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Application of TELEMAC-2D and SISYPHE to complex estuarine regions to inform future management decisions

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***Abstract* — Complex, high resolution, finite-element TELEMAC-2D grids have been developed to simulate ocean/fluvial interaction in three shallow, intensively managed Welsh estuaries. In each case, important ecosystems and developed areas are exposed to flooding from both tidal and fluvial events. Of particular concern is how the estuaries will be affected by future sea-level rise due to climate change, and how best to manage the estuaries in the future.**

Each grid has been generated using BlueKenue© and comprises several sub-grids to resolve important aspects of the estuary, such as river channels and flood embankments. Accurate representation of these features is paramount to flood risk modelling. A selection of present-day mean and extreme hydrodynamic/fluvial scenarios has been simulated, as well as future climate change scenarios. These simulations have highlighted the need for local management so that coastal flooding and morphological change are minimised, whilst preserving important ecosystems such as protected salt marshes and peat bogs. Alterations were made to the grids in order to address possible management options such as coastal realignment. In this way, key implications for flood risk, sediment transport and morphological change can be predicted which will aid management decisions.

I. INTRODUTION

Some of the most challenging environments faced by ocean modellers are estuaries. These regions are where fresh river water interacts with saline water to produce strong baroclinic currents; where shallow water depths generate highly nonlinear tidal perturbations; and where complex topography and anthropogenic coastal interventions ultimately control circulation. Estuaries provide important modelling case studies because they are often surrounded by protected ecosystems, and harbour significant human populations which exploit the area for leisure and tourism.

Around the coast of Wales, UK, there are several estuaries which urgently require coastal management to reduce flood risk. These estuaries have been heavily managed over the past century and coastal realignment has reduced their natural tidal prisms. De-facto coastal defences are becoming overtopped more regularly, due to sea-level rise and increased storm surge and high river flow events. Flooding episodes drain slowly and hence impact on important ecosystems and infrastructure. In order to understand the influence of climate change on coastal flooding, and the impact of different management options, a three-year project in collaboration with the Countryside Council for Wales (CCW) was undertaken where TELEMAC-2D was applied to three representative Welsh estuaries (Fig. 1), namely the Dyfi Estuary [1-3], the Burry Inlet [4], and the Mawddach Estuary [5]. A fundamental aim of the study was to develop hydrodynamic solutions based upon accurate, two-dimensional model grids of each estuary. The grids incorporate anthropogenic features, such as coastal breakwaters, railway embankments and sea walls, whilst resolving small-scale bed features in the near shore zone and extending off-shore to allow the simulation of tidal propagation. Each application has investigated flooding, circulation and sediment transport for a selection of mean and extreme climatic scenarios.

The three case studies are described in Section II. Application of TELEMAC-2D, the flow module, and SISYPHE, the sediment transport module, to each estuary is explained in Section III, including model validation and a summary of the scenarios that have been modelled. Some of the key results are presented in Section IV, followed by discussions and conclusions in Section V.

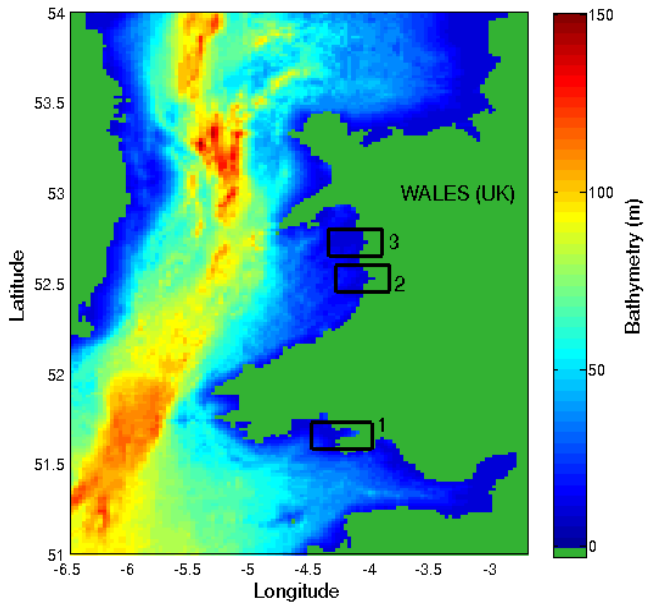

Figure 1. Map showing the three Welsh estuary case studies (boxed areas), modelled using TELEMAC-2D (1-The Burry Inlet, 2-the Dyfi Estuary, and 3-the Mawddach Estuary). The domains overlie model output of bathymetry in the Irish Sea from a (finite-difference) POM simulation, which was used to provide elevation/velocity boundary harmonics for each of the nested TELEMAC-2D models.

II. CASE STUDIES OF WELSH ESTUARIES AND RATIONALE

This paper summarises three model studies of estuaries on the Welsh coast. The three regions are dynamically similar in that they are typically shallow and comprise medium grained sands, representing the later stages after the Holocene transgression (rapid infill of deep wide estuaries). The estuaries have a main ebb-dominated channel, flanked by extensive (flood-dominated) tidal flats and salt marshes. In all cases, the estuary mouth is constricted in width due to the presence of a spit. As a consequence, the strongest tidal flow occurs through the estuary mouth. Another common feature of all the case studies is that the natural size and tidal prism of the estuaries has been reduced over the past century by coastal realignment and land reclamation. This process occurred during war times when land for agriculture was at a premium. Embankments and coastal defences that were previously sufficient for withstanding extreme high water levels are now being overtopped, and these flooding episodes are becoming more regular.

The Burry Inlet, south Wales, is the largest of the three estuaries (16 km in length with a spring tidal prism of 1×10^{12} m^3), and contains a sizable population on its north coast which is at high risk from flooding. The south coast contains extensive protected salt marshes which are also at risk from increased tidal inundations, together with increased sediment erosion. There is also a risk that the spit could be breached, due to wave-induced erosion on its seaward side, which would expose the salt marsh directly to the open sea.

The natural tidal prism of the Dyfi Estuary, mid-Wales, is severely restricted by an (active) railway embankment, and also embankments on the river flood plains to protect agricultural land. Because of these embankments, high river flow that coincides with high spring tide leads to significant flooding at Machynlleth, a town near the tidal limit. Issues that now face coastal management here are whether to reinforce the embankments, or realign some of them to reduce flood risk, at the cost of land depletion, some of which comprises protected marsh ecosystems.

The third case study, the Mawddach Estuary in mid-Wales, faces many similar management issues as the neighbouring Dyfi Estuary because it is a similar inter-tidal environment that has also been affected by coastal realignments. Fig. 2 shows sub-sections of the model grid of the Mawddach Estuary, generated using BlueKenue©. The top panel illustrates the bathymetry of the estuary and evaluation of the surrounding terrestrial areas. The bottom panel shows a section of the mesh in the lower-estuary which is composed of several sub-meshes so that important features such as the main ebb channel (green mesh) and embankments or flood defences (red lines) are correctly resolved. For all case studies, bathymetric data comprised high-resolution LIDAR (Light Detection And Ranging) data within the estuary, and either Admiralty chart data or boat survey measurements off-shore. Unfortunately, bathymetry of the river channels was not available and, so, LIDAR-measured river heights were reduced by 2 m uniformly.

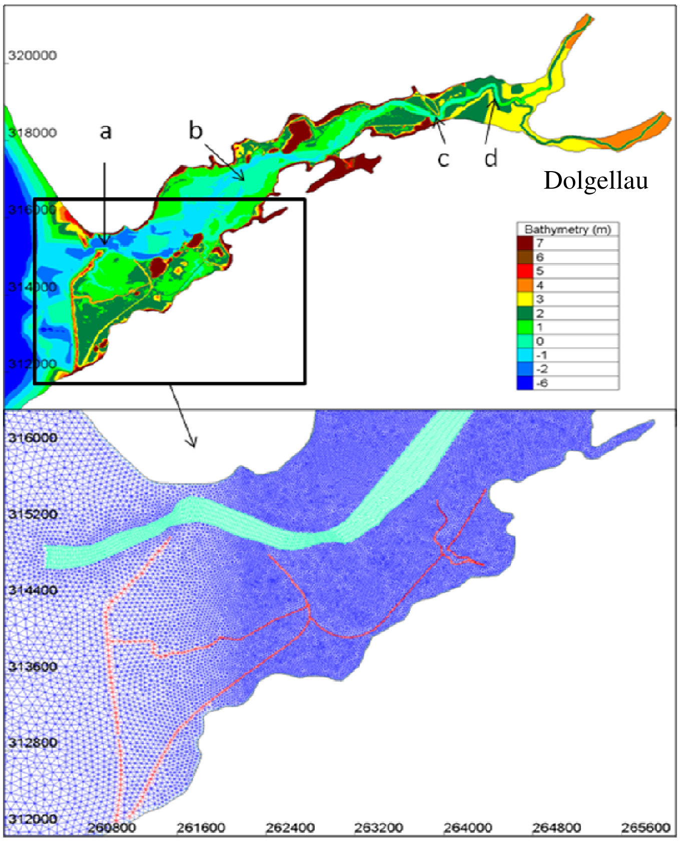

Figure 2. A sub-section of the TELEMAC-2D finite-element grid for the Mawddach Estuary, Wales, UK. The upper panel shows the estuary bathymetry and the lower panel shows a section of the finite-element grid, which comprises several sub-meshes so that key features (embankments and channels) are accurately resolved. Points (a-d) refer to the associated time series in Fig. 6.

III. MODEL APPLICATION

TELEMAC-2D is an ideal modelling framework for the estuarine environment due to its finite element grid which allows graded mesh resolution. Areas that require high bathymetric accuracy (e.g. complex coastlines, meandering river channels, or anthropogenic features such as embankments and sea defences) can be well resolved, whereas the off-shore grid-spacing can be increased to maximise computational efficiency.

The model, used here in 2D, vertically averaged mode (V5P9), is based on the shallow water Saint-Venant equations of momentum and continuity, derived from the Navier-Stokes equations by taking the vertical average, see [6]. A hydrostatic assumption is valid in this application where bed slopes are small and, hence, vertical accelerations caused by the pressure are balanced by gravity. The classical k-ε turbulence model has been adapted into vertically averaged form to include additional dispersion terms [7]; this parameterisation of the internal friction has been used throughout this study with a constant friction coefficient of 3×10^{-2} m, implemented in Nikuradse's law of bottom friction. Turbulent viscosity has been set constant with a viscosity (molecular + turbulent) coefficient equal to 10^{-2} m^2 s^{-1}. Coriolis effects have also been included. The simulations were forced with tidal elevations and velocities at the off-shore boundaries (calculated from an outer nested model [8]), and with known river flowrates at the inland river boundaries. Atmospheric forcing has been neglected in the simulations. A tracer was simulated as a proxy for salinity with constant seawater temperatures of 10°C. Therefore, densities are updated according to the salinity gradients. However, in the presence of tidal flats, erroneous salinity values were encountered. Unfortunately, there was insufficient time available to investigate this issue further, but the hydrodynamics were not affected.

Many processes in the coastal zone, such as sediment dynamics, often need to be modelled in a three-dimensional framework, especially when strong vertical stratification is present, e.g. [9]. However, 3D modelling requires extensive field validation which was not available for the present study. In practice, the present estuaries are essentially vertically well mixed in terms of density stratification because the freshwater input is small in comparison with the tidal prism [10]. It is therefore sufficient for this study to use TELEMAC-2D since the vertical approximations associated with averaging are likely to be small.

SISYPHE is the sediment transport module coupled with TELEMAC-2D to produce simulations of bed evolution. The Soulsby-Van Rijn transport formula [11] was used here where total (bed load plus suspended load) sediment transport is calculated. An equilibrium model was then used for bed level changes resulting from divergences in the transport (i.e. an advection-diffusion scheme was not implemented). The transport rate formula is expressed:

$$q_{tot} = A_s \overline{U}\left[\left(\overline{U}^2 + \frac{0.018}{C_D} U_{rms}^2\right)^{0.5} - \overline{U}_{cr}\right]^{2.4} \tag{1}$$

The formula (1) applies to total sediment transport rate per width of the flow in combined waves and currents, where A_s represents the bed load plus suspended load transport, $\overline{U}$ = depth-averaged velocity, U_{rms} = root-mean-square wave orbital velocity (here set to zero), and C_D = drag coefficient due to the current alone. The threshold current velocity [12] is expressed:

$$\overline{U}_{cr} = 0.19(d)^{0.1}\log_{10}(4h/d) \tag{2}$$

for $1\times10^{-4} < d < 5\times10^{-4}$ m, where d = mean grain diameter and h = water depth.

The Soulsby-Van Rijn formula is intended for conditions in which the bed is rippled with a bed roughness length scale implicitly equal to 6 mm. The 'sloping bed' term that would appear in a complete statement of the Soulsby-Van Rijn formula is handled separately by an equivalent 'switch' in SISYPHE. The module also includes a parameterisation of secondary currents due to vertical eddy circulation. The surface wave module, TOMAWAC, was not utilised; therefore, all simulations hereafter do not account for surface wave effects. While wave effects are important on the open coast [10], the present focus is on the interior of the respective estuaries only.

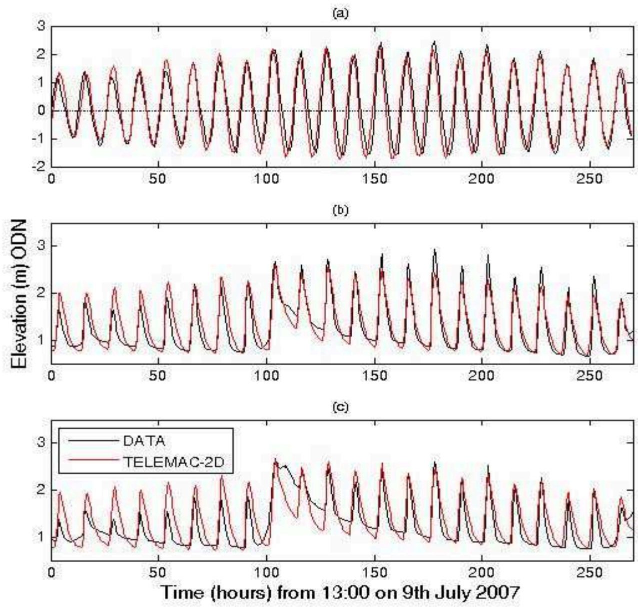

Figure 3. Model validation: observed and simulated elevations at (a) Aberdyfi, (b) Dyfi Junction Station and (c) Pennal Bend in the Dyfi Estuary during July 2007. The tidal wave, which passes from neaps to springs, becomes more asymmetric with distance into the estuary, showing a shorter flood and longer ebb. A large river discharge event can clearly be seen in both the observations and the model at 110 hours.

The flow model was validated in the Dyfi Estuary using data collected during 9[th] – 21[st] July, 2007 [2]. Tidal elevations were measured at 3 locations within the estuary (Aberdyfi, Dyfi Junction, and Pennal Bend; points (a) to (c), respectively, in Fig. 5). TELEMAC-2D was run for this period, forced with tidal elevations and with river inputs based on the observed river flowrates. The data and model simulations were mainly in good agreement at Aberdyfi, as shown in Fig. 3a. A high run-off event can clearly be seen in (b) and (c) after 100 hours, followed by a slowly diminishing water level after the rain event onto which the tidal signal was superimposed. The elevations in the river are poorly simulated at times, most notably during the first half of the field survey. River elevations are difficult to simulate in relatively small estuaries because the detailed shape of the channel and position of the tide gauge have a great influence on the local water level. Unfortunately, there was insufficient sediment transport data available for validation of the SISYPHE module. However, TELEMAC has been tested extensively elsewhere against similar case studies [e.g. 13-15].

A set of tidally-forced, idealised model scenarios, together with fluvial inflow from the river channels, has been designed as a sensitivity exercise whereby the simulations represent mean and 'extreme' climatic conditions, both in the present-day and in the future. In this way, the specific model input variables that affect the circulation (tidal amplitude, storm surge, river flowrates and sea-level rise) can be examined. The scenarios are summarised in Table 1. For all the scenarios, the model was forced with the primary tidal constituents (M_2 and S_2) and run for a period of 8 days in order to capture both neap and spring tidal conditions.

Table 1. Summary of the modelled scenarios.

Model Scenario		Duration and Tidal forcing	Storm surge	River flowrates	Sea-level rise
1	**Baseline mean case**		---	Annual mean	---
2	**Extreme storm surge**		1 in 100 yrs (= 2 m)	Annual mean	---
3	**Extreme high river flowrates**	Neap-Spring cycle	---	1 in 100 yrs	---
4	**Extreme low river flowrates (drought)**	M_2+S_2 tidal amplitudes	---	0.0	---
5	**Combined extreme conditions**		1 in 100 yrs (= 2 m)	1 in 100 yrs	---
6	**Future extreme conditions**		1 in 100 yrs (= 2 m)	1 in 100 yrs	100 yrs (= 1.0 m)

IV. RESULTS

In each of the three estuarine case studies, increased sea levels of 1 m and above had the most dramatic influence on flooding episodes, rather than high river events. Such a circumstance is caused by an extreme storm surge or due to predicted sea-level rise in 100 years. Presently, most embankments and coastal defences are not overtopped during high spring tide, yet with increased sea levels of 1 m or more, overtopping occurs and protected marshes and urban areas are flooded. For example, Fig. 4 shows high spring tide water levels in the lower Mawddach Estuary, with and without a 2 m storm surge. The embankments shield the village of Fairbourne and the protected Arthog Bog from flooding in the former case, but not with an extreme storm surge. Another important result, that is generic to all three case studies, is that by removing some or all of the embankments, tidal inundations and excess fluvial waters are able to spread out laterally across the flood plains, which reduces water levels up-stream in the river channels. Therefore, informed management decisions can reduce flood risk in low-lying areas in the upper estuaries.

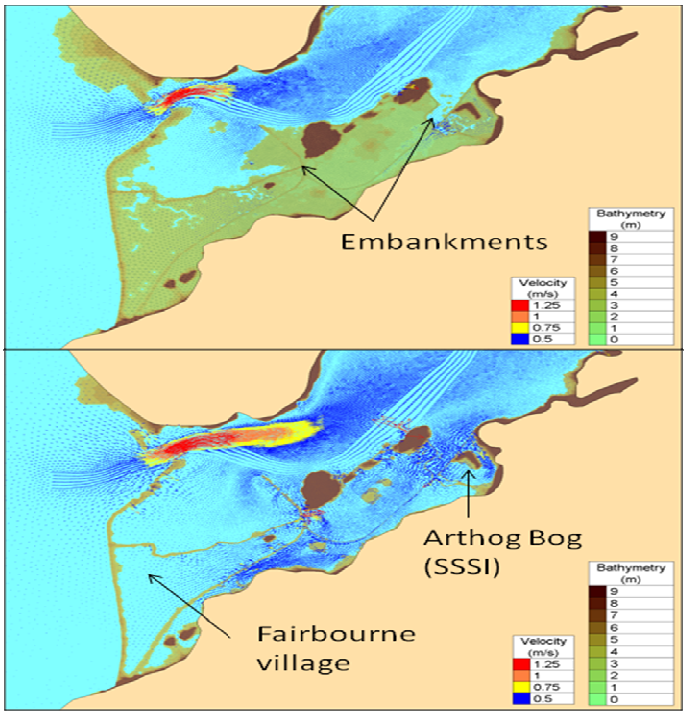

Figure 4 - A sub-section of the Mawddach Estuary, showing flooding at high spring tide (top) and with an additional 2 m storm surge (bottom). Bathymetry in dry areas is shown, where several embankments (coastal defences) can be identified (light brown lines). The bathymetry is overlain with water depths (light blue) and velocity vectors.

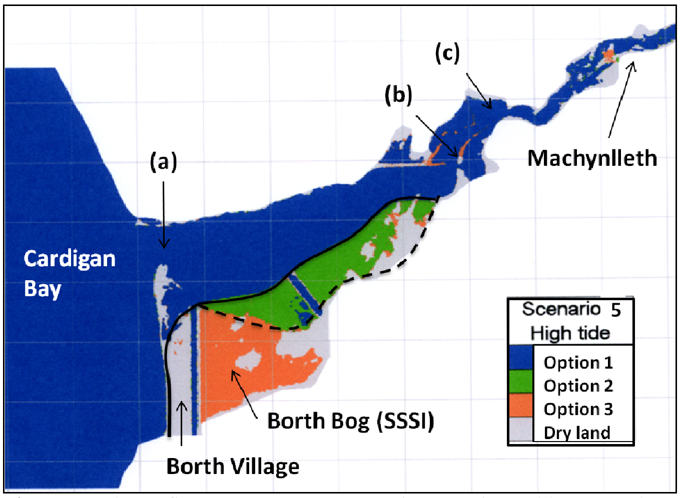

Figure 5 - The Dyfi Estuary management options. Option 1: blue areas show flooding when existing rail embankments (solid black line) are raised by 2 m. Option 2: green areas show additional flooding when a section of the rail embankment is realigned further south (dashed black line). Option 3: orange areas show further flooding when the same section of the rail embankment is removed all together. The validation points (a - c) are marked (see Fig. 3).

The Dyfi Estuary simulations show that with no coastal management in the future, areas of salt marsh will diminish due to coastal squeeze, and the scarce ecosystem of Borth Bog will change due to increased flooding. Borth Village will also be at risk to flooding. However, the model predicts that coastal realignment can protect some areas of Borth Bog and Borth Village, while allowing the salt marsh to migrate landwards. For example, Fig. 5 shows flooding for three management scenarios. For option 1, the embankments (which act as de-facto flood defences) have been reinforced by raising their height by 2 m. The present estuary shape is maintained but increased sea level will cause areas of salt marsh (located on the estuary-side of the embankments) to diminish. For option 2, a section of the rail line has been realigned further south. This allows the northern bog (which is less important as most of it comprises agricultural land) to flood so that salt marsh migration can take place, yet protects the majority of the peat bog and residential properties in the south. Option 3 shows that the entire Borth Bog will flood in extreme conditions (Scenario 5) if this section of the embankment is removed.

The morphodynamics of shallow, vertically well mixed estuaries, characterised by tidal flats and deeper channels, have been investigated to find out what contributes to flood/ebb-dominant sediment transport in localised regions (see [2] for more details). Applied to the Dyfi, the results show that shallow water depths lead to flood-dominance in the inner estuary while tidal flats and deep channels cause ebb-dominance in the outer estuary. With an artificially ‘flattened’ bathymetry (i.e. no tidal flats), the net sediment transport switches from ebb-dominant to flood-dominant where the parameter a/h (local tidal amplitude ÷ local tidally-averaged water depth) exceeds 1.2. Sea-level rise will reduce this critical value of a/h and also reduce the ebb-directed sediment transport significantly, leading to a flood-dominated estuarine system. A similar pattern, albeit with greater transport, was simulated with tidal flats included and also with a reduced grain size.

Simulations in the Burry Inlet show that there is an increasing risk of flooding on the urbanised north coast, which could affect the towns of Llanelli and Burry Port, and also in the southern estuary salt marsh which is of great environmental importance (see Fig. 6). An extreme tidal/fluvial simulation (Scenario 5), for example, increased the tidal prism by 100 %, compared with Scenario 1, and shifted the tidal limit 3 km further up-stream. Velocities increased by 50 % throughout the estuary. Consequently, Whiteford Spit experienced significant erosion with sediment transported northward and deposited off-shore in the ebb delta.

Fig. 6 shows the effects on sediment transport (compared with the present-day Grid 1) of two management options: (*i*) removing (Grid 2) and (*ii*) restoring (Grid 3) a breached training wall in the main estuary channel. Velocities and sediment transport rates were reduced locally, where the wall had been removed, but increased further up-estuary. The re-built wall constricts the flow which increased erosion either side of the wall, but reduced sediment transport further up-estuary.

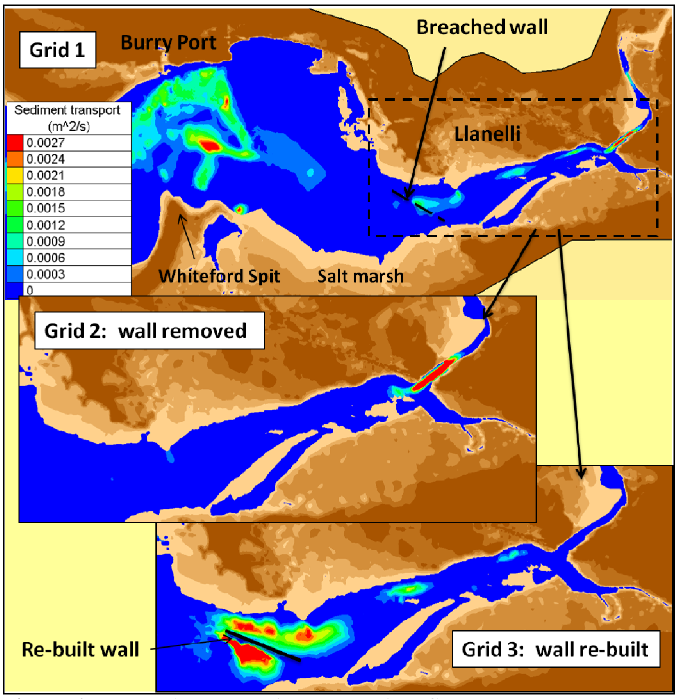

Figure 6. Burry Inlet - Scenario 1 (mean river flowrates, no surge, no sea-level rise): sediment transport rates during peak flood flow for Grid 1(present estuary shape - breached training wall in main channel), Grid 2 (wall removed) and Grid 3 (wall re-built). The brown areas are dry land.

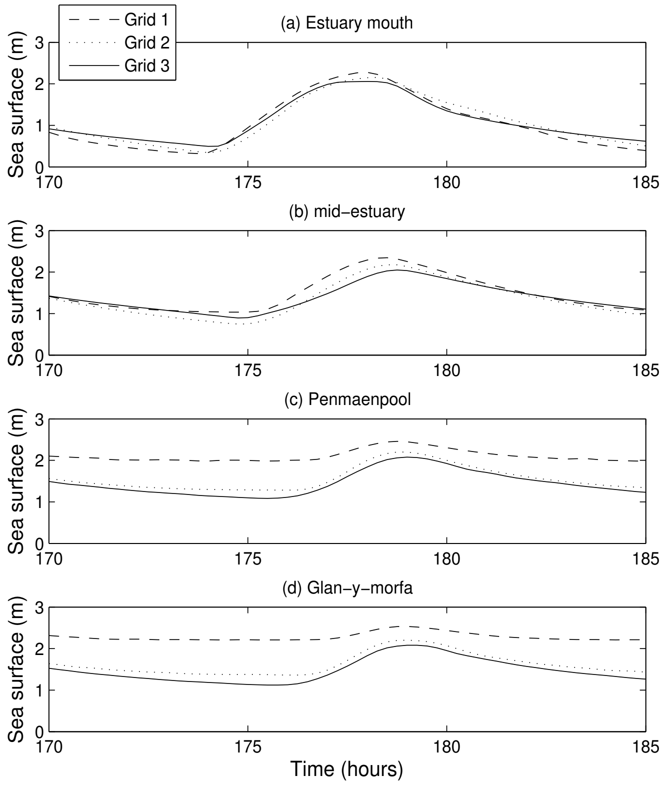

Figure 7. Mawddach Estuary - Scenario 1 (mean river flowrates, no surge, no sea-level rise): sea surface heights for Grid 1(present estuary shape), Grid 2 (all embankments removed - natural shape) and Grid 3 (upper-estuary embankments removed - possible management option). Each consecutive panel, located further up-estuary (see Fig. 1), shows tidal propagation during spring tide. Sea surface heights are significantly reduced with embankments removed.

The Mawddach Estuary simulations have shown that removing some embankments, hence increasing the size of the estuary and its tidal prism, will reduce flood risk in the upper estuary and in the river channels. Consequently, flood risk in the town of Dolgellau (see Fig. 2) will be reduced. This is because intruding tidal and fluvial waters are able to spread out laterally across the flood plains, reducing water levels up-stream. Fig. 6 shows water heights over a spring tidal cycle, at four locations within the Mawddach Estuary (see also Fig. 2), for Scenario 1 simulations on three different grid configurations (Grid-1: present estuary shape, Grid-2: natural estuary shape - all embankments removed, and Grid-3: managed estuary shape - some embankments removed). In the upper estuary and river channel, water heights are reduced by up to 1 m for Grids-2 and -3, where the flood plains have been opened up allowing water in the channel to spread out laterally. This is a very important result for coastal management as it suggests that coastal realignment, which is also relatively cheap, can be highly effective in reducing flood risk up-estuary.

V. DISCISSION

Estuarine environments have always been populated, originally due to trade and industry, but more so today because people are attracted by their outstanding natural beauty. In order to preserve these environments for future circumstances involving climate change, coastal management strategies are essential. Through this study, and other modelling projects, interested authorities in Wales are now realising the potential that modelling has in aiding coastal management.

This study has shown that TELEMAC-2D is a suitable modelling framework for estuarine case studies, for the most part because of the finite-element grid (orthogonal or curvilinear grids will not generate comparable resolution as efficiently). Simulations of very shallow water depths and tidal flats (where cells can 'dry out') are also essential features which are included in TELEMAC-2D. However, secondary baroclinic flows, which are often generated in estuaries (although shallow depths ensure a vertically mixed water column for the present case studies), will not be simulated in a depth-averaged model and, therefore, three-dimensional modelling will be required.

Nevertheless, there are some major shortcomings to this study, caused primarily by coarse grid resolutions and limited model validation. Whilst grid resolutions as fine as 10 m seem sufficient for most coastal applications, increasing the resolution further would significantly improve the accuracy of the simulations. For example, small-scale features such as creeks can have a significant impact on drainage times on the flood plains. Impermeability of the bed together with unresolved drainage channels lead to unrealistic 'pooling' of water behind overtopped embankments. Therefore, the severity of flooding may be over-estimated in some of the simulations. Such errors could be reduced with additional coding to either mimic an impermeable bed or realistic drainage, both of which would require validation.

Future, similar, estuarine modelling will require accurate high-resolution (< 5 m) bathymetric data, including off-shore measurements and bathymetry of the river channels. Unfortunately, time constraints of the present study did not allow for extensive validation of the hydrodynamics and sediment transport. Given more time, these issues could be easily addressed which would greatly improve the results presented here. All that being said, the models have given considerable insight into local circulation patterns that were previously not understood. The results presented here have provided a foretaste of the vast potential that can be gained from forecast simulations, from the perspective of coastal planners.

ACKNOWLEDGEMENTS

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