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Sediment pathways and the analysis of dredging on sediment deposition along the Norfolk and Lincolnshire coasts – UK

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Abstract— **This study presents an application of the TELEMAC suite in order to assess the sediment pathways in a coastal domain where marine aggregates extraction takes place. The effect of dredging on coastal sediment deposition is analysed by considering the transport of sediment from a dredging area over an otherwise stationary bed assuming equilibrium conditions. Transport is driven by the hydrodynamics of tides, waves and surges and simulations are run for times of around a year over which the morphodynamic system is assumed to be otherwise in equilibrium. By determining the coastal sediment deposition resulting from a volume of sediment superposed on the dredging area, the nearshore-offshore linkage may be estimated. The finite-element software suite, TELEMAC system, comprising TELEMAC-2D (currents), TOMAWAC (wave action) and SISYPHE (sediment transport) is used. As well as coastal sediment deposition, large-scale, residual sediment pathways for the coastal domain are produced. The influence of waves is assessed. Case studies are undertaken for one important dredging area off the Norfolk and Lincolnshire coasts in the UK.**

I. INTRODUCTION

The influence of dredging on coastal processes and erosion has been the subject of much debate. There is folklore that sand extracted offshore eventually deprives sand from beaches causing or accelerating coastal erosion. We are here concerned with dredging off the Norfolk and Lincolnshire coasts which provides about 10% of the aggregate for the UK construction industry and is thus of major strategic importance [1]. Dredged material from UK waters is also exported to the Netherlands, Belgium and France. In addition over 80 million cubic meters of marine aggregates have been used in the UK for beach replenishment since the late 1960's, to mitigate coastal erosion [1].

This profitable activity is highly regulated. It affects areas used by marine pipelines, by offshore wind farms and for navigation. Dredging activities can modify the seabed composition up to several kilometres from the trench or the pit, impacting seabed fauna and flora [2, 3]. Since extracting sediment from the seabed reduces the volume of sediment offshore, offshore dredging may impact coastal evolution. Because of the complex nonlinear processes involved in coastal morphology, it is difficult task to isolate the influence of dredging from the background morphodynamic behaviour.

The relation between offshore dredging and coastal stability has been reported in the literature. Many studies, based on numerical modelling, focus on the effect of sandpits or trenches on tidal flows and wave propagation [4, 5, 6]. Results are site specific and tend to show that offshore dredging has minimal influence on nearshore wave height and longshore sediment transport. Idealised numerical modelling has shown that dredged, shore-connected sand ridges would recover and that sediment required to rebuild the sand ridges is provided both by offshore and nearshore zones [7]. Large scale effects using process-based numerical modelling have also been studied by [8]. Depending on the geometry of the sand pit, the extent of the area influenced by the dredging can reach 200 km^2. Flume and wave tank experiments show that sand extraction can affect shoreline stability depending either on the position of the trench or on the wave climate [9]. During the last decade, projects have been undertaken to tackle the issue of the impact of offshore dredging. The SANDPIT project [10] proposed guidelines for stakeholders, and detailed laboratory and field measurements were made in order to improve numerical modelling of sediment transport. Within the framework PUTMOR [11], extensive monitoring of a sand extraction pit was undertaken. A variety of numerical models developed to study the offshore morphological effect of marine aggregate extraction is reviewed in the EU MARSAND project [12].

The area of interest in the present study is the South-Western part of the North Sea (Fig. 1). The bathymetry of this area has prominent tidal sandbanks. Their interaction with the local flows and waves were studied by [13] highlighting the implications for adjacent nearshore stability. Some of these seabed features are moribund and others are mobile. [14] used a long temporal series of surveys to assess the mobility of the sandbank system of Great Yarmouth. The sediment circulation in the vicinity of moribund sandbanks was analysed by [15]. Clockwise sediment transport was shown around the sandbanks confirming numerical modelling undertaken by [16]. A general assessment of the regional sediment transport pathways was performed during the Southern North Sea Sediment Transport Study [5]. The longshore transport estimated through this latter study was in agreement with previous studies [17, 18].

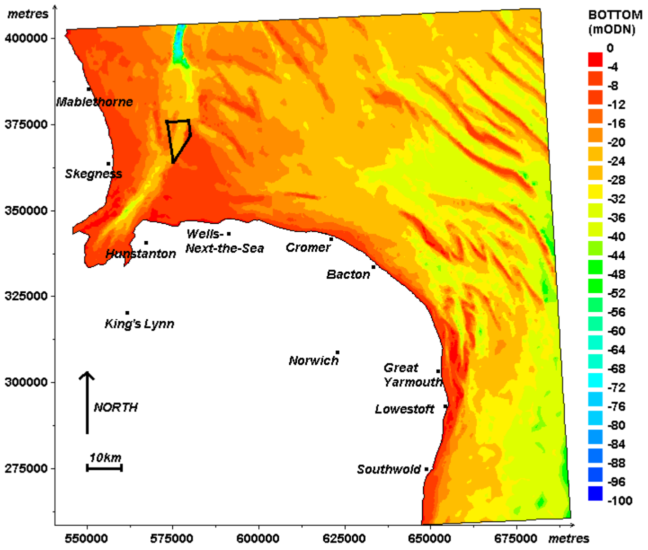

Figure 1. Map of coastal domain showing bathymetry, with bold line enclosing the Humber dredging area.

The availability of hindcasts for offshore waves and surges [19, 20] provide hydrodynamic boundary conditions for modelling within extensive coastal domains, enabling new insights to be provided by process-based morpho-dynamic modelling. Here, offshore boundary conditions for waves, surges and tides [21] enable the assessment of sediment pathways on the upper part of the continental shelf. The analysis and modelling strategies are presented in section 2 and 3. After analysing the sensitivity of the model to the sediment transport formulation and the relative influence of waves on sediment pathways in section 4, section 5 presents the results of the dredging impact on bed evolution. Section 6 discusses the sediment pathways followed by a source of sediment located in the Humber dredged area. Conclusions are drawn in the last section.

II. PRESENT ANALYSIS STRATEGY

Sediment transport is driven by the hydrodynamics of tidal currents and waves, and surges in extreme conditions. Most transport models determine the flux which defines bed evolution through sediment mass conservation. By running hydro-morphodynamic models for a large domain including the dredged area it is difficult to determine the effect of removing sand since the origin of sediment deposited near the shore or elsewhere is not identified.

To determine the influence of dredging we adopt an inverse approach. We consider an initial condition of a volume of sand distributed over the dredging area. This volume is then dispersed due to the hydrodynamic forcing of sediment transport over the otherwise stationary bathymetry of the coastal domain. In this way the deposition resulting only from the initial volume can be determined everywhere, including importantly the nearshore region. The flux out of the domain may also be determined. An equilibrium state may otherwise be assumed for a period of about a year. Since the dispersion of a volume from an area is now known, the sediment pathways are also known. The volume of sand deposited nearshore is defined as that deposited long a thin strip parallel to the shoreline.

III. MODELLING STRATEGY

Numerical simulations of wind-generated waves, tides and surges propagation are made using the TELEMAC system [22]. Based on the finite element method, the system is a convenient tool enabling high spatial resolution in the zones with complex bathymetry while optimising computing time. It incorporates a wave action conservation equation solver –TOMAWAC, a Saint-Venant equation solver–TELEMAC-2D, and a sediment mass conservation equation solver –SISYPHE.

A. *Computational domain*

The computational domain for this study includes the coastal zone extending from the Humber Estuary in the North to Southwold in the South (Fig.1). The coastline is assumed to be at the lowest astronomical tide (LAT).

The finite element method allows flexible refinement in zones with complex bathymetry. The spatial resolution of the model varies from 250m to 4000m. Fine resolution is imposed along the coastline and the sandbanks. The number of nodes is 29762 with 58689 triangular elements.

The initial bathymetry reference is Chart Datum (CD). A conversion is performed to convert the CD reference to Ordnance Datum at Newlyn (ODN). To do so, one needs to know the difference between the mean sea level (MSL) and the LAT. The tidal model of Continental Shelf of the UK coasts, CS3X, developed by [20], has its free surface elevation reference at the MSL. From the tidal results of this model run over 40 years, the lowest tidal water level can be estimated. This level provides an estimate of the difference between the LAT and the MSL. This estimate depends on the number of tidal waves represented with the CS3X model. According to the data at Cromer and Lowestoft, the relation between LAT and MSL is respectively –2.75m and –1.50m. Our method leads to an overestimate with these data of less than 0.15m.

B. *Wave propagation module*

The module, TOMAWAC, is run in non-stationary mode, solving the equation of the conservation of wave action with the following source terms: wave-wave interaction, energy dissipation by bottom friction and depth-induced breaking, and refraction due to bathymetry gradient. Water depth evolution, due to tides and surges, is taken into account. [23] found that wind stress within the domain and wave refraction by currents had little influence on wave propagation for this coastal area. Including wind stress within the coastal domain only had a noticeable effect on nearshore wave heights for speeds higher than about 20m.s^{-1}.

When waves are entering the domain, a JONSWAP spectrum is imposed at the offshore boundaries of the model. A free condition is assumed when offshore waves are travelling out from the domain. The spectral frequency and directional resolutions were set to 22 frequencies (from 0.05 to 0.37Hz) and 24 directions. The JONSWAP bottom friction coefficient of 0.038m^2/s^3 and the formulation for depth-induced wave breaking of Battjes and Janssen are used. The time step is set at 6min. [24] previously calibrated and validated the model.

C. *Hydrodynamic tide/surge module*

The propagation of barotropic tides and surges is computed using TELEMAC-2D, which solves the depth-averaged shallow water equations. Converged results were obtained with a time step of 90s. The model takes into account bottom friction, Coriolis force and wave radiation stresses. Along the offshore boundaries, water depth and current velocities are imposed. At the coastline, a free slip condition is prescribed. Bottom friction parameterisation is based on bottom roughness with a Nikuradse coefficient dependent on mean sediment size and bed forms. A spatially uniform coefficient is used here. A constant value of the Coriolis parameter is also used.

D. *Sediment transport and bed evolution module*

The conservation of sediment mass is solved using a finite volume scheme. Special treatment for a non-erodible bed is included within SISYPHE [25]. Along the coastline, zero sediment flux is imposed. At the outer boundaries, the condition depends on the flow. For an inflow, there is no sediment flux and no bed evolution. For an outflow, a zero gradient of sediment flux is imposed. The time step is the same as for TELEMAC-2D.

Sediment transport modelling depends on sediment grain size and semi-empirical formulae to relate flow conditions to sediment flux. Two different grain sizes representative of the area of interest are considered: median grain sizes, d_{50}, of 400 µm and 200 µm. Two widely used total load formulations for sediment transport rate are tested: due to Bijker and Soulsby−van Rijn [25].

E. *Coupling procedure for sediment transport due to tides, surges and waves*

For tides alone TELEMAC-2D and SISYPHE are internally coupled to simulate sediment transport and bed evolution [25]. In addition wave propagation generates radiation stresses which influence currents and sediment transport. Wave-integrated parameters and radiation stress were thus determined by running TOMAWAC with water elevations from a tide-only TELEMAC-2D run, usually for a period of one year. These are then input into the coupled TELEMAC-2D and SISYPHE system to give sediment transport due to currents and waves combined. Radiation stress in principle has an effect on water elevation but the resulting effect on wave propagation was found not to be significant.

F. *Boundary conditions*

Wave, surge and tide data imposed along the outer boundaries are provided by UKCP09 [21]. The UKCP09 outputs are hourly water elevations, depth-averaged current components and six-hourly integrated wave parameters, with a spatial resolution of approximately 12km. All these parameters are linearly interpolated both temporally and spatially along the offshore boundary of our domain.

The UKCP09 dataset is a climatic projection, set up to study the marine impact of climate change in the UK coastal waters, based on SRES scenarios [26]. However, mean and extreme statistics from 1960 to 1990 are consistent with hindcast data using re-analysed wind data ERA40 [21]. The boundary conditions correspond to the year 1989, which is an average year in terms of the number of storm events.

G. *Dredging input*

To study the distribution of sediment located within particular offshore areas, the model is set up with a non-erodible bed everywhere. After one semi-diurnal tidal cycle used for model spin-up, a volume of sediment is deposited uniformly within the offshore area under consideration. The thickness of the layer equals the ratio between the prescribed volume and the dredged surface area. The location of the licensed area is provided by the Crown Estate. For our application, a volume of 1.5×10^6 m^3 is deposited, which represents a layer of 2cm.

IV. SENSITIVITY TESTS

Prior assessing the sediment pathways, some sensitivity tests are performed on the median grain size, the sediment transport formulations and on the influence of waves on sediment transport.

A. *Median grain size and sediment transport formulations*

Theses tests were performed to study the residual transport with only tides present. Sediment is assumed to be transported everywhere and vectors of residual sediment flux direction are presented for one neap-spring tidal cycle in Fig. 2. The results for the vector fields and hence sediment pathways are very similar for all cases, but the magnitudes of sediment transport rate were different. Higher rates are obtained for the smaller d_{50}. The Soulsby−van Rijn formulation gives rates higher than the Bijker formulation by a factor of about 10. This difference is partly due to the fact that the Soulsby-van Rijn formulation is implemented with a higher bottom friction coefficient, as observed in [27].

Previous research has carried out intercomparisons between the two formulae for sediment transport induced by waves and currents [27, 28]. For all conditions, the Soulsby-van Rijn formula provided greater sediment transport rates than the Bijker formula.

B. *Wave influence on sediment transport*

The relative influence of waves on the sediment transport is estimated in terms of residual sediment transport by defining the following ratio:

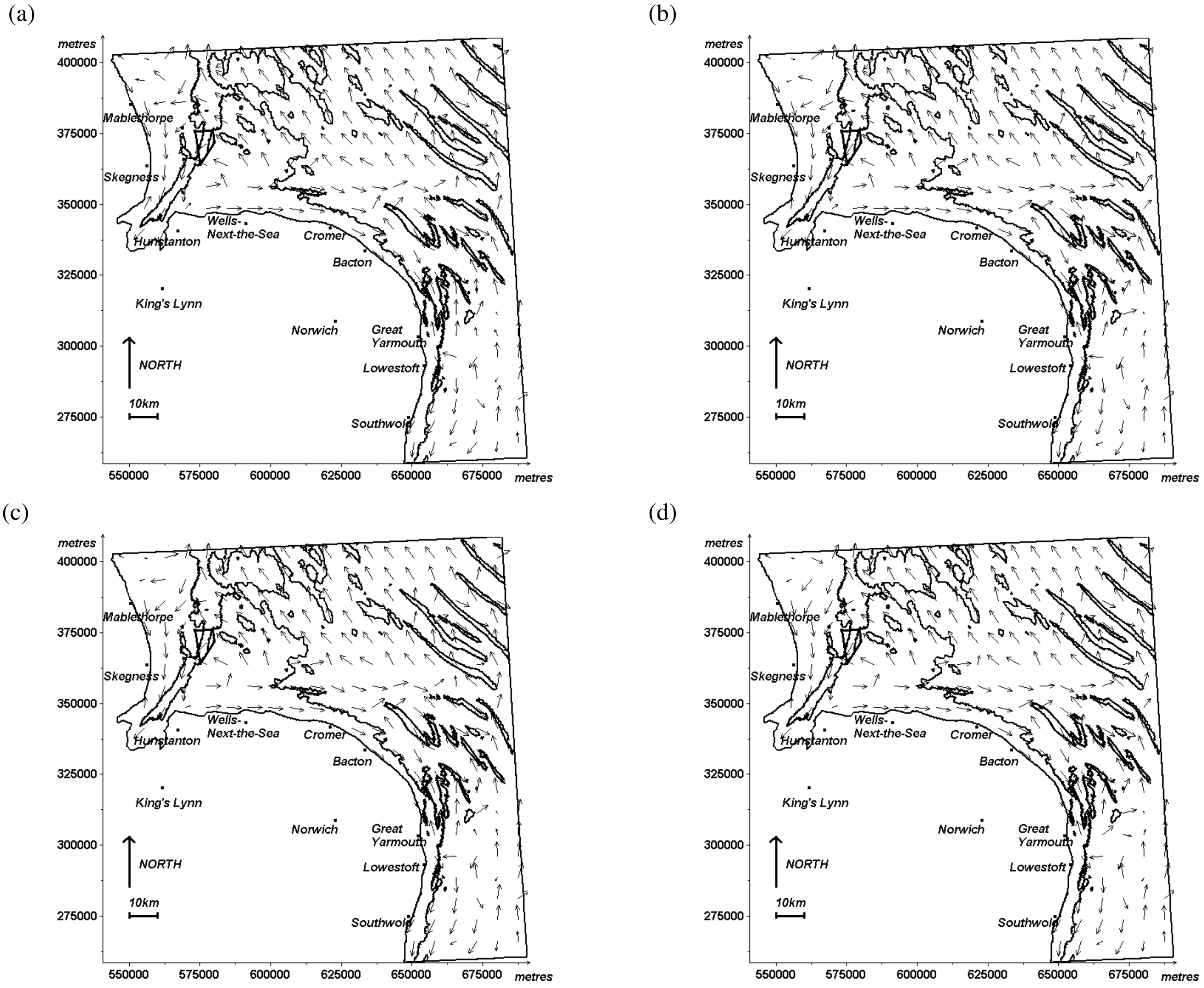

Figure 2. Residual sediment transport directions for the Soulsby-van Rijn total load formula (a,b) and the Bijker total load formula (c,d). d_{50} is 200µm for the left column and 400µm for the right column. The vectors are interpolated on a 5000m regular grid. Thick black contours represent licensed dredging areas location. -20mODN isobaths are in black lines.

$$r = \frac{\left|\overline{Q}_{T+W}\right| - \left|\overline{Q}_T\right|}{\left|\overline{Q}_T\right|} \qquad (1)$$

where $\overline{Q}_{T+W}$ and $\overline{Q}_T$ are the annual residual sediment flux vectors for combined wave and tide simulation and tide alone simulation respectively. For $|r| = 0$ waves have no effect and increasing $|r|$ shows an increasing effect of waves relative to tides. Fig. 3a presents the spatial distribution of r with a sediment size of 400µm and using the Soulsby–van Rijn total load formula. Note r may be negative showing that waves can reduce sediment transport. Wave influence is noticeable where water is shallow, over the sandbanks and along the coastline. In deeper water, to the north, sediment flux is dominated by waves while to the east and south by tides.

The influence of waves on the sediment transport direction is also assessed through the difference in the direction between the vector for residual sediment transport due to tides and waves, $\overline{Q}_{T+W}$, and the vector due to tides alone, $\overline{Q}_T$. Fig. 3b shows that waves modify sediment transport direction in some very local areas, mainly around the sandbanks off Great Yarmouth.

V. TRADITIONAL ASSESSMENT OF DREDGING IMPACT

To tackle the issue of non linearity induced by offshore material extraction, the following procedure is adopted:

- one morphological simulation with an initial non modified seabed level,
- one morphological simulation with an initial seabed level modified by a dredging intervention,
- computation of the difference between these two simulations.

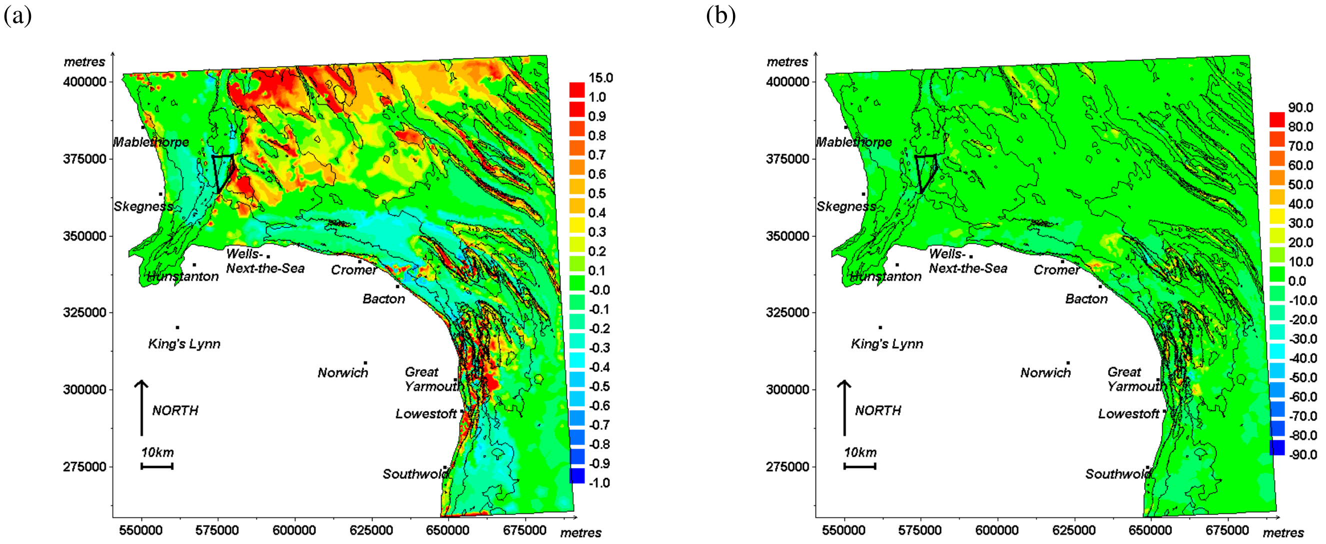

Figure 3. Wave influence on the annual residual sediment transport: (a) relative flux difference, r, (b) direction difference in degrees. Thin lines represent −10m, −20m and −30m isobaths.

The latter computation will provide the influence of dredging. In this section, this traditional assessment is performed considering only tides. The bed evolutions over one year are estimated using the filtering input method proposed by [29] and adapted by [30]. The Soulsby–van Rijn model is here applied. A 1m depth pit is simulated in the Humber area. Fig.4 presents the difference between the non modified and modified simulations, showing the extent of the domain affected by the dredging. The maximum differences are about 5cm after one year along the Lincolnshire coast, but some differences are also noticeable further south and along the sandbanks.

VI. SEDIMENT PATHWAYS

Three different characteristics are presented. Firstly, the temporal evolution of sediment volume within the dredging area, settling on the coast and leaving the domain are computed. Then the spatial distributions of sediment are presented. Finally the distributions of volume exiting the domain are shown.

A. *Temporal volume evolution*

The volume of sediment, V, within a given area, A, included within the computation domain, Ω, is defined as the summation of the layer thickness, E, above the non erodible bed at points within the given area:

$$V(t)=\sum_{i=1}^{N}\int_{\Omega}E(t)\chi_A\psi_i d\Omega \qquad (2)$$

where N is the number of points in the computation domain, ψ_i is the i–th point-related basic function. The characteristic function χ_A associated with the area, A, is equal to 1 for any point within A and zero otherwise. The area used to compute the volume settling along the coastline is defined as the ensemble of the meshes having at least one node located along the coastline. This area is called the coastline area.

Results for the temporal evolution of volumes within the dredging area, volumes settling on the coastline and leaving the domain are presented in Fig. 5.

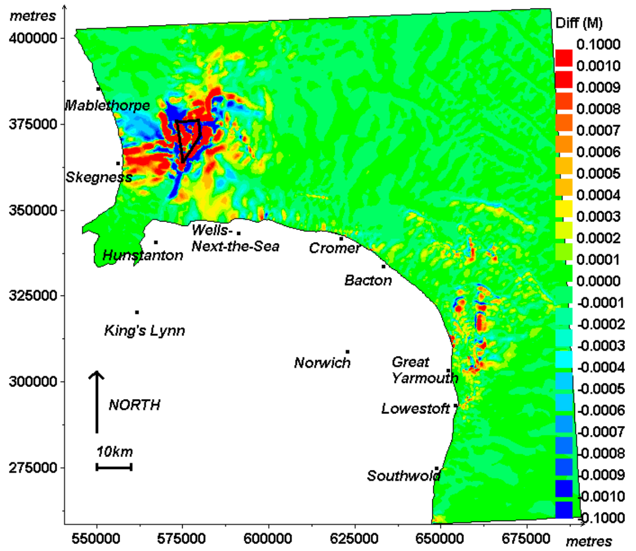

Figure 4. Differences in bed evolution due to a 1m deep pit.

Both the Bijker and the Soulsby–van Rijn sediment transport formulae are used. The results are sensitive to the formulation. However, the movement of sediment from the dredging area towards the coastline is captured by both formulations. The sediment deposited along the coast is significant. For this dredging area, the model is run for 4 years. It appears that if waves are not included in the computation, the volume of sediment within the coastline area becomes constant. This is not the case if waves are added, especially when the Soulsby-van Rijn formulation is used. The volume along the shoreline eventually starts to decrease as the sediment is exiting the domain.

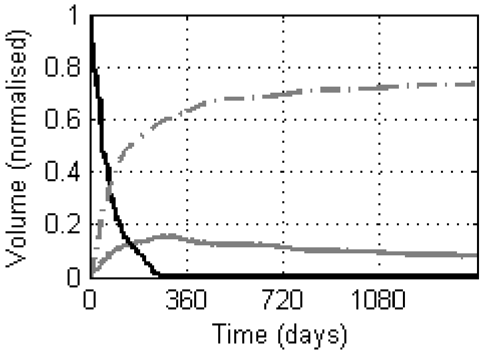

Figure 5. Temporal evolution of volumes for the Soulsby-van Rijn formulation within the dredged area (black line), the coastline area (grey line) and exiting the domain (grey dashedline).

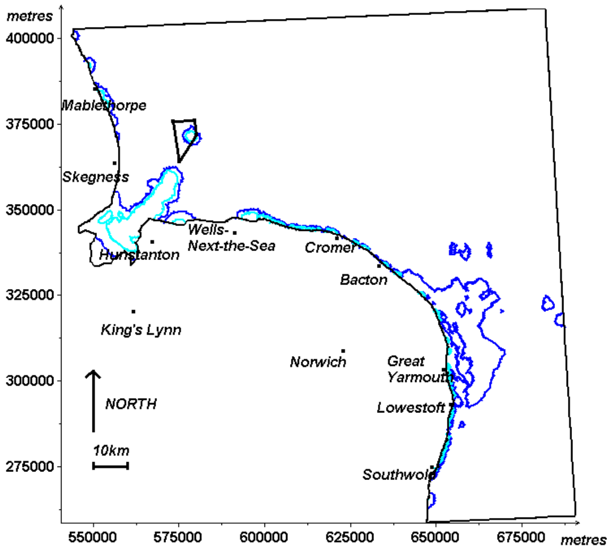

Figure 6. Spatial distribution of sediment released from the dredging area after one year, using the Soulsby van Rijn formulation without waves.

B. Spatial distribution

The sediment spatial distribution is represented as isolines of bed levels. Two isolines are chosen to represent 0.01% and 1% of the initial sediment layer. Results are presented only for the case of Soulsby–van Rijn formulation (Fig. 6).

Results show that the sediments are deposited all along the coastline from Mablethorpe in the north down to Southwold. More sediment remains along the Lincolnshire coast after one year if the waves are excluded. A large amount of sediment initially settles in the deep channel entering the Wash, the bay located between Skegness and Hunstanton.

Materials extracted by offshore dredging are not only used for the construction industry but also for beach nourishment. Locations along the coastline where sediments are deposited, shown in Fig. 6, due to sediment dumped on the dredging area would be appropriate for beach replenishment to mitigate the negative impact of dredging for marine aggregates on coastline stability.

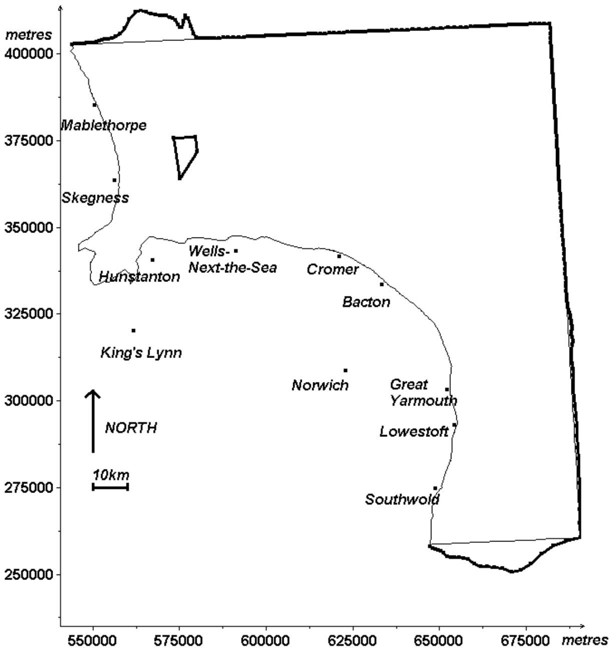

Figure 7. Spatial distribution of sediment volume exiting the domain after one year shown by thick curves with relative magnitude normal to the domain boundary, using Soulsby–van Rijn formula.

C. Sediment exiting the domain

The spatial distribution of volume exiting the domain in one year is shown by the curves along the seaward boundaries of the domain in Fig. 7. The relative magnitude is represented by the normal to the boundary. Results are presented only for the Soulsby–van Rijn formulation. The sediment leaves the domain through the western part of the northern boundary and through the southern boundary.

VII. CONCLUSION

Temporal sediment distributions resulting from a volume deposited on a dredging area has been simulated using the TELEMAC-2D / TOMAWAC / SISYPHE software system. A computational domain extending from Lincolnshire to Norfolk has been studied over a time span of about one year. Sediment pathways are shown and volumes deposited along a coastal strip extending about 240m from the low water spring contour have been estimated. Assuming that the bathymetry is otherwise in equilibrium, this enables the sediment pathways between the dredging area and the adjacent coastline to be determined. For the Humber dredging area results indicate that about 15% of the volume extracted offshore does not reach the nearshore strip (as it would normally in equilibrium conditions) thus reducing beach volumes and thus reducing coastal protection.

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