

Effects of extraction of sand on the bottom shear stress on the Belgian Continental Shelf

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Introduction

In the Belgian implementation of the European Marine Strategy Framework Directive (Belgian State, 2012), it was stated that human impacts need consideration when the bottom shear stress, calculated with a validated numerical model, increases with more than 10 % at a specified distance of the activity. In this contribution, the impact of extraction of marine aggregates on the bottom shear stress on the Belgian Continental Shelf is evaluated with this respect.

Since in the Belgian implementation, it is explicitly stated that the evaluation has to be executed with a validated numerical model, an evaluation of the quality of bottom shear stress models is described in the first part of the paper. Firstly, the numerical models are described. The hydrodynamic model, that is used to calculate the currents and the water elevation, and the wave model, calculating the significant wave height, wave frequency and wave direction, are presented. Furthermore, different models that are found in literature to calculate the bottom shear stress under the influence of currents and waves are shortly discussed. Secondly, some measurements of the bottom shear stress at the offshore Hinder Banks are described. Acoustic Doppler Current Profiler (ADCP) data are used to calculate the bottom shear stress from the logarithmic profile of the currents in the lower part of the water column. Different measurement campaigns were executed at two stations in the Hinder Banks area. In the next sections, the validation of the hydrodynamic and wave model and of the bottom shear stress models is discussed.

In the second part of the paper, some applications are presented. First, the impact of large-scale extraction of marine aggregates is evaluated. Three different scenarios for the extraction of 35 Mm³ of marine aggregates in the extraction zone 4 in the Hinder Banks area, are modelled and the effect on the bottom shear stress in the area is assessed.

In a second application, the effects of the new extraction limit levels, that are proposed by Degrendele (2016) and Degrendele et al. (this volume), on the bottom shear stress are evaluated. The change in bottom shear stress for three different scenarios are modelled and evaluated. Two possible solutions are proposed for those cases, where the next extraction limit levels lead to a too high increase in bottom shear stress.

Some conclusions are formulated in the last section.

Validation of the bottom shear stress model

Numerical models

Introduction

To calculate the bottom shear stress under the influence of the currents and the waves, numerical models are used. A three-dimensional hydrodynamic model is used for the calculation of the water elevations and the currents. A third generation wave model is used to calculate the waves. Both models will be discussed shortly.

Furthermore, different methods and models are available in literature to calculate the bottom shear stress from the currents and waves. The different models that are used in this study are discussed in the next section.

Hydrodynamic model OPTOS-FIN

The three-dimensional hydrodynamic modelling software COHERENS calculates the currents and the water elevation under the influence of the tides and the atmospheric conditions. The model was developed between 1990 and 1998 in the framework of the EU-MAST projects PROFILE, NOMADS and COHERENS. The hydrodynamic model solves the momentum equations and the continuity equation with, if necessary, equations for the sea water temperature and salinity. COHERENS disposes over different turbulent closures. A good description of the turbulence is necessary for a good simulation of the vertical profile of the currents. A new version of the COHERENS software has been developed recently (Luyten et al., 2014), mainly allowing the model to use parallel computing, while adding also some new features, such as improving the numerical scheme and adding a wetting-drying mechanism. The model is further extended with a sediment transport module and a morphological module.

The model OPTOS-FIN is based on this COHERENS code and is implemented on the Belgian Continental Shelf with a grid with a resolution of 14.29" in longitude (272 to 278 m) and 8.33" in latitude (257 m). This model has 10 σ -layers distributed over the total water depth. Along the open boundaries, the OPTOS-FIN model is coupled with three regional models. The OPTOS-CSM model comprises the entire Northwest European Continental Shelf and calculates the boundary conditions of the North Sea model OPTOS-NOS. The latter model calculates the boundary conditions of the OPTOS-BCZ model, which is implemented for the Belgian waters with a three times coarser resolution than the OPTOS-FIN model. The OPTOS-CSM model calculates the depth-averaged currents and is driven by the water elevations at the open sea boundaries, using four semi-diurnal and four diurnal constituents. The bathymetry of OPTOS-FIN model is shown in *Figure 1*.

The OPTOS-FIN model was validated in the framework of the BELSPO Marebasse project (Van den Eynde et al., 2010) and the BELSPO BOREAS project (Mathys et al., 2012). More recently a first validation was executed of the model in the Hinder Banks area, using bottom-mounted ADCP results, hull-mounted ADCP measurements and Wave Glider (Liquid Robotics) measurements (Van den Eynde et al., 2014).

Wave model WAM

The WAM model is a third generation wave model, developed by the WAMDI Group (1988) and described by Günther et al. (1992). The WAM model is used both for research and for operational wave forecasting. It includes 'state-of-the-art' formulations for the description of the physical processes involved in the wave evolution. In comparison with the 2nd generation model, the wave spectrum has no restrictions and the wind sea and the swell spectrum are not treated separately.

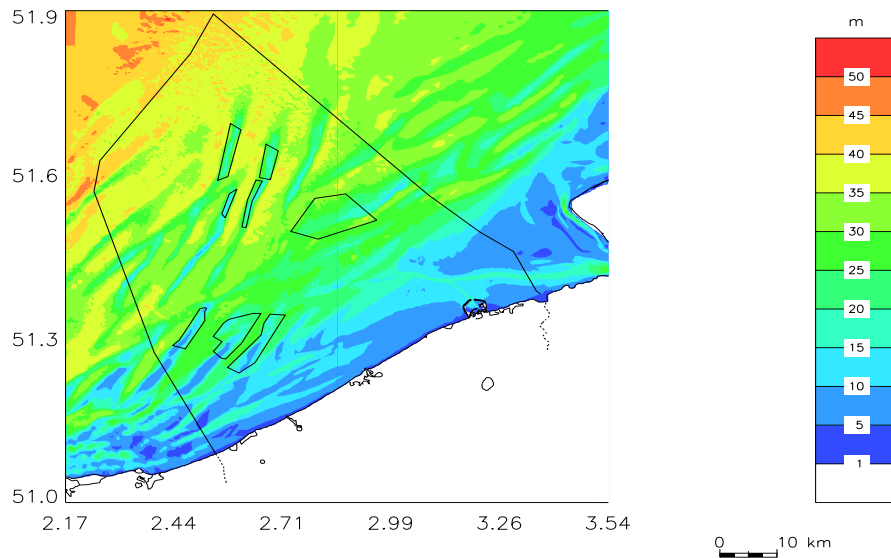


Figure 1: Bathymetry of the OPTOS-FIN model. Superimposed are the aggregate extraction sectors.

At the Operational Directorate Natural Environment, the model is running on three coupled model grids. The coarse model grid comprises the entire North Sea, the fine model models the central North Sea and the local model calculates the waves in the Southern Bight. The local model has a grid resolution of 0.033° in latitude and 0.022° in longitude.

The WAM model was recently validated by Van den Eynde (2013).

Calculation of the bottom shear stress

The calculation of the bottom shear stress is the topic of much research. The bottom shear stresses under the influence of currents alone and under the influence of waves alone over a flat bed are quite well known. However, the calculation of the bottom shear stress under the combined influence of currents and waves over a rippled sea bed is complex. The calculation of the bottom shear stress under the influence of currents and waves is not the simple vector addition of the bottom stress vectors for the currents and the waves alone, as non-linear interactions increase the mean bottom shear stress (averaged over a wave cycle).

Furthermore, the bottom roughness length, which is an important factor for the calculation of the bottom shear stress, is influenced by different factors. At the bottom itself, the roughness is a function of the grain size. This bottom shear stress, felt by the sediments, is called the skin friction. However, at a distance more than a tenth of the length of the bottom ripples, the bottom roughness is also influenced by the bed load and by the height and the length of the bottom ripples. Further away from the bottom, a new logarithmic profile is followed with an apparently increased total bottom roughness. The ratio between the skin bottom roughness and the total bottom roughness varies between 1.5 and 20.

For the calculation of the bottom shear stress under the influence of currents and waves, many different models can be found in literature, varying from simple models to very complex iterative models, resolving the stresses in the wave boundary layer and during a complete wave cycle. These very complex models are however very time consuming and not really useful to be used in sediment transport models. Recently, more realistic and simple models for the combined bottom shear stress were proposed in literature. Three new

formulations were implemented and tested, for both the mean bottom stress over a wave cycle and the maximum bottom stress, within a wave cycle.

The Soulsby (1995) formula is the most simple one, consisting of the results of a two-coefficient optimisation of a simple model to 131 data points, from more complex theoretical models. More recently, Soulsby and Clarke (2005) developed a new model, assuming an eddy viscosity varying over the water column, but constant in time. The eddy viscosity in the wave boundary layer is only a function of waves and currents, so that no iterative calculations are needed. Malarkey and Davies (2012) extended the theory of Soulsby and Clarke (2005) to include additional non-linearity in the model. More information and some comparison of the results of the different models can be found in Van den Eynde (2015).

As indicated above, the bottom shear stress under the influence of currents and waves is a function of the bottom roughness length. Both for the skin bottom roughness as for the total bottom roughness, models can be found in literature, which are, amongst other, function of the median grain size, the size of the bottom ripples and the bed load transport. Different models were implemented to calculate the bottom roughness as a function of empirical models for the bottom geometry (e.g., Soulsby and Whitouse, 2005) and the bed load transport. More information and some comparison of the results of the different models can be found in Van den Eynde (2015).

ADCP measurements of currents and bottom shear stress

For the validation of the bottom shear stress in the Hinder Banks area, different measurement campaigns, using a bottom-mounted ADCP (RDI Workhorse 1200 kHz), have been executed (Van Lancker et al., 2014; 2015). This ADCP measures the profile of the water currents from the bottom upwards. The campaigns BM01, BM02, BM04 and BM05 have been executed on the same place at (51° 30.6' N, 2° 37.94'), along the eastern flank of the Oosthinder sandbank. The campaigns BM03, BM06 and BM07 have been executed around a location (51° 24.78'N, 2° 31.61'E) in the Habitat Directive area, in the south part of the Hinder Banks, in the trough of a very-large dune. Both stations are indicated in *Figure 2*. Remark that the settings (bin size, range) and the time step of the measurements were not identical during the different measurements campaigns.

The bottom shear stress can be calculated from the assumed logarithmic profile of the currents near the bottom, by fitting the measured profile to this logarithmic profile, using a least squares method. Wilkinson (1984) developed expressions for the confidence limits (for a certain degree of confidence) for the estimations of the bottom roughness length and the bottom shear stress, using the Student's t distribution for the number of freedoms, equal to the number of velocities taken into account minus 2.

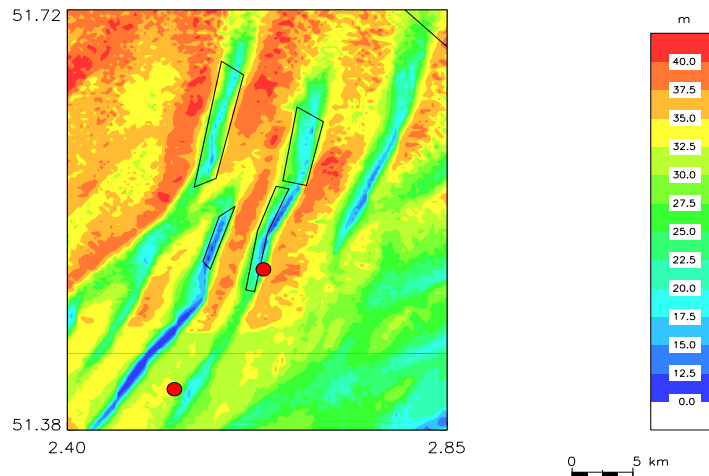


Figure 2: Position of the ADCP measurements (red circles). Polygons indicate the four aggregate sectors in the Hinder Banks region.

Validation of the models

Depth-averaged currents

The depth-averaged currents from the bottom-mounted ADCPs are compared with the model results. The measurements are first averaged over depth and further averaged over time, to obtain time series with a time step of 30 minutes.

Overall, the current magnitudes and current directions are quite well reproduced by the model for the measurements at the Hinder Banks, i.e., campaigns BM01, BM02 and BM04. In the campaign BM01, the currents were slightly overpredicted, certainly for the slack waters, while in campaign BM02, the overprediction of the currents mainly occurred during high currents. In campaign BM04, a slight overprediction of the lower currents and an underprediction of the higher currents occurred. Also the current directions are well modelled during these campaigns. Overall, the results of the model are clearly satisfactory at the station east of the Oosthinder.

For the measuring campaigns in the Habitat Directive area, south of the Hinder Banks, the results of the model are less satisfactory. Both for the campaign BM03 as for the campaign BM06, the currents by the model clearly overpredict the currents, certainly during high currents. These less satisfactory results are probably due to the specific bathymetry in the area, near the steep slope of the very large dune. Flow reversal probably exists slowing down the currents in the area. This is not well represented in the model bathymetry.

Wave height

The significant wave height, modelled with the WAM model, were compared with buoy data at the station MOW7 at the Westhinder sand bank (data from Flemish Banks Monitoring Network, Flemish Government, Agentschap Maritieme Dienstverlening en Kust).

Good results are obtained for the station at the east flank of the Oosthinder. For campaign BM01 and BM02 a scatter index of only 17 % is found; for the BM04 campaign, the scatter index is 25 %. The bias is always less than 0.07 m. These results are clearly satisfactory. For the station in the Habitat Directive area, the results are less good. The bias is higher with an underprediction of 0.12 m and 0.16 m for campaign BM06 and BM03

respectively. Also the scatter index for the BM03 campaign is higher (30 %). This probably is again an effect from specific tide-topography interactions at this station.

The waves during the periods of the measurement campaigns remain limited. During the campaign BM01 and BM02, the significant wave height remains most of the time below 2.0 m. During campaign BM04, a peak in significant wave height was reached of about 3.0 m. During the campaigns in the Habitat Directive area, south of the Hinder Banks, the waves remain lower and did not exceed 1.5 m.

Bottom shear stress

The bottom shear stress can be calculated from the current profile. In *Figure 3*, the mean profiles in the lowest 6 m of the water column for the entire campaign BM01 are presented as a function of the current direction. The highest currents are the currents in south-south-west (ebb) and in north-north-east (flood) direction. For the higher currents, the averaged currents show a relatively smooth logarithmic profile. For the slack-water profiles, the current profiles are more constant over the water depth. Remark that the current measurements in the Habitat Directive Area are lower and less logarithmic. It is clear that the individual profiles can differ more from the logarithmic profile.

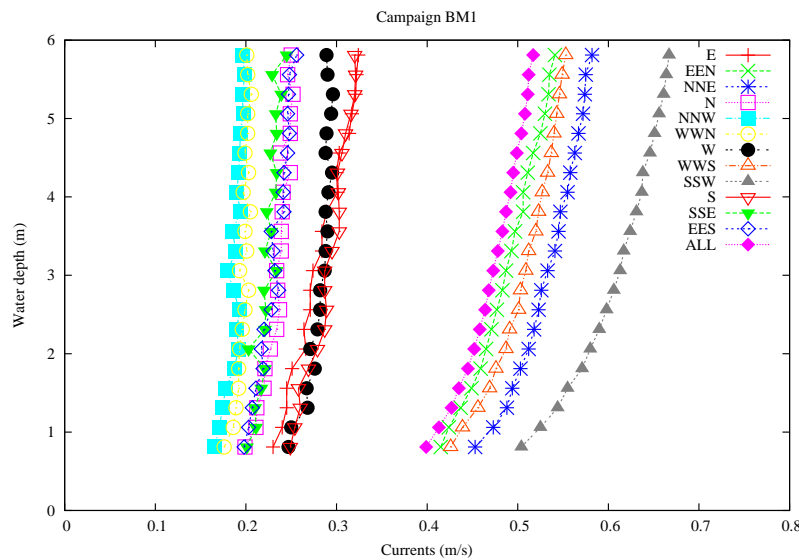


Figure 3: Mean current profiles in the lower part of the water column for campaign BM01, as a function of the current direction.

In *Figure 4*, the time series of the bottom shear stress, calculated using the lowest 5 m of the water column, is shown for day 1 to day 3 of campaign BM01. One can clearly see that there is still a lot of scatter in these measurements. To remove some of the scatter, a moving average filter is applied to the data with a window of two hours. Also the confidence limits (95 %) are presented in the figure.

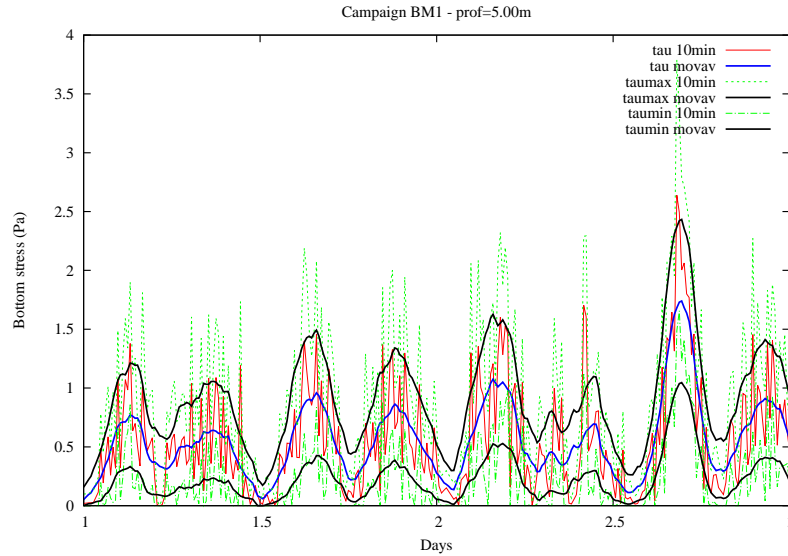


Figure 4: The calculated bottom shear stress (τ) and the maximum and minimum bottom stress with a confidence of 95 % (τ_{max} and τ_{min}) during day 1 to day 3 of campaign BM01 (moving average over 2 hours).

To compare these measurements with the model results of the three models, using a constant bottom roughness length, tests were executed with values for the bottom roughness length varying between 0.004 m and 0.6 m. The best overall result (lowest mean RMSE over all campaigns) was obtained with the Soulsby model, although the results with the Soulsby-Clarke and the Malarkey-Davies model were very comparable. The optimal bottom roughness for the Malarkey-Davies model for BM01, BM02 and BM04 is 0.01 m.

In Figure 5, the modelled bottom shear stress is given for campaign BM01, together with the measured bottom shear stress. Also the confidence limits (95 %) of the measurements are given in the plot. While the height of the peaks may differ considerable, the tidal signal is well reproduced by the model. In more than 92 % of the cases, the model results remains between the 95 % confidence limits of the measurements.

Overall, one can conclude that using a constant bottom roughness length, the numerical models give satisfactory results. A bottom roughness length of 0.01 to 0.03 m should be used. For the campaigns BM03 and BM06, where the measurements are taken in the Habitat Directive Area, the results are less good, mainly due to the very specific tide-topography interaction.

As mentioned before, the bottom roughness length can be calculated by the numerical model itself, based on empirical models for the bottom roughness length, due to bed load and due to bottom ripples. Also the dimensions of the bottom ripples are calculated by empirical models in this case. Tests however showed that the simulated bottom roughness lengths were too high and that the modelling of the bottom roughness length did not improve the results. Therefore, in the current study, a constant bottom roughness length was further used.

Remark that a further validation of the bottom shear stress models was executed, using high frequency measurements of the currents near the bottom (Van den Eynde, 2015; 2016a). For these measurements an Acoustic Doppler Velocity (ADV) profiler was used, which was mounted on a benthic bottom lander. This lander was deployed on the sea bed near the MOW1 measuring pole, in the neighbourhood of the harbour of Zeebrugge. Research showed that the turbulent kinetic energy (TKE) method showed the most promising results for the estimation of the bottom shear stress from the high frequency current measurements. The validation of the bottom shear stress models showed similar results as those reported here, showing that the bottom shear stress models give satisfactory estimates of the measurements.

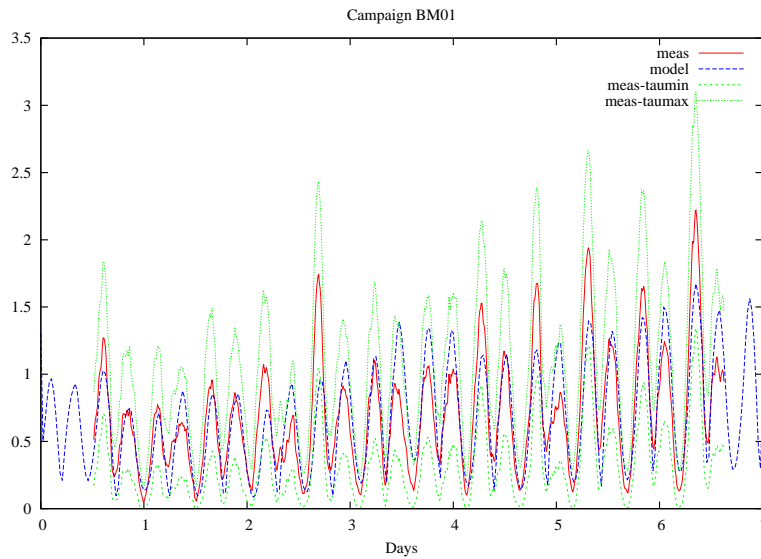


Figure 5: Time series of measured bottom shear stress (with confidence limits of 95 %) and modelled bottom shear stress, with a constant bottom roughness length, for campaign BM01.

Modelling the effect of extraction on bottom stress in the Hinder Banks area

Introduction

In the framework of Europe’s Marine Strategy Framework Directive (MSFD), Belgium prepared a report, in which different indicators were defined that could be used to evaluate the impact of human activities at sea (Belgian State, 2012). These indicators are grouped to several descriptors that together need monitoring to reach a Good Environmental Status of the marine waters by 2020. Amongst these descriptors, descriptor 7, on hydrographic conditions, uses the bottom shear stress. In that report, it is stated that human impact asks consideration when the bottom shear stress, calculated by a validated mathematical model over a spring-neap tidal cycle, 1) increases by more than 10 %, or 2) that the ratio of the period for erosion and the period for deposition is larger than -5 % or +5 %. Furthermore, it is stated that the impact should stay in a distance less than the square root of the area of the zone of activity, measured from the boundary of the area. This zone is referred to further as the “buffer zone”, where an increase or decrease of the bottom shear stress with more than 10 % is allowed, without further consideration.

In the Zone 4 for the extraction of marine aggregates, in the Hinder Banks area, a maximum of 35 million m³ of marine aggregates is allowed to be extracted over a period of 10 years. In this section, the effect of this maximum extraction on the bottom shear stress is evaluated, with respect to the method, defined in the MSFD.

Simulations

Three different scenarios are studied. In all scenarios, all material above a certain depth is extracted in the different sectors for extraction. In the first scenario, this depth can differ in the different sectors. In this scenario, in each sector the same maximum depth is extracted, starting from the minimum water depth in the sector. To arrive at a total of 35 million m³, a maximum extraction of 6.93 m from the top of the sandbank is applied. Almost 35 % is in this case extracted in Sector 4a (north-east), which has the largest area. In the second scenario, extraction is executed in the four sectors, to the same critical depth. In this case, extraction is executed up to a depth of 19.70 m in all sectors. In this case, most of the material is extracted in Sector 4d, since this is the sector with the shallowest water depths. In this zone, an extraction of more than 10 m is

executed, to extract almost 44 % from this zone alone. In the last scenario, only material is extracted in Sector 4c, the sector, which is used most intensively at the moment and which is the closest to the coast (south-west). An extraction of almost 12 m is executed in this case, to a water depth of 26.05 m.

To evaluate whether the impact needs consideration, the changes in bottom stress, larger than 10 %, should stay in a distance less than the square root of the area of the zone of activity, measured from the boundary of the area (the buffer area). Note however, that not the entire area where extraction is permitted is effectively used.

For the different bathymetries, the bottom shear stress is calculated using the three-dimensional hydrodynamic model COHERENS OPTOS-FIN. The standard COHERENS bottom shear stress model is used, which is based on a simple quadratic bottom shear stress. The influence of waves is not taken into account at the moment. This is based on analyses showing that in deeper waters, waves do not influence the bottom shear stress significantly. Furthermore, in the report on the Belgian implementation of the MSFD (Belgian State, 2012), the influence of the waves on the bottom shear stress is not mentioned.

The simulations were executed for a full spring-neap tidal cycle, i.e., from March 29, 2013, 00h00 till April 14, 2013, 12h00.

Results

In *Figure 6*, the changes in bottom shear stress are shown, averaged over the full spring-neap tidal cycle, for the first scenario, where in each sector the same thickness in sediment is extracted from the top of the sand bank, i.e., 6.93 m. One can see that the effect remains limited to the sector of extraction. To evaluate the results more in detail, three areas are defined: the sector of extraction, the area within a distance equal to the square root of the sector of extraction from the border as defined in the MSFD report, the so-called buffer zone, and the area outside this buffer zone. Results show that in the extraction sector itself, the changes can vary between +9.7 % to -27 %, while also in the buffer zone, the changes can be larger than 10 %, i.e., an increase with 15 % (see *Table 2*). However, outside this buffer zone, the difference is limited to -2.2 % to +3.5 %. In *Figure 6*, also the position of the points outside the buffer zone is given where the changes in bottom shear stress are higher than 2 %. The area is limited to a small area south east of Sector 4d.

In *Figure 7*, the number of model grid points are plotted, where the change in bottom shear stress exceeds a certain percentage, for the different zones (extraction zone, buffer zone, outside buffer zone). For the extraction zone, the number of points decreases from 496 points, with a change higher than 1 % to 69 points, with a change higher than 10 %. Remark that a grid cell represents an area of around 70,000 m² (or 0,07 km²). In the buffer zone, where impact is allowed, in 770 grid cells, the change is higher than 1 %, but only in 6 grid cells, a change higher than 10 % is encountered. Finally, in 322 grid cells, outside the buffer zone, the change is higher than 1 %, in 17 grid cells the change is higher than 2 % and only in 3 grid cells, the change is higher than 3 %.

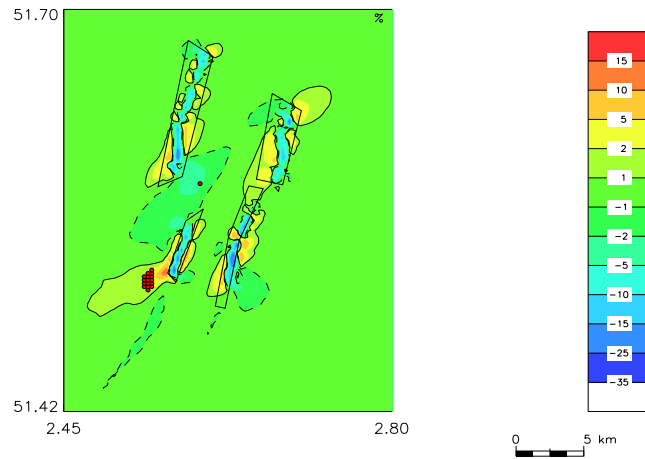


Figure 6: Aggregate sectors in the Hinder Banks along which changes of mean bottom shear stress over a spring-neap tidal cycle for scenario 1 are shown. Also indicated are the points, outside the buffer zone, where the increase/decrease is more than 2 %.

Table 2: For the three simulations ('sim'), minimum and maximum change of bottom shear stress (in percentage) in the different areas (extraction sector, buffer zone, outside buffer zone).

	Extraction zone		Buffer zone		Outside buffer zone	
	Min	Max	Min	Max	Min	Max
Sim 1	-27.33	9.71	-4.89	15.05	-2.16	3.52
Sim 2	-38.90	14.45	-6.48	26.80	-3.02	6.46
Sim 3	-35.59	12.62	-7.87	21.50	-3.46	2.58

In scenario 2, extraction is executed to a certain critical depth, resulting in less extraction in Sectors 4a, 4b and 4c and much more extraction in the shallow Sector 4d, where a maximum of more than 10 m is being extracted. In the extraction zones itself, a maximum change in bottom shear stress is found between +14 % to almost -39 % (see Table 2), which is considerable more than for scenario 1. Also in the buffer zone, the changes in bottom shear stress are higher, up to 27 %. However, also in this case, the change in bottom shear stress in the zone, where impact is not allowed, i.e., outside the buffer zone, remains limited and is lower than 10 %. In this case, the maximum changes found vary from -3 % to +6.5 %. The areas, where an increase or decrease of more than 2 % are located outside the buffer zone, are mainly located west and south of Sector 4d.

It is clear that the impact of scenario 2 is higher than for scenario 1, but that also in this scenario, the impact remains limited and that no changes of more than 10 % are observed in the area where impact is not allowed.

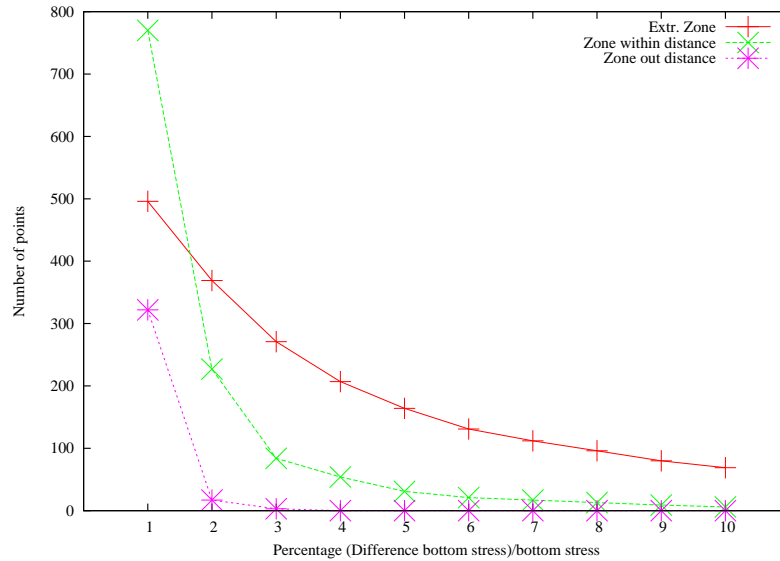


Figure 7: Number of points where the difference in bottom shear stress is exceeding a certain percentage, for the three defined areas for scenario 1.

In the last scenario, all extraction was executed in Sector 4c, the zone which is mostly used in the actual situation. A maximum of almost 12 m is being extracted. Although in this case, all extraction is executed in one sector only, the changes in the bottom shear stress remain limited. In the sector itself, the effect of an extraction of almost 12 m is of course considerable, with a maximum decrease of the bottom shear stress of -36 % and a maximum increase of 13 % (see Table 2, see Figure 8). Remark however that this is less than in scenario 2. Also in the buffer area, the changes in bottom shear stress are high, up to -8 % to +22 %. However, also for this scenario, bottom shear stress changes remain limited outside the buffer area and stay below 10 %. The maximum and minimum changes in this case are -3.5 % to +2.5 %. Apparently, the effect of the extraction in Sector 4d is larger than that of the even larger extraction in Sector 4c. This is due to the fact that the bathymetry in Sector 4d is shallower. In Figure 8, also the position of the area outside the buffer zone is indicated where the change in bottom shear stress is higher than 2%. This zone is mainly situated west of the extraction zone, while also in the southeast a small zone is present.

Conclusions

Three scenarios were modelled to investigate the influence of a large-scale extraction of marine aggregates (35 million m³) on the bottom shear stress in the extraction zone 4 in the Hinder Banks area. In the framework of the MSFD, Belgium stated that a human activity needs consideration when the bottom shear stress changes over more than 10 %, at a place that is farther away from the border of the zone of impact than the square root of the area of the zone of impact. This was tested for the three scenarios. The first scenario used the same maximal extraction depth in the four extraction sectors, in the second scenario the four sectors were extracted to the same final water depth, while in the third scenario, all the extraction was executed in Sector 4c. The simulations showed that for all three scenarios, the changes of the bottom stress in the area, where no impact was allowed, remains limited to less than 6 %. This is mainly due to the rather deep waters in the Hinder Banks area. More information and further results on these simulations can be found in Van den Eynde (2016b).

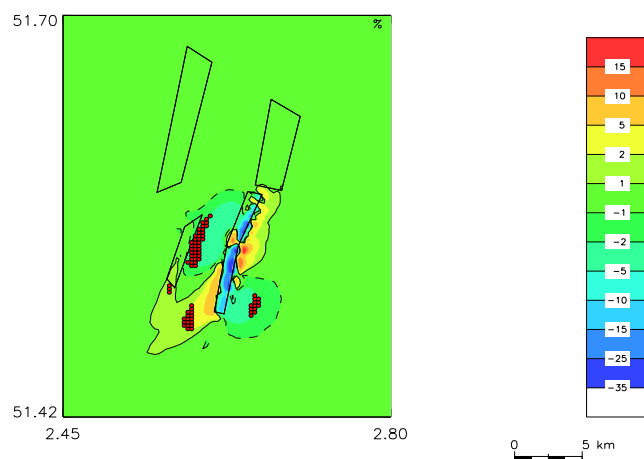


Figure 8: Aggregate sectors in the Hinder Banks along which changes of mean bottom shear stress over a spring-neap tidal cycle for scenario 3 are shown. Also indicated are the points, outside the buffer zone, where the increase/decrease is more than 2%.

The effect of the newly proposed extraction limit level on the bottom shear stress changes

Introduction

Over the last 6 years, the extraction of marine aggregates is increasing considerably. While in the period 2003-2010, the total volume of extracted marine aggregates on the Belgian Continental Shelf remained below 2.5 Mm³, since 2011 the extraction increased, with peaks in 2013, with an extraction of more than 4.0 Mm³, and 2014, with an extraction of even more than 6.0 Mm³ (Van den Branden et al., 2016). The volumes are mostly needed in response to the needs of the Coastal Safety Plan bringing the level of protection against extreme storm events at a 1:1000 years return period, including a +30 cm sea level rise by 2050 (www.kustveiligheid.be).

The limits of the extraction is at the moment set at 5 m below the reference level, that was defined by the Continental Shelf Service of the FPS Economy (COPCO) (Law of 13 June 1969 on the exploration and the exploitation of non-living resources of the territorial sea and the continental shelf, changed by the law of January 20 1999 and April 22 1999). The reference model is based on a depth digital terrain model in the extraction zones, measured during multibeam surveys in the first half of the previous decennium. Based on this limit, three areas in the extraction zone 2 (KBMA, KBMB and BRMC), where extraction led to a deepening of more than 5 m, were closed (Figure 9). Also in other areas in zone 1 (TBMA) and zone 4 (HBMC), this limit is approached, which will lead to the closure of these areas following the current legislation.

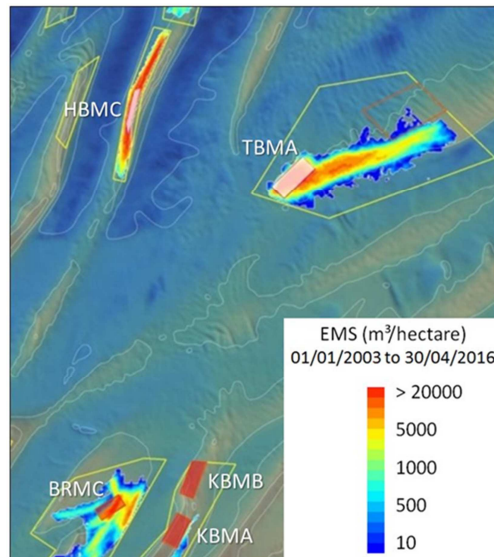


Figure 9: Areas closed for extraction (red) and areas where the limit is almost reached (rose) (From Degrendele, 2016).

However, this method does not account for the geology of the area, nor the differences in impact per sector. Furthermore, the sustainable character of the marine aggregate extraction is at stake. The areas with the best quality sands (medium to coarse sands) are being closed while zones with economically less interesting quality (fine sands) remain open. Therefore COPCO started with a new project to define a new extraction limit level based on scientific and economic criteria (Degrendele, 2016; Degrendele et al., this volume). The goal of the new extraction limit level is to limit the impact of the extraction in the most ecologically sensitive areas and to increase the economic sustainability, by accounting for the available volumes and the quality of the sands. Three scenario levels were proposed: a maximum, minimum and medium scenario based on these new criteria. Remark that in these new scenarios, the total volume of the reserves, i.e., the total volume that could be extracted, decreases from about 1,050 Mm³ to 927 Mm³, 538 Mm³ or 599 Mm³ respectively. At the moment, scenario 3 is the preferred one.

In this section, the effect of this newly proposed extraction limit level on the changes in the bottom shear stress is evaluated, with respect to the MSFD regulations, as mentioned already in the previous section.

Simulations

To assess the impact of the maximum extraction of the marine aggregates, taking into account three scenarios for the new extraction limit level, the new bathymetries were first introduced in the OPTOS-FIN bathymetry. Based on the 5 m x 5 m resolution bathymetries for the extraction zones and for the new extraction limit levels, provided by COPCO, new bathymetries with the resolution of the OPTOS-FIN model were set up and introduced in the model bathymetry. In Figure 10, the original bathymetry, the bathymetry of the extraction limit level, using scenario 3 and the difference between both are shown for the Sector 2b (Buiten Ratel). The difference between the original level and the level after extraction varies between 0 m and 7 m in this sector.

The volumes of extraction, calculated for the three extraction limit levels (scenario 1 to 3) are similar to the ones, calculated by COPCO, but are slightly smaller than those. This is mainly due to the difference in resolution.

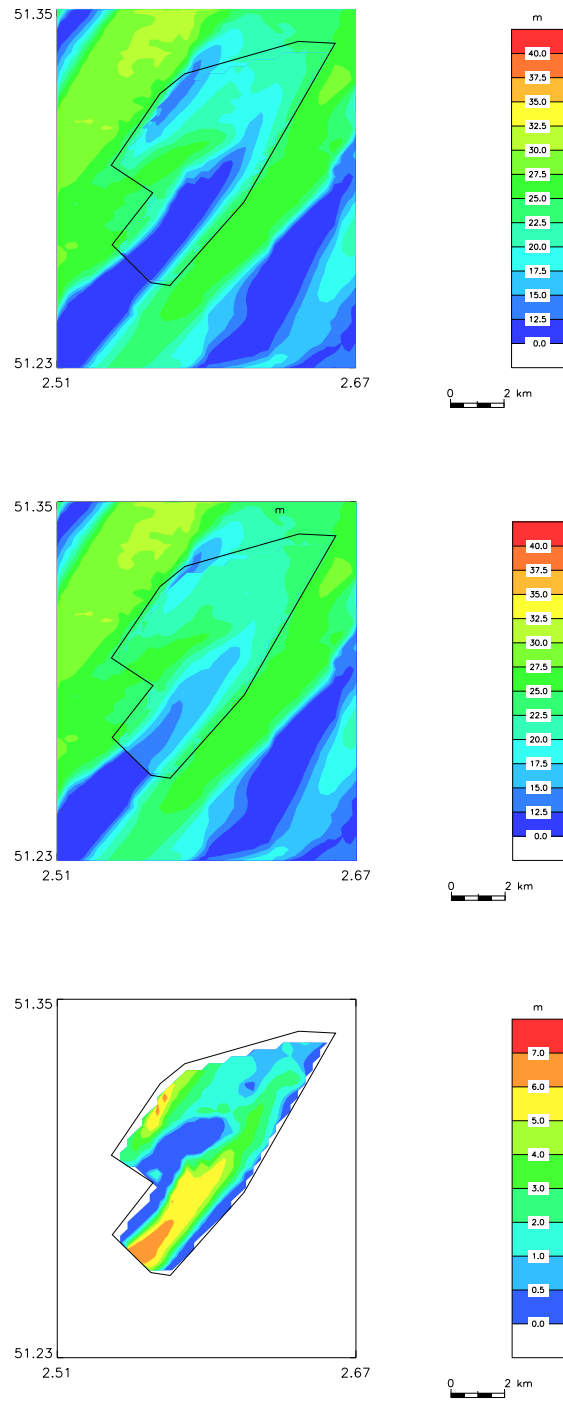


Figure 10: Upper: bathymetry of the extraction zone 2b (Buiten Ratel); Middle: bathymetry of the extraction limit level for scenario 3 in the extraction zone 2b; Lower: difference between the original bathymetry and the extraction limit level for scenario 3.

For each of the scenarios, the changes in bottom shear stress were evaluated. Also here, the COHERENS bottom shear stress is used in these first tests. The simulations were executed for a full neap-spring tidal cycle

(September 8, 2013, 01h00 till September 22, 2013, 19h30). The main goal was to determine whether outside the buffer zone for each extraction area, the bottom shear stress increased or decreased with more than 10 %.

Results

In *Figure 11*, as an example, the bottom shear stress changes are shown for the bottom shear stress using the original bathymetry and the bottom shear stress, using the bathymetry of the extraction limit level, scenario 3. One can see that in the extraction zones, due to the deepening, the bottom shear stress decreases. Outside the extraction zones, the bottom shear stress increases. Furthermore one can see that the zone of influence can be considerably, extending to the coast itself, but that the changes outside the buffer zone, remain limited.

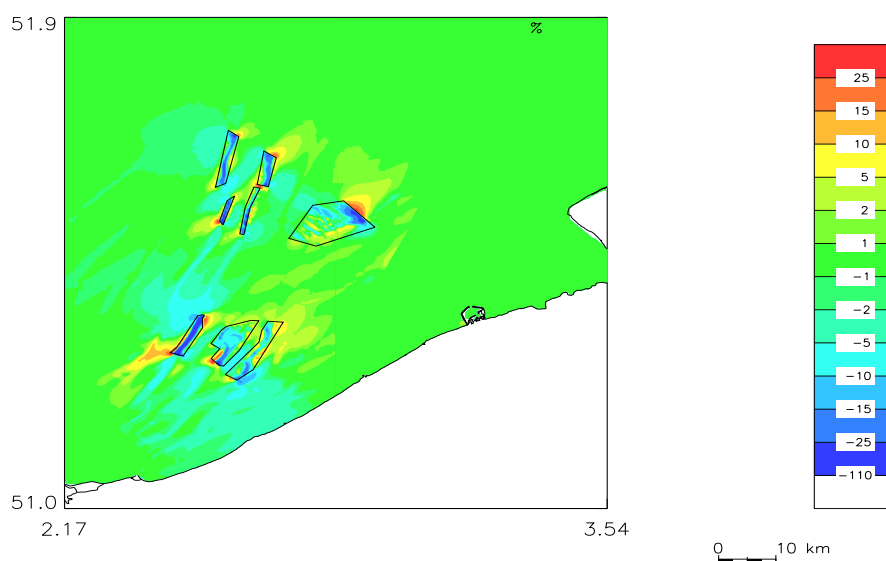


Figure 11: Bottom shear stress change on the Belgian Continental Shelf for the extraction limit level scenario 3.

In *Figure 12* the minimum and the maximum change of the bottom shear stress is shown for the different extraction zones and for the area outside the buffer zone, in the buffer zone and in the extraction zone itself, for scenario 3. The largest decrease of bottom shear stress is inside the extraction zone, while the largest increase is in the buffer zones. The largest influences are found for the extraction zone 2c, the Oostdijck sandbank, where a decrease of -56 % is found in the extraction zone itself, and an increase of +73 % is found in the buffer zone. Outside the buffer zone, the maximum increase is +13.6 % respectively, near Sector 2c. Remark that for scenario 1, also near Sector 4d an increase of the bottom shear stress outside the buffer zone of more than 10 % is found (+11.7 %). In an area of 4.90 km² outside the buffer zone around Sector 2c, an increase in bottom shear stress is found of more than 10 % for scenario 3, while for scenario 1, an area of 8.38 km² and 0.21 km² outside the buffer zones around Sector 2c and 4d are found respectively. This means that also for the more moderate scenario 3, extraction up to the newly proposed extraction limit level for Sector 2c would induce an increase of more than 10 % outside the buffer zone, which is in conflict with the regulation for the MSFD.

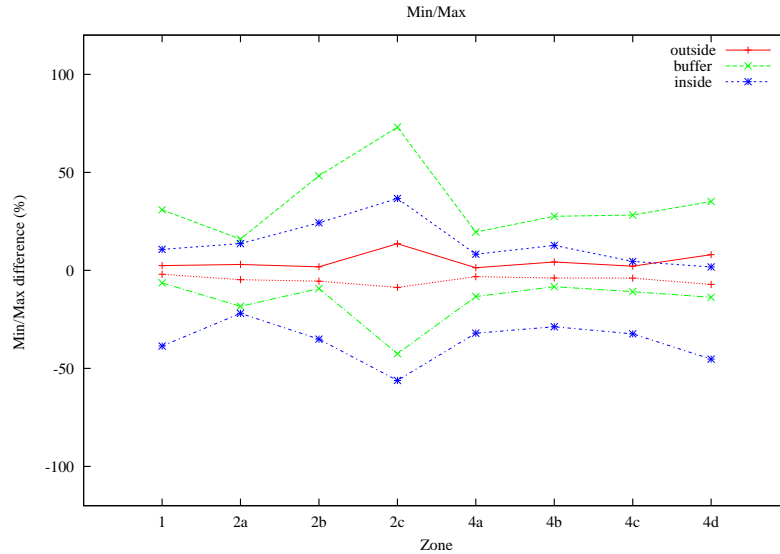


Figure 12: Minimum and maximum bottom shear stress change in the different zones outside the buffer zone (outside), in the buffer zone (buffer) and in the extraction zone (inside), for scenario 3.

Improvement of scenario 3

The current research shows that the newly proposed extraction limit level, using scenario 3, would lead to problems with the current regulations of the MSFD. The extraction of marine aggregates in the extraction Sector 2c up to the new extraction limit level would lead to an increase of the bottom stress with more than 10 % outside the buffer zone (as modelled with a validated numerical model during a neap-spring tidal cycle). Two solutions to overcome this were investigated. In the first solution, the reference level was increased in the entire zone, with a fixed level, varying from 2 m to 4 m. In the second solution, no extraction was allowed below a certain minimum depth. This minimum depth varied between 18 m to 15 m.

For the first solution (see Figure 13), increasing the extraction limit level with only 2.5 m still resulted in an area of about 2.0 km², where the increase in bottom shear stress was larger than 10 %, outside the buffer zone. Only with an increase of 4.0 m, no increase of more than 10 % was still present, outside the buffer area. In this case still 48.6 Mm³ was available for extraction. Remark that this is a considerable decrease compared to the original volume of 104.5 Mm³, that could be extracted when applying the original scenario 3 extraction limit level.

In the second solution (Figure 14), a minimum depth of about 15 m, is needed, to ensure that no changes in bottom shear stress larger than 10 % would occur outside the buffer area. Remark that in this case, only some 34.8 Mm³ is left for extraction. This is clearly the less suitable solution. More refinement could be proposed to still ameliorate the proposed solution.

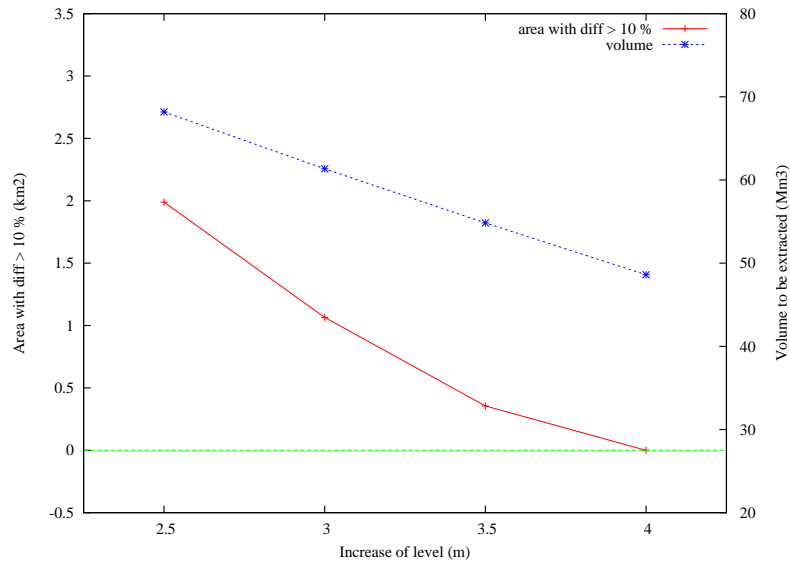


Figure 13: Area outside the buffer zone where the bottom shear stress difference is larger than 10 % (in km²) and volume to be extracted (in Mm³) for the solution 1, as a function of the increase of extraction limit level.

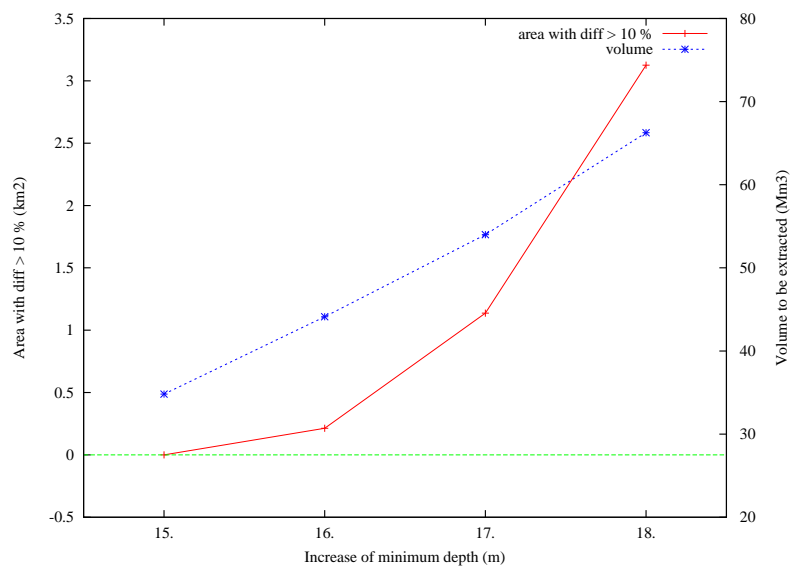


Figure 14: Area outside the buffer zone where the bottom shear stress difference is larger than 10 % (in km²) and volume to be extracted (in Mm³) for the solution 2, as a function of imposed minimum depth.

Conclusions

The bottom shear stress model was used to test whether the newly proposed extraction limit levels, proposed by Degrendele (2016) and Degrendele et al. (this volume), would still be compliant with acceptable bottom shear stress changes as defined in the Belgian implementation of the MSFD, i.e., no increase or decrease of more than 10 % outside a buffer zone around the aggregate extraction sectors. This new extraction limit level would replace the existing level, which limits the extraction at 5 m below a reference level that was previously defined by COPCO. It was shown that for the scenario 3, which is the preferred scenario, no problems are foreseen, except for the extraction Sector 2c on the Oostdijck sandbank. The compliancy with MSFD specifications would remain if the new extraction limit level would be raised with 4 m in this extraction zone. However, this results in a significantly reduced volume of extractable sediments. Remark that such exercises

are done for the first time; previously, extraction levels were merely defined on an *ad hoc* basis. More information on these simulations and results can be found in Van den Eynde (2017).

Overall conclusions

In the present contribution, the effect of extraction of marine aggregates on the bottom shear stress was evaluated in the framework of the Marine Strategy Framework Directive. In the Belgian implementation of this directive, it was stated that a human impact needs consideration when the bottom shear stress, calculated with a validated numerical model, changes with more than 10% at a specified distance of the activity. In this paper, the validation of the numerical model is presented first. Thereafter, two applications of the bottom shear stress model are presented that evaluate the impact of marine aggregate extraction.

In a first part of this contribution, the validation of the numerical model was presented. After presentation of the hydrodynamic, wave and bottom shear stress models, the validation of the hydrodynamic and wave model was discussed. The validation showed that the currents at a regular sandbank location were well modelled. However, in morphologically complex locations results are less good. This is probably due to complex tide-topography interaction. Also waves were modelled satisfactorily.

Bottom shear stress measurements were obtained by applying a logarithmic profile to the current profile, measured with a bottom-mounted ADCP. The method of Wilkinson (1984) was applied to estimate the confidence limits.

The validation of the bottom shear stress model showed that the bottom shear stress could be reasonably modelled by the numerical models. Using a constant bottom roughness, best results were obtained by the Soulsby model, using a constant bottom roughness length of 0.01 m. Similar results were obtained by the other models. The bias was around 0.20 Pa, with a root-mean square error of about 0.35 Pa, for campaign BM01. Over more than 90 % of the time, the modelled bottom shear stress was between the 95 % confidence limits. Less good results were obtained for measurements in morphologically complex areas. This is probably due to the less quality of the modelled currents and to the specific tide-topography interactions at the site. No better results were obtained when calculating the bottom roughness length by empirical models.

Also high frequency current measurements were used to estimate the bottom shear stresses, mostly near the measuring station MOW1, near the harbour of Zeebrugge. Also these measurements were used for the validation of bottom shear stress models. Remark however, that the estimation of the bottom shear stresses is still a difficult task and that the less quality of the bottom shear stress measurements hampers a solid validation of the bottom shear stress models. More high quality measurements of the bottom shear stress are needed, possibly using different techniques in measurements. Certainly in more offshore regions, like the Hinder Banks, more high quality measurements of the bottom shear stress are needed.

In the second part of this contribution, two applications were presented. Firstly, three scenarios were simulated to investigate the influence of a large-scale extraction of marine aggregates (35 million m³) on the bottom shear stress in zone 4 of the Hinder Banks. The first scenario used the same maximal extraction depth in the four extraction sectors, in the second scenario the four sectors were extracted until the same final water depth. In the third scenario, all the extraction was executed in Sector 4c. The simulations showed that for the three scenarios, the changes of the bottom shear stress in the area, where no impact was allowed, remained limited to less than 6 %. This is mainly due to the rather deep waters in the Hinder Banks area.

In the second application, the new extraction limit levels proposed by COPCO (Degrendele, 2016; Degrendele et al., this volume) were evaluated. Results showed that for the scenario 1, too high bottom shear stress changes could be expected around the extraction Sectors 2c and 4d. For the scenario 3, only too high bottom

shear stress changes were expected, outside the buffer zone, for extraction Sector 2c. Two solutions were investigated. It was shown that increasing the reference level with 4 m ensured that no too high bottom shear stresses were obtained outside the buffer zone, while trying to maximize the remaining extractible volume.

The current simulations evaluated the extraction of marine aggregates in the Hinder Banks area, and evaluated the new proposed extraction limit levels, with respect to the current Belgian implementation of the MSFD regulations. Some adaptations were proposed to the new extraction limits, to assure that they are in line with the MSFD regulations. Remark however, that the MSFD regulations are subject to review and changes and that the evaluation therefore could change as well. In this respect, some remarks could be made. First of all, the concept of buffer zone might need some consideration. At the moment, the buffer zone is larger for a larger 'zone of activity'. Defining a larger zone of activity therefore could make the buffer zone larger and minimize the possible problems with respect to the descriptor 7. Furthermore, the buffer zone does not all take into account the ecological values of the area. This also could become more important in the future. On the other hand, the effect of waves on the bottom shear stress is not at all considered in the present regulations. However, it is well known that waves can have a significant influence on the bottom shear stress and could therefore be included in the evaluation of bottom shear stress changes. Finally, it is well known that sandbanks can play an important role in the breaking of the waves more offshore and therefore in the protection against coastal erosion. Also this is not at all taken into account and might be a subject of future research.

The present paper therefore must be considered as contribution to the evaluation of the impact of extraction of marine aggregates on changes in bottom shear stress and hydrological conditions in general, but it is clear that further research is still needed.

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References

- Belgian State, 2012. Omschrijving van de Goede Milieutoestand en vaststelling van Milieudoelen, Kaderrichtlijn Marine Strategie, Art 9 & 10, 33 pp.
- Degrendele, K., 2016. Bepalen van een nieuw referentieoppervlak. Tussentijds rapport. FOD Economie, K.M.O., Middenstand en Energie, Kwaliteit en Veiligheid, Kwaliteit en Innovatie, Continentaal Plat, Brussel, België, 19 pp.
- Degrendele, K., M. Roche and H. Vandenreyken, 2017. New limits for the sand extraction on the Belgian part of the North Sea? This volume.
- Günther, H., S. Hasselmann and P.A.E.M. Janssen, 1992. Wamodel Cycle 4. DKRZ Technical Report No. 4, Hamburg, October 1992, 102 pp.
- Luyten, P. (editor), 2014. Coherens – A coupled hydrodynamic-ecological model for regional and shelf seas: user documentation. Version 2.6. RBINS Report, Royal Belgian Institute of Natural Sciences, Operational Directorate Natural Environment, Brussels, Belgium, 1554 pp.
- Malarkey, J. and A.G. Davies, 2012. A simple procedure for calculating the mean and maximum bed stress under wave and current conditions for rough turbulent flow based on Soulsby and Clarke's(2005) method. Computers and Geosciences, 43, 101-107.
- Mathys, P., J. De Rouck, L. Fernandez, J. Monbaliu, D. Van den Eynde, R. Delgado and A. Dujardin, 2012. Belgian Ocean Energy Assessment (BOREAS). Final Report. Belgian Science Policy Office, Brussels, 171 pp.
- Soulsby, 1995. Bed shear-stresses due to combined waves and currents. In: Advances in Coastal Morphodynamics. M.J.F. Stive, H.J. de

- Vriend, J. Fredsøe, L. Hamm, R.L. Soulsby, C. Teisson and J.C. Winterwerp (eds.), 4-20 to 4-23. Delft Hydraulics, The Netherlands.
- Soulsby, R.L. and S. Clarke, 2005. Bed shear-stresses under combined waves and currents on smooth and rough beds. Report TR 137. HR Wallingford, Wallingford, United Kingdom, 42 pp. (http://www.estproc.net/EstProc_library.htm).
- Soulsby, R.L. and R.J.S. Whitehouse, 2005. Prediction of ripple properties in shelf seas. Mark 2 Predictor for Time Evolution. Final Technical Report. Prepared for US Office of Naval Research, Contract No. N00014-04-C-0408. Report TR154, HR Wallingford, 41 pp + App.
- Van den Branden, R., G. De Schepper and L. Naudts, 2016. Zand- en grindwinning op het Belgisch deel van de Noordzee. Electronic Monitoring System (EMS) voor de monitoring van de aggregaatextractie: jaarrapport 2014-2015. RBINS-OD Nature-MSO. Report MDO/2016-02/ZAGRI, 60 pp.
- Van den Eynde, D., 2013. Comparison of the results of the operational HYPAS and WAM models. Report OPTOS/1/DVDE/201303/EN/TR1, Royal Belgian Institute for Natural Sciences, Operational Directorate Natural Environment, Brussels, Belgium, 39 pp.
- Van den Eynde, D., 2015. Measuring, using ADV and ADP sensors, and modelling bottom shear stresses in the Belgian coastal waters. Report ZAGRI-MOZ4/1/DVDE/201502/EN/TR02, Royal Belgian Institute for Natural Sciences, Operational Directorate Natural Environment, Brussels, Belgium, 49 pp.
- Van den Eynde, D., 2016a. Measuring, using ADV and ADP sensors, and modelling bottom shear stresses at the MOW1 site (Belgian Continental Shelf). Report MOMO-INDI67/1/DVDE/201608/EN/TR01. Royal Belgian Institute for Natural Sciences, Operational Directorate Natural Environment, Brussels, Belgium, 47 pp.
- Van den Eynde, D., 2016b. The impact of extraction on the bottom shear stress in Zone 4. Report ZAGRI-MOZ4/1/DVDE/201604/EN/TR01, Royal Belgian Institute for Natural Sciences, Operational Directorate Natural Environment, Brussels, Belgium, 52 pp.
- Van den Eynde, 2017. The impact of extraction on the bottom shear stress using the proposed new extraction limit levels. Report, Royal Belgian Institute for Natural Sciences, Operational Directorate Natural Environment, Brussels, Belgium. In preparation.
- Van den Eynde, D., A. Giardino, J. Portilla, M. Fettweis, F. Francken and J. Monbaliu, 2010. Modelling the effects of sand extraction, on the sediment transport due to tides, on the Kwinte Bank. *Journal of Coastal Research*, SI Eumarsand, 51, 101-116.
- Van den Eynde, D., M. Baeye and V. Van Lancker, 2014. Validation of the OPTOS-FIN model in the exploration 4 zone. Report ZAGRI-MOZ4/X/DVDE/ 201401/EN/TR/1, Royal Belgian Institute for Natural Sciences, Operational Directorate Natural Environment, Brussels, Belgium, 40 pp.
- Van Lancker, V., M. Baeye, M. Fettweis, F. Francken and D. Van den Eynde, 2014. Monitoring of the impact of the extraction of marine aggregates, in casu sand, in the zone of the Hinder Banks. Report MOZ4-ZAGRI/X/VVL/201401/EN/SR01, Royal Belgian Institute of Natural Sciences, Operational Directorate Natural Environment, 384 pp. (9 Annexes).
- Van Lancker, V., M. Baeye, D. Evagelinos & D. Van den Eynde, 2015. Monitoring of the impact of the extraction of marine aggregates, in casu sand, in the zone of the Hinder Banks. Period 1/1 – 31/12 2014. Brussels, RBINS-OD Nature. Report <MOZ4-ZAGRI/I/VVL/201502/EN/SR01>, 74 pp. (+5 Annexes, 109 pp).
- The WAMDI Group, 1988. The WAM Model – A Third Generation Ocean Wave Prediction Model. *Journal of Physical Oceanography*, 18, 1775-1810.
- Wilkinson, R.H., 1984. A Method for Evaluating Statistical Errors Associated with Logarithmic Velocity Profiles. *Geo-Marine Letters*, 3, 49-52.