EVOLUTION OF NATURE-BASED DREDGING SOLUTIONS AT HARWICH, UK

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Abstract: Harwich Harbour, in the Southeast of the UK, is the location of the Port of Felixstowe and the confluence of the highly protected Stour and Orwell Estuaries. The maintenance of the approaches to the Port of Felixstowe is carried out by the Harwich Haven Authority and entails the dredging of up to 3 Mm^3 of mud by trailer suction hopper dredger, almost all of which is placed offshore. Deepening of the approach channel to the Port of Felixstowe in 1998/2000 resulted in regulatory agreements for an innovative sediment recycling strategy (or mud engine) to offset the perceived effects of the deepening. This sediment recycling involves the release of a proportion of the material dredged from the maintenance areas of the Port of Felixstowe within both estuaries to enhance the sediment supply to the intertidal areas within each estuary. The present sediment recycling methodology consists of the release into the water column of around 50,000 tonnes/year of fine sediment from small trailer suction hopper dredgers, releasing on the flood tide in a number of campaigns throughout the year. Survey evidence and detailed numerical modelling shows that this strategy is effective for improving habitat, but it is still not optimal, either environmentally or on grounds of dredging efficiency, because of the current requirement for offshore disposal of most of the dredged material from the Harbour. As a result, Harwich Haven Authority intend to develop their dredging and sediment recycling strategy further. To this end they have patented and trialled an agitation dredger which removes the need for offshore disposal, greatly reduces production of CO2 and dredging costs, and takes a leap forward in providing a more nature-based dredging solution providing the recycling of sediment within the estuarine system.

Key words: Dredging with nature**,** sustainability, agitation**,** sediment recycling, efficiency

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1 INTRODUCTION

As for many ports throughout the world, the Port of Felixstowe, the UK's largest container port lies within an estuary system which contains ecologically important areas of coastal habitat. The approach channel and berths of the port require (on average) around 2.4 Mm^3 (and up to 3 Mm^3) of maintenance dredging of mud (HR Wallingford, 2019), all of which takes place within the confluence of the Stour and Orwell Estuaries, at a location known as Harwich Harbour (Figure 1). Hosting internationally important populations of several species of wetland birds (JNCC, 2008), the mudflats and saltmarsh of the Stour and Orwell Estuaries are together designated as a Special Protection Area and a Ramsar site.

This paper describes the evolution of the dredging strategy at Harwich Harbour over the last 25 years. Over this period the dredging strategy has changed from one of a traditional dredging approach without consideration of the long-term consequences of offshore placement on the estuary system – to a strategy based on dredging accompanied by regular beneficial use – and most recently, to a nature-based strategy where the focus is much more on low-carbon technologies, and which aims to address all the challenges of economics, ecology, climate-change and coastal resilience.

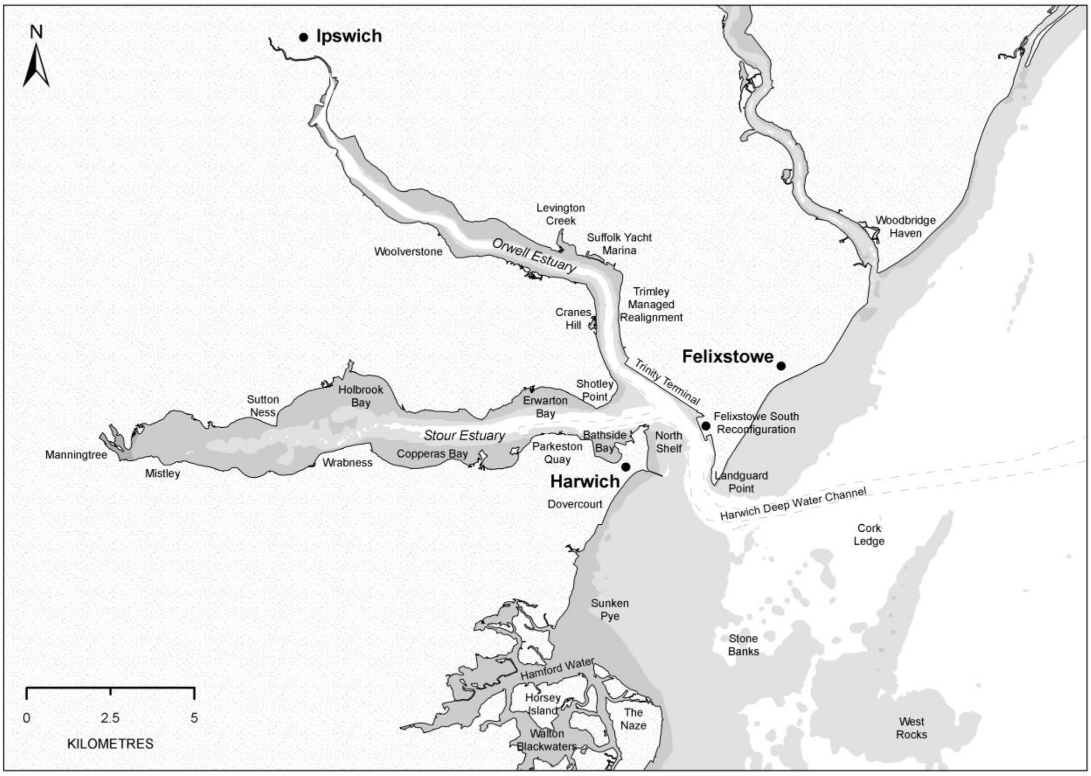

Figure 1. Stour/Orwell Estuary System

2 THE FIRST STEP – A MOVE TO SUBSTANTIVE BENEFICIAL USE

Up to the present day, the main maintenance dredging methodology used at Harwich Harbour has been trailer suction hopper dredging (TSHD) with plough dredging also used in the berths to make sediment more accessible for dredging by TSHD. There are four main maintenance areas (Figure 2). Like many other ports and harbours the maintenance material dredged from the approaches and berths in Harwich Harbour is placed offshore – currently at a location around 30 km away. The trapping of sediment in deepened navigation channels, and the subsequent removal of this sediment by dredging and disposal at an offshore location, can result in long-term morphological impacts resulting from the depletion of sediment within a coastal system (e.g., Parson and Russell, 2012; Spearman et al., 2014; Mangor et al., 2017; Gailani et al., 2019). Studies have shown that deepening of the Port of Felixstowe approach channel, accompanied by offshore disposal, causes a relatively small but adverse effect on the intertidal areas of the Stour/Orwell Estuary system (HR Wallingford, 1998, 2001a, 2019).

The studies undertaken to identify the potential impacts arising from the 1998/2000 deepening of the approach channel from -12.5 mCD to -14.5 mCD (HR Wallingford, 1998) identified a risk of reduction in sediment supply to the intertidal areas within the estuary system and hence a risk of enhanced erosion of these designated areas. The predicted risk of enhanced erosion was in the context of an estuary system which had experienced long-term intertidal erosion. The Stour Estuary system has experienced erosion of its intertidal mudflats since the 1920s when much of the prevalent eel-grass population, which had a binding effect on sediment, died off due to a fungal disease. It is estimated that 15 Mm^3 of net intertidal erosion occurred within the Stour/Orwell Estuary system over the last century (Beardall et al., 1991). The mitigation proposed to offset this risk was sediment recycling – also known as trickle charging or strategic beneficial placement. Although the first of its kind in the UK (Spearman et al., 2014), and, because of the muddy nature of the sediment, less common world-wide (e.g., Gailaini et al., 2019), this mitigation method was accepted by the regulators and consent for the deepening was given.

The sediment recycling was accompanied by a long-term monitoring strategy which included estuary-wide bathymetric, LiDAR, benthic and bird-count surveys every 5 years and continual communication between the Conservator responsible for the dredging, Harwich Haven Authority, and the regulators and stakeholders (Spearman et al., 2014). This continual monitoring and communication allowed an adaptive approach and a balancing of different stakeholder interests which proved extremely effective, particularly during the initial period of sediment recycling when there were significant changes to the sediment recycling methodology. Initially the sediment recycling was set at 137,000 tonnes dry solids per year (TDS/yr) and comprised a mixture of subtidal and water column recharge both in the estuaries and in the Harbour. This was increased to around 200,000 TDS/yr after the first few years with the intention of trying to create an identifiable positive impact on intertidal areas. Following this increase, however, fishermen were reporting silt build-ups and changes of substrate in many areas both inside and offshore from the estuary (HR Wallingford, 2007). Additional bathymetric information and further modelling had also led to reduced concerns about the extent of any increase in intertidal erosion rate arising from the deepening (HR Wallingford, 2001a; Spearman, 2014). For these reasons in 2008 the annual amount of sediment recycling was reduced to 50,000 TDS/yr, limited to water column recharge in the lower parts of the Stour and Orwell Estuaries, and the method of release adapted to better disperse into the water column.

Sediment recycling can occur in the Stour/Orwell at any time of the year but it is normal for 3 sediment recycling campaigns to be carried out annually. Sediment recycling campaigns typically occur over a 4 or 5 day period with 3 to 5 placement operations on each flood tide. Typically placement occurs at each of the three placement sites (Erwarton Bay, Copperas Bay and the Lower Orwell – see Figure 3) in succession. Placement typically occurs over a period of around 20 minutes with the dredger (hopper capacity: 1,500 m^3) moving landwards at an over-the-ground speed of 2-2.5 m/s. Typically each placement discharges an average of 560-570 tonnes dry solids each over this 20 minute period. The intention is to release the sediment slowly to increase the mixing of the placement into the water column. To date this modified mitigation (representing placement of approximately 4% of the maintenance dredging mass/volume) appears to have been successful in enhancing intertidal habitat whilst not causing adverse effects on fishery interests. At the time of writing an estuimated 2.3 Mtonnes or 4.6 Mm^3 of maintenance material has been recycled.

3 EVALUATION OF THE BENEFIT OF THE EXISTING SEDIMENT RECYCLING

One of the big issues with non-direct placement (trickle charging or strategic beneficial use) using muddy material is that the changes in bed level resulting from placement are generally of the order of a few centimetres/year or less, widely distributed, and varying spatially (e.g., Baptist et al., 2019; HR Wallingford, 2019). Measurements of the bed level change in this case are further complicated by:

- The stochastic nature of winds and waves which can lead to rapid changes in accretion/erosion following placement meaning monitoring periods can be insufficiently long to be representative.
- The difficulty of determining the morphological change resulting from the beneficial use from that resulting from the background sediment transport without intervention. Baptist et al. (2019) for instance found that the greatest rates of accretion occurred during a period of reduced rate of placement and a direct link between beneficial placement and intertidal sedimentation could not be made.

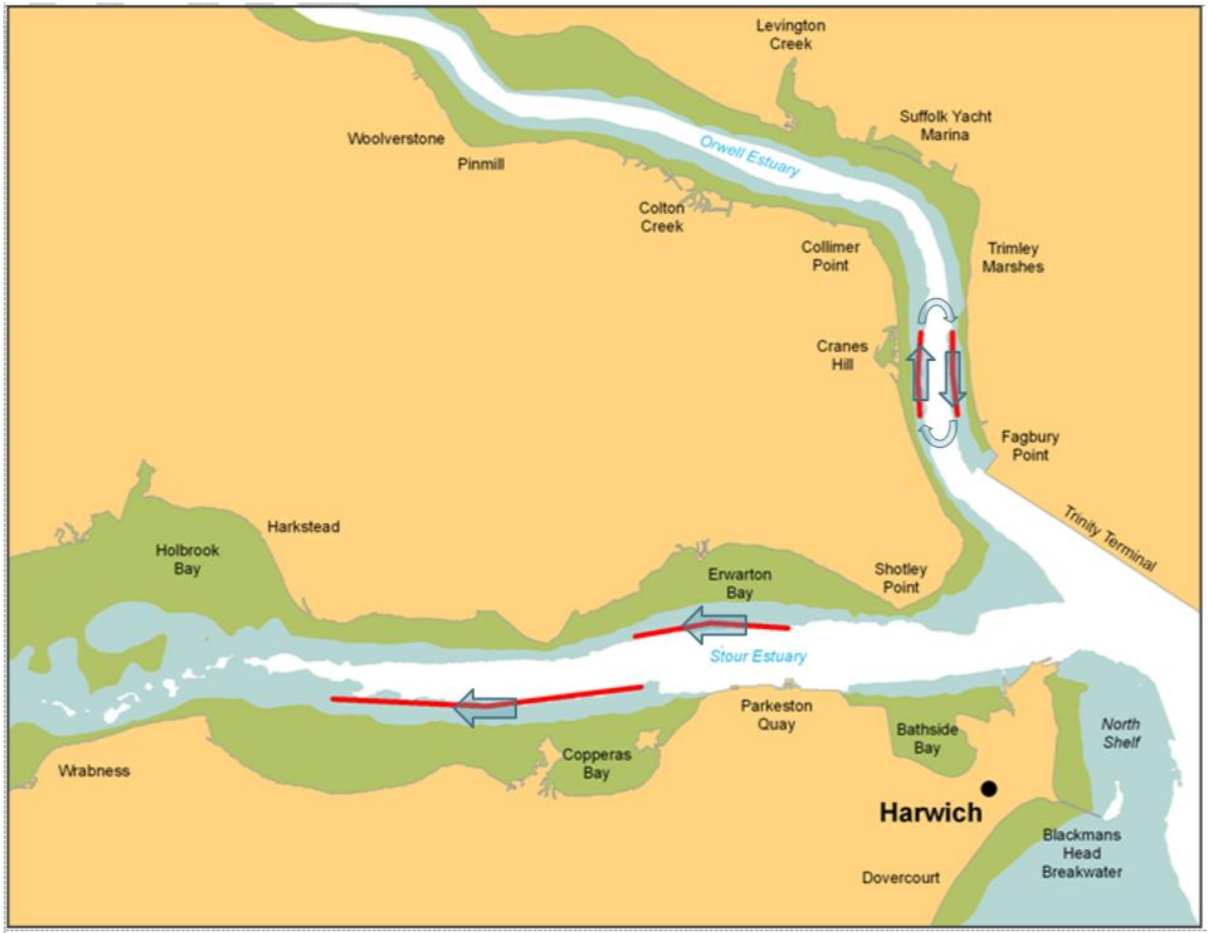

Figure 2. Sediment recycling methodology (Figure reproduced with the permission of HHA)

The net benefit of the sediment recycling in the Stour/Orwell was evaluated using the long-term bathymetric/LiDAR modelling (HR Wallingford, 2017) and detailed morphological modelling (using TELEMAC-3D, *www.opentelemac.org*) validated against the observed estuary evolution and also against comprehensive sediment transport and current measurements undertaken at various times over the same period (HR Wallingford 2001b, HR Wallingford 2021). This modelling is described in detail in HR Wallingford (2021). Through the development of a robust and detailed model and use the model to reproduce the change in morphology both with the effects of sediment recycling included and without, the net effect of the sediment recycling can be identified.

The additional annual deposition (or reduced erosion) resulting from the sediment recycling is summarised in Figure 3 which shows the spatial distribution of the deposition arising from sediment recycling.

The fate of the placed material was calculated from the results and it was found that in the estuary system as a whole, 21% of the recycled sediment settled on the intertidal and shallow subtidal in the estuaries with percentages of 17.5% (Stour) and 3.5% (Orwell). It was also found that nearly half of the released material re-deposited in the dredged harbour and berthing areas of the Harbour and Parkeston. In terms of the shallow subtidal and intertidal volume change (Table 4). the placement greatly increases the overall annual rate of accretion in the Stour and significantly reduced the overall erosion within the Orwell and changed the overall balance in the estuary system from erosion to overall accretion.

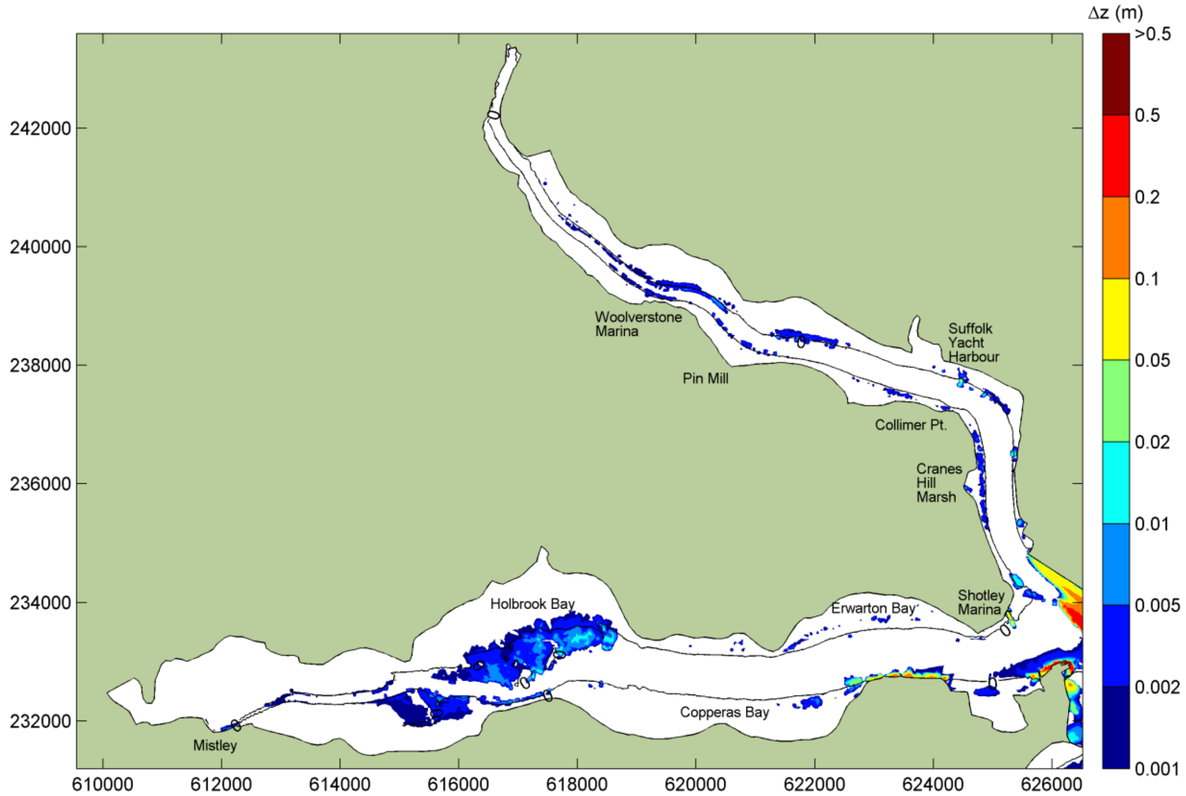

Figure 3. Predicted changes to the annual evolution of the estuary system arising from the sediment recycling (iso-contour shown is the 0 mCD contour) (Figure reproduced with the permission of HHA)

Table 4. Predicted annual changes in volume (m^3/yr) above the -1 mCD contour (intertidal and shallow subtidal) in the Stour and Orwell Estuary

	Stour	**Orwell**	**Total**
Without placement	6,500	-9,200	-2,700
With placement	28,600	-4,700	23,900

In terms of change in intertidal area the placement caused an increase of 1.7 ha/yr above CD, the lowest limit of intertidal area (the vast majority of which is in Stour) but resulted in a smaller increase of 0.8 ha/yr above Mean Low Water (of which around 60% was in the Stour). Mean Low Water is the lower limit of designated habitat (SPA/Ramsar) in this system. These results for the first time represent robust evidence of the benefits of sediment recycling of muddy material, enabling regulators and stakeholders to have confidence in this method as a mitigation solution.

It should be noted that whilst the sediment recycling is effective at providing habitat benefit, it is relatively costly because it involves only dredging on the flood tide and it requires the use of an efficient but small dredger (capacity around 1,500 m^3), which are limited in availability.

4 STRIVING FOR IMPROVEMENT– MOVING TO A NATURE-BASED DREDGING STRATEGY

Although the survey evidence and detailed numerical modelling both show that the existing sediment recycling strategy is effective for improving habitat, it is still not optimal, either environmentally or on grounds of dredging efficiency, because of the current requirement for offshore disposal of the vast majority of the maintenance dredged material. The offshore disposal leads to long dredging cycles (around 4 hours) and, given that loading times are short (in the region of 35 minutes, based on data provided by HHA) the overall dredging efficiency of TSHDs, is relatively low, even if larger vessels are used. Furthermore, the long travel distance leads to high fuel costs and hence high CO_2 emissions. Even the successful sediment recycling is not efficient because of the flood-only basis of dredging. These economic and climate-related costs have led HHA to examine other dredging solutions to address the combined challenges of safe navigation, dredging cost, habitat improvement and climate change.

As a result, HHA have developed their dredging and sediment recycling strategy further. To this end they have patented and trialled an agitation dredging approach, called *Dredging With Nature*®, which removes the need for offshore disposal and greatly reduces production of CO_2 and dredging costs. The agitation dredging is proposed using a new type of dredger patented by HHA (Figure 4). Essentially the dredger, known as the *Tiamat*®, is similar to a water injection dredger (WID) design, in that it uses jets to inject water into the bed, in order to mobilise the sediment. However, rather than using the water jets to create a highly-concentrated near bed sediment layer which flows downslope under its own weight, as occurs with WID (e.g., IADC, 2013), the intention here is to *agitate* or resuspend the sediment so that it is carried away by tidal currents. The design of the dredger incorporates the transfer of near bed concentrated plumes to a release pipe discharging at height above the bed to facilitate the dispersion of the sediment. The *Tiamat*® is designed to be deployed beneath any workboat equipped with a winch and lifting frame.

Figure 4. Mark 1 *Tiamat*®, March 2020 (Figure reproduced with the permission of HHA)

The overall concept for this agitation dredging is that the smaller cheaper dredger operates with lower instantaneous production rates (whilst still maintaining an overall production rate comparable with appropriately-sized TSHDs) requiring more frequent dredging and a semi-continuous release of (previously deposited) sediment into the water column to be carried away from the harbour by tidal currents. As such the methodology is considerably closer to what would be the natural state of the estuary without deepening when sediment temporarily depositing at slack tide would be resuspended as currents pick up and carried upstream to replenish intertidal flats or offshore depending on the tidal state. This approach therefore represents a step-change in nature-based dredging.

The use of the *Tiamat*® is currently awaiting regulatory approval as the current dredging method, use of TSHD with regular benefical (sediment recycling) placements, is still part of the consent agreement for the previous deepening. Once consent is obtained it is intended for maintenance dredging to be based on the new agitatation strategy. However, it should be noted that it is not intended for the use of TSHDs to fully cease in Harwich Harbour. The sediment depositing in the Harbour is typically around 90% silt/clay and 10% sand. If agitation methods are solely used for dredging, over the long term the Harbour will become sandier and the effectiveness of the agitation methodology will greatly reduce. It is therefore expected that TSHDs will be used at intervals to prevent a significant change in substrate.

5 EVALUATING THE AGITATION DREDGER PERFORMANCE

The performance of the *Tiamat*© was tested in a series of trials. Here we focus in particular on the results of the trial of October 2020 which included bathymetric surveys, density measurements and plume monitoring amongst other activities. This field data enabled the productivity of the agitation method to be identified which was then used, together with the modelling approach developed in HR Wallingford (2019), to assess the beneficial effects of agitation dredging on the intertidal areas of the estuary system (HR Wallingford, 2021). The October 2020 trial consisted of agitation dredging in each of the Dredge Areas shown in Figure 2 in turn (Dredge Area 1, 2, 3, 4, then 1, 2, 3, 4, again, etc.) over a period of 4 weeks, dredging roughly 8½ hours per day.

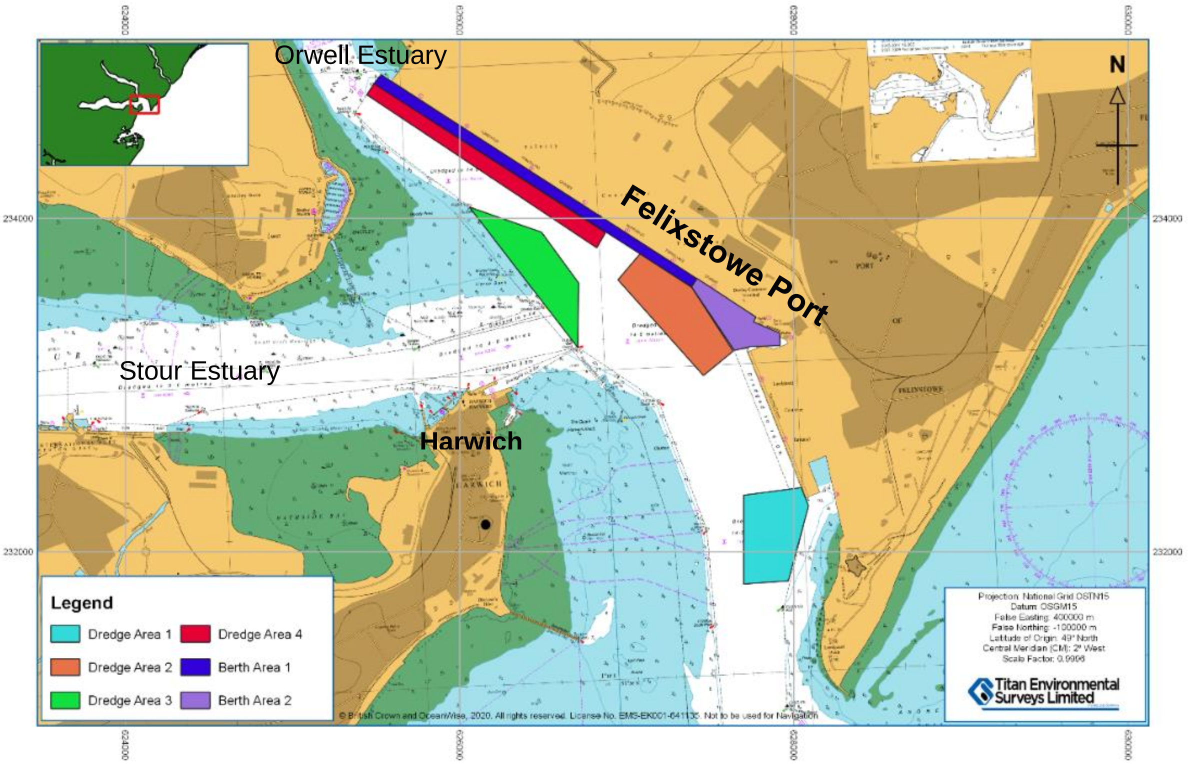

Figure 5. Maintenance areas in dredged in the October 2020 trial (Figure reproduced from Titan, 2020) (Figure reproduced with the permission of HHA)

Density measurements taken from the maintained areas during, and following cessation of agitation dredging, allowed the estimation of the mass of sediment removed from the bed and released into the water column. This data is summarised in Figure 6 which shows the average bed level of different density horizons over the course of the dredging. Analysis of the density measurements over the different maintenance areas imply an average productivity during dredging, and hence a plume release rate, of 288 kg/s (HR Wallingford, 2021b) or 4,670 TDS over 4½ hours (the typical dredging cycle of a TSHD dredger at this location, based on HHA data). This productivity rate is larger than a typical TSHD productivity (for a capacity of 8,000-9,000 m^3) of 3,260 TDS per cycle (based on HHA data). Plume measurements using calibrated ADCP backscatter and the SEDIVIEW system were used to derive a mean rate of release for the agitation dredger plumes of 427 kg/s which is of the same order as that of the density measurements, but higher.

The calculated source term of 288 kg/s derived from the density measurements was used as the source term for modelling the impact of the agitation dredging on morphology throughout the estuary. For this modelling the the validated TELEMAC-3D morphological model discussed above in Section 3 was used. The agitation dredging was reproduced in the model using the actual path of the dredger during the trial.

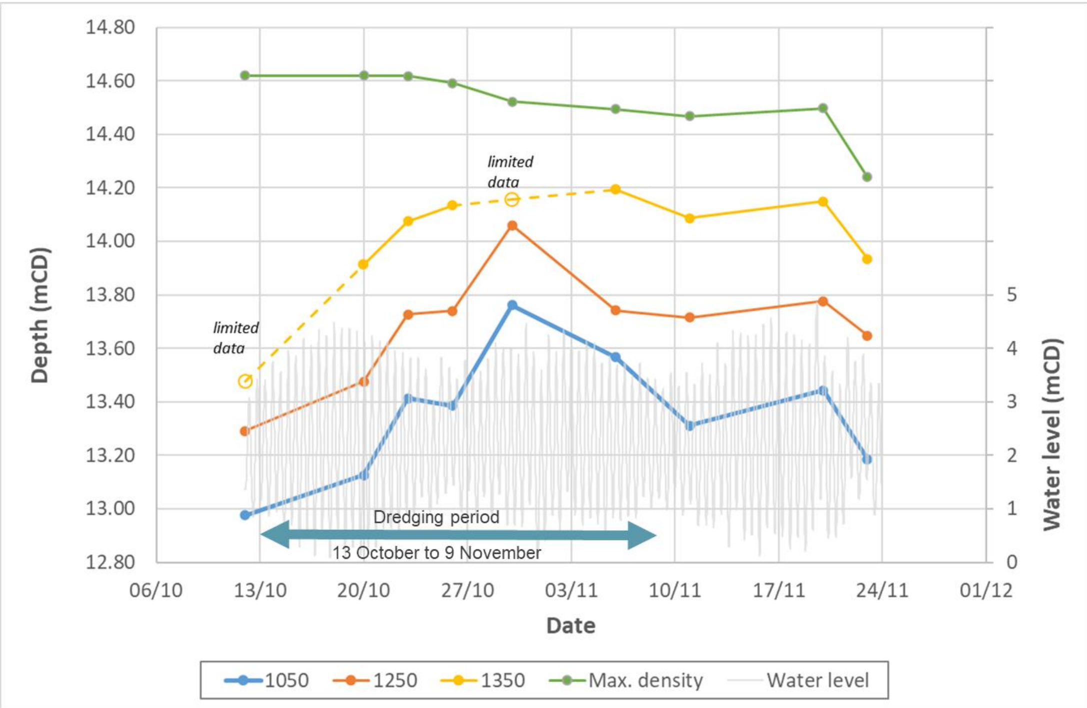

Figure 6. Measured depth below Chart Datum of different density horizons in the dredging areas over time (averaged across all measurements) together with the tidal water levels (shown in grey) over the same period (Figure reproduced with the permission of HHA)

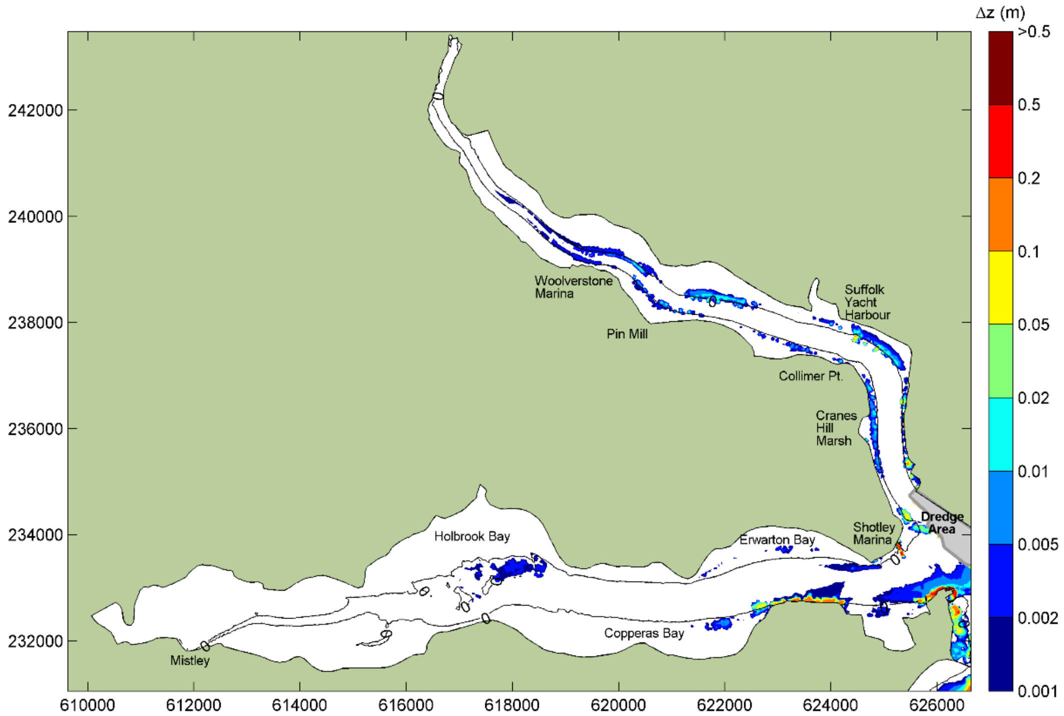

Figure 7. Predicted changes to the annual evolution of the estuary system arising from agitation dredging (iso-contour shown is the 0 mCD contour) (Figure reproduced with the permission of HHA)

The morphological model was used to reproduce the annual morphological change both with the proposed agitation dredging (expected to be around 10 hours per day for 4 weeks, around 5 times per year) and without any agitation dredging. The difference between these predictions gave the net effect of the agitation dredging itself (Figure 7).

Analysis of the model predictions indicated that (based on the trial dredge) the agitation dredging would create 0.4 ha/yr of extra mudflat above 0 mCD and 0.6 ha/yr of extra mudflat above MLW with most of the latter occurring in the Orwell. As MLW is the lower limit of designated habitat it can be seen that agitation dredging delivers nearly as much habitat benefit for a fraction of the cost and a fraction of the CO_2 emissions of the TSHD dredging with sediment recycling described in Sections 2 and 3.

6 DISCUSSION

HHA's approach to dredging of the approaches to the Port of Felixstowe has evolved over the past 25 years. This evolution has been made possible through a combination of factors including knowledge building (including modelling and long-term monitoring), and communication with regulators and stakeholders. These elements of successful infrastructure development have been highlighted by many practitioners (e.g., Laboyrie, 2018, Gailani et al., 2019) but nevertheless the point is worth emphasising again. Success is built upon robust evidence and the sharing of this evidence with, and listening to, other interested parties.

The evolution at Harwich Harbour has taken place in parallel with initiatives from other organisations which highlight the potential for solutions that holistically address the challenges of economics, climate change ecology and coastal resilience – for instance *Engineering with Nature*© (*https://ewn.erdc.dren.mil*) or *Building with Nature* (*https://building-with-nature.eu*) – and has been influenced by these initiatives along the way and the experience of other ports as they address these challenges. The evolution of HHA's dredging strategy can be thought of as progressing through 3 stages (See Figure 8):

- Stage 1 (prior to 1998 dredging): dredging designed to deliver safe navigation only.
- Stage 2 (1998 to present day): the move to incorporate regular beneficial use in order to, at least partially, address the issues of ecology and coastal resilience. This was initiated in response to a legal mitigation requirement, but the beneficial use surpassed its original purpose.
- Stage 3 (the present) redesign of the dredging strategy to address all of the challenges of economics, ecology, climate change and coastal resilience - and a move to nature-based dredging.

Figure 8. The progression of port dredging towards a more nature-based focus

These 3 stages of port dredging strategies can be thought of as the general progression of ports as they respond to the ideas, benefits and developing experience of *Engineering with Nature*© /*Building with Nature* type initiatives. This progression will take time as knowledge is gained and the needs of opposing stakeholders are reconciled. Moreover, not every port will be able to progress fully along the continuum illustrated in Figure 8. While all ports will have scope to improve, some may be constrained to some extent by their environments, significant economic considerations or particular stakeholder concerns.

The environmental benefit of agitation dredging identified above represents the results of implementation of the new methodology for the present approach channel depth of -14.5 mCD. In 2022 capital dredging will commence to deepen the approach channel to -16 mCD (Royal HaskoningDHV, 2019). Studies to evaluate the benefit arising from the use of agitation dredging in the deepened channel are not yet completed but the early results imply, as one would expect, a slightly reduced benefit compared to that shown in Section 5 above. This reduced effect is expected to be more than offset by optimising the agitation dredging to promote more flood tide dispersion of sediment. The studies to date (HR Wallingford, 2021) have shown that by ensuring that the northernmost and westernmost maintenance areas (Areas 4 and 3, respectively, in Figure 5) are dredged on the flood tide, and in particular the early flood tide, the amount of (dredged) sediment dispersing upstream into the Orwell and Stour, respectively, can be substantially increased from that presented above. This optimisation will also help to minimise the amount of resuspended sediment that is not dispersed out of the Harbour by tidal currents and which re-settles locally in the dredged areas.

7 CONCLUSIONS

The monitoring and modelling studies undertaken by HHA over the last 25 years have enabled the implementation and calibration of a demonstrably robust and effective sediment recycling strategy. More recently these studies, and the collaboration with a specialist dredging contractor, have led to the development of Dredging With Nature© - an agitation-based dredging approach. Using the same modelling approaches developed for the sediment recycling, the benefits to intertidal habitat arising from the proposed agitation dredging are shown to deliver similar habitat benefits, but at a much-reduced cost and with much-reduced carbon emissions.

The evolution of the dredging strategy at Harwich Harbour is an example of a more general progression currently experienced by many ports and harbours world-wide. To begin with (stage 1) port maintenance strategies are designed to deliver safe navigation only. Then (stage 2) a port will seek to use more and more of its dredged material for beneficial use, in order to address the issues of ecology and/or coastal resilience. The last stage is where the port completely redesigns its dredging strategy to address all of the challenges of economics, ecology, climate change and coastal resilience - and moves to a more nature-based dredging approach. This progression takes time as knowledge is gained and the needs of opposing stakeholders are reconciled and not every port will be able to progress fully along these stages.

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