashin (1949) and Price and Kendrick (1963) have demonstrated that anthropogenic changes in the estuary have already altered the ability of the channel to meander freely. For example, construction of the training walls in Liverpool Bay, started in 1901, to fix the position of the main navigation channel to the Port of Liverpool suppressed channel meandering and confined more of the ebb tide to the trained channel. This in turn led to a strengthening of the flood tide along the Lancashire and North Wirral coastlines. Enhancement of the flood tide would have contributed to an increase in siltation in both the trained navigation channel and the estuary itself. On this basis, Price and Kendrick suggested that where meandering in the estuary is suppressed there is a resulting loss in volume. Although Inglis (1964) pointed out that channel stabilization only caused deterioration if it led to a loss of flow energy. The ability to model such effects is essential if numerical morphological models are to have a wider-applicability to such studies.

More recent studies (Haigh *et al.*, 2005) have suggested that the use of morphological models to predict channel switching using our current understanding of the mechanisms causing these events are unable to predict a channel switch. This could be be due to the correct processes not being represented in the modelling system, or that our understanding of the nature of such events is flawed. However, a principal mechanism of erosion in the estuaries such as the Mersey, where there are extensive areas of drying banks is block failure, this is a mechanism that is not incorporated into our sediment transport models.

Therefore, there is already a built in limitation in the numerical morphological tools being applied.

VII. CONCLUSIONS

The objective of the study was to assess the suitability of a process-based morphological model to be applied to the investigation of the long-term impact of placing structures within an estuary. An initial modelling investigation compared a numerical simulation with that of a physical model. From this initial study it was concluded that:

- A processed-based morphological model has demonstrated the ability to reproduce realistic channel–shoal systems. This would suggest that the numerical model possesses the requisite processes necessary to allow these estuarine channel-shoal systems to evolve.

From these modelling results it was concluded that such models can be applied to the investigation of practical engineering issues such as the long-term impact of placing a structure, in this case a bridge, within an estuary system. However, before undertaking any comparison of an estuary without and with structures in place a series of sensitivity tests were carried out. From these tests it was concluded that:

- When run in ‘real time’ (i.e. no morphological updating is applied) the results are generally insensitive to most model parameter settings. Changing the parameters such as grain size (within a reasonable range) do not appear to influence the eventual morphological pattern obtained only the time-scale taken for the pattern to form or the length-scale of the pattern formed.

- However, the initial depth of sediment, appears to have a much greater influence on the channel-shoal formation. This would suggest that this is a key parameter if the model is to have any chance of reproducing real morphological change. Therefore, the imposition of the Holocene surface as the initial depth of sediment may be important.

- From the model tests undertaken the results suggest that the model is insensitive to the effect of various boundary forcing applied to the morphological model such as tide-surge conditions, wind and varying freshwater flows., at least in a time-scale corresponding to the morphological change imposed when running the model with no morphological scaling.

- Based on the results obtained the greatest limitation of the model is an apparent inability to create any form of dynamic equilibrium even when applying a varying wind speed and direction. The model results all show the development of a static equilibrium.

From the simulations with bridge piers in place the model results enable limited conclusions to be drawn as to the longer-term effects. In general:

- The model provides insight into the effects any significant loss in flow cross-section may have on morphological development.

- Some inference can be made, based on the results, that if the simulation with the structures in place shows the same result as that with no structures present then the impact will be not be significant on the estuary system as a whole.

However, the model currently appears incapable of reproducing any form of dynamic equilibrium and, therefore, has implications for modelling longer-term impacts. As our understanding of the physics behind estuary processes continues to improve and as our ability to model them also advances then morphological models will become more valuable tools. However, there will always be limitations with such approaches due to the uncertainties present in the natural system.

VIII. REFERENCES

[1] Yalin, M.S. (1971). *Theory of hydraulic models*. MacMillan, London.

[2] Hibma, A. (2004). *Morphodynamic modelling of estuarine channel-shoal systems*. Ph.D thesis, Technical University of Delft.

[3] Vernon-Harcourt, L.F. (1890). Effect of training walls in an estuary. *Paper read to the Royal Society, London, January 30.*

[4] Townend, I.H. (2006). Personal communication.

[5] Cashin, J. A. (1949) “Engineering Works for the Improvement of the Estuary of the Mersey”, *Journal of the Institution of Civil Engineers*, No. 7, 296-368.

[6] Price, W.A. and Kendrick, M.P. (1963). Field and model investigation into the reasons for siltation in the Mersey Estuary. Proc. Inst. Civil Engrs., April, Vol 24, pp 473-518.

[7] Inglis, C. (1964). In: Field and model investigation into the reasons for siltation in the Mersey estuary, Price, W.A. and Kendrick M.P., Reply to the Discussions, Proc. Inst. Of Civil Engrs., Vol. 27, March, pp. 613-647.

[8] Haigh I.D., Norton P.A. & Townend I. H. (2005). Understanding and Predicting Morphological Change in the Inner Humber Estuary. In: *Coastal Engng. 2004, Proc. of 29 Int. Conf.*, Lisbon, Portugal, 19 –24 Sept, 2004.