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SAFE DISPOSAL OF DREDGED MATERIAL IN A SENSITIVE ENVIRONMENT BASED ON INNOVATIVE PLUME PREDICTIONS

ABSTRACT

Ras Laffan Port Expansion Programme foresees in a major extension of Ras Laffan Port (Qatar) to accommodate ongoing growth of the country's LNG production. Marine works related to dredging, reclamation and construction of breakwaters were inherently associated with the release and accumulation of fine material within the new port area. This fine material had to be removed. As it was not suitable for filling purposes, it had to be disposed in an offshore disposal area.

To demonstrate that such disposal operations could be carried out without violating strict environmental criteria around the disposal areas, a state-of-the-art 3D plume model was used to simulate a variety of disposal scenarios. The results provided valuable insight in the dynamics of sediment plumes over a spring-neap cycle. To enable operational use on-board, a novel interpretation method was developed to transform the model predictions into so-called "Safe Disposal Maps". These maps showed green areas where disposal operations could safely be carried out as a function of the tide conditions at hand.

This article adopts the Ras Laffan case to demonstrate the capability of presentday

numerical models to provide realistic simulations of sediment plumes and – equally important – the applicability of such complex techniques in dredging practice through innovative interpretation of model results. In the context of increasing environmental awareness on dredging projects worldwide, the availability of such tools is of crucial importance to enable reliable impact assessments and environmentally safe planning of dredging operations.

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Above: Qatar's large reserves of natural gas prompted the decision to implement a land reclamation project, known as the Ras Laffan Port Expansion programme, which will provide a major extension of Ras Laffan Port to accommodate the continued growth of the country's LNG production.

INTRODUCTION

Qatar's North Field is the focus of attention of some of the world's largest oil conglomerates. Studies have shown that the certified reserves currently stand at more than 25 trillion cubic metres of natural gas.

Large-scale investments in LNG infrastructure enable ongoing growth of the country's annual LNG production, which is expected to reach 77 million tonnes per annum by 2010. Ras Laffan is expected to become the major GTL terminal, the single largest complex and most comprehensive gas processing city in the world and one of the biggest producers of ethylene and derivatives (Figure 1). In this context, QP has decided to extensively expand Ras Laffan Port and Ras Laffan Industrial City. The new port will accommodate around 225 million tonnes of products per year, more than double its present capacity.

The first stage of the works commenced in 2005 and covered the large civil marine work related to the engineering, procurement, installation and construction for dredging, reclamation and breakwaters.

The approximate quantities involved were:

- 20 million m³ of hard rock dredging with cutter suction dredgers.

- 27 million m³ of sand reclamation from offshore borrow areas.
- 16 million tonnes of rock from Qatar for breakwater construction.
- 7 million tonnes of rock from overseas for breakwater construction.

These large-scale dredging and reclamation activities were inherently associated with the release of fine excess material (because of cutter spill and overflow losses during barge loading), resulting in the accumulation of fine material in the new port area. This material had to be removed. As it was not suitable for filling purposes, it had to be disposed in an offshore disposal area. Numerical models were used to demonstrate that dredging and disposal operations could safely be carried out without violating environmental requirements. This article adopts the Ras Laffan case to demonstrate the capability of present-day numerical models to provide realistic simulations of sediment plumes and – equally important – the applicability of such complex techniques in dredging practice through innovative interpretation of model results.

SAFE DISPOSAL OF DREDGED MATERIAL IN A SENSITIVE ENVIRONMENT

To guarantee safe disposal of excess material at sea, careful selection of a disposal site is of paramount importance. The Environmental

Impact Assessment for the Ras Laffan Port Expansion project had demonstrated that the nearshore coastal zone (with water depths less than 20 m) and the waters to the southeast of Ras Laffan are the most sensitive locations from the perspective of biological productivity, fisheries and ecological habitats. Offshore disposal at water depths above 20 m is thus preferred.

The sand mining area JV4 is located at 19 km northwest of Ras Laffan Port, at water depths of 19 to 25 m (Figure 2a). As a result of the extraction of approximately 6 million m³ of material for the present port expansion, it offers sufficient space to accommodate the anticipated 3 million m³ of excess material from Ras Laffan Port. Hence no reduction of water depth would occur. An extended environmental study, carried out prior to the start of the sand mining operations, revealed that the seabed in the JV4 area was mostly covered with soft material and that benthic communities were not particularly rich. This observation applied to the full sand mining area. The authors are not aware of previous use of JV4 for earlier sand mining operations, however, if so, it is very unlikely that these earlier operations covered the full area of JV4. Consequently, it could be concluded that local ecological sensitivity for the JV4 area was low by nature. To avoid further disturbance in other, pristine areas, it was decided to select

JV4 as the primary disposal location. The sand mining activities in JV4 were subject to environmental requirements to minimise possible environmental impacts to surrounding waters. These requirements stated that during dredging, the concentration of suspended solids was not allowed to exceed a depth-averaged limit level of 30 mg/l on an environmental boundary surrounding JV4 (Figure 2b). To verify whether these requirements were met, the suspended solids concentration (SSC) was measured on a daily basis, at 21 locations along the environmental boundary. SSC measurements were carried out by lowering and subsequently raising a calibrated YSI turbidity sensor through the water column. This yields a vertical concentration profile, which was averaged over depth. Owing to the relatively large distance to the dredging operations, vertical concentration profiles were found to be virtually depth-uniform. A proposal was offered to apply the same environmental requirements to the execution of the disposal activities as were used earlier during the sand mining operations.

To obtain permission for the start of the disposal works, authorities demanded a demonstration that the disposal operations could be carried out without exceeding SSC limit levels at the environmental boundary under all possible current and weather conditions. A state-of-the-art numerical model was used to do so.

MODEL PREDICTION OF PLUME DISPERSION

In order to evaluate the dynamic plume created by the process of jet release by trailing suction hopper dredgers, and the subsequent descent and collapse, a computational grid of

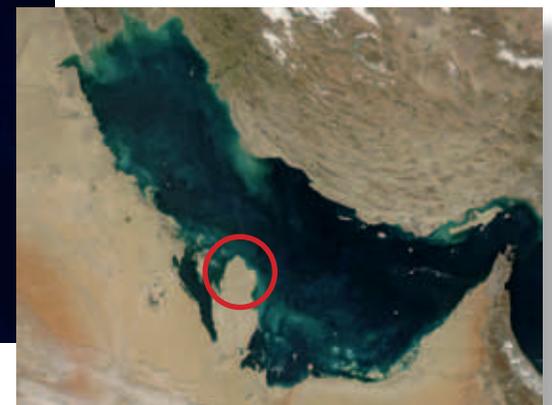


Figure 1. Left, Satellite photo of the Ras Laffan Port area in July 2009 after execution of the massive Ras Laffan Port Expansion project; Right, Site overview of Ras Laffan Port, located in the Arabian Gulf.



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an existing hydrodynamic model for the Ras Laffan region was refined in and around the JV4 area.

Approach

The work method for the removal of unsuitable fine material from Ras Laffan Port foresees the use of trailing suction hopper dredgers (TSHD) (Figure 3). After sailing to JV4, this fine material is disposed by opening the bottom doors of the TSHD. This yields a fluid-like jet of fine material that rapidly descends to the seabed (e.g. Van Rijn, 2005). The bulk behaviour of this water-sediment mixture is important, rather than the settling velocity of the individual particles (Winterwerp, 2002). After impact upon the bed, the sediment load will radially flow away from the point of impact over the bed as a

density current in the lower 15 to 20% of the water column. This phase is characterised by rapid dissipation of energy and settlement of material. The process of jet release, descent and collapse is generally referred to as the dynamic plume (e.g. Spearman *et al.*, 2007).

While the fine material jet descends through the water column, part of the material gets eroded from the outside of the bulk load (slurry jet) and suspended in the surrounding water (entrainment). After impact on the seabed, resuspension of fine material occurs from the near-bed density current, caused by turbulence-induced upward mixing at the upper surface of the mud layer.

Both mechanisms yield entrained sediments that act as the source term for the so-called passive plume. The passive plume is capable of transporting low-density material away from the direct disposal site owing to advection with tidal currents and diffusion processes.

The near-bed density current propagates, depending on initial density and momentum of the sediment-water mixture, over a distance of typically 100 to 500 m. Given the size (several kilometres) and bed slope (typically 1:1000) of JV4, no sediment will be lost from the disposal area owing to migration of the near-bed density current. As a result, the model study focused on the assessment of suspended sediment losses.

Appropriate representation of these processes asked for the use of two coupled models. The first, Jet3D (Koster, 1988; Morelissen, 2007) determined near-field entrainment rates over the vertical during descent of the dynamic plume from the TSHD. Jet3D is a semi-empirical model which calculates the dispersion and entrainment effects of jets based on an experimental database. The second model, Delft3D (e.g. Lesser *et al.*, 2004), assessed the resuspension from the density current and far-field dispersion of disposed sediments. The coupling of the two models is shown in Figure 4. The calculated entrainment rates from Jet3D together with the durations of disposals served as input for a three-dimensional flow and sediment dispersion model.

Model schematisation

For the purpose of this study, the computational grid of an existing hydrodynamic model for the Ras Laffan region was refined in and around the JV4 area. The resolution of the new JV4 model varied from 375 x 155 m offshore to 35 x 35 m inside the JV4 area. The hydrodynamic model simulates tide-driven flows only; no wind or wave effects are taken into account.

The model is set up in three-dimensional mode with 10 vertical layers with increasing resolution towards the bed. This allows for appropriate representation of the near-bed

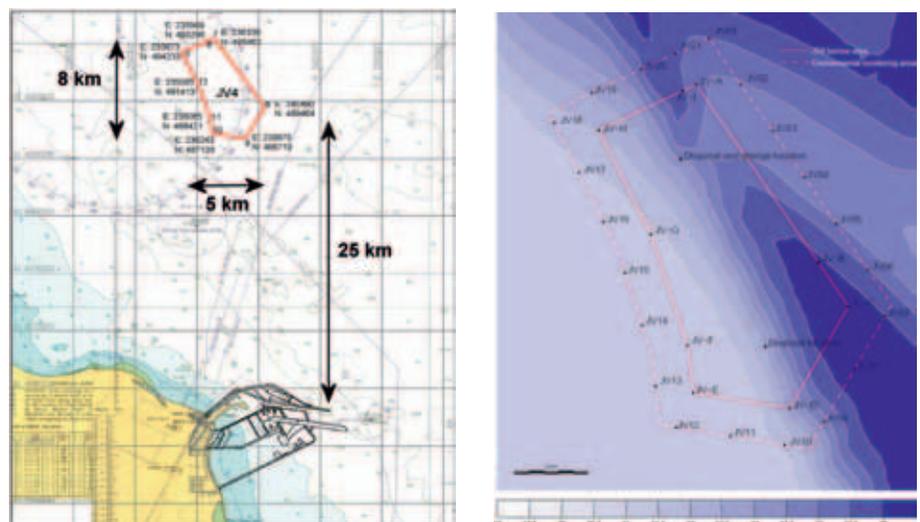


Figure 2. (a) Location of JV4 sand mining area with respect to Ras Laffan Port and (b) environmental boundary surrounding JV4. Area JV4 was identified as the most suitable disposal site.



Figure 3. One of the trailers, the TSHD Oranje, working at Ras Laffan Port Expansion project.

density currents. Model validation against current magnitude and direction data sampled near Ras Laffan Port revealed good performance of the tidal model, with differences in measured and computed current magnitude typically well below 10%.

During storm conditions, differences tend to increase, as a result of differences in wind set-up on both sides of Ras Laffan Port. However, as this phenomenon does not play a role at deeper water where JV4 is located, the conclusion was that the tidal model is suitable for providing the flow conditions to assess plume dispersion during disposal activities at JV4.

Each disposal event was characterised by a means of a fines release of 8400 kg/s during 300 seconds. Jet3D simulations revealed that approximately 10% of this was entrained during vertical descend through the water column. The remaining 90% of the material forms a density current (after impact on the seabed and a hydraulic jump at some distance from the disposal, cf. Figure 4).

Both source terms serve as input for the Delft3D plume dispersion model. The sediment involved is schematised by means of three fractions with a D_{50} of 5, 18 and 43 μm , respectively. The model accounts for the effect of hindered settling, while a minimum settlement velocity of 0.10 mm/s is adopted to account for the process of flocculation. The model also computes the settling of the sediments at the bed when the bed shear stresses become small.

The disposals have been applied at two different locations in the JV4 area in order to take into account the variation of the bed slope, water depth and tidal currents. The

disposal locations have remained the same throughout the simulations. As a result of the frequent disposals, a dredging-induced sediment plume will be produced around these disposal locations. This plume is able to enlarge during some tidal phases and in some cases because of the cumulative build up of sediment concentrations in time. SSC maps are regularly mapped as output during the simulation.

Model results: SSC maps

The results shown here represent a scenario with two dredgers, each with a cycle time of 6 hours. Each cycle starts with a disposal event (5 minutes), followed by sailing to the mining location within JV4 (20 minutes), dredging (95 minutes – 20 of which with no overflow) and activities outside JV4 (sailing to port, pumping ashore, clean-up dredging and sailing back to JV4, total 240 minutes). The scenario thus combines the disposal of fine sediments in the SE part of JV4 with

subsequent sand mining in the NW part of JV4. This allows for a realistic representation of dredging processes in the area as well as to examine possible accumulation of suspended sediment concentrations originating from multiple dredging activities at the same time.

The model simulations for this scenario result in the prediction of SSC maps throughout a 14-day spring-neap cycle. Results are presented by means of depth-averaged suspended sediment concentrations above natural background level.

An example SSC map is shown in Figure 5. Suspended sediment concentrations in the plume typically range between 0 and 50 mg/l, with higher values above 50 mg/l only found in the direct neighborhood of the dredging equipment. The black line denotes the instantaneous location of the (depth-averaged) 30 mg/l concentration contour, while the red line marks the location of the cumulative 30 mg/l exceedence contour. The exceedence contour marks the outer limit of the area where computed suspended sediment concentrations have (at least once) exceeded the 30 mg/l environmental limit level – for the fixed disposal location considered in the simulations. In addition, the SSC maps provide background information on the current tide conditions (water level, flow magnitude & direction) as well as the status of the dredging works (disposal, sailing or dredging).

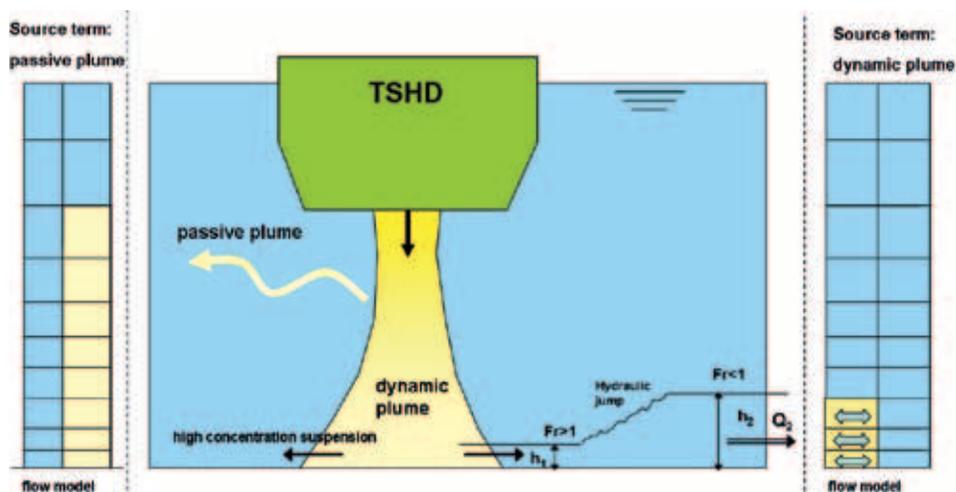


Figure 4. Coupling of Jet3D and Delft3D models for simulation of Ras Laffan disposal cycles: Jet3D describes the release, descend and collapse of the dynamic plume, which yields the input SSC for the Delft3D model. The latter describes the dispersion of the passive plume owing to advection with tidal currents and diffusion processes.

Animations of such SSC maps over time clearly show the dynamics of Ras Laffan sediment plumes, characterised by large variations in plume direction and extent. In addition, they show the accumulation of suspended sediments in the water column resulting from cumulative dredging and disposal events. Plume excursion typically increases during spring tide.

Perhaps somewhat surprisingly, maximum plume excursions are not found for disposals during periods of maximum tidal velocities, but for disposals carried out 1 to 3 hours before reaching peak flow velocity. Subsequent flow acceleration causes a maximum excursion of the sediment plume, whereas for disposal at peak velocity, subsequent flow deceleration reduces plume excursion, hence mitigates dredging impacts. This observation reveals the added value of using a non steady-state hydrodynamic model that accurately resolves the dynamics of the tidal motion.

The results presented in Figure 5 can be considered as conservative, particularly because of the chosen schematisation of fines (smallest fraction 5 µm with settlement velocity 0.10 mm/s) and the way Jet3D results for a single jet have been interpreted for use with a TSHD with 44 bottom doors, hence 44 different jets. Theoretically Jet3D describes the dynamics of an individual jet fully enclosed by fresh water; however, in reality, each of the 44 jets underneath the TSHD will interact with neighboring plumes during descent under the vessel. Consequently, real-world sediment entrainment rates to the surrounding water

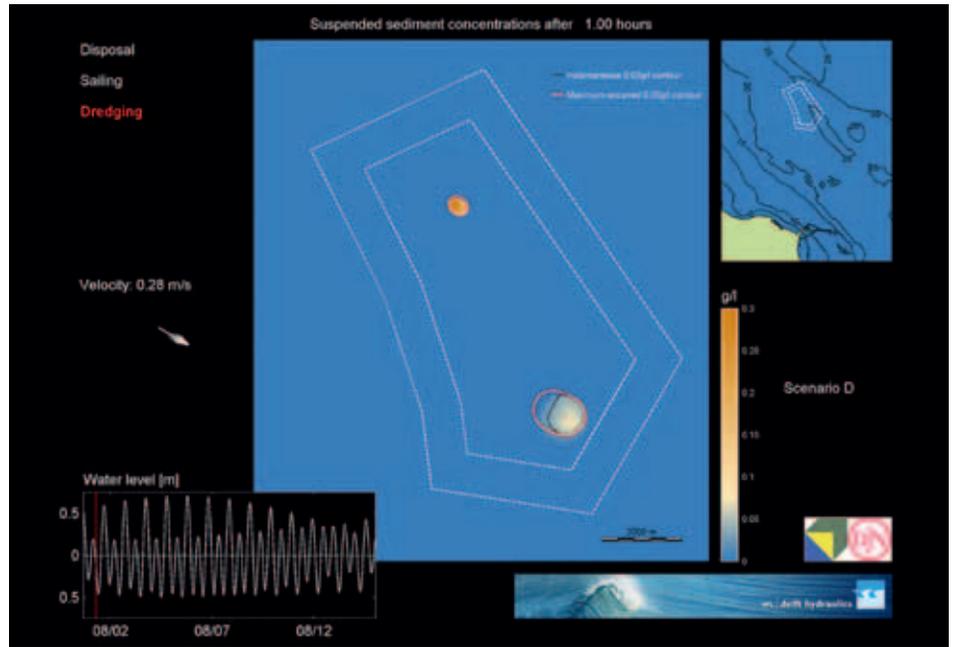


Figure 5. Model-predicted SSC map for combined dredging (NW part) and disposal (SE part) activities at Ras Laffan JV4. The black line denotes the instantaneous location of the 30 mg/l contour, the red line marks the exceedance line of the 30 mg/l SSC level. The latter is needed for the generation of the Safe Disposal Maps.

are likely to be smaller than predicted by the models, hence calculated suspended sediment concentrations in the plume can be considered as conservative.

OPERATIONAL PLANNING OF DREDGING ACTIVITIES AT RAS LAFFAN

The operational planning of these disposal activities included the development of Safe Disposal Maps based on the SSC maps and the use of the Safe Disposal Maps on a trip-by-trip basis.

Safe Disposal Maps

The time series of SSC maps throughout a spring-neap cycle provides the starting point for the generation of so-called Safe Disposal Maps. These maps mark the area where sediment can safely be disposed (i.e. without violating the environmental requirements), as a function of the tidal conditions at the time of disposal. Safe Disposal Maps are generated for 10 different tidal stages, each characterised by the flow velocity and direction at the time of disposal. The selected tidal stages are summarised in Figure 6.

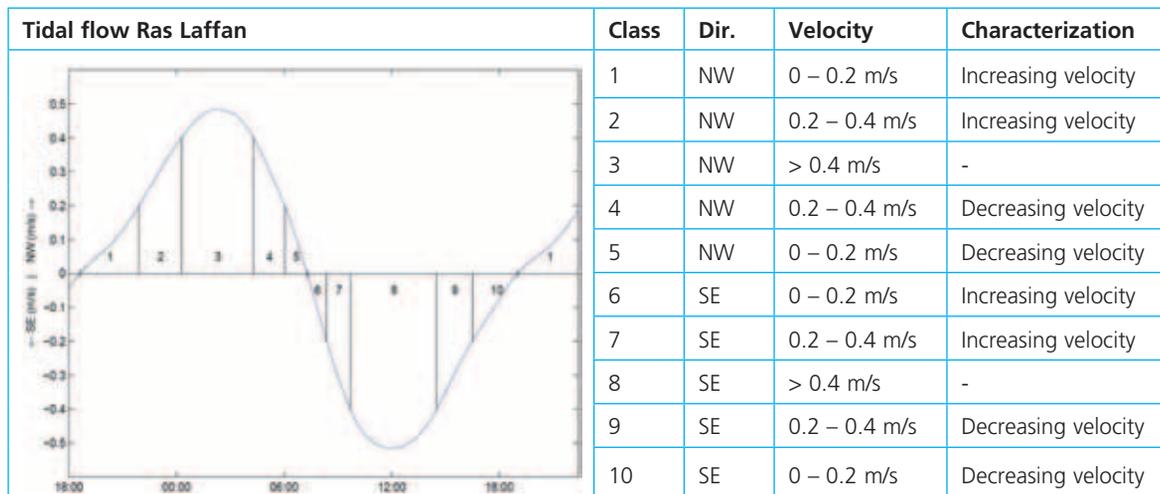


Figure 6. Definition of tidal stages for generation of Safe Disposal Maps.

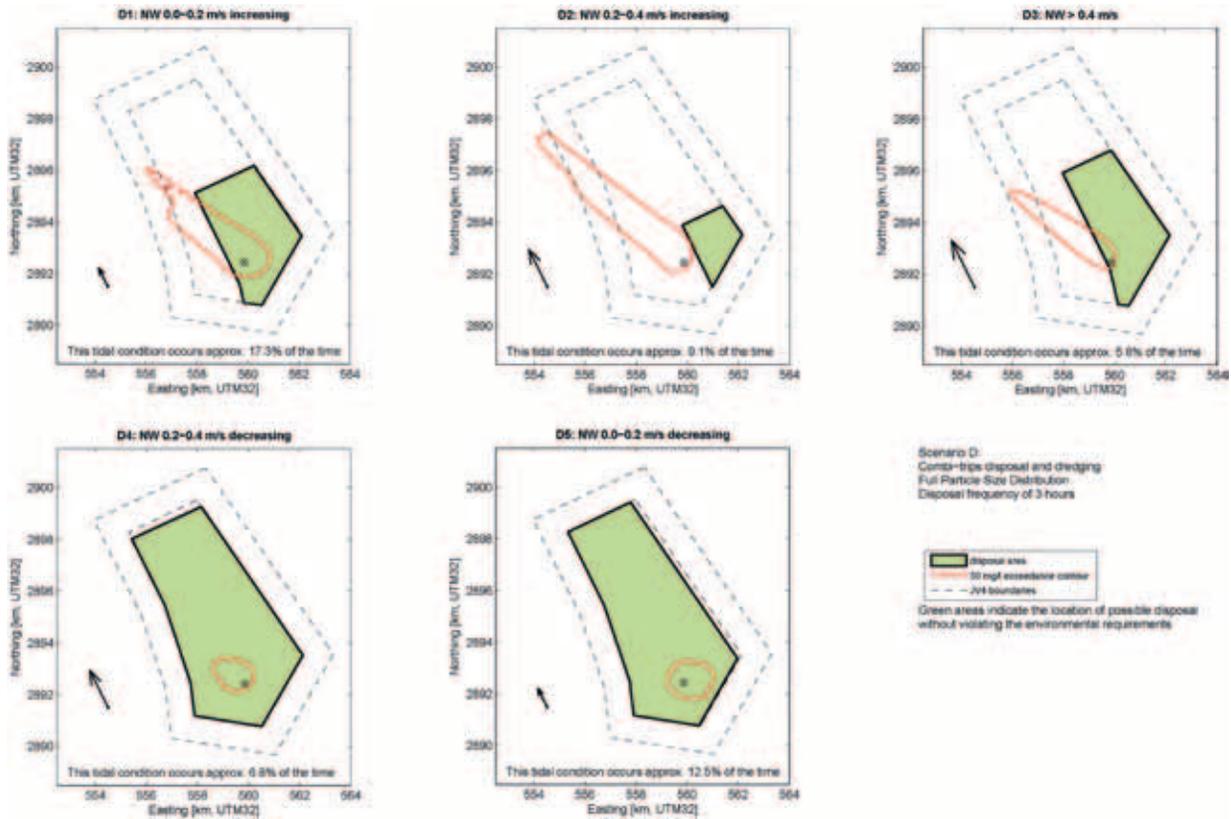


Figure 7a. Safe Disposal Maps Ras Laffan JV4 for five tidal stages during flood.

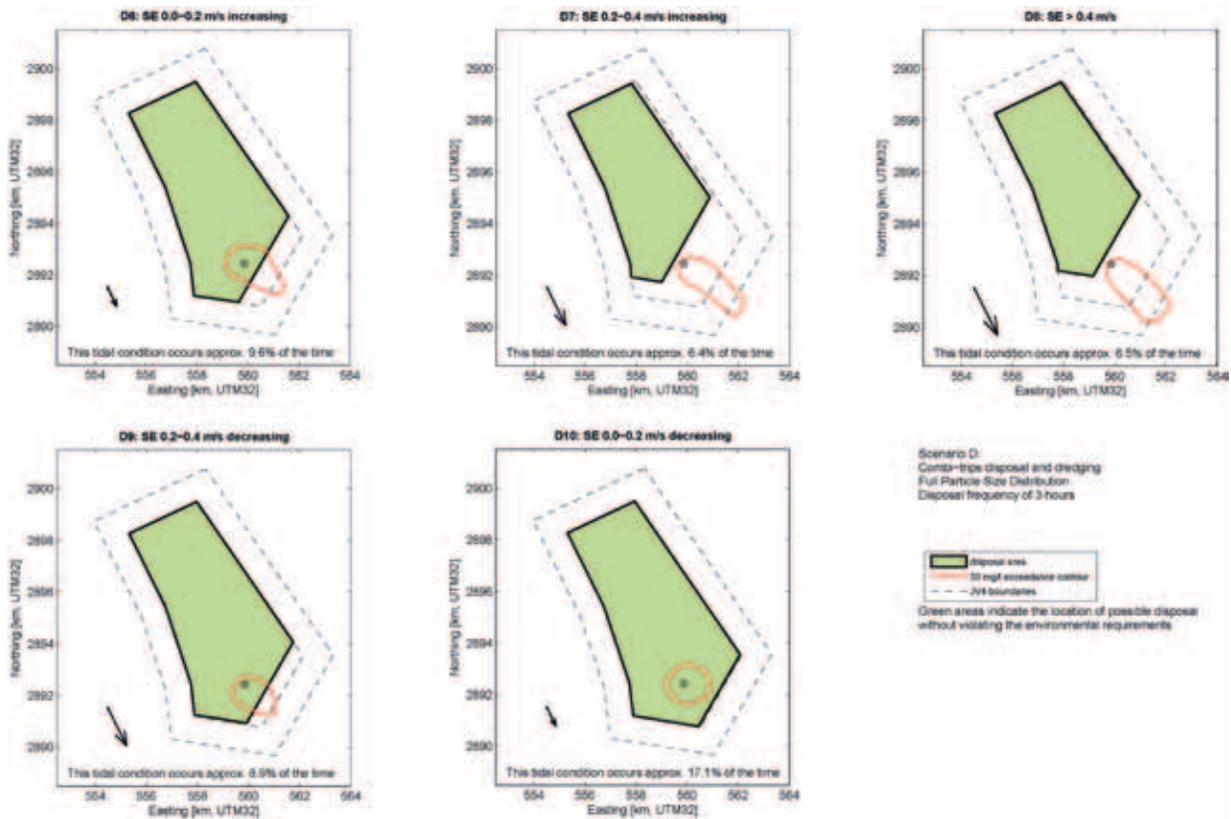


Figure 7b. Safe Disposal Maps Ras Laffan JV4 for five tidal stages during ebb.

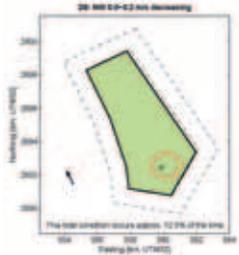
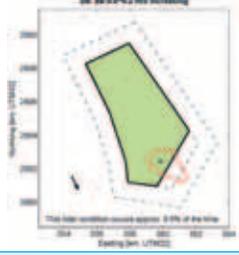
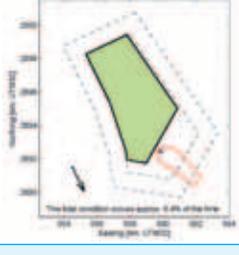
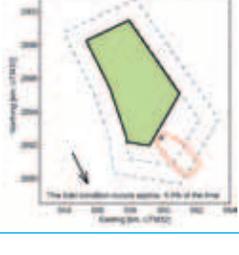
Date	Time	Current magnitude	Directions	Reference	Map
02-July-2008	05:00:00	0.20 m/s	NW	Map D5	
02-July-2008	05:20:00	0.14 m/s	NW	Map D5	
02-July-2008	05:40:00	0.08 m/s	NW	Map D5	
02-July-2008	06:00:00	0.04 m/s	NW	Map D5	
02-July-2008	06:20:00	0.06 m/s	SE	Map D6	
02-July-2008	06:40:00	0.12 m/s	SE	Map D6	
02-July-2008	07:00:00	0.18 m/s	SE	Map D6	
02-July-2008	07:20:00	0.24 m/s	SE	Map D7	
02-July-2008	07:40:00	0.29 m/s	SE	Map D7	
02-July-2008	08:00:00	0.34 m/s	SE	Map D7	
02-July-2008	08:20:00	0.38 m/s	SE	Map D7	
02-July-2008	08:40:00	0.41 m/s	SE	Map D8	
02-July-2008	09:00:00	0.43 m/s	SE	Map D8	
02-July-2008	09:20:00	0.45 m/s	SE	Map D8	
02-July-2008	09:40:00	0.46 m/s	SE	Map D8	
02-July-2008	10:00:00	0.46 m/s	SE	Map D8	

Figure 8. Planning table for safe disposal operations.

To generate the Safe Disposal Maps, all disposal events throughout a 14-day spring-neap cycle plus their associated sediment plumes were categorised according to the tidal classes specified in Figure 6. For each class, the location of the 30 mg/l exceedence contour was determined based on the evolution of the set of sediments plumes in that class. By moving the exceedence contour within the JV4 area along the environmental boundary, areas of *unsafe* disposal are being blanked. Consequently, the remaining area can be marked *safe* disposal zone, or suitable area. In this way, Safe Disposal Maps were generated for all 10 tidal classes specified in Figure 5.

The outcome of this novel post-processing on model results is presented in Figure 7 (a and b) for the situation of combined dredging/disposal with two TSHDs. The figures show the 30 mg/l exceedence contour (red line) for each of the 10 tidal classes at hand. The results confirm that maximum plume excursions are found for disposals during flow acceleration and, to a lesser extent, during peak tidal velocities.

For disposal during flow deceleration, plume excursions are minimal and SSC typically drop well below 30 mg/l within 1 km from the disposal location. These observations apply

to both ebb and flood tides, though absolute plume excursions are larger during flood. As the ebb tidal velocities (towards NW) are only slightly dominant compared to the occurring flood velocities (towards SE), the latter observation indicates that cumulative effects of ongoing dredging and disposal operations plays an important role here.

The green-shaded areas in Figure 7a and 7b denote the regions where disposal operations can safely be carried out for that particular tidal class. A minimal area of the safe disposal zone is found for situations of flow acceleration, although the available safe area for those

conditions (increasing flow velocities between 0.2–0.4 m/s towards NW) still measures about 5 km². As expected, safe disposal areas tend to increase with decreasing excursion of the 30 mg/l exceedence line. Ultimately, for situations of flow deceleration, virtually the entire JV4 region can be used for disposal activities without violating the environmental limits.

From the Safe Disposal Maps the conclusion can be drawn that disposal operations can safely be carried out during each phase in the tidal cycle. However, depending on the tidal phase at the time of disposal, restrictions may exist in the chosen disposal location within JV4. The latter particularly applies to periods of tidal flow acceleration which are associated with maximum dispersion of the dredging-induced sediment plumes.

Operational use of Safe Disposal Maps

The Safe Disposal Maps can be used in practice for the determination of suitable disposal locations on a trip-by-trip basis. Steering parameters are the expected tidal conditions (flow magnitude, acceleration or deceleration and direction) at the time of disposal. These parameters can reliably be predicted with the help of a validated numerical model.

For the Ras Laffan Port Expansion project, time series of tidal flows at JV4 were predicted at 20-minute intervals, for the entire period that dredging and disposal operations were carried out. The predicted tidal conditions allow for the identification of the appropriate tidal class and associated Safe Disposal Map for each time step. Results are summarised by means of planning tables for safe disposal operations (Figure 8), which were provided to site.

The planning tables and underlying Safe Disposal Maps were successfully used while carrying out dredging and disposal activities for the Ras Laffan Port Expansion project. During execution of the works, turbidity levels along the environmental boundary surrounding JV4 were measured on a daily basis. No environmental limit exceedence was measured throughout the period of dredging and disposal operations, thus confirming good performance of the disposal strategy based on Safe Disposal Maps.

CONCLUSIONS

Application of two coupled models to simulate dynamic plume behaviour and subsequent passive plume dispersion during dredging and disposal operations at Ras Laffan (Qatar) has demonstrated the capability of present-day numerical models to provide realistic simulations of dredging-induced sediment plumes over a spring-neap cycle.

Perhaps somewhat surprisingly, maximum plume excursions are not found for disposals during periods of maximum tidal velocities, but for disposals carried out 1 to 3 hours before reaching peak flow velocity, during flow acceleration. In addition, cumulative effects caused by ongoing dredging and disposal operations in the area were found to be important.

Novel interpretation of model-predicted patterns of suspended sediment concentration over a spring-neap cycle has resulted in so-called Safe Disposal Maps. These maps were generated for 10 different phases of the tidal cycle and mark the area where disposal operations can safely be carried out. The maps revealed that disposal operations can safely be carried out during each phase of the tidal cycle, although restrictions may apply to the choice of the disposal location depending on the tidal conditions at the time of disposal.

This is particularly the case during periods of tidal flow acceleration, which are associated with maximum dispersion of the dredging-induced sediment plumes.

To facilitate operational use of the Safe Disposal Maps, planning tables were generated based on calculations with a validated hydrodynamic model. The planning tables and underlying Safe Disposal Maps were successfully used while carrying out dredging and disposal activities for the Ras Laffan Port Expansion project.

No environmental limit exceedence was measured throughout the period of dredging and disposal operations, thus confirming good performance of the disposal strategy based on Safe Disposal Maps.

This research has thus demonstrated the applicability of complex numerical models in dredging practice through novel interpretation of model results. In the context of increasing environmental awareness on dredging projects worldwide, the availability of such tools is of crucial importance to enable reliable impact assessments and environmentally safe planning of dredging operations.

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