6. The impact of sand extraction on the wave height near the Belgian coast

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6.1. Introduction

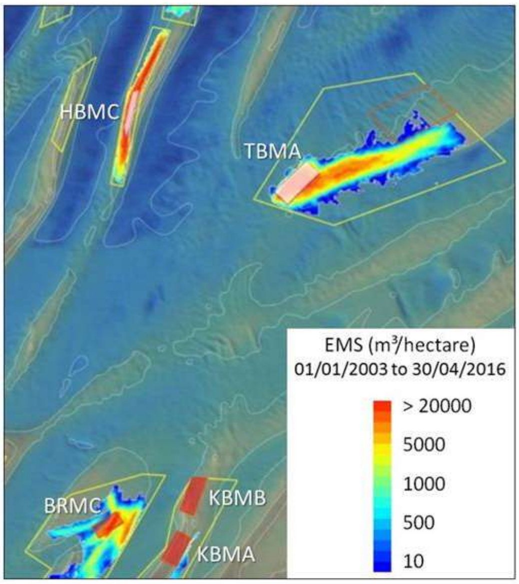
Over the last years, the extraction of marine aggregates is increasing considerable. While in the period 2003-2010, the total volume of extracted marine aggregates on the Belgian Continental Shelf stayed below 2.5 Mm^3, since 2011 the extraction increased, with peaks at 2013, with an extraction of more than 4.0 Mm^3, and 2014, with an extraction of even more than 6.0 Mm^3 (Van den Branden et al., 2016). Furthermore, since 2012, concessions were granted in the region of the offshore Hinderbanks. 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 (www.kustveiligheid.be).

The limits of the extraction in the Belgian Law was set at 5 m below the reference level, that was defined by the Service Continental Shelf of the Federal Public Service 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 20th, 1999 and April 22th, 1999). This reference model was based on a detailed terrain model of the sea bottom in the extraction zones, measured during multi-beam surveys in the first half of the previous decennium. Based on this limit, three areas in the extraction Sector 2 (KBMA, KBMB and BRMC), where extraction led to a deepening of more than 5 m, were closed (see Figure 1). In other areas in Sector 1 (TBMAB) and Sector 4 (HBMC), this limit was approached as well.

This method however didn't take the structure of the sea bottom and the differences in impact into account. Furthermore, the sustainable character of the marine aggregate extraction became at risk. The areas with the best quality sands (median size to coarse sands) were being closed while zones with economically less interesting quality (fine sands) remained open. Therefore, COPCO defined a new extraction limit level, which was based on scientific and economic criteria (Degrendele, 2016; Degrendele et al., 2017; Degrendele et al., this volume). The goal of this new extraction limit level is to limit the impact of the extraction in the most sensitive areas for sediment and habitat and to increase the economic sustainability, by accounting for the available volumes and the quality of the sands. Using the new extraction limit, the total volume of the reserves, i.e., the total volume that can be extracted, decreases from about 1050 Mm^3 to 599 Mm^3. However, the extraction will happen on a more sustainable way and taking into account the economic interests.

In Van den Eynde (2016; 2017), the effect of this new proposed extraction limit level on the changes in the bottom stress were evaluated, according to the Belgian implementation of the European Marine Strategy Framework Directive (Belgian State, 2012; 2018). In this Directive, it was stated that human impacts need consideration when the bottom shear stress, calculated with a validated numerical model, changes with more than 10 % at a specified distance of the activity. The impact of extraction of marine aggregates, up to the new proposed extraction limit levels, was evaluated with this respect. Simulations were executed with numerical models to test whether the three newly proposed extraction limit levels were within these constraints. Some small changes were suggested to adapt the new extraction limit to assure that no violation of this regulation would occur.

Figure 1: Areas, closed for extraction (red) and areas where the limit is almost reached (rose).



Source: Degrendele, 2016.

In this article, the effect of the change of the extraction level limit on the wave propagation on the Belgian continental shelf is investigated. This is done using the SWAN wave model. From these results the effect of the extraction on coastal protection is evaluated.

Remark however that in the current report the Sector 4a is not considered anymore and a new extraction Sector 5 is being defined (see Figure 2). The simulations are executed for these extraction sectors. Remark also that in the current article Sector 3 (Sierra Ventana) is out of scope. This extraction section is considered an area where sand is extracted that was previously deposited there and is therefore not taken into account.

In the first section the numerical model is shortly presented. The second section discusses the setup of the model grid. In the third section, the simulations are presented, while a discussion is presented in the next section. A conclusion is formulated in the last section.

6.2. Numerical model

For the propagation of the waves over the shallow Belgian coastal waters, different models can be used. For the operational forecasts of the waves on the Belgian coast, the third generation WAM model is used (WAMDI Group, 1988; Günther et al., 1992). The local grid however has only a resolution of 0.033° in latitude and 0.022° in longitude, which is more than 1.5 km.

Therefore, for this study the SWAN model (e.g., Ris, 1997; Booij et al., 1999; Holthuijsen et al., 1989, 1993, 2003) is used. The SWAN model is a third-generation wave model that computes random, short-crested wind-generated waves in coastal regions and inland waters. The model calculates in time and space, the generation of waves, their propagation and shoaling, non-linear wave-wave interaction, white-capping, bottom friction and depth-induced breaking. In comparison with the WAM model, the model is more suited to calculate the propagation of the waves in the nearshore area. The main disadvantage is that the models is preferably used in stationary mode. The SWAN model is implemented (see next session) on a grid of 250 m x 250 m, better representing the sand banks. This is needed to evaluate the effect of sand extraction on the wave propagation.

In the current project, the SWAN cycle III version 40.51 is used (SWAN, 2006a, 2006b), with most of the default values. The wave spectra in the model are described for 37 frequencies within the frequency range of 0.025 Hz to 0.85 Hz. The frequencies are logarithmic distributed. The full directional range is covered with a resolution of 10°. The model uses the 3th generation source terms, including linear and exponential wind growth, white capping, non-linear 4-wave interactions (so-called quadruplets), depth-induced wave breaking, bottom friction and non-linear shallow water 3-wave interactions (so-called triads). The triads and bottom friction, non-active by default, were activated.

The model was run in stationary mode, with default accuracy parameters and with maximum 40 iterations. Normally around 7 iterations are used in the current calculations.

While recent research by Zijlema et al. (2012) showed that in older versions of SWAN (like the 40.51 version) wave growth by wind was overestimated, which was compensated by larger bottom friction for wind sea, the lower bottom friction was not included here, because the new wave growth formulations were not included in the 40.51 version of the model.

6.3. Bathymetry

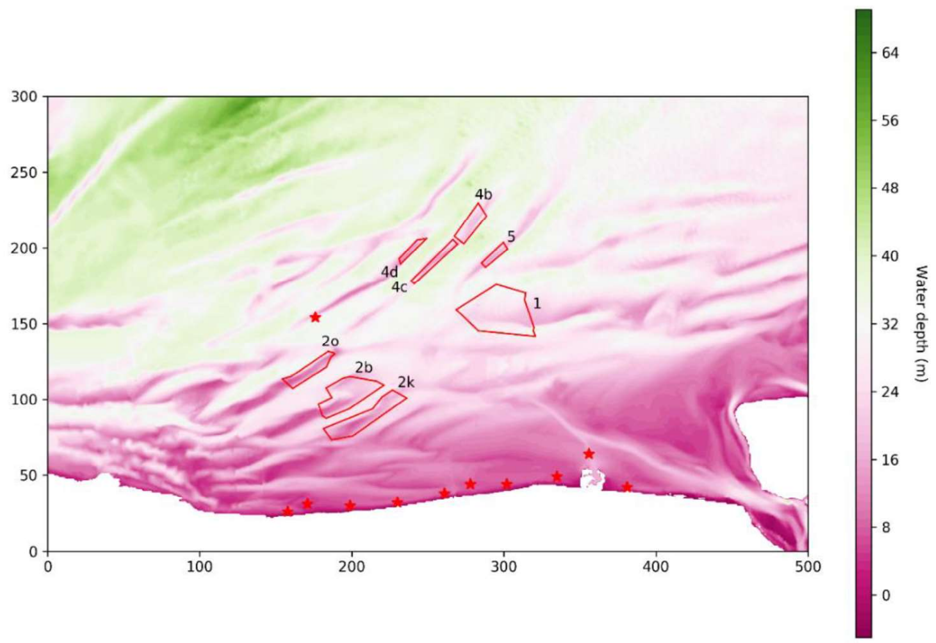
6.3.1. Extended SWAN bathymetry

In the framework of the CLIMAR project (Van den Eynde, 2011; Van den Eynde et al., 2011), the SWAN model was used to simulate the propagation of the waves from offshore to the Belgian coast and to investigate the effect of sea level rise on the wave propagation. For that application, the model was implemented on a Cartesian grid, rotated over 25.5° anti-clockwise, along the Belgian coast, with a resolution of 250 m x 250 m, a grid that was prepared by KULeuven & FHR (2004). The rotation is needed to assure that the distance from the coast to the offshore boundaries are similar. This assures that the time of the waves, travelling from the offshore conditions to the shore takes the same time, which is useful, using the model in stationary mode. The lower left point of the grid had the co-ordinates (50°54'00", 2°07'12"). For the current application, a more extended model grid was set up, based on the new bathymetries that were developed for the new hydrodynamic model train, based on the COHERENS software, that is being installed at the RBINS-OD Nature (Dulière, 2017).

The bathymetry is shown in Figure 2. In the figure, also 10 possible output points before the Belgian coast are shown where the output could be used by coastal models such as the XBeach model (Roelvink et al., 2009; 2015) and the UNIBEST-CL+ model (https://www.deltares.nl/en/software/unibest-cl/). The XBeach model is operated by Flanders Hydraulics Research (FHR) to evaluate the changes of the beach profiles during storms (De Roo et al., 2015; Kolokythas et al., 2016). The UNIBEST-CL+ model is operated to simulate larger scale coastline dynamics. These points were taken from IMDC (2009) to represent the wave climate for the 10 coastal municipalities.

Figure 2: New extended SWAN grid.

Reference levels is Mean Sea Level. Points are output points at the coastal municipalities and the wave buoy at Westhinder (offshore). The extraction zones are indicated. Coastal points from West to East: DPa: De Panne, Kok: Koksijde, Nwp: Nieuwpoort, Mid: Middelkerke, Oos: Oostende, Brd: Bredene, DHn: De Haan, Bla: Blankenberge, Zbr: Zeebrugge, Knk: Knokke. Offshore point Whi: Westhinder.



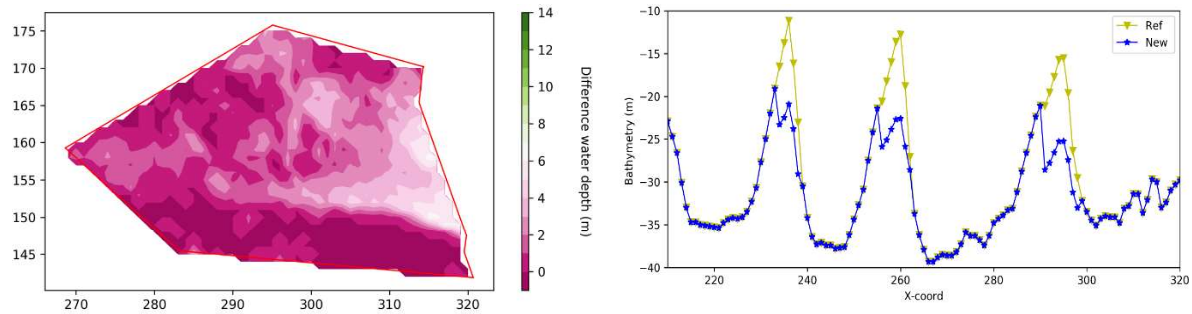
6.3.2. Inclusion of the new reference level

To check the influence of the sand and gravel extraction, the bathymetry of the SWAN grid is adapted in the extraction zones to the new extraction level. For the present bathymetry and for the new extraction limit level, bathymetrical files were received on a grid of 5 m x 5 m for the different sectors from COPCO. To make the inclusion of these data consistent, both data sets were included in the SWAN bathymetry. A similar procedure is used, as was used in Van den Eynde (2016; 2017).

It can be noted that small differences between the reference bathymetry provided by COPCO and the bathymetry of the new SWAN grid, ranging between +0.17 m and -0.75 m were observed. To make the calculation of the effect of the change in bathymetry, due to extraction, more consistent, the COPCO bathymetries were corrected.

After the preparation of the new reference bathymetry, the same procedure was followed to prepare the new bathymetry, where the bathymetry in the extraction zones was lowered to the new extraction limit. In Figure 3, the difference between the reference bathymetry and the extraction limit bathymetry is shown for sector 1. Also the difference between the reference bathymetry is shown for a cross-section of the bathymetry at model coordinate Y=195, where the sectors 4c, 4d and 5 are cut.

Figure 3: Left: Difference between the reference bathymetry and the extraction limit bathymetry for the sector 1. Right: Difference between the reference bathymetry and the extraction limit bathymetry at Y=195.



Sector 1 is clearly the largest zone, with a size of 73 km², while sector 4d and the new sector 5 are the smallest ones, with a size of only 5.2 km² and 6.2 km² respectively. The largest amount can be extracted in sector 1, namely about 93 Mm³. In the other sectors, the extractable amount varies between 35.7 Mm³ (sector 4d) and 85.4 Mm³ (sector 2b). Remark that in the sector 1 only 1.28 m can be extracted on average over the entire sector, while in sector 5, more than 7 m can be extracted on average over the zone. In total a volume of 508 Mm³ can be extracted in the different sectors.

6.4. Effect of extraction on wave propagation

6.4.1. Effect of boundary conditions

Simulations were executed for winds to the shore, covering the wind directions from South-West (SW) over North (N) to North-East (NE) with a resolution of 22.5°. Remark that the winds from NNW is almost a wind perpendicular to the shore. At the boundaries a JONSWAP spectrum is applied with a peak enhancement parameters γ of 3.3, representing a (fully developed) wind sea spectrum. The directional width is set to 30°, in agreement with the results of the tests by IMDC (2009). The waves are characterised by a significant wave height *Hs*, a peak period *Tp* and a wave direction *Dir*. A constant wind was applied with a wind speed *Ws*. The wave direction at the boundary was assumed to be the same as the wind direction.

In IMDC (2009) some tests have been executed to check the influence of applying boundaries at the northern boundary alone or at the northern and western boundary of the model grid. It was stated that applying waves at the eastern boundary was not important, due to the limited effect of these boundaries at the Belgian coast, as they used the model grid, set up by KULeuven and FHR (2004), which was limited offshore to Westhinder. The results showed that for the Belgian coast, the effect of the boundaries was not too important. Since the model grid has been extended considerable to the North in this project, some initial test to check the influence of the boundary conditions on the results at the Belgian coastal stations were carried out. Results showed that the differences in this case are mainly at the western and eastern boundaries and that the difference at the Belgian coast is limited.

6.4.2. Simulations for normal climate

For the effect of the extraction of sand at the propagation of the waves to the Belgian coast, a total of 108 simulations have been executed. Three different wave heights were applied at the boundaries of the model, i.e., *Hs* = 2 m, 3 m and 4 m. In Verwaest et al. (2008), a wave climate for the Belgian coast, based on measurements at station Westhinder was derived. They estimated that around 9.4 % of the time, wave heights of 2 m or higher were encountered at Westhinder with wind/wave direction between SW, N and NE. Waves with significant wave height of 3 m and 4 m are already more extreme cases.

Furthermore, in Verwaest et al. (2008) a relation was proposed between the wave height and the peak period and between the wave height and the wind speed for the waves with significant wave height of 2 m, which are peak period *Tp*= 7 s and wind speed *Ws* = 14 m/s. Based on these relationships, values were proposed for significant wave heights of 3 m and 4 m as well. Simulations were performed for 9 different wave and wind directions, going from SW to NE, with a resolution of 22.5°. Furthermore, simulations were executed for low waters and high waters. Low water was set at 0 m TAW, i.e. at -2.33 m below MSL, while high water was set at +2.33 m MSL. To test the effect of the extraction of sand, simulations were of course executed for the reference bathymetry and for the bathymetry with the new proposed extraction limit level. As such, a total of 108 simulations have been executed.

Results at the coastal stations

For the significant wave height of 2 m at the boundaries, the difference at the coastal stations is limited to 0.02 m or less, both for the HW and the LW water levels, except for station Middelkerke, where a decrease in wave height is expected for HW water level and for waves from WSW of -0.03 m (Figure 4). The effects at the coast are therefore limited. Overall, a small decrease in significant wave height could be expected for some western stations (Nieuwpoort, Middelkerke), while a small increase is expected for some central stations (Oostende, Bredene, De Haan). The effects are slightly larger for the HW water level than for the LW water level.

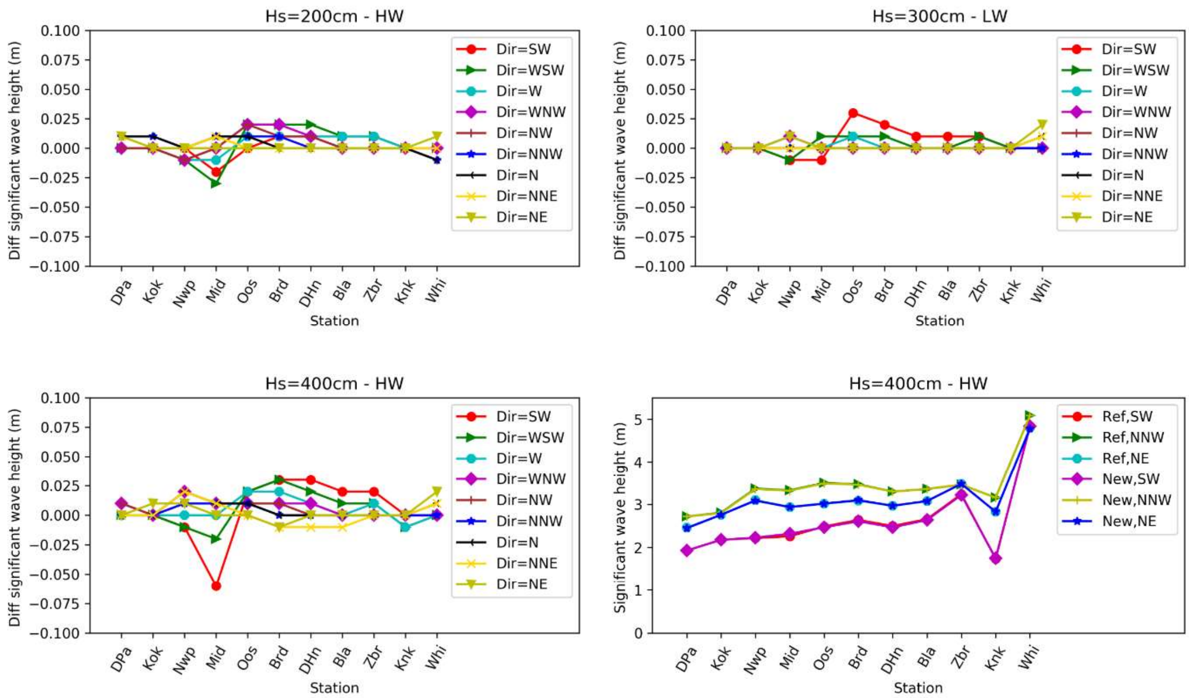
Similar results are found for a significant wave height of 3 m at the boundaries (Figure 4). At stations Middelkerke, a decrease is found of significant wave height of -0.04 m for winds coming from WSW and SW and for HW. On the other hand, an increase of +0.03 m is found for station Oostende for wind from SW. Also here, for the rest, the differences remain limited to 0.02 m.

For significant wave heights of 4 m at the boundaries and wind speeds of 22 m/s, the changes remain limited (Figure 4). The decrease at station Middelkerke for HW and winds from SW is -0.06 m now, while for the same wind direction, the increase in significant wave height at stations Bredene and De Haan is +0.03 m now. For the rest the results are limited to 0.02 m. Although there are differences for the difference coastal stations and for the wind direction, the influence of the sand extraction is limited (Figure 4). Remark that also at station Westhinder, the changes remain very limited. Only for winds from NE and wave height of 4 m at the boundaries, an increase in wave height is found of +0.04 m.

One can conclude that the highest effects are to be expected at HW water levels, that in the area Nieuwpoort-Middelkerke a small decrease is expected and in the area Oostende-Bredene-De Haan a small increase is expected. Furthermore, the highest changes are expected for the largest waves and for the winds from SW and WSW. Overall, however, the effects remain very limited.

The changes to the mean period near the coast remain limited to less than -0.09 s or +0.07 s, and are the largest for winds coming from SW. Also the changes in wave direction remain limited to less than +1.7 degrees or -1.4 degrees.

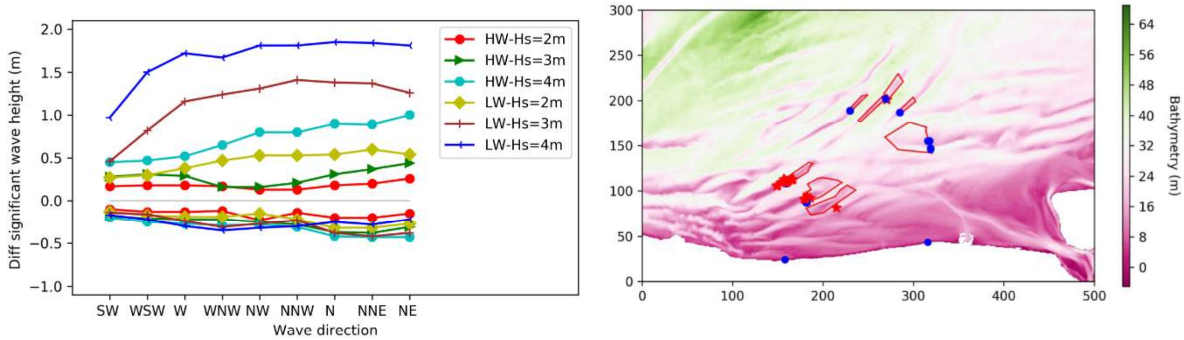
Figure 4: Upper left and right and bottom left: Increase of significant wave height at coastal stations and Westhinder for simulation with the new extraction limit compared to without extraction. Upper left: waves at boundary with significant wave height of 2.0 m, wind speed = 14 m/s, different wave and wind directions, HW situation (MSL +2.33 m). Upper right: waves at boundary with significant wave height of 3.0 m, wind speed = 18 m/s, different wave and wind directions. LW situation (MSL -2.33 m). Bottom left: waves at boundary with significant wave height of 4.0 m, wind speed = 22 m/s, different wave and wind directions. HW situation (MSL +2.33 m). Bottom right: significant wave height at coastal stations and Westhinder for simulation with the new extraction limit (NEW) compared to without extraction (REF). Waves at boundary with significant wave height of 4.0 m, wind speed = 22 m/s, different wave and wind directions. HW situation (MSL +2.33 m).



Results on entire Continental Shelf

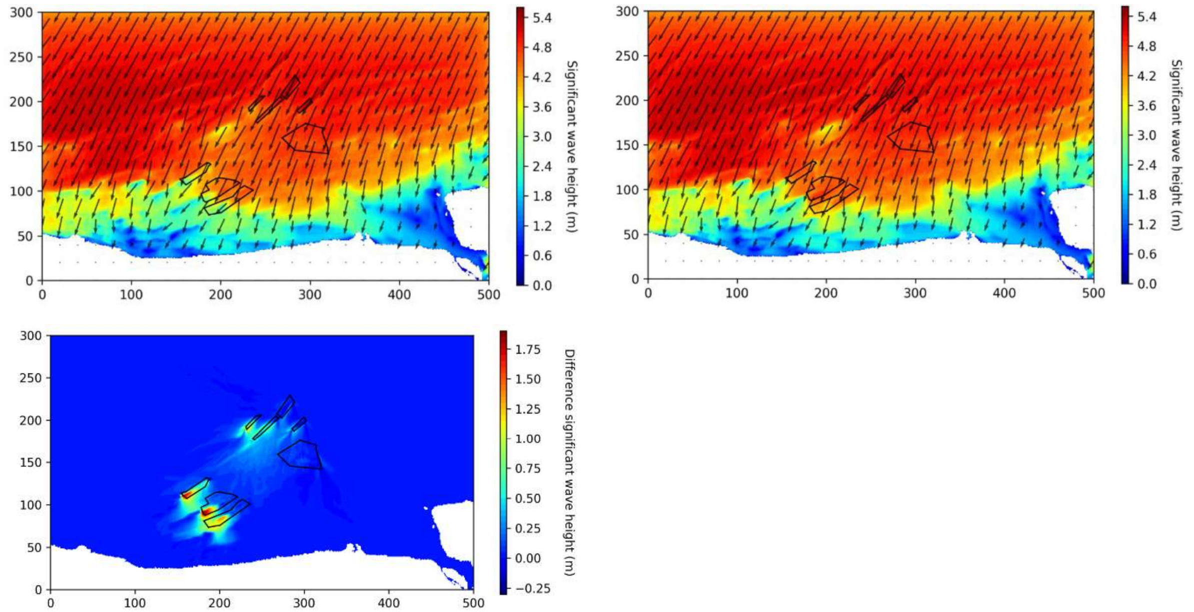
On the entire model grid, the differences can be of course larger, certainly near the changes in the bathymetry. The largest decrease in wave heights is limited to -0.43 m (Figure 5). The decrease is larger for the waves coming from N to NE. The maximum increase in wave height is more variable. The difference are larger for higher significant wave heights at the boundaries, but also the water level is of great importance. The maximum increase for low water (MSL -2.33 m) and for wave heights of 3 m at the boundaries is much larger than the maximum increase for high water (MSL +2.33 m) and for wave heights of 4 m at the boundaries (Figure 5). The largest decreases are for waves coming from NNW (perpendicular to the coast) to NE and are found south or east of the extraction zones 1, 4 and 5, and at two points near the coast. The decrease of wave height is possibly due to the less shoaling. The maximum increase during HW is +1.0 m for waves coming from NE, raising to +1.85 m during LW for winds coming from N. The largest increases are mostly found southwest or south of the extraction zones 2, around the extraction zone Oostdyck. This is mainly due to the fact that the waves are less breaking, due to bottom friction.

Figure 5: Right: largest increase and decrease in significant wave height at the model grid for simulation without extraction and with the new proposed extraction limit as a function of the wind direction, for three different wave heights at the boundaries (Hs=2 m – Ws=14 m/s; Hs=3 m – Ws=18 m/s; Hs=4 m – Ws=22 m/s) and for HW and LW water levels. Left: Position of the points were highest increase (red stars) and highest decrease (blue dots) in significant wave height are found for all simulations.



The effect in the neighbourhood of the extraction zones can be quite considerable, with an increase in significant wave height south of the extraction zone 2at the Buitenratel up to +1.85 m, but that the effect at the Belgian coast is negligible (Figure 6).

Figure 6: Results for simulation with waves at boundaries: Hs=4.0m, Dir=N; wind speed Ws=22 m/s. Upper left: Significant wave height with original bathymetry. Upper right: Significant wave height with extraction limit bathymetry. Lower left: Difference in significant wave height.



6.4.3. Simulations for 1000 yearly storm

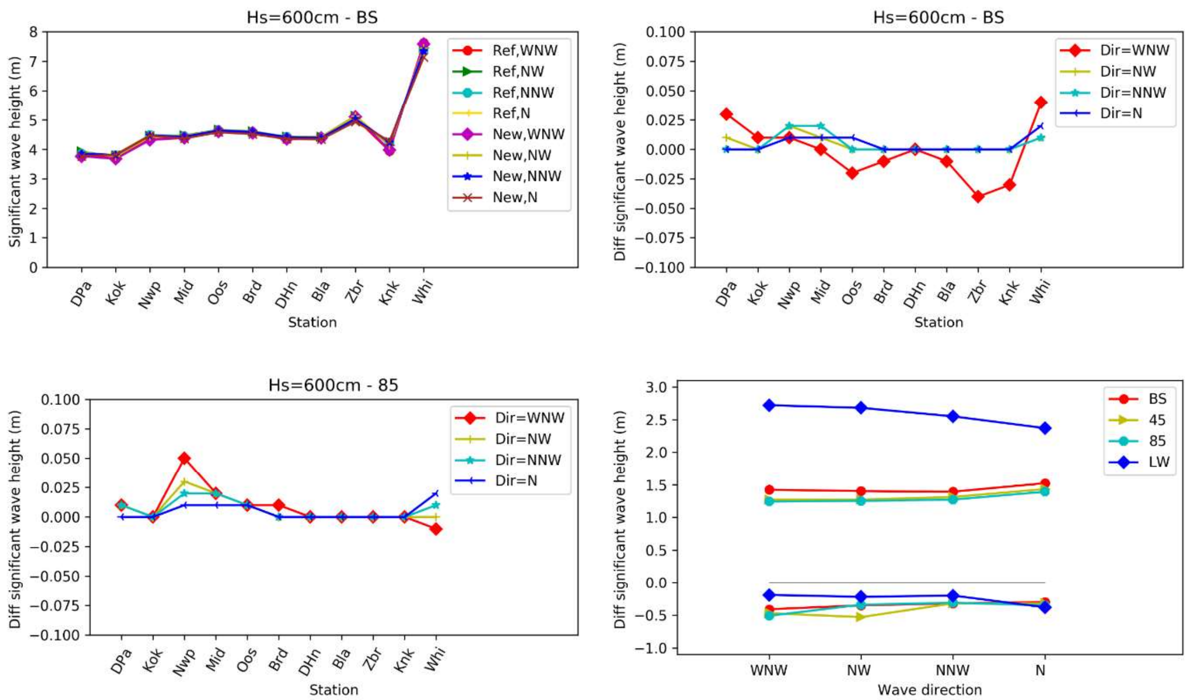
Also simulations were executed for the so-called 1000 yearly storm. In this case waves of 6 m are applied at the boundaries, the water level is set at 7 m above TAW (i.e., at 4.67 m above MSL). The peak frequency is set at 10.5 s and the wind velocity is put at 30 m/s (De Roo et al., 2014). Normally these boundary conditions are taken at station Westhinder. In this case the same boundary conditions were taken at the boundary of the new grid, which is extended more to the North. The simulations were done for 4 wind directions, which are N, NNW, NW and WNW since these directions contribute to the resulting extreme wave height near the coast and depending on the location, one direction can have more impact due to sand mining than the other. To take into account possible sea level rise on a longer term, reference was taken to the report of CREST and Coastal Project Coastal Vision (2019), were four common climate change scenarios for the Belgian coast were proposed. For the current study, the values based on the IPCC (2013) RCP4.5 and RCP8.5 were selected, using a sea level rise of +0.60 m and +0.85 m respectively for the year 2100.

Although it is very unlikely that a 1000 yearly storm with waves with significant wave height up to 6 m at the boundary occur with no storm surge, the simulations were also done with a very low water situation, namely with water level at MSL -2.33 m as reference. The simulations were executed for the reference bathymetry and for the bathymetry with the new extraction limit for extraction.

Results at the coastal stations

During this 1000-yearly storm, the significant wave height at De Panne and Koksijde remains below 4 m, while at the coastal stations from Nieuwpoort to Blankenberge, the significant wave height varies around 4.5 m (Figure 7). At Zeebrugge, the station a little bit more offshore, a significant wave height of more than 5 m is reached. At Westhinder, a significant wave height of more than 7.5 m is reached for winds from the WNW. Overall the highest wave heights are obtained for winds from the NW. The simulated wave heights at the coastal stations correspond well with the characteristic values given for the 1000 yearly storm conditions along the coastline in De Roo et al. (2014).

Figure 7: Upper left: Significant wave height at coastal stations and Westhinder for simulation with the new proposed extraction limit (New) compared to without extraction (Ref). Waves at boundary with significant wave height of 6.0 m, wind speed = 30 m/s, water level at 4.67 m MSL (1000 yearly storm). Results for different wave and wind directions. Upper right: Increase of significant wave height at coastal stations and Westhinder for simulation with the proposed extraction limit compared to without extraction, water level at 4.67 m MSL. Lower left: Increase of significant wave height at coastal stations and Westhinder for simulation with the proposed extraction limit compared to without extraction, water level at 5.52 m MSL (1000 yearly storm + sea level rise RCP 8.5).



The effects at the coastal stations and at Westhinder remain limited also for this case (Figure 7). Most effects are seen for waves and winds coming from NW and especially WNW. Only in these cases changes of more than 0.02 m are expected. The largest increase in significant wave height is for a sea level rise of +0.85 cm, where the increase in significant wave height is +0.05 m at station Nieuwpoort. For the current sea level, at station Zeebrugge and Knokke a decrease of significant wave heights is found of -0.04 m and -0.03 m respectively. Overall the effects are negligible.

For the situation with the 1000 yearly storm during low water level, the changes at the coastal stations are even less and are always below 0.02 m. Only for winds from N, an increase in significant wave height of +0.02 m is found for station De Panne. The differences are less than 1% of the obtained wave height in the considered points.

Results on entire Continental Shelf

The results at the Belgian Continental Shelf, more offshore, near the extraction zones are much higher, as expected. The maximum decrease in wave heights is again limited to -0.53 m, in this case for RCP 4.5 and for waves from NW. The maximum increase in wave heights for the 1000 yearly storm is +1.52 m for the waves coming from the North. This maximum increase is slightly lower when sea level rises of +0.60 m or +0.85 m are taken into account. For the 1000 yearly storm during low water (MSL -2.33 m) the maximum increase in significant wave height is much higher, up to +2.72 m, in this case from waves coming from the WNW.

6.5. Discussion

To evaluate the effects on coastal protection one considers the normal wave climate as well as the wave conditions during 1000 yearly storm conditions. The water levels can be assumed to be unaltered by the extraction scenarios due to the small size of the extraction zones compared to the southern North Sea area at which scale tides and storm surges are generated.

The normal wave climate drives changes in the coastline position. Positive gradients in alongshore transport and net cross-shore transport which is off-shore directed induce erosion of the coastline. The intensities of these transports are proportional with the significant wave height. From the SWAN model results, one observes very small changes of the significant wave heights along the coast, less than ±1 % on average. The impact of these changes on coastline erosion can be considered negligible.

The conditions during a 1000 yearly extreme storm determine the coastal safety level. Higher wave heights will result in larger erosion of dunes and dry beaches and in more overtopping of sea dikes and structures in the harbours. From the SWAN model results, one observes a very small increase of the wave height, 0.05 m maximum. However, this increase is so small that it can be considered negligible for the evaluation of the coastal safety level. This is confirmed by results of an earlier evaluation of sand extraction at the Kwintebank from coastal safety perspective (Verwaest and Verelst, 2006).

It can be concluded that the effect on coastal protection of the sand extraction scenarios considered is negligible. This conclusion is attributed to the large distance from the extraction sectors to the coastline, namely more than 10 km.

6.6. Conclusions

In the present study, the effect of extraction of marine aggregates on wave propagation to the Belgian coast was studied. More specifically, the impact of a newly extraction limit levels (Degrendele, 2016; Degrendele et al., 2017, this volume), on the wave propagation was investigated.

For the current climate 108 different simulations were executed with different significant wave heights at the boundaries (2 m, 3 m and 4 m), for different water levels (high water and low water) and for different wind and wave directions from SW to NE with an increment of 22.5°. The results showed that the effect of the extraction on the significant wave height at the coastal stations is very limited. Although in the neighbourhood of the extraction zones, an increase of significant wave height is possible up to +1.85 m, the effect at the coastline is negligible. Therefore, it can be concluded that the impact of the extraction scenarios considered on coastline erosion can be considered negligible.

For 1000 yearly storm conditions, some simulations were executed, including the effect of possible sea level rise (up to +0.85 m) until 2100. It was clear that large effects on the wave heights can be expected near the extraction zones, especially during low water situations, but that the effect at the coastline remains very limited to an increase of +0.05 m maximum (less than 1% increase). It can be concluded that the impact of the extraction scenarios on the coastal safety level is negligible.

References:

Belgian State, 2012. Omschrijving van de Goede Milieutoestand en vaststelling van Milieudoelen, Kaderrichtlijn Marine Strategie, Art 9 & 10, 33 pp.

Belgian State, 2018. Actualisatie van de initiële beoordeling voor de Belgische mariene wateren. Kaderrichtlijn Mariene Strategie – Art. 8 lid 1a & 1b. BMM, Federale Overheidsdienst Volksgezondheid, Veiligheid van de Voedselketen en Leefmilieu, Brussel, België, 243 pp.

Booij, N., R.C. Ris and L.H. Holthuijsen, 1999. A third-generation wave model for coastal regions, Part I, Model description and validation. Journal of Geophysical Research, C4, 104, 7649-7666.

CREST and Complex Project Coastal Vision, 2019. Output Workshop 'Climate Scenarios Flemish Coast', 12 December 2018, 23 pp.

De Roo, S., K. Trouw, I. Ruiz Parrado, T. Suzuki, T Verwaest and F. Mostaert, 2014. Het Hydraulisch Randvoorwaardenboek (2014). Rapport WL2016R14_014_2, Waterbouwkundig Laboratorium, Borgerhout, België, 59 pp.

De Roo, S., T. Suzuki, G. Kolokythas, G. Zhao and T. Verwaest, 2015. Numerical Modelling Of 2d Wave Transformation Processes From Nearshore To A Shallow Foreshore: Comparison Between The Mike21, Swash And Xbeach Models. E-proceedings of the 36th IAHR World Congress 28 June – 3 July, 2015, The Hague, the Netherlands, 6 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, 19 pp.

Degrendele, K., M. Roche and H. Vandereyken, 2017. New limits for the sand extraction on the Belgian part of the North Sea? Proceedings Study day, Belgian marine sand: a scarce resource? 9 June 2017, Ostend, K. Degrendele and H. Vandenreyken (eds.), FPS Economy, S.M.E.s, Self-employed and Energy, 135-146.

Degrendele, K., Roche, M., Barette, F., Vandenreyken H., 2021. The implementation of the new reference level for sand extraction on the BCS, in: Vandenreyken, H. (Ed.), Sea Sand in a 360° Perspective.

Dulière, V., 2017. Model bathymetries for the new North Sea COHERENS set up. Technical Report, Royal Belgian Institute of Natural Sciences, Operational Directorate Natural Environment, 5 pp.

Günther, H., S. Hasselmann and P.A.E.M. Janssen, 1992. Wamodel Cycle 4. DKRZ Technical Report No. 4, Hamburg, October 1992, 102 pp.

Holthuijsen, L.H., N. Booij and T.H.C Herbers, 1989. A prediction model for stationary, short-crested waves in shallow water with ambient currents. Coastal Engineering, 13, 23-54.

Holthuijsen, L.H., N. Booij and R.C. Ris, 1993. A spectral wave model for the coastal zone. Proceedings of the 2nd International Symposium on Ocean Wave Measurement and Analysis, New Orleans, USA, 630-641.

Holthuijsen, L.H., A. Herman and N. Booij, 2003. Phase-decoupled refraction-diffraction for spectral wave models, Coastal Engineering, 49, 291-305.

IMDC, 2009. Afstemming Vlaamse en Nederlandse voorspelling golfklimaat op ondiep water. Deelrapport 5: Rapportage jaargemiddelde klimaat. Rapport I/RA/11273/09.091/SDO. Rapport in opdracht van Vlaamse Overheid, Deperatement Mobliliteit en Openbare Werken, Afdeling Waterbouwkundig Laboratorium, 101 pp.

International Panel of Climate Change (IPCC), 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

Kolokythas, G.A., S. Raquel and M.R. Delgado Blanco, 2016. Morphological Evolution of a Bed Profile Induced By a Storm Event at the Belgian Coast Predicted By XBeach Model. Proceedings of the Twenty-sixth (2016) International Ocean and Polar Engineering Conference, Rhodes, Greece, June 26-July 1, 2016. International Society of Offshore and Polar Engineers (ISOPE), 1239-1246.

KULeuven and Flemish Hydraulics Laboratory, 2004. Veiligheidsniveau Vlaanderen Kustverdediging: opmaak van een numerieke golfdatabank voor de Vlaamse kust (model 644).

Ris, R.C., 1997. Spectral modelling of wind waves in coastal areas. PhD Dissertation, Delft University of Technology, Department of Civil Engineering. Communications on Hydraulic and Geotechnical Engineering, Report No. 97-4. Delft, The Netherlands.

Roelvink, D., A. Reniers, A.P. Van Dongeren, J.V.T. de Vries, R. McCall and J. Lescinski, 2009. Modelling storm impacts on beaches, dunes and barrier islands. Coastal Engineering, 56, 1133-1152.

Roelvink, R., A. van Dongeren, R. McCall, B. Hoonhout, A. van Rooijen, P. van Geer, L. de Vet, K. Nederhoff and E. Quataert, 2015. XBeach Technical Reference: Kingsday Release. Model description and reference guide to functionalities. Deltares, The Netherlands, 114 pp.

SWAN, Simulating Waves Nearshore, 2006a. User Manual, Cycle III verions 40.51, Technical University Delft, The Netherlands, 137 pp.

SWAN, Simulating Waves Nearshore, 2006b. Technical Documentation, Cycle III version 40.51, Technical University Delft, The Netherlands, 105 pp.

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, 2011. Assessment of the primary impacts of global climate change using numerical models: hydrodynamic, wave and sediment transport modelling. Report CLIMAR/1/DVDE/201111/EN/TR5. Prepared for Federal Science Policy Office, Project CLIMAR, contract SD/NS/01, Management Unit of the North Sea Mathematical Models, Brussels, 61 pp.

Van den Eynde, D., R. De Sutter, L. De Smet, F. Francken, J. Haelters, F. Maes, E. Malfait, J. Ozer, H. Polet, S. Ponsar, J. Reyns, K. Van der Biest, E. Vanderperren, T. Verwaest, A. Volckaert and M. Willekens, 2011. Evaluation of climate change impacts and adaptation responses for marine activities: CLIMAR. Final Report. Belgian Science Policy, Research Programme Science for a Sustainable Development, Brussels, 114 pp.

Van den Eynde, D., 2016. The impact of extraction on the bottom shear stresses in Zone 4. Report ZAGRI-MOZ4-INDI67/1/DVDE/201604/EN/TR01, Royal Belgian Institute of Natural Sciences, Operational Directorate Natural Environment, 52 pp.

Van den Eynde, D., 2017. The impact of extraction on the bottom shear stress using the proposed new extraction limit levels. Report ZAGRI-MOZ4-INDI67/1/DVDE/201706/EN/TR02, Royal Belgian Institute of Natural Sciences, Operational Directorate Natural Environment, 37 pp.

Verwaest, T. and K. Verelst, 2006. Effect bodemverlaging Kwintebank op de kustveiligheid. Waterbouwkundig Laboratorium: Antwerpen. 11 pp. + bijlagen.

Verwaest, T., S. Doorme, K. Verelst and K. Trouw, 2008. The wave climate in the Belgian coastal zone. In: LITTORAL 2008. A Changing Coast: Challenge for the Environmental Policies. Proceedings. 9th International Conference, November 25-28, 2008, Venice, Italy, 8 pp.

The WAMDI Group, 1988. The WAM Model – A Third Generation Ocean Wave Prediction Model. Journal of Physical Oceanography, 18, 1775-1810.

Zijlema, M., G.P. Van Vledder and L.H. Holthuijsen, 2012. Bottom friction and wind drag for wave models. Coastal Engineering, 65, 19-26.