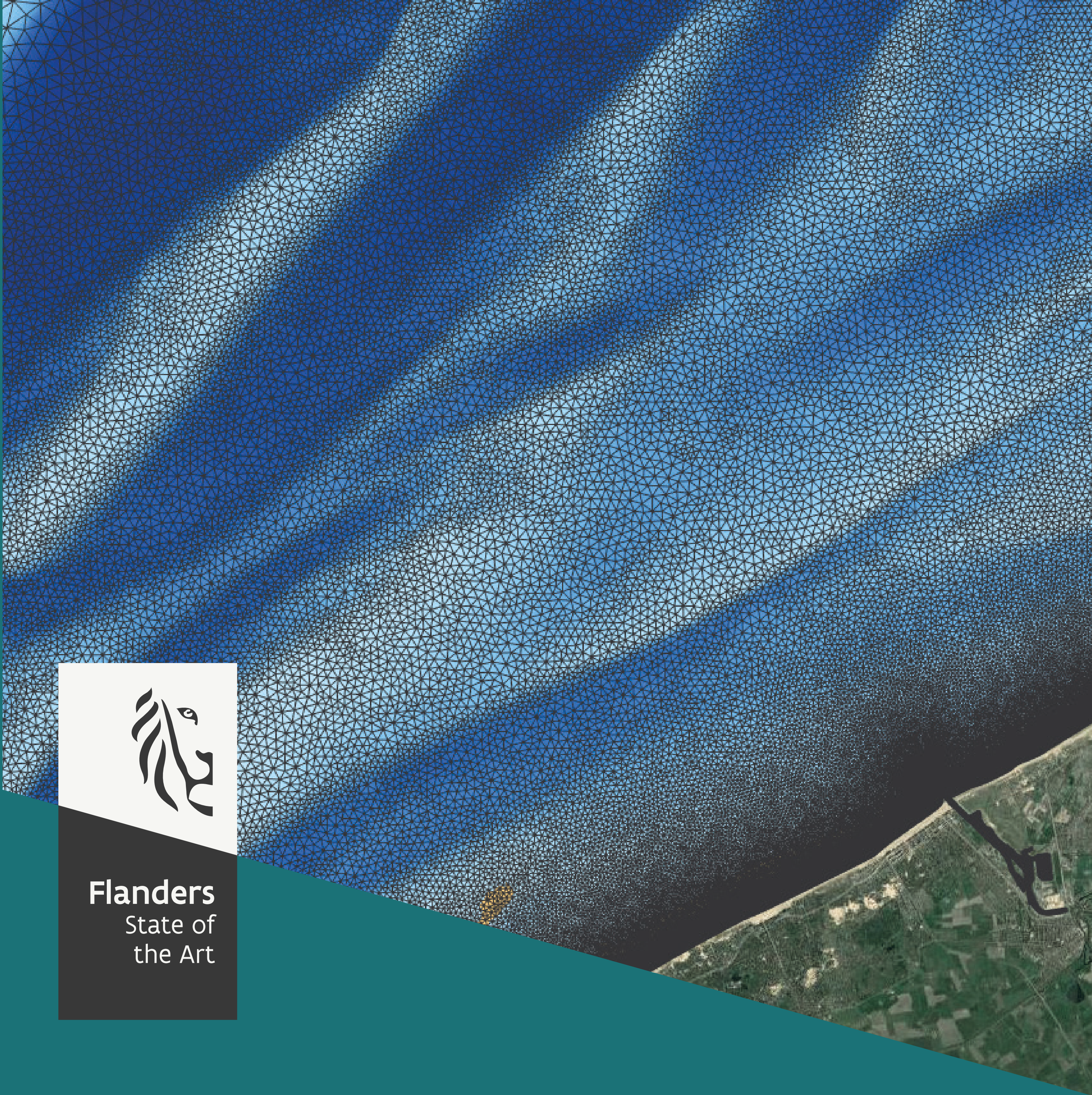

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Morphodynamic modelling of the Belgian Coastal zone

Sub report 1 – Scaldis-Coast progress report 1

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Sub report 1 – Scaldis-Coast progress report 1

Kolokythas, G.; Wang, L.; Breugem, A.; De Maerschalck, B.

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Abstract

Within the current project the Scaldis-Coast model will be updated, further developed and improved. The presented report is the first progress report on the progression made in the first year. The model has been updated and tested with the new TELAMAC-MASCARET v8p3 release with a new sedimenttransport- and bed-update module called GAJA, replacing the previous SYSIPHE module. It was found that the update of the model with the new release didn't have any significant impact on the model results. Only at the northern boundary some unrealistic sedimentation patterns where observed after the update, which require more investigation and probably a bug fixing or work around. However, this local sedimentation is far outside the domain of interest and has no significant influence on the bed evolution of the Belgian coast.

Furthermore, efforts have been taken in improving the Bijker sediment transport formula used in the model. It was observed than when the model was used for some extreme sea level rise scenarios some unexpected strong cross-shore transport occurred, nevertheless cross-shore processes are not included in the model yet. Based on an extensive set of model tests, two modification of the formulations showed some major improvements of the model behaviour:

- Replacement of the default wave-current bed shear stress formula in Bijker's transport formula with the τ_{cw} formula proposed by Soulsby (1995), known as the DATA2 method and based on a fit to laboratory and field measurements
- Replacement of the default (fixed) breaking wave parameter (*b)* in in Bijker's transport formula with a spatial-temporal varying expression that depends on the wave height and water depth ratio (Bijker, 1971).

Two other improvements, but with less impact have been implemented as well:

- Use of the formula for deviation (correction of sediment transport direction due to slope effect) by Talmon et al. (1995) instead of the default one (Koch and Flokstra , 1981)
- Minimum depth for bed load equal to 0.1 m (instead of 0.01 m)

The findings mentioned above were confirmed through a series of applications, which included: (a) the calculation of the annual longshore transport volumes along the Belgian coast and (b) a storm event (Ciara) in February 2020 with important impact at the marina of Blankenberge (c) a long-term morphological hindcasting (years 1986-1996) at the area east of Zeebrugge port related to the extension of the port which was completed in 1986.

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1 Introduction

Within the framework of the project *Vlaamse Baaien* and his succeeder Complex Project Coastal Vision, Flanders Hydraulics took the initiative to develop an integrated hydro-morphodynamic coastal model for the Belgian Coast called Scaldis-Coast. The Scaldis-Coast model is build within the TELEMAC-MASCARET model suite. It is a highly efficient and flexible model that is applicable for short and long term morphodynamics both in the tidally driven off-shore and wave driven near-shore part of the Belgian coastal zone and Scheldt mouth area. Scaldis-Coast consists a 2D TELEMAC hydrodynamic module (Kolokythas *et al.*, 2021), a TOMAWAC wave propagation module (Wang *et al.*, 2021) and a sediment transport and bed update morphodynamic module (Kolokythas *et al*., 2023).

The computational domain spans from the French coast near Calais to the Dutch coast between the Eastern Scheldt and the Grevelingenmeer, including the Eastern and Western Scheldt estuary. The offshore boundary is at at a distance of about 30 km from the coast. The resolution of the model varies from 750 m offshore to 25 m nearshore with automatic refinement around complex geometries like breakwaters, but also at locations with steep slopes in the bathymetry. With a morphological acceleration factor of twenty (MORFAC = 20) the computational cost is about 1,5 to 2 days on a 100-cores high performance computer for a ten years morphological run.

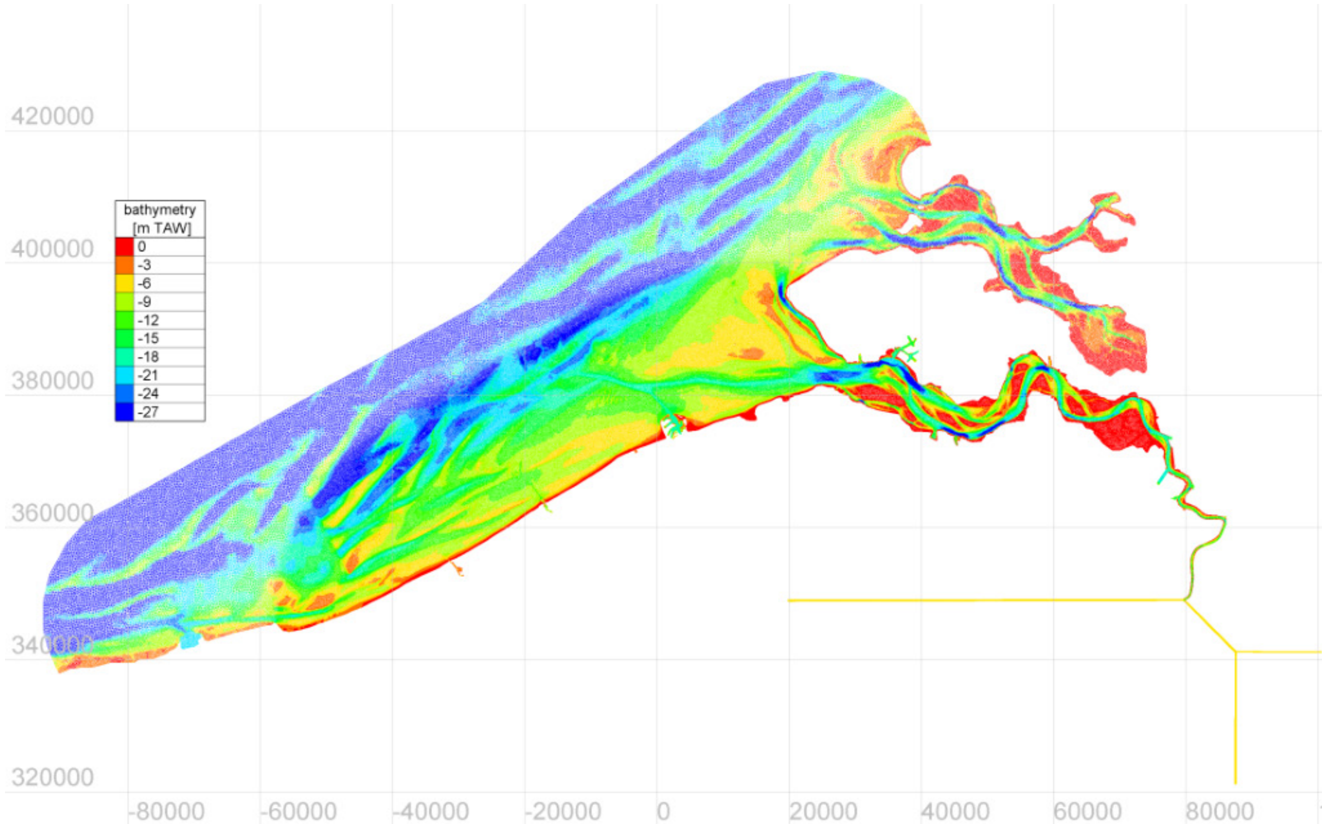

Figure 1 – Scaldis-Coast model

Within the current project, the model will be further improved by updating the model to the latest software releases, improving the sediment transport formula, developing and implementing new cross-shore transport formulations and improving the implementation of sediment mixtures in the bed. The current report gives an overview of the project progress of the first year: improvement of the sediment transport formula and software update tot Telemac v8p3 with the GAJA sediment transport and bed update module.

2 Improvement of the sediment transport formulation

Within the project *Kustvisie* it was noticed that for the three meter sea level rise scenario, a strong cross-shore transport occurred (Studieteam Hoogtij(d), 2023). However, since the latest model does not have physical cross-shore transport mechanisms implemented, this cross-shore transport was considered as unreliable. In the sections below, the Bijker transport formula and the slope effect formula is reconsidered and in depth investigated.

2.1 Sea level rise scenario tests

2.1.1 Investigated scenario

In the investigated scenario a sea level rise (SLR) of 300 cm was considered. In the reference scenario, a 10-year morphodynamic simulation driven by waves and currents was performed.

The simulation results showed strong cross-shore transport occurring at the nearshore region along the Belgian coast, where wave-induced processes prevail. This behavior is indicated by the strong sedimentation-erosion patterns observed along the coastline, as shown in Figure 2, and by the significant beach retreat at the area of Wenduine as shown in Figure 3. Since cross-shore transport mechanisms are not yet implemented in ScaldisCoast model, it is conjectured that other parameters such as the bed slope effect and the utilized transport formula are responsible for this debatable results. In order to get a deeper insight of the mechanisms that drive this behavior, a series of sensitivity tests is performed.

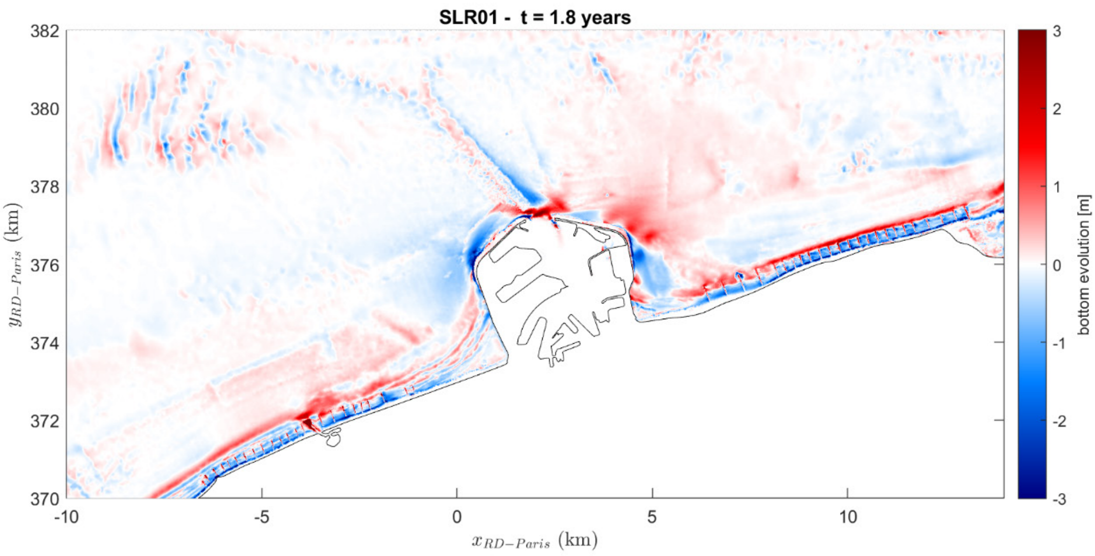

Figure 2 – Bottom evolution at the eastern Belgian coast after a simulation of 1.8 years for the reference scenario.

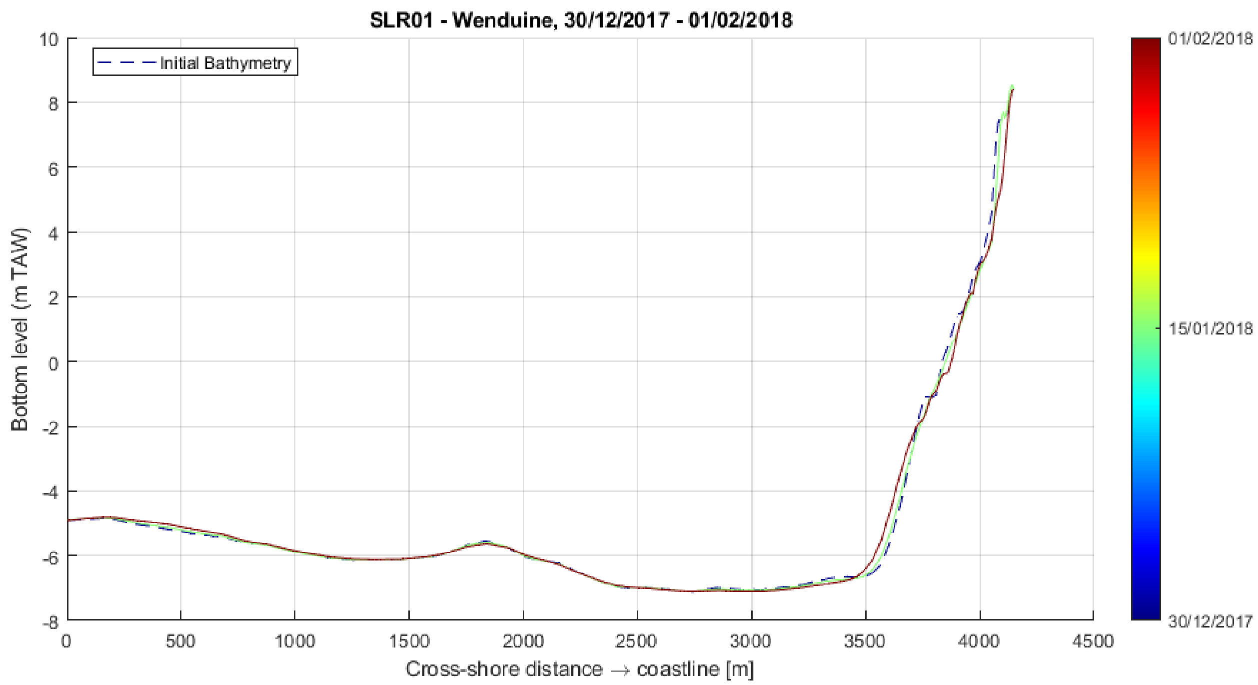

Figure 3 – Bottom profile evolution at Wenduine after a simulation of 1.8 years (33 hydrodynamic days) for the reference scenario.

2.1.2 Theoretical background

Correction of the direction of sediment transport

In SISYPHE the correction of the bed load transport direction due to the effect of an inclined bed (slope effect deviation) is implemented by the following expression:

$$\tan \alpha = \tan \delta - T(\partial Z_f/\partial n) \quad (1)$$

where T is a coefficient that depends on the Shields number ϑ, i.e. the dimensionless shear stress, and where α is the direction of bed load transport with respect to the flow direction, δ is the direction of bottom shear stress with respect to the flow direction, Z_f is the bed level, n is the coordinate along the axis perpendicular to the flow.

Coefficient T can be calculated by the following expressions:

$T=4/(6\vartheta)$ (Koch and Flokstra, 1981) or (2)

$T = 1/(\beta_2\sqrt{\vartheta})$, where $\beta_2=0.85$ (Talmon, 1995) (3)

Figure 4, which is illustrative of the T coefficient variation with ϑ (Shields number), shows that Koch & Flokstra formula gives much larger values of T compared to the one of Talmon, especially around the threshold for the initiation of sediment motion, i.e. around $\vartheta_{cr} \approx 0.05$ (for typical sands). Therefore, Koch & Flokstra formula leads to a larger correction of the transport direction due to slope effect compared to the one of Talmon, as a larger value of T is introduced in Eq. (1).

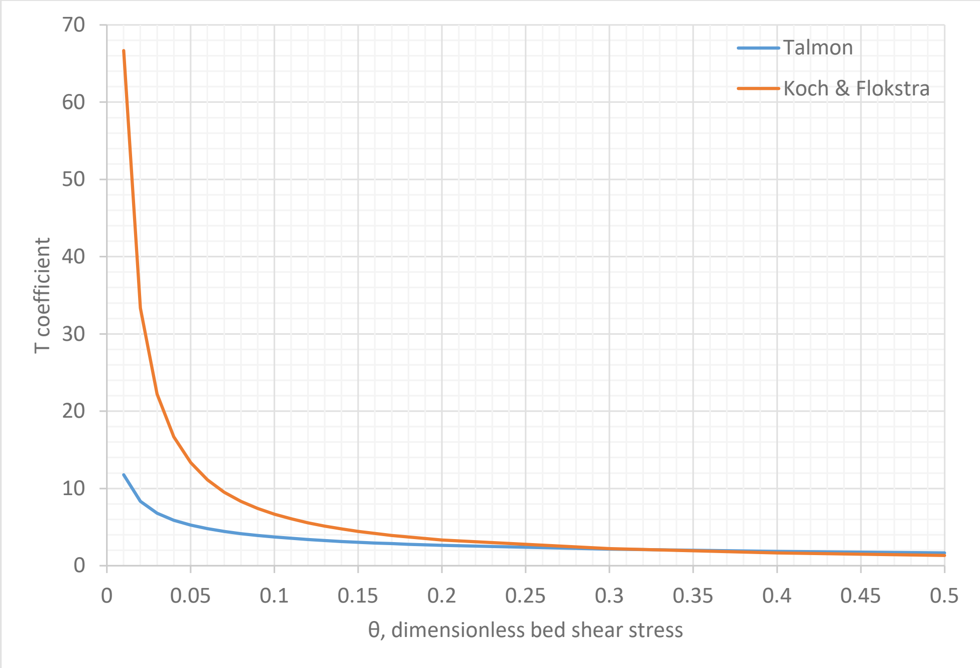

Figure 4 – T coefficient values by Koch & Flokstra and Talmon versus dimensionless bed shera stress (θ).

Another issue for discussion on slope effect deviation in SISYPHE, is that the correction of the transport direction is based on the current bed shear stress (ϑ) ignoring the contribution of wave stirring. In order to include the contribution of waves in the total bottom friction, the Bijker's (1967) model for the bottom shear stress in case of wave-current interaction could be implemented. The (dimensionless) total bed shear stress, ϑ_{cw}, is given by the following expression:

$$\vartheta_{cw} = \vartheta_c + 0.5\vartheta_w \tag{4}$$

where ϑ_c = current shear stress and ϑ_w = maximum wave shear stress.

Introduction of ϑ_{cw} [Eq. (4)] in the definition of coefficient *T* causes reduction of the latter, and consequently the deviation from the initial transport direction (given by Eq. (1)) is now smaller, which in turn means that the bed slope effect is now weaker at the areas where the bottom 'feels' the action of waves, i.e. the shallower areas.

Formula for wave-current bed shear stress

For combined action of waves and currents the bottom shear stress τ_{cw} introduced in the Bijker's transport formula in SISYPHE, is given by the following expression (Bijker, 1967):

$$\tau_{cw} = \tau_c + 0.5\tau_w \tag{5}$$

where τ_c = current shear stress and τ_w = maximum wave shear stress.

Another simple formula that could be used for the wave-current bed shear stress τ_{cw} was proposed by Soulsby (1995), it is known as the DATA2 method and it is based on a direct fit to 131 laboratory and field measurements. The DATA2 formula is given by the following expression:

$$\tau_{cw} = \tau_c \cdot \{1 + 1.2[\tau_w/(\tau_c+\tau_w)]^{3.2}\} \tag{6}$$

Bijker's breaking wave parameter *b*

The Bijker's formula included in the SISYPHE module, gives the total transport rate as the summation of the

(a) bed load rate:

$$Q_b = b d_{50} (\tau_c/\rho)^{1/2} \exp\left(-0.27 \frac{(\rho_s-\rho) g d_{50}}{\mu \tau_{cw}}\right) \quad (7)$$

where b (=2, by default in SISYPHE) is the breaking wave parameter (used as a calibration factor), d_{50} is the mean grain diameter, μ is a correction factor which accounts for the effect of ripples, ρ and ρ_s are the water and sediment densities, respectively.

(b) the suspended load rate:

$$Q_s = Q_b I \quad (8)$$

where I is a term that comes after depth-integration and by assuming a Rouse (equilibrium) profile for the concentration and a logarithmic profile for the mean velocity profile (more information at SISYPHE User's Manual).

The breaking wave parameter b, which appears in the bed load transport equation [Eq. (7)], can be calculated as a function of the wave height and water depth ratio (H_w/h), by the following expression (Bijker, 1971):

$$\begin{aligned} b &= 2, && \text{for } H_w/h < 0.05 \\ b &= 2 + 3(H_w/h - 0.05), && \text{for } 0.05 \le H_w/h < 0.4 \\ b &= 5, && \text{for } 0.4 \le H_w/h \end{aligned} \quad (9)$$

2.1.3 Model set-up and settings in brief

Detailed description of the model set-up is beyond the scope of the present report and it can be found in (Studieteam Hoogtij(d), 2023). Some useful notes on the model set-up are summarized in the following:

- The computational grid utilized in the present simulations is a variant of the ScaldisCoast morphodynamic model presented in Kolokythas *at al*. (2023). In the updated version, a landward extension is implemented so that the model can include the effects of the sea level rise of 3m at the area close to the coastline.
- The hydrodynamic forcing of the model is based on the implementation of the representative tide technique, i.e. two tidal cycles are repeatedly applied for the whole simulation period. Reduced wave conditions are also considered by applying a 6-month time-series, which is representative of the wave conditions in the decade (2009-2018). Detailed information for the reduction of the hydrodynamic forcing can be found in chapters 3 and 4 in Kolokythas *at al*. (2023).
- The simulation period in the reference scenario is considered equal to 10 years. In order to reduce the computational time a morphological acceleration factor (MORFAC) equal to 20 is considered. The morphology module SISYPHE is utilized for all the simulations.

The main settings of the model for the reference SLR scenario are presented in Table 1. As the numerical experiments presented in the following sections only include adjustment of the morphological parameters and settings, emphasis is given in the settings of SISYPHE module.

Table 1 – Main settings of the ScaldisCoast model for the reference SLR scenario.

Parameter	Value
TELEMAC-2D	
Version of TELEMAC	TELEMAC v8p3 (tomawaclmdc branch)
Time step	6 s
Initial conditions	developed flow field after spin-up of 1 day
Coupling period for TOMAWAC	300 (30 min)
TOMAWAC	
Time step	600 s
SISYPHE	
Bed-load transport formula	4: Bijker (1967) – breaking wave parameter *b* =2
Suspension	No
Sediment diameters (D_{50})	200-500 µm (based on sediment map)
Morphological factor	20
Slope effect	Yes
Formula for slope effect	1: Koch & Flokstra (1981) / BETA = 1.3
Formula for deviation	1: Koch & Flokstra (1981)
Minimum depth for bedload	0.01 m (default)
Minimal value of the water height	0.01 m (default)
Option for the treatment of tidal flats	1 (default)
Sediment slide	Yes
NESTOR	Yes

2.1.4 Sensitivity tests

As previously mentioned the numerical experiments presented in this report focus on SISYPHE tuning. A list of selected tests is given in Table 2. Note that the simulation period of these test simulations is about 1.8 years (660 days), which was selected as a good balance between the fulfilment of the illustrative purposes of the results and the reduced computational cost. The main parameters/considerations investigated are:

- Slope effect / Formula for deviation
- Minimum depth for bed load
- Introduction of wave-current bed shear stress in deviation formula (instead of current shear stress)
- Introduction of motion initiation threshold (critical Shields) in Bijker's transport formula
- Consideration of new wave-current bed shear stress formula (in Bijker's transport formula and in deviation formula)
- New breaking wave parameter (*b)* in in Bijker's transport formula

Table 2 – List of sensitivity tests for sediment transport tuning in SISYPHE.

Run ID	Description
Simulation period: 33 hydrodynamic days / 660 morphological days	
SLR01	Reference settings (Table 1)
SLR03	Slope effect → Formula for deviation = 2 (Talmon et al., 1995)
SLR04	Minimum depth for bedload = 0.1 m
SLR05	Minimum depth for bedload = 0.1 m + Minimal value of the water height =0.1
SLR06	Minimum depth for bedload = 0.1 m + Formula for deviation = 2 (Talmon et al., 1995)
SLR08	SLR06 settings + Option for the treatment of tidal flats = 2
SLR09	Minimum depth for bedload = 0.2 m + Formula for deviation = 2 (Talmon et al., 1995)
SLR12	SLR06 settings + wave-current bed shear stress (τ_{cw}) in deviation formula
SLR13	SLR06 settings + critical Shields θ_{cr} threshold in deviation formula ($\theta_c > \theta_{cr}$)
SLR14	SLR03 settings + Option for the treatment of tidal flats = 2
SLR15	SLR06 settings + Bed-load transport formula = 71 (van Rijn, 2007)
SLR16	SLR06 settings + critical Shields θ_{cr} threshold in Bijker's transport formula ($\mu\theta_{cw} > \theta_{cr}$)
SLR17	SLR06 settings + critical Shields θ_{cr} threshold in Bijker's transport formula ($\mu\theta_c > \theta_{cr}$)
SLR19	SLR06 settings + critical Shields θ_{cr} threshold in deviation formula ($\theta_{cw} > \theta_{cr}$)
SLR20	SLR06 settings + τ_{cw} given by Soulsby (1995) in Bijker's transport formula
SLR21	SLR06 settings + τ_{cw} given by Soulsby (1995) in Bijker's transport formula & in deviation formula
SLR22	SLR04 settings + τ_{cw} given by Soulsby (1995) in Bijker's transport formula
SLR26	SLR06 settings + Varying *b* (beta) in Bijker's transport formula
SLR27	SLR06 settings + τ_{cw} given by Soulsby (1995) & varying *b* (beta) in Bijker's transport formula

The evaluation of the SISYPHE tuning is mainly performed by comparison of the bed level change at the coastal area between Wenduine and port of Zeebrugge at the end of the simulation period (of 1.8 years). The comparison focuses on the differences between the magnitude and the shape of the resulting sedimentation-erosion patterns at the aforementioned area.

Comparing Figure 5 and Figure 6, which depict respectively, the morphological evolution for the reference settings (SLR01) and that of the adjusted Formula of deviation (SLR03), which is now calculated by Talmon et al. (1995), it can be observed that SLR03 test presents milder in magnitude sedimentation-erosion (sed-ero) patterns along the coastline. This behaviour is expected as Talmon formula leads to smaller transport direction correction compared to the (default) Koch and Flokstra formula.

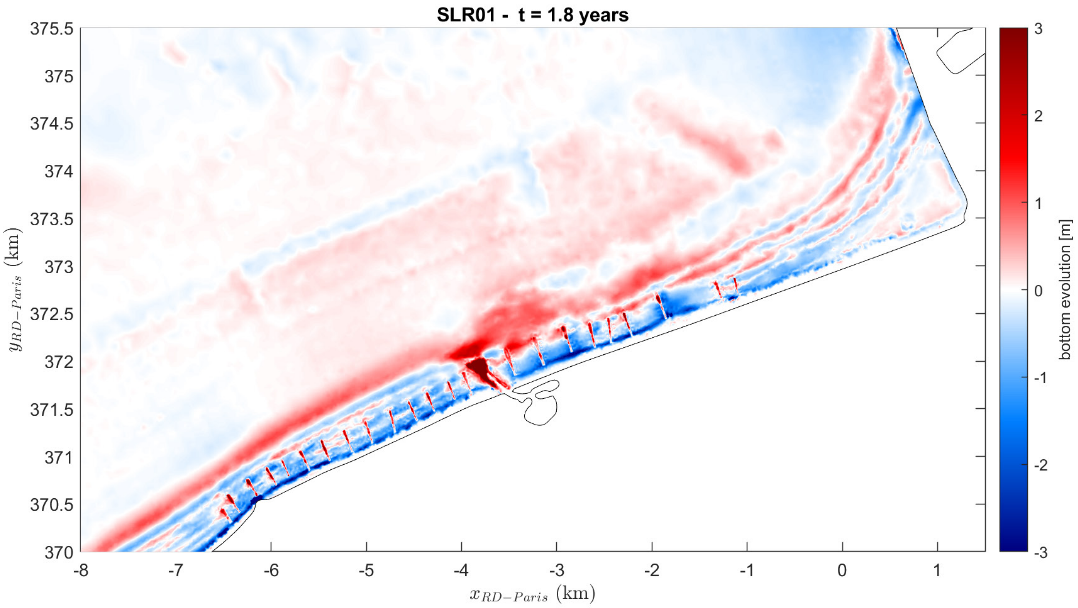

Figure 5 – Bottom evolution at the area around Blankenberge for the reference settings.

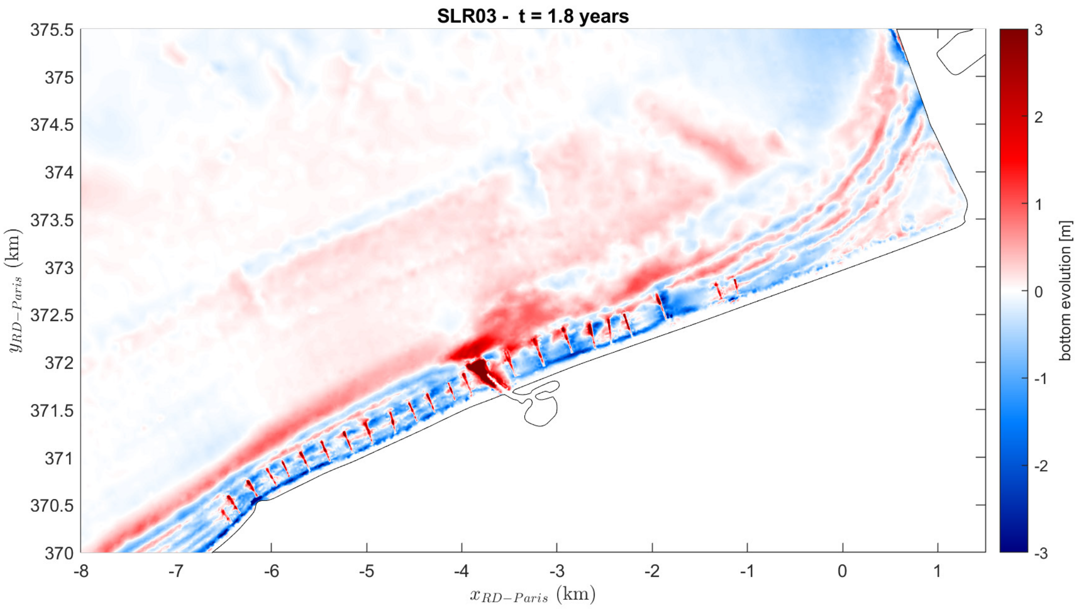

Figure 6 – Bottom evolution at the area around Blankenberge [Formula for deviation=2 (Talmon et al.)].

Figure 7 shows the evolution results of SLR04 test, in which the Minimum depth for bed load is set equal to 0.1 m, instead of the default value of 0.01 m. This setting cancels sediment transport occurring in (very shallow) water depths less than 0.1 m. Slight differences can (hardly) be observed when comparing these sed-ero patterns to those of the reference run (Figure 5). However, careful observation reveals a seaward movement of the erosion line along the coastline. In Figure 8, the results of the combined influence of SLR03 and SLR04 settings on the bed evolution, is presented. As expected sed-ero patterns along the coast are relatively weaker and simultaneously the erosion line has moved seaward compared to the reference run. As this two settings (introduced together in SLR06 test) have shown a positive impact in the numerical predictions, they are qualified as basic settings in the majority of the following tests.

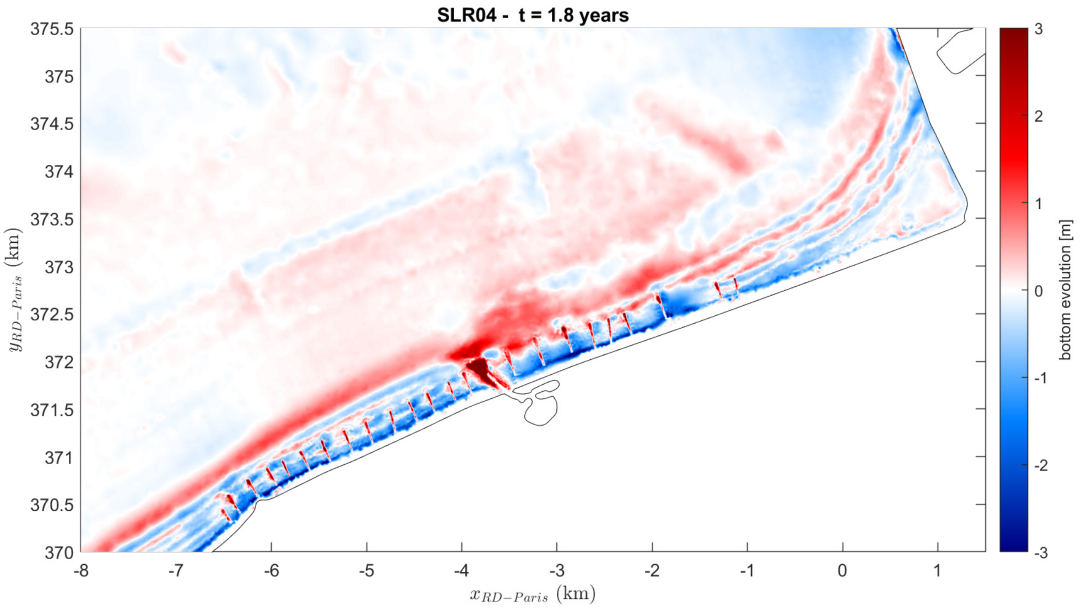

Figure 7 – Bottom evolution at the area around Blankenberge [Minimum depth for bedload=0.1 m].

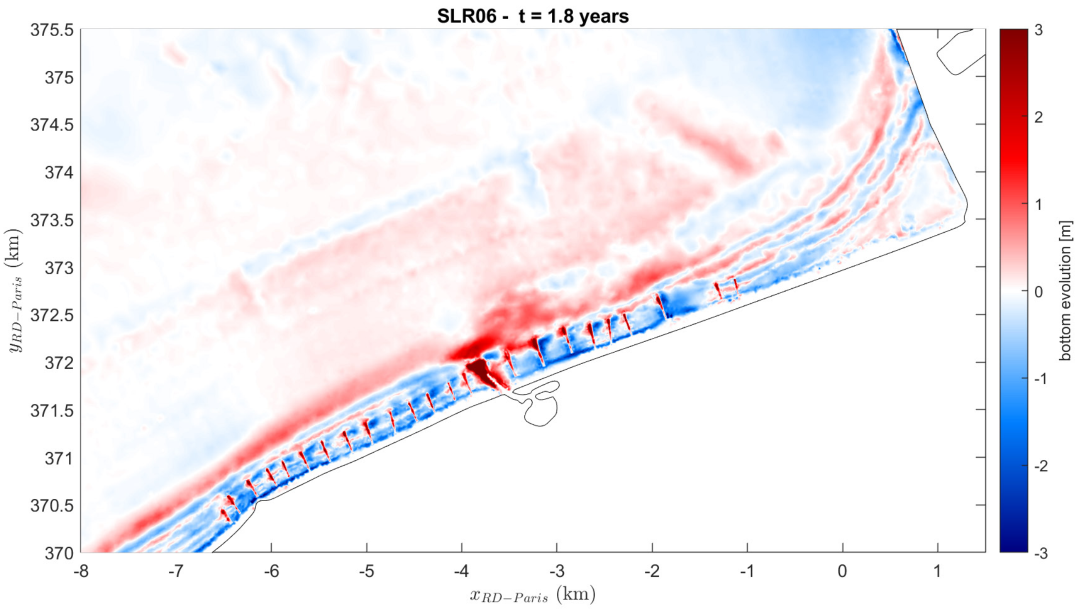

Figure 8 – Bottom evolution at the area around Blankenberge [Minimum depth for bedload=0.1 m + Formula for deviation=2 (Talmon et al.)].

The bed evolution results of SLR12 test, in which SLR06 settings are retained and the wave-current bed shear stress (τ_{cw}) is introduced in the deviation formula of Talmon (instead of the pure-current bed shear stress), are presented in Figure 9. These results are now compared to those of SLR06 test (Figure 8). It can be observed that the sed-ero patterns are relatively weaker, indicating that the strong cross-shore transport noticed in previous tests (mainly in the reference run) is now more attenuated. This behaviour is due to the reduced transport direction correction as explained in section 2.1.2.

Figure 10 shows the bed evolution results of SLR17 test, in which SLR06 settings are retained and the motion initiation threshold (critical Shields) is introduced in Bijker's transport formula. Comparison of the results to those of SLR06 test (Figure 8) indicates that the sed-ero patterns are again relatively weaker and similar to those of SLR12 test, indicating again milder cross-shore transport.

It has to be noted that in the specific test, the pure-current bed shear stress (ϑ_c) was inserted in the criterion of motion initiation ($\mu\vartheta_c > \vartheta_{cr}$). A similar test (SLR16) where wave-current bed shear stress (ϑ_{cw}) was considered in the criterion of motion initiation, led to slight differences (not presented here) compared to SLR06 run. The reason is that ϑ_{cw} is much larger than ϑ_{cr} is the shallow waters, due to the wave dominance, and therefore the influence of the criterion of motion is expected to be very limited. Note that introducing similar criteria for motion initiation in the implementation of the deviation formula due to slope effects (tests SLR13 & SLR19), the bed evolution results are only slightly affected (results are not presented here).

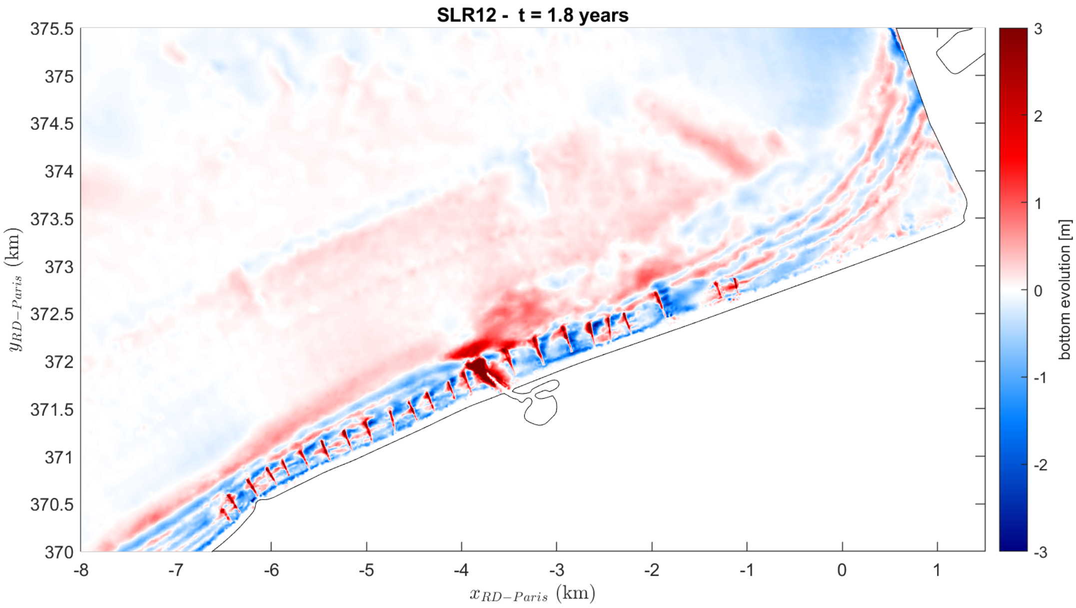

Figure 9 – Bottom evolution at the area around Blankenberge [SLR06 + τ_{cw} by Bijker (1967) in deviation formula of Talmon et al.] .

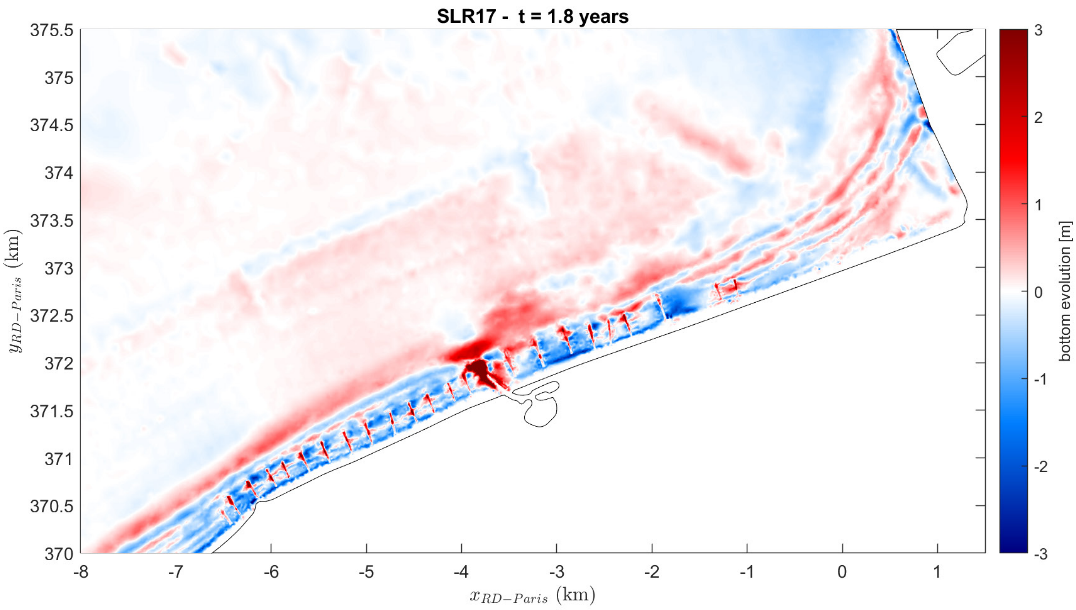

Figure 10 – Bottom evolution at the area around Blankenberge [SLR06 + motion threshold introduced in Bijker's transport formula ($\mu\theta_c > \theta_{cr}$)].

Figure 11 shows the bed evolution results of SLR20 test, in which SLR06 settings are retained and τ_{cw} given by Soulsby (1995) is introduced in Bijker's transport formula. Comparison of the results to those of SLR06 test (Figure 8) indicates that the sed-ero patterns are now significantly weaker not only nearshore but also in relatively deeper waters. The continuous erosion pattern along the coast is not present anymore, indicating the substantial reduction of the cross-shore transport. Moreover the erosion pattern between the last groin east of Blankenberge beach and the western breakwater of Zeebrugge port is also not present anymore. Apparently, the contribution of wave-stirring on the total bed shear stress in the formula by Soulsby (1995), is less significant than that of the Bijker's formula (1967) for τ_{cw}. However, the simultaneous introduction of τ_{cw} in the formula of Talmon for deviation, makes almost no difference, as shown in Figure 12 (SLR21 test).

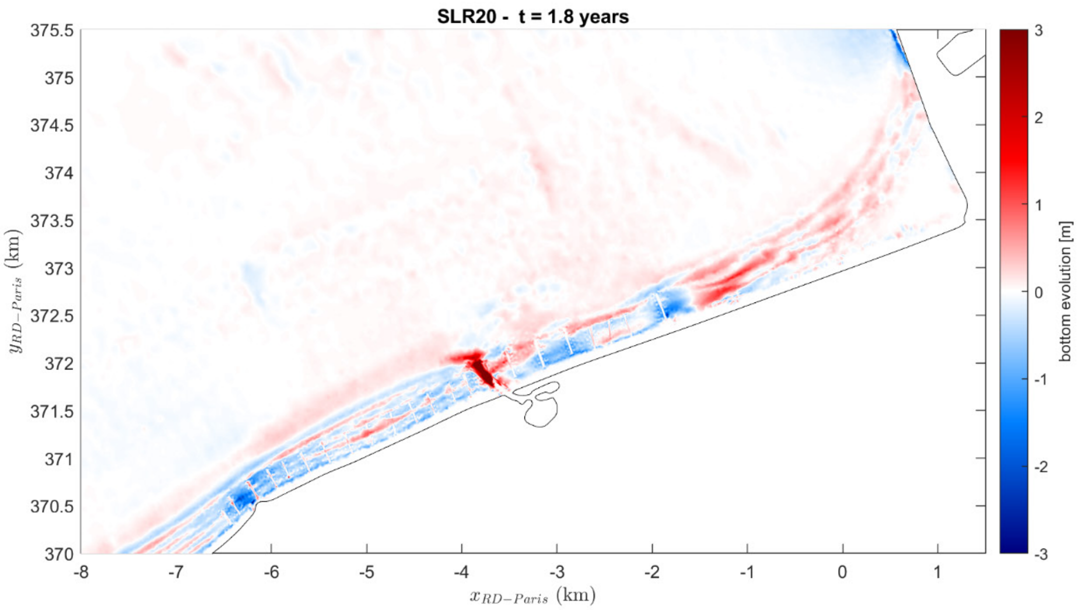

Figure 11 – Bottom evolution at the area around Blankenberge [SLR06 + τ_{cw} by Soulsby (1995) in Bijker's transport formula].

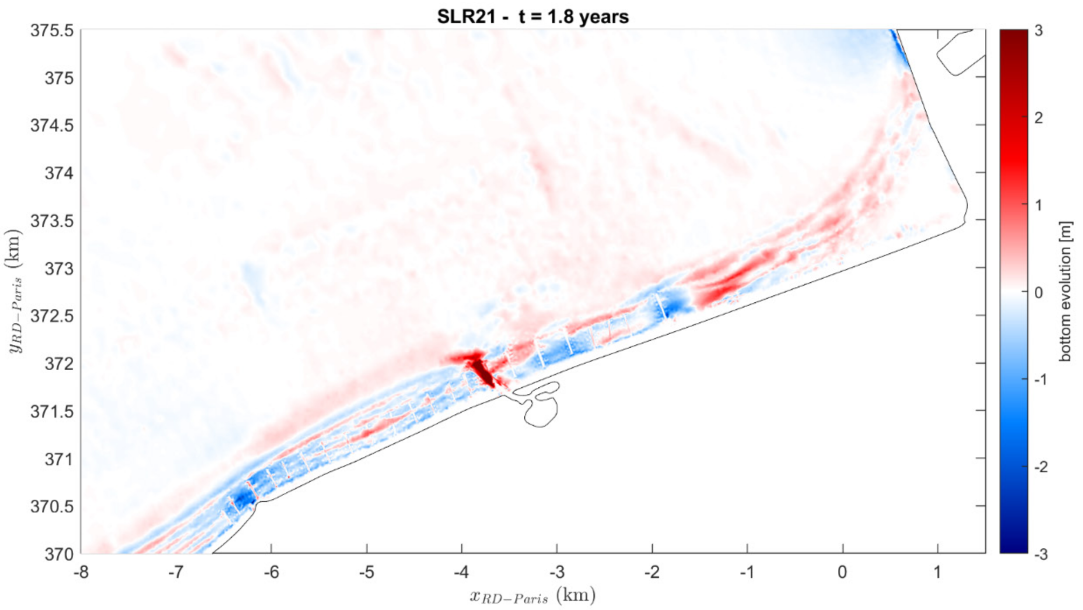

Figure 12 – Bottom evolution at the area around Blankenberge [SLR06 + τ_{cw} by Soulsby (1995) in Bijker's transport formula & in deviation formula of Talmon et al.].

Keeping the settings of SLR20 test the same, while changing the formula for deviation to the default one (Koch and Flokstra) before introducing τ_{cw}, has also negligible impact on the evolution results as shown in Figure 13 (SLR22 test). The main conclusion of this subset of tests is that the correction of transport direction due to slope effects becomes less important, when the wave-current bed shear stress changes drastically.

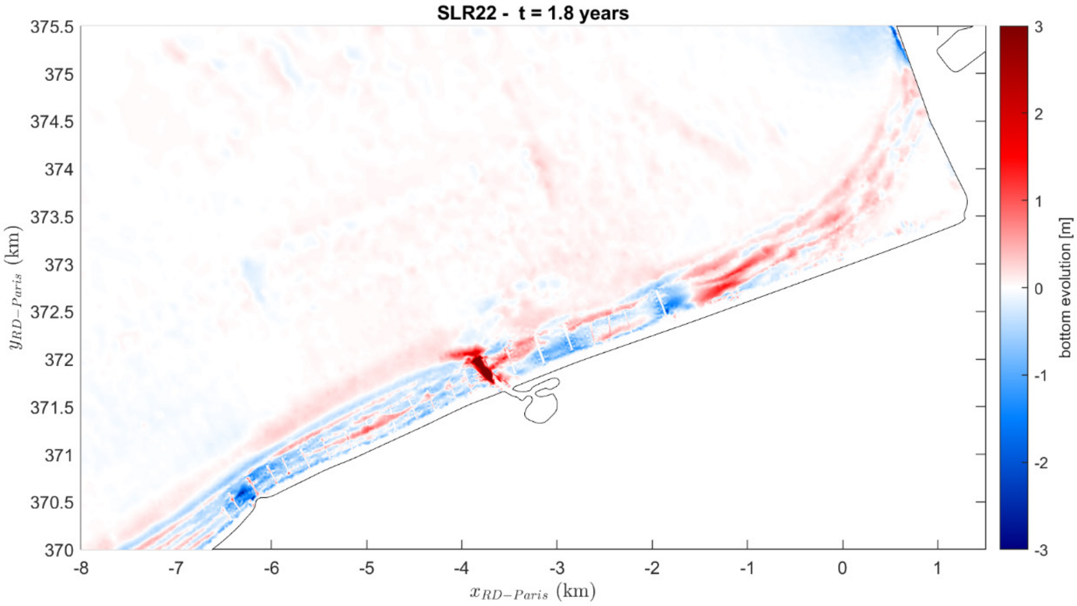

Figure 13 – Bottom evolution at the area around Blankenberge [SLR04 settings + τ_{cw} by Soulsby (1995) in Bijker's transport formula].

In the last two tests presented in this section, the sensitivity of the bed evolution in the introduction of a varying breaking wave parameter (b) in the Bijker's transport formula, is evaluated. Figure 12 shows the bed evolution results of SLR26 test, in which SLR06 settings are retained and the varying b parameter given by Eq. 9 (section 2.1.2) is introduced in Bijker's transport formula. Comparison of the results to those of SLR06 test (Figure 8) indicates that the sed-ero patterns at the coastal region are now much stronger, while in deep waters only limited differences are observed. This behaviour is expected since the varying b parameter, Figure 1 – which increases with increasing wave height-water depth ratio (becoming up to 2.5 times larger the default value b=2), leads to substantially larger transport rates at shallower waters.

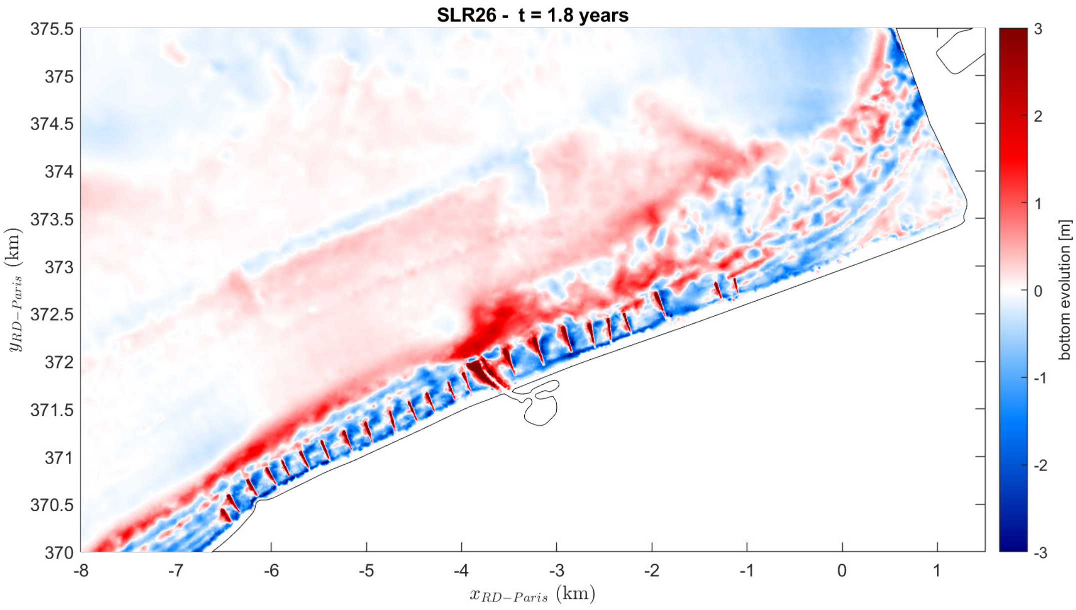

Figure 14 – Bottom evolution at the area around Blankenberge [SLR06 settings + varying b (beta) in Bijker's transport formula].

Figure 13 shows the bed evolution results after combining the introduction of the varying *b* parameter together with the introduction of τ_{cw} given by Soulsby (1995) in Bijker's transport formula (SLR06 settings are retained). The increased magnitude of the sed-ero patterns noticed in the previous test (SLR26) is not anymore present. It seems that increase of transport rates imposed by the varying b parameter is mitigated by the milder total shear stress formula by Soulsby (1995). All in all, the results from SLR27 test seem to be a good balance between the relatively strong sed-ero patterns of SLR06 test and the relatively weak ones of SLR20 test.

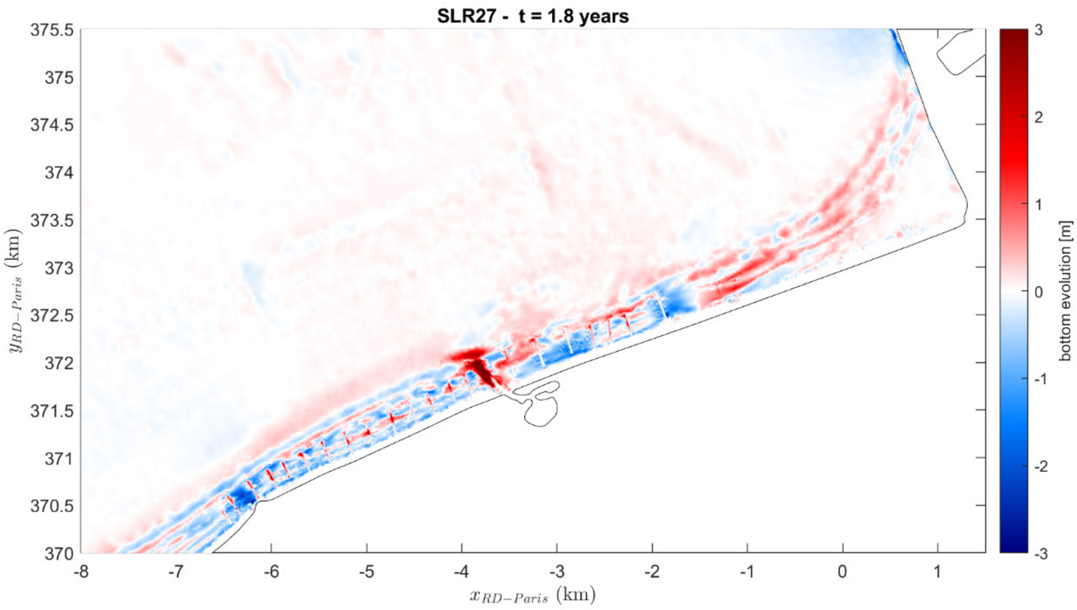

Figure 15 – Bottom evolution at the area around Blankenberge [SLR06 settings + τ_{cw} by Soulsby (1995) & varying b (beta) in Bijker's transport formula].

The significant limitation of beach retreat achieved by the considerations of the last-presented test (SLR27) compared to that of test SLR06, can be observed comparing the bottom profile evolution at the area of De Haan shown in Figure 16 to that of Figure 17. It is reminded that SLR06 test has already presented positive behaviour in the limitation of overestimated cross-shore transport predicted by the reference scenario. It seems, though, that that test SLR27 restricts even more the cross-shore transport which cannot be physically explained. The same conclusion results from the comparison of Figure 18 and Figure 19, which present the bottom profile evolution at the area of Wenduine. These figures can also be compared to Figure 3 which depicts bottom profile evolution at Wenduine for the reference test (SLR01).

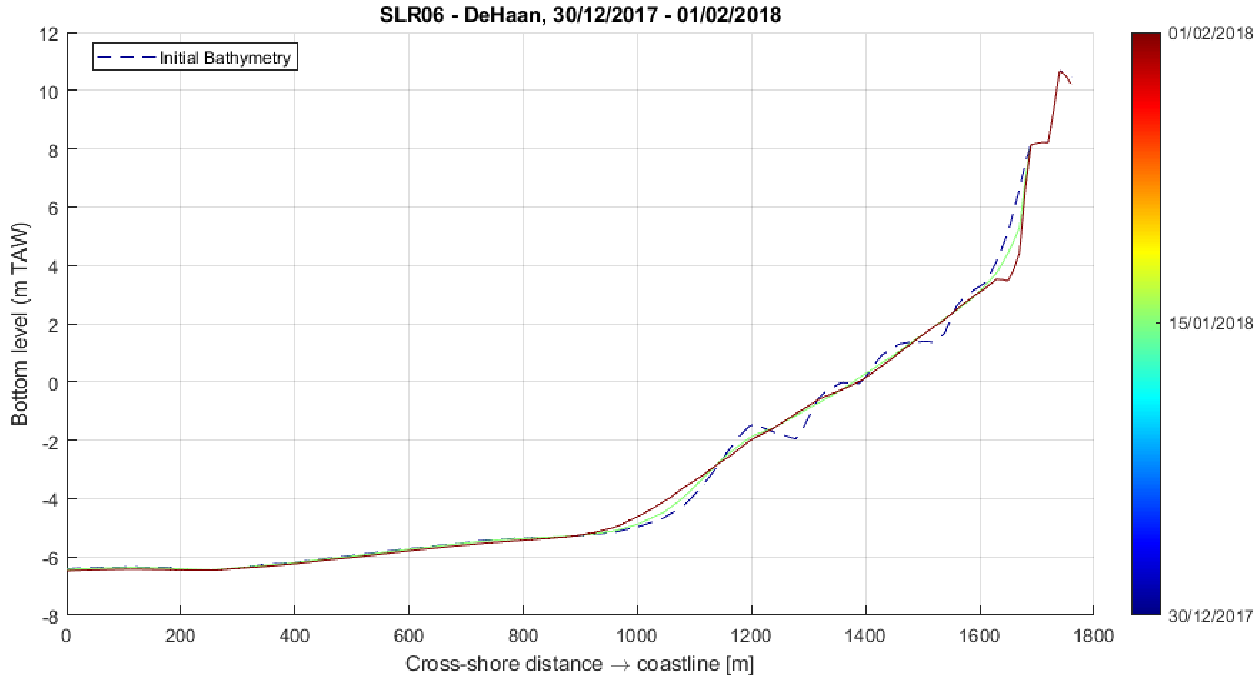

Figure 16 – Bottom profile evolution at De Haan after a simulation of 1.8 years (33 hydrodynamic days) for the SLR06 settings.

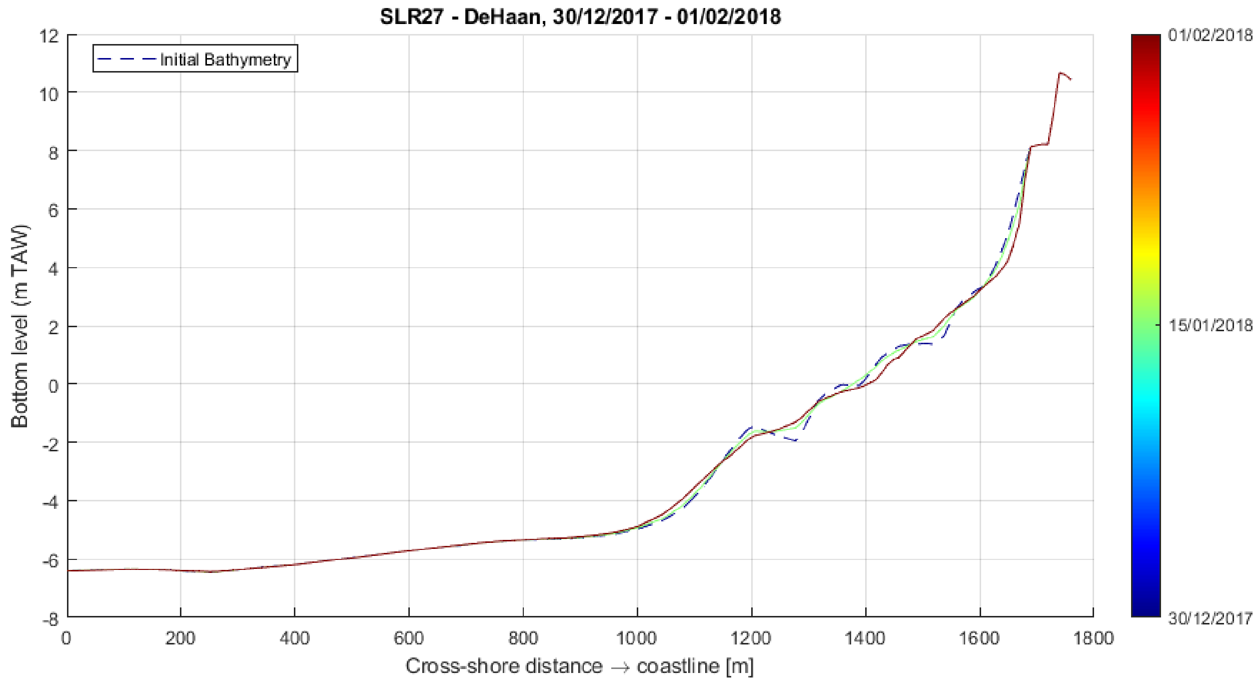

Figure 17 – Bottom profile evolution at De Haan after a simulation of 1.8 years (33 hydrodynamic days) for the SLR27 settings.

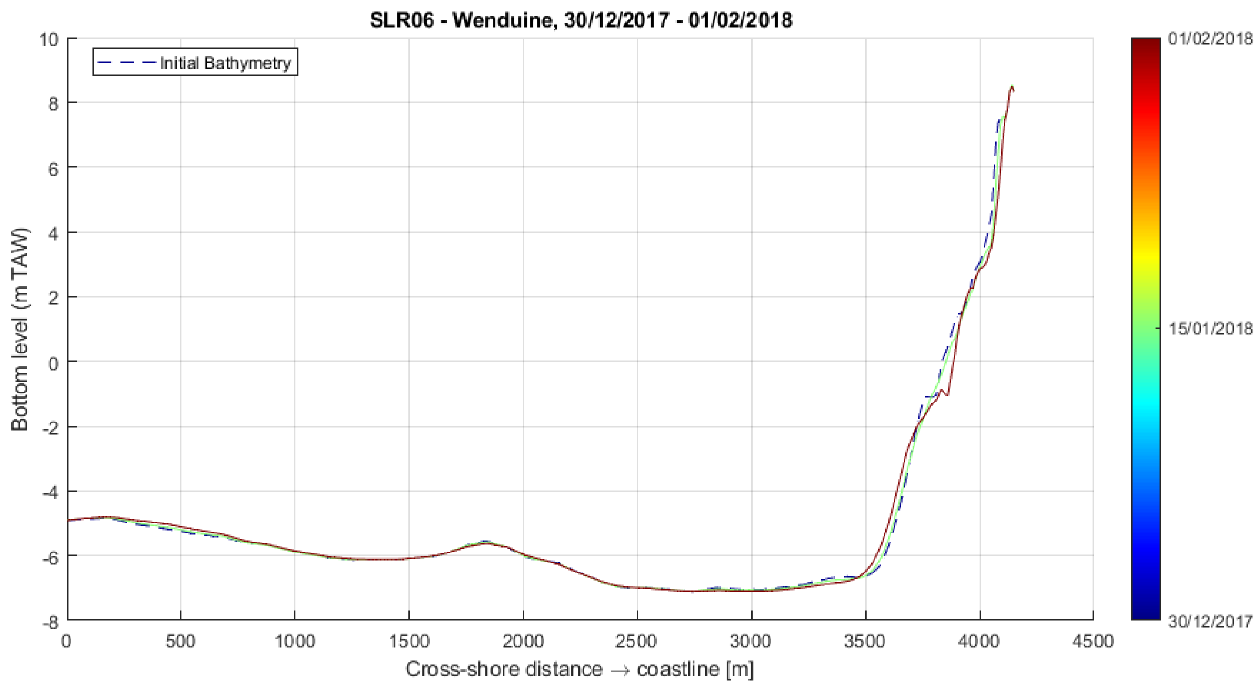

Figure 18 – Bottom profile evolution at Wenduine after a simulation of 1.8 years (33 hydrodynamic days) for the SLR06 settings.

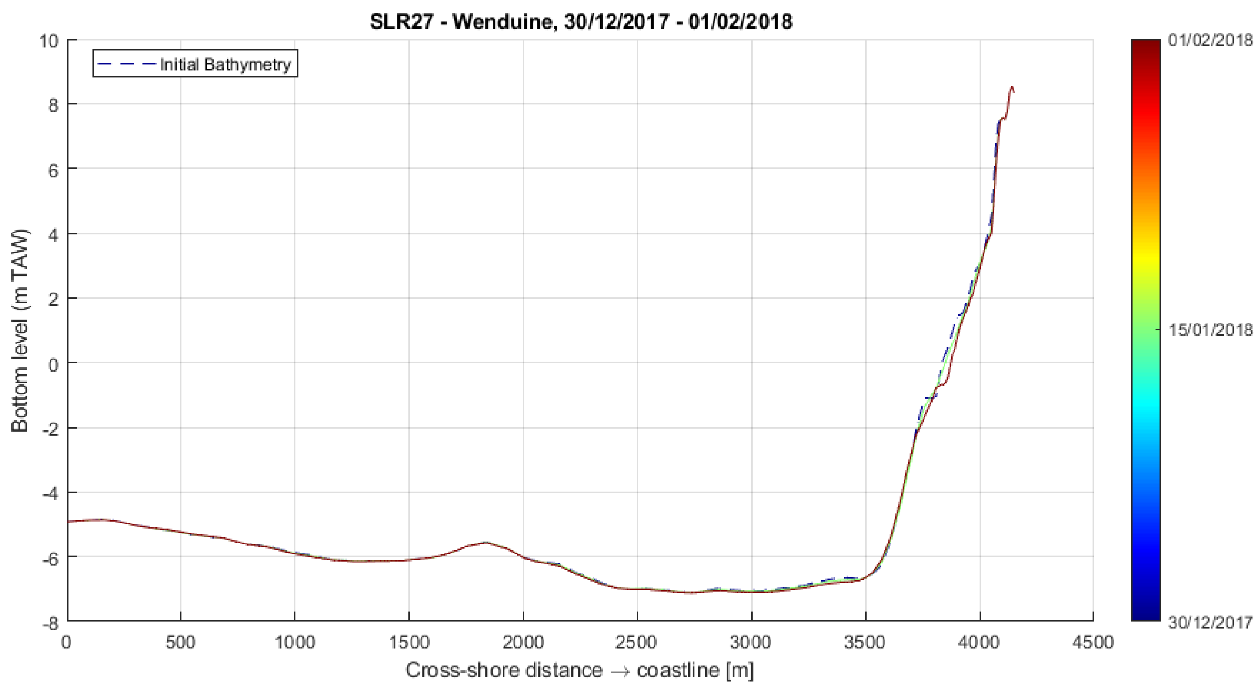

Figure 19 – Bottom profile evolution at Wenduine after a simulation of 1.8 years (33 hydrodynamic days) for the SLR27 settings.

2.1.5 Long-term morphology evolution

In this section, the evaluation of the predictions of two long-term (10-year) morphological simulations (SLR29 and SLR30) with settings identical to those of SLR20 and SLR27 sensitivity tests, is performed. The evaluation is based on the comparison of the bottom evolution at the coastal area of Wenduine-Blankenberge, between the aforementioned simulations and the simulations with the default Bijker's transport formula and the van Rijn's formula (2007) presented in (Studieteam Hoogtij(d), 2023). As a reminder, the improved sediment transport settings are summarized here:

- **SLR29**: τ_{cw} given by Soulsby (1995) & varying *b* (beta) in Bijker's transport formula / Formula for deviation = 2 (Talmon et al., 1995) / Minimum depth for bedload = 0.1 m
- **SLR30**: τ_{cw} given by Soulsby (1995) / Formula for deviation = 2 (Talmon et al., 1995) / Minimum depth for bedload = 0.1 m

The comparison of the 10-year bed evolution predicted by different ScaldisCoast model settings is given in Figure 20. The two upper panels (*a*) and (*b*) correspond to the results of the two reference simulations, i.e. the van Rijn's (2007) formula run and the default Bijker's formula run, respectively. The two bottom panels (*c*) and (*d*) correspond to the results of the two test simulations SLR29 and SLR30, respectively. The differences between the reference runs are obvious in the nearshore area of Wenduine, where van Rijn's formula predicts significant erosion, while default Bijker's formula predicts sedimentation which is apparently due to the overestimated beach erosion (enhanced bed slope effects). The two bottom figures do not present significant differences among them. However, the differences compared to the default Bijker's formula results (panel *c*) are easily noticeable. The intense sed-ero pattens along the coastline are not present any more, while limited erosion is observed nearshore, in front of Wenduine. This behaviour is indicative of the positive contribution of the sediment transport settings. It has to be noted, though, that the SLR29-SLR30 predictions, present substantial differences compared to the van Rijn's formula run (panel *a*).

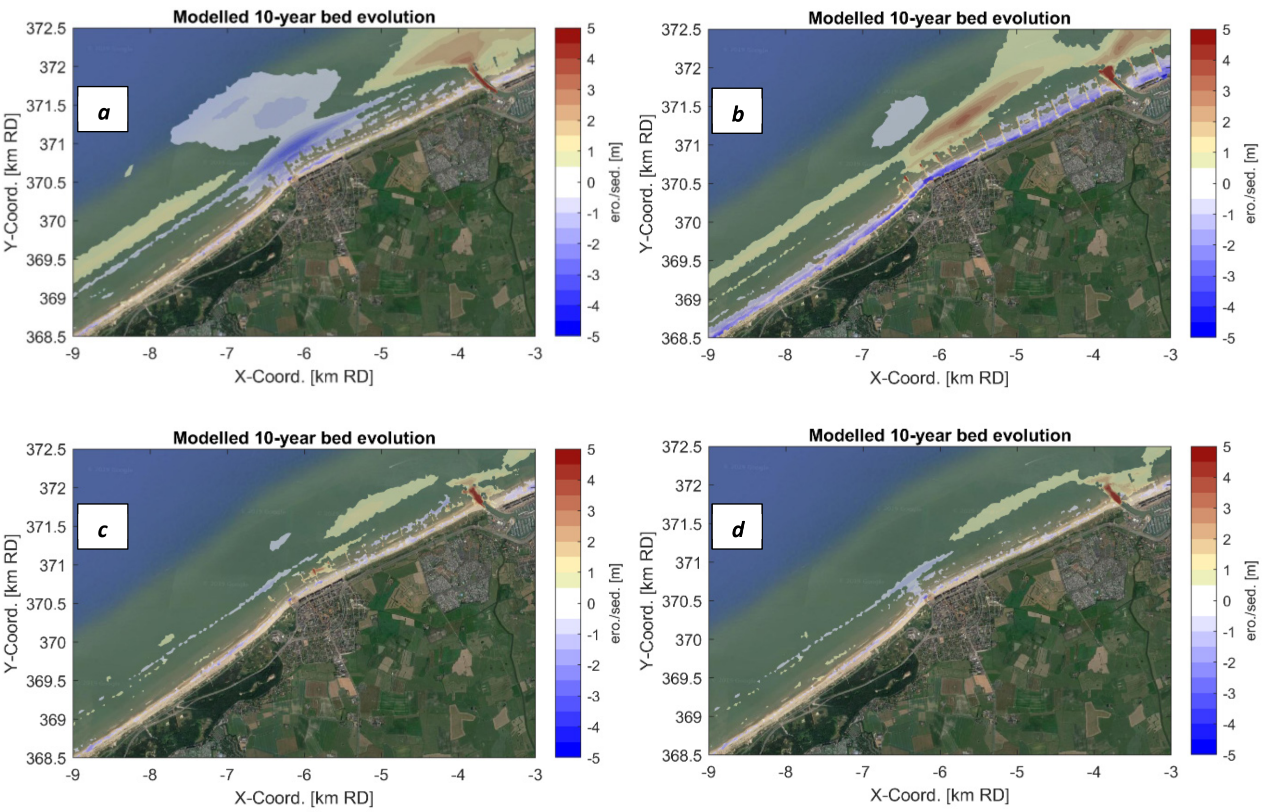

Figure 20 – 10-year bottom evolution at the area around Wenduine and Blankenberge for (a) van Rijn's transport formula (Kustivisie project); (b) default Bijker's transport formula (Kustvisie project); (c) test SLR29 settings; (d) test SLR30 settings.

2.2 More applications of improvements in sediment transport modelling

In the following sections the optimal settings and considerations that were successfully tested previously, are utilized in various morphological simulations from the past for further evaluation of their performance. The optimal settings/considerations, which come from SLR20 and SLR27 tests, are repeated here:

- Introduction of wave-current bed shear stress (τ_{cw}) by Soulsby (1995) in Bijker's transport formula
- Introduction of varying breaking wave parameter (*b)* in Bijker's transport formula
- Formula for deviation given by Talmon et al (1995)
- Minimum depth for bed load equal to 0.1 m

The numerical exercises include (a) the calculation of the annual longshore transport volumes along the Belgian coast and (b) a storm event (Ciara) in February 2020 with important impact at the marina of Blankenberge (c) a long-term morphological hindcasting (years 1986-1996) at the area east of Zeebrugge port related to the seaward extension of the port.

2.2.1 Annual longshore transport exercise

The simulations of this exercise were performed by using the ScaldisCoast model presented in Kolokythas *et al.* (2023). The basic information on the hydrodynamic forcing of the model and the simulation period is summarized in the following:

- The hydrodynamic forcing of the model is based on the implementation of the representative tide technique, i.e. two tidal cycles are repeatedly applied for the whole simulation period. Reduced wave conditions are also considered by applying a 6-month time-series, which is representative of the wave conditions in the decade (2009-2018).
- The simulation period in the reference scenario is considered equal to 10 years. In order to reduce the computational time a morphological acceleration factor (MOFAC) equal to 20 is considered.

For this exercise, the main settings of the TELEMAC-2D and SISYPHE modules are identical to those presented in Table 1 for the sea level scenario (section 2.1.1). The differences are only found in the wave modelling module (TOMAWAC):

- TOMAWAC time-step = 120 s (instead of 600 s). The increased time-step utilized in the SLR simulations was coupled with a new parameterization of wave breaking dissipation that was not implemented in the present exercise.

As mentioned before, only the optimal settings and considerations that came from the sea level rise modelling exercise, are investigated here. A list of selected tests is given in Table 3.

Table 3 – List of sensitivity tests for longshore sediment transport tuning.

Run ID	Description
Simulation period: 186 hydrodynamic days / 10 morphological years	
HSW113b*	Reference run *full name of run: HSW113b_BK_layer_GT_update
aHSW113	τ_{cw} given by Soulsby (1995) in Bijker's transport formula
bHSW113	τ_{cw} given by Soulsby (1995) & varying *b* (beta) in Bijker's transport formula
gHSW113	τ_{cw} given by Soulsby (1995) & varying *b* (beta) in Bijker's transport formula Formula for deviation = 2 (Talmon et al., 1995) / Minimum depth for bedload = 0.1 m

The effect of the improvements in sediment transport formulation is investigated through the comparison of the resulting net annual longshore transport by the aforementioned tests, integrated across the surf zone along the entire Belgian coastline. The results of the three first test runs of Table 3, i.e. HSW113b, aHSW113 and bHSW113 are presented in Figure 21. Note that the resulting longshore transport volumes by test gHSW113 are not included in Figure 21, since they were very similar to those of test bHSW113. In this diagram, positive values correspond to eastward transport, positive gradients (upslopes) correspond to erosion while negative gradients (downslopes) represent accumulation of sediment.

In absolute values, the reference simulation predicts annual transport volumes ca. 240,000 m^3 at the area of Wenduine-Blankenberge and an average value of 60,000 m^3 at the area east of Zeebrugge. Obsviously, the reference simulation predicts the largest annual transport volumes compared to the other two test simulations. For example, the predicted volumes by the reference run at the area between Ostend and Wenduine are up to 2 times and 2.7 times larger than those of tests bHSW113 and aHSW113, respectively. However the observed differences are much smaller at the area between the port of Zebrugge and Zwin. As expected, test bHSW113, in which the varying *b* parameter is introduced in Bijker's formula, leads to relatively larger transport volumes compared to aHSW113, especially at the area Ostend-Wenduine (ca. 1.3 times larger). On the other hand, the predictions of these two test runs are very similar at the area Zeebrugge-Zwin.

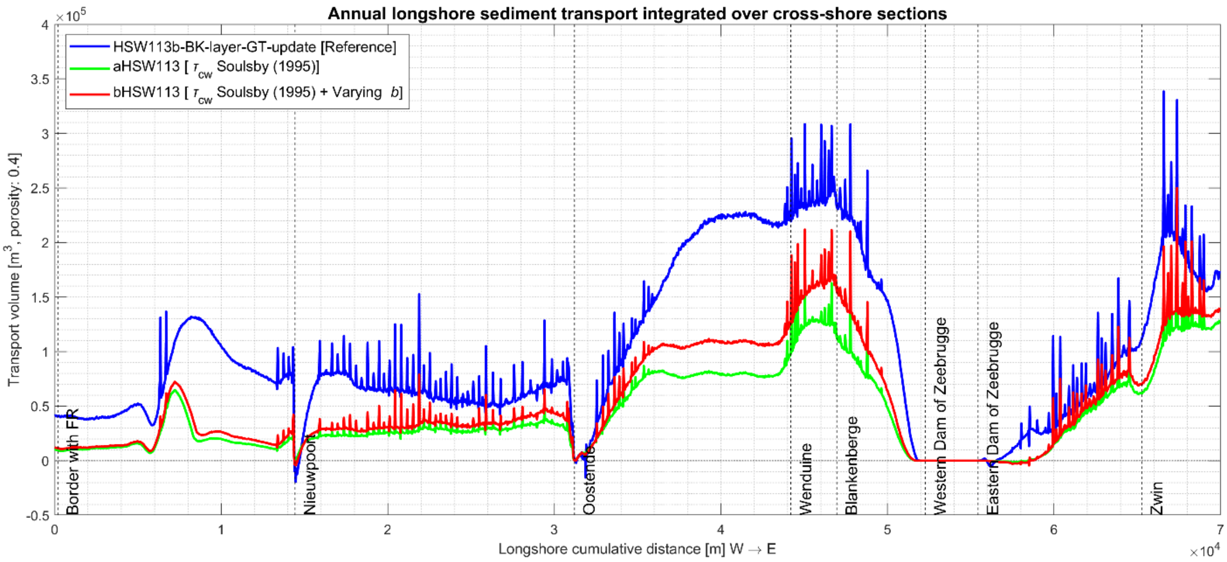

Figure 21 – Net annual longshore transport, integrated across the surf zone of the Belgian coast, calculated by the reference test, and tests aHSW113 [τ_{cw} by Soulsby (1995) in Bijker's formula] and bHSW113 [τ_{cw} by Soulsby (1995) & varying b in Bijker's formula].

2.2.2 Ciara storm exercise

The ScaldisCoast validation exercise for a short-term incident, i.e. Ciara storm, presented in Kolokythas *et al.* (2023) is repeated here in order to evaluate the performance of the sediment transport modelling improvements. The basic information on the model setup is summarized in the following:

- The model is forced by the hydrodynamic boundary conditions (water levels and velocities) by the regional ZUNO model (Maximova *et al.*, 2016), while wave and wind conditions come from the measurement station of Westhinder. Note that both the hydrodynamic and the wave modelling predictions had been successfully validated by comparison to measurements from different stations at the Belgian coastal zone.
- The simulation period is considered equal to 10 days, i.e. simulation starts on February 5 (ca. 4 days before the storm) and finishes ca. 2 days after the storm. Note that no morphological acceleration was applied (MOFAC=1).

The main settings of the model for the reference Ciara storm simulation are presented in Table 1. As the numerical experiments only include adjustment of the morphological parameters and settings, emphasis is given in the settings of SISYPHE module.

Table 4 – Main settings of the ScaldisCoast model for the reference Ciara storm simulation.

Parameter	Value
TELEMAC-2D	
Version of TELEMAC	TELEMAC v7p3r1
Time step	6 s
Initial conditions	developed flow field after spin-up of 1 day
Coupling period for TOMAWAC	300 (30 min)
TOMAWAC	
Time step	120 s
SISYPHE	
Bed-load transport formula	4: Bijker (1967) – breaking wave parameter *b* =2
Suspension	No
Sediment diameters (D_{50})	200 µm (based on sediment map for the area of Blankenberge)
Morphological factor	1
Slope effect	Yes
Formula for slope effect	1: Koch & Flokstra (1981) / BETA = 1.3
Formula for deviation	1: Koch & Flokstra (1981)
Minimum depth for bedload	0.01 m (default)
Sediment slide	No
NESTOR	No

A list of the performed tests, which include simulations with the optimal settings and considerations from the sea level rise modelling exercise, are presented in Table 5.

Table 5 – List of sensitivity tests for the Ciara storm modelling exercise.

Run ID	Description
dHSW101_03b	Reference settings (Table 4)
eHSW101_03b	τ_{cw} given by Soulsby (1995) in Bijker's transport formula
cHSW101_03b	τ_{cw} given by Soulsby (1995) & varying *b* (beta) in Bijker's transport formula
fHSW101_03b	τ_{cw} given by Soulsby (1995) & varying *b* (beta) in Bijker's transport formula Formula for deviation = 2 (Talmon et al., 1995) / Minimum depth for bedload = 0.1 m

The evaluation of the improvements in SISYPHE is performed by comparison of the simulated and surveyed bed level changes at the the entrance of the marina of Blankenberge at the end of the period February 6 -14 (8 days), i.e. after the end of Ciara storm event. Moreover the measured and the modelled volumes of total (gross) sedimentation within the area that surveys took place, are compared.

In Figure 22, the measured bottom evolution at the entrance of Blankenberge marina, which results from the difference of a pre-storm survey (February 6) and a post-storm survey (February 14), is presented. The measurements indicate the significant accumulation of sediment at the entrance of the marina, and the calculated gross sedimentation volumes are found equal to about 46,000 m^3.

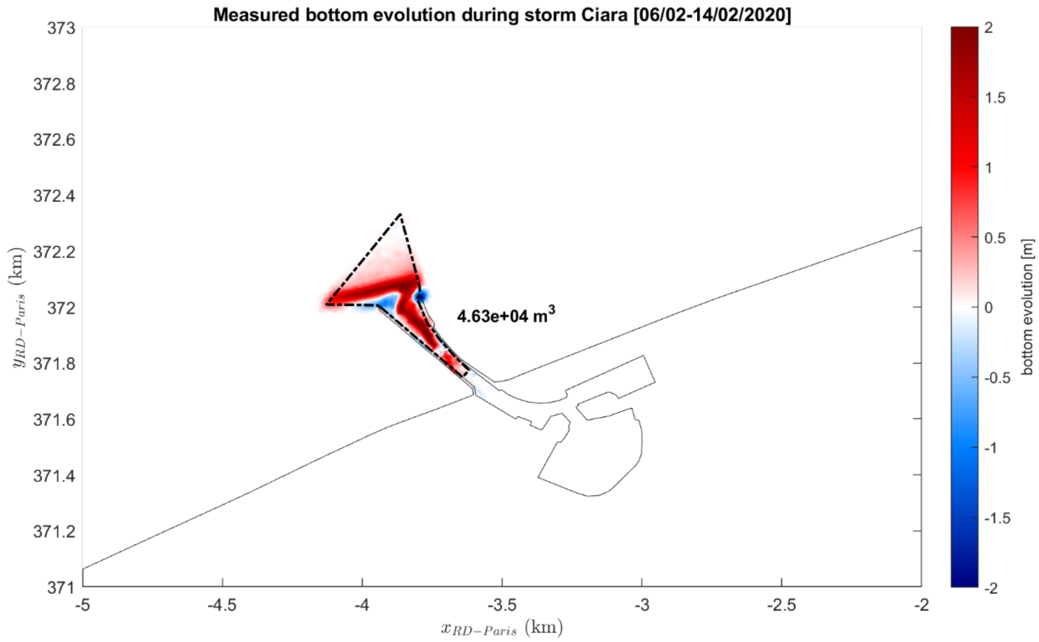

Figure 22 – Measured bottom evolution and sedimentation volumes at the entrance of Blankenberge marina after Ciara storm event.

The numerical results by the reference simulation (dHSW101), presented in Figure 23, indicated a fair agreement with the measured ones, both in the shape of the sed-ero patterns at the marina entrance and in the calculated sedimentation volume (ca. 51,000 m^3). On the other hand, introducing τ_{cw} by Soulsby (1995) in Bijker's transport formula (see bed evolution in Figure 24), results into substantial attenuation of the sedimentation pattern at the entrance, which is also expressed by the significant reduction in the calculated volumes (ca. 37,000 m^3).

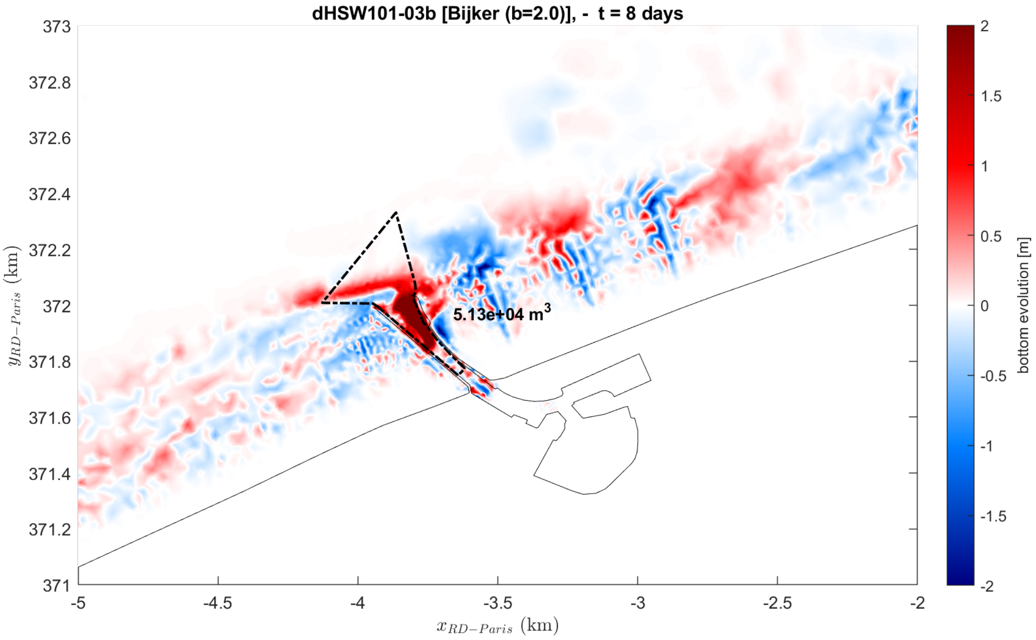

Figure 23 – Modelled bottom evolution at the area of Blankenberge marina after Ciara storm event for the reference settings.

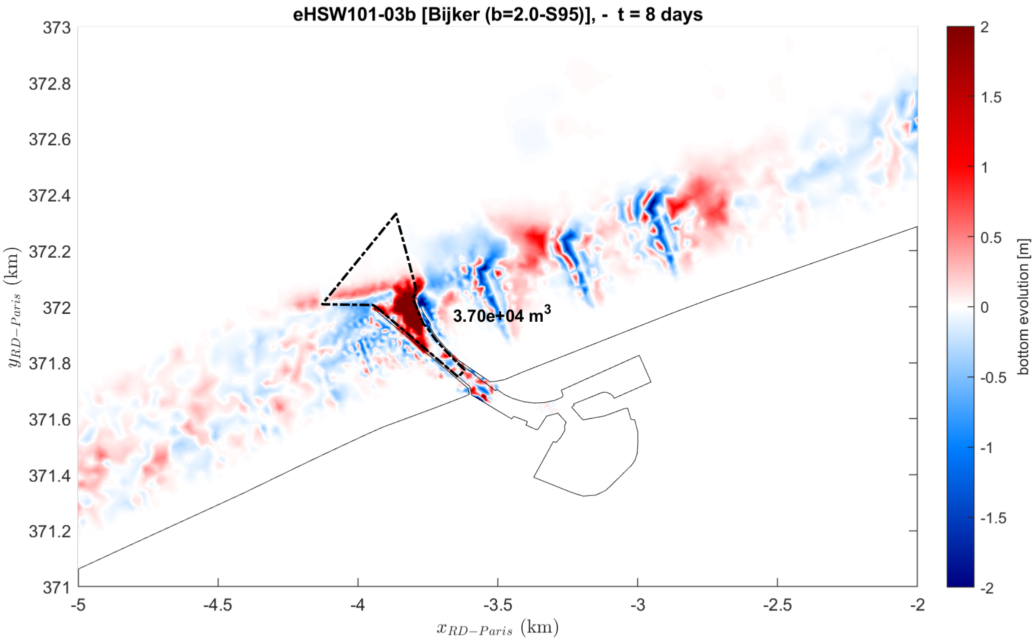

Figure 24 – Modelled bottom evolution at the area of Blankenberge marina after Ciara storm event [τ_{cw} by Soulsby (1995) in Bijker's transport formula].

Combining the introduction of τ_{cw} given by Soulsby (1995) together with the introduction of the varying *b* parameter in Bijker's transport formula, a better performance of the model is achieved, as shown in Figure 25 (run cHSW101). The shape and the magnitude of the sed-ero patterns at the marina entrance and the calculated sedimentation volume (ca. 45,000 m^3), are in good agreement with the measured ones presented in Figure 22.

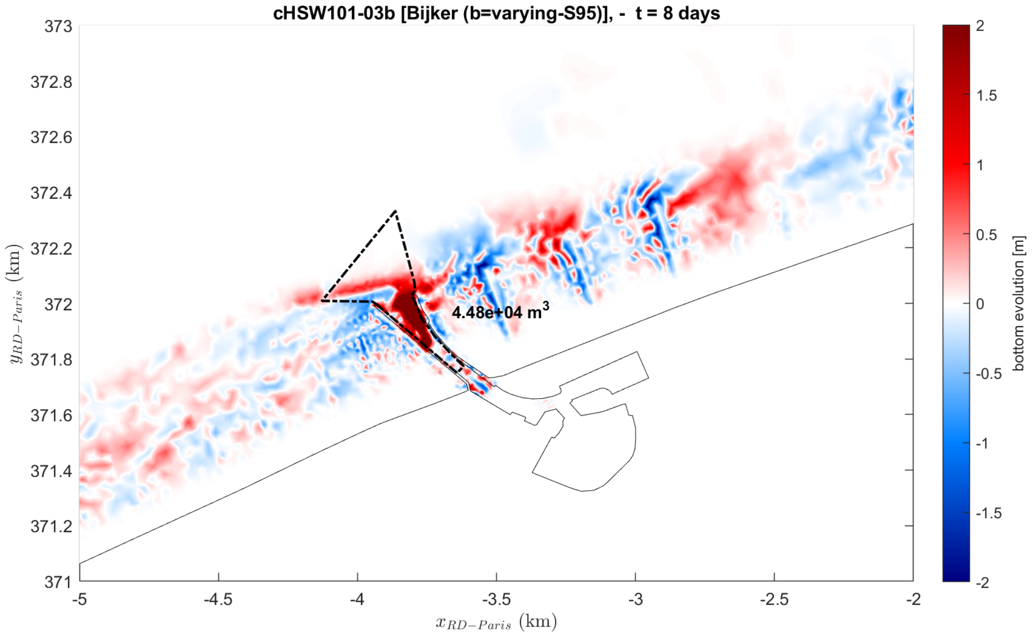

Figure 25 – Modelled bottom evolution at the area of Blankenberge marina after Ciara storm event [τ_{cw} by Soulsby (1995) & varying b (beta) in Bijker's transport formula].

Retaining the settings of last-presented simulation (cHSW101) and choosing the deviation formula by Talmon et al. and a minimum depth for bedload equal to 0.1 m, only slightly affects the numerical sed-ero patterns, as shown in Figure 26 (run fHSW101). As for the predicted sedimentation volumes (ca. 46,000 m^3) are now almost identical to the measured ones.

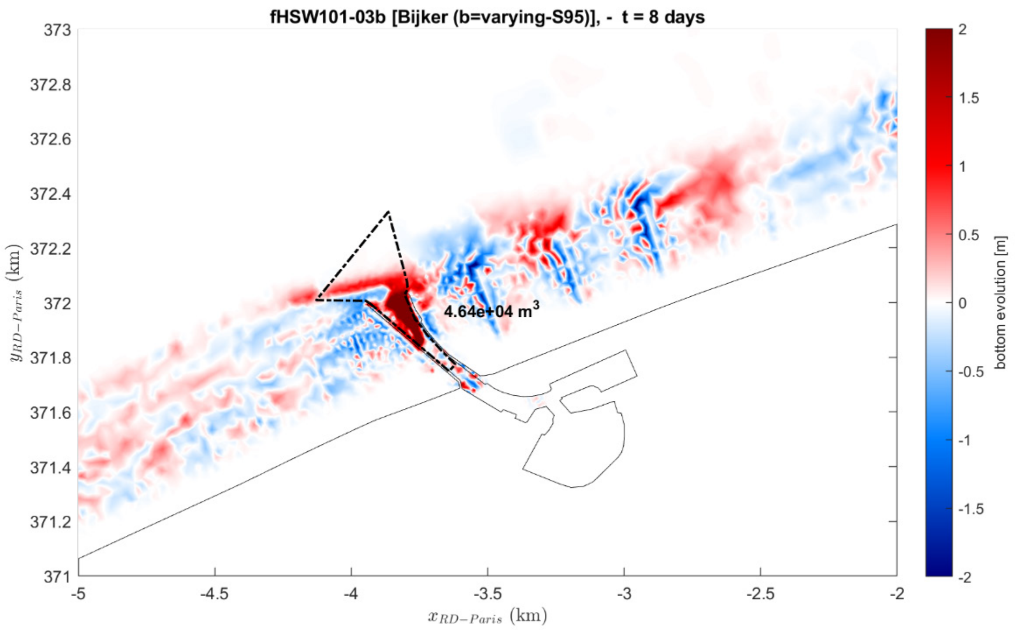

Figure 26 – Modelled bottom evolution at the area of Blankenberge marina after Ciara storm event [τ_{cw} by Soulsby (1995) & varying b (beta) in Bijker's transport formula / Formula for deviation by Talmon et al. / Minimum depth for bedload = 0.1 m].

2.2.3 1986-1996 morphological hindcasting

The last application for the evaluation of sediment transport improvements is the long-term morphological hindcasting that was initially presented in Kolokythas *et al.* (2023). The main goal of this application was the evaluation of ScaldisCoast model in representing the morphological changes in the eastern Belgian coast triggered by the seaward expansion of the port of Zeebrugge, which was completed in the year 1986. Detailed information about the model set up can be found in the afore mentioned report. However, some useful notes on the model set-up are summarized in the following:

- The introduced historical bathymetry was a compilation of data from or around the year 1986, depending on the availability. Historical bathymetric data from or around the year 1996 was utilized in order to create the measured bed evolution map at the area of interest, which was used in the comparison to the numerically predicted bed evolution.
- The hydrodynamic forcing of the model is based on the implementation of the representative tide technique, i.e. two tidal cycles are repeatedly applied for the whole simulation period. Schematized wave conditions are also considered by applying a 'structured' time-series consisting of 12 simplified wave and wind conditions, which are representative of the conditions of a typical year at the Belgian coast.
- The simulation period in the reference scenario is considered equal to 10 years. In order to reduce the computational time a morphological acceleration factor (MOFAC) equal to 10 was considered.

The main settings of the model for the reference hindcasting simulation (swc011B) are presented in Table 6. Note that at this application, single-fraction sediment was considered with d_{50} = 250 µm in the entire computational domain. For the specific d_{50} value, the breaking wave parameter in Bijker's value was selected (after calibration procedure) equal to *b*=5.5.

The only test simulation performed in the framework of this exercise is the introduction of τ_{cw} given by Soulsby (1995) in Bijker's transport formula (test Aswc011B). Varying *b* parameter (in the range between 2 and 5) is not expected to perform well in the specific application, since its calibrated value is even larger than the upper limit value, therefore this setting is not activated. Moreover, taking into account the results of the applications presented in the previous sections, it is expected that the formula for deviation and the minimum depth for bed load would have negligible influence in the results of the test simulation.

Table 6 – Main settings of the ScaldisCoast model for the reference morphological hindcasting simulation (swc011B).

Parameter	Value
TELEMAC-2D	
Version of TELEMAC	TELEMAC v7p2 (cookiecutter branch)
Time step	6 s
Initial conditions	developed flow field after spin-up of 4 diurnal tides
Coupling period for TOMAWAC	300 (30 min)
TOMAWAC	
Time step	120 s
SISYPHE	
Bed-load transport formula	4: Bijker (1967) – breaking wave parameter *b* =5.5
Suspension	No

Sediment diameters (D_{50})	250 µm (single-fraction)
Morphological factor	10
Slope effect	Yes
Formula for slope effect	1: Koch & Flokstra (1981) / BETA = 1.3
Formula for deviation	1: Koch & Flokstra (1981)
Minimum depth for bedload	0.01 m (default)
Sediment slide	Yes
NESTOR	No

The evaluation of the improvements in Bijker's transport formula is performed by comparison of the bed level changes at the coastal area in the vicinity of the port of Zeebruge entrance, at the end of the simulation period, i.e. after 10 years. Moreover the modelled sediment volume changes in selected polygons at the area of interest, are compared to the measured ones in order to get a better evaluation of the performance of the improved simulation settings.

The numerical results of the reference simulation (swc011B) and the test simulation (Aswc011B) are presented in Figure 27 and Figure 28, respectively. Comparison between them shows limited differences in the magnitude of the sed/ero patterns in relatively deeper waters, including the areas enclosed in the polygons where the volume change is calculated. On the other hand, in shallower regions, even relatively far from the coastline, and in the nearshore areas, where the wave action is dominant, the differences are significantly larger. Note that the pronounced sed/ero zone (elongated blue-red pattern) of the reference simulation (Figure 27), which spans along the coastline at the west and the east of port of Zeebrugge, is found to be a lot attenuated in the test simulation with the improved Bijker's transport formula (Figure 28).

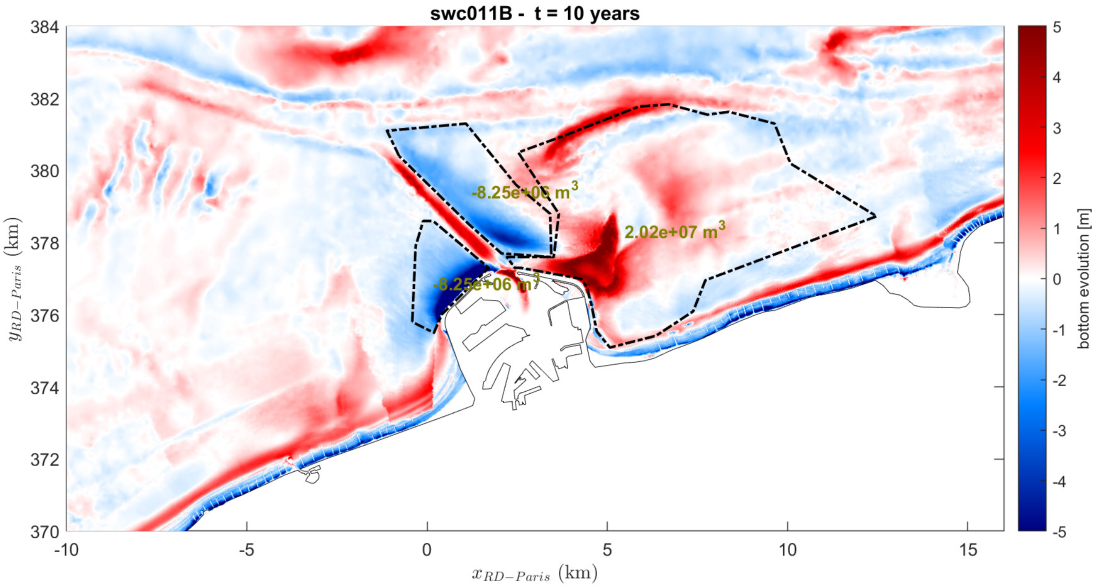

Figure 27 – Modelled bottom evolution for the reference simulation after a simulation period of 10 years; Sand volume change is calculated in the depicted polygons.

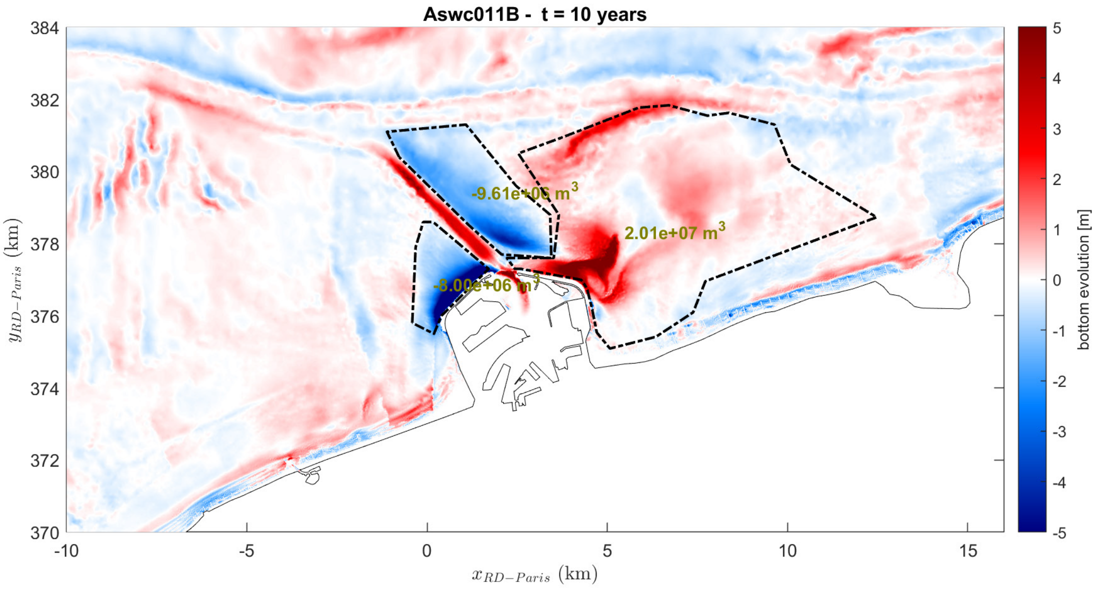

Figure 28 – Modelled bottom evolution for the test simulation Aswc011B after a simulation period of 10 years; Sand volume change is calculated in the depicted polygons.

The modelled and the measured sediment volume changes in the selected polygons shown in Figure 27, are gathered in Table 7. The test simulation (Aswc011B) performs similarly to the reference one, when comparing the volume change in Paardenmarkt and in the Western Breakwater polygons. At the Eastern Breakwater polygon, though, the test simulation predicts larger erosion volumes, but still comparable to the measured ones.

The larger erosion volumes can be explained by the absence of sedimentation inside of the borders of the Eastern Breakwater and Paardenmarkt polygons. The overestimation of the accumulated sediment volume at Paardenmarkt is common for both the reference and the test runs.

Table 7 – Modelled and measured sediment volume changes inside the polygons of Figure 27 for the period 1986-1996.

Area (polygon)	Volume change 1986-1996 [x10^6 m^3]		
	Modelled swc011B	Modelled Aswc011B	Measured
Eastern Breakwater	-8.3	-9.6	-9.0
Western Breakwater	-8.3	-8.0	-7.4
Paardenmarkt	+20.2	+20.1	+14.5

2.3 Summary and conclusions

Numerical simulations of a 3-meter sea level rise (SLR) scenario, by means of ScaldisCoast model, had shown that strong cross-shore transport directed offshore took place at shallow waters. As this cross-shore transport was considered as debatable, the utilized sediment transport formulation, i.e. Bijker's transport formula and the slope effect formula, were reconsidered and in depth investigated in the present report.

The SLR scenario exercise was repeated here and several numerical experiments were performed focusing on the morphology module (SISYPHE) tuning. The main considerations that were found to substantially affect the morphology module performance, presenting a positive contribution in the limitation of the strong cross-shore transport are:

- Replacement of the default wave-current bed shear stress, τ_{cw}, formula in Bijker's transport formula with the τ_{cw} formula proposed by Soulsby (1995), known as the DATA2 method and based on a fit to laboratory and field measurements
- Replacement of the default (fixed) breaking wave parameter (*b)* in in Bijker's transport formula with a spatio-temporal varying expression that depends on the wave height and water depth ratio (Bijker, 1971).

Before applying the aforementioned replacements in the Bijker's transport formula, sensitivity tests indicated two other settings that affected (in less extent) the results:

- Use of formula for deviation (correction of sediment transport direction due to slope effect) by Talmon et al. (1995) instead of the default one (Koch and Flokstra , 1981)
- Minimum depth for bed load equal to 0.1 m (instead of 0.01 m)

It was found, though, that the influence of transport deviation and the minimum depth for bedload parameters, was minimized after applying the improvements in Bijker's transport formula.

The findings mentioned above were confirmed through a series of applications, which included: (a) the calculation of the annual longshore transport volumes along the Belgian coast and (b) a storm event (Ciara) in February 2020 with important impact at the marina of Blankenberge (c) a long-term morphological hindcasting (years 1986-1996) at the area east of Zeebrugge port coupled with the expansion of the port.

3 Adapting the ScaldisCoast model to TELEMAC v8 and GAIA

This project can be considered as a continuation of our previous work on ScaldisCoast model (15_068-VlabaKustzone). In our earlier project, the morphodynamics of ScaldisCoast model has been validated. The validation of the model was performed by SISYPHE of TELEMAC v7p2.

In this new project, we aim to gain more insights on the morphology evolution of the Belgian coast using ScaldisCoast model. Because now TELEMAC has been updated to v8p3 in which the new module GAIA becomes available and is regarded as successor of SISYPHE to simulate morphodynamics, we intend to further develop ScaldisCoast model with the new module GAIA in the new version of TELEMAC. However, we need to first examine possible differences which result from the new module and new version.

3.1 SISYPHE run with v8p3

The ultimate objective of the project is to develop a reliable morphology model using the new module GAIA. In order to ensure the smooth progression of the project, the module SISYPHE was first examined in the new version v8p3 of TELEMAC.

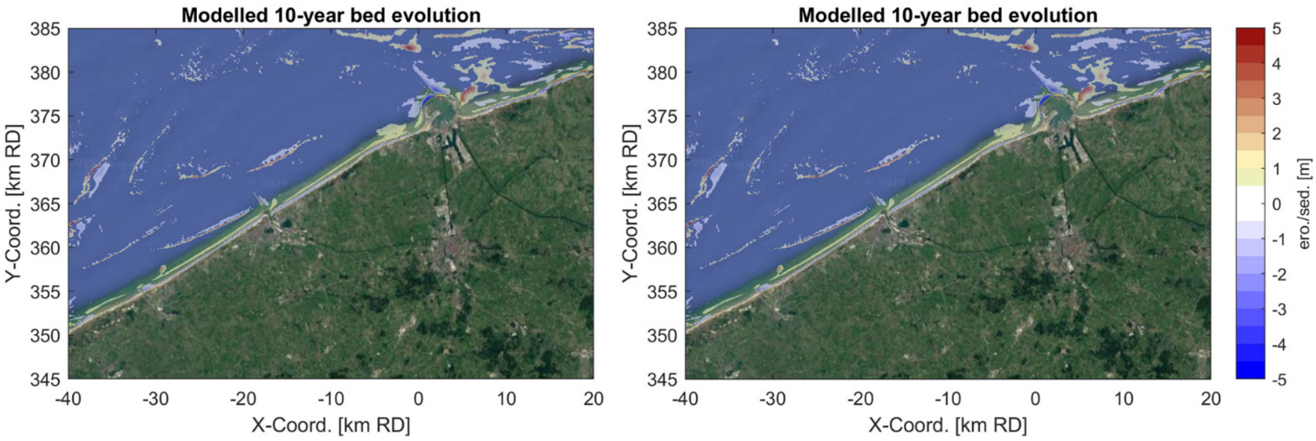

Figure 29 – 10-year bed evolution along the Belgian Coast (left: SISYPHE, v7p2; right: SISYPHE, v8p3).

In the Belgian coastal zone, the morphological results from both versions of SISYPHE are almost identical, as displayed in Figure 29. Additionally, the two versions of the model have demonstrated a high level of consistency in estimating longshore transport, as shown in Figure 30. A more detailed comparison is conducted in the vicinity of Wenduine (Figure 31). It reveals that the new version still produces nearly same outcomes as the old one. A calculation of net erosion is performed within the magenta box, which gives a value of 227,300 m^3 for the new version, only 0.18% larger than 226,900 m^3 obtained from the old version.

However, if the intercomparison is carried out in the full domain of the model, a substantial sedimentation could be found at the northeast boundary for the new version (indicated by a dash circle in Figure 32), but not for the old version. The reason for such a difference is currently unclear yet. But this difference does not seem to impact the results in the area of our interest.

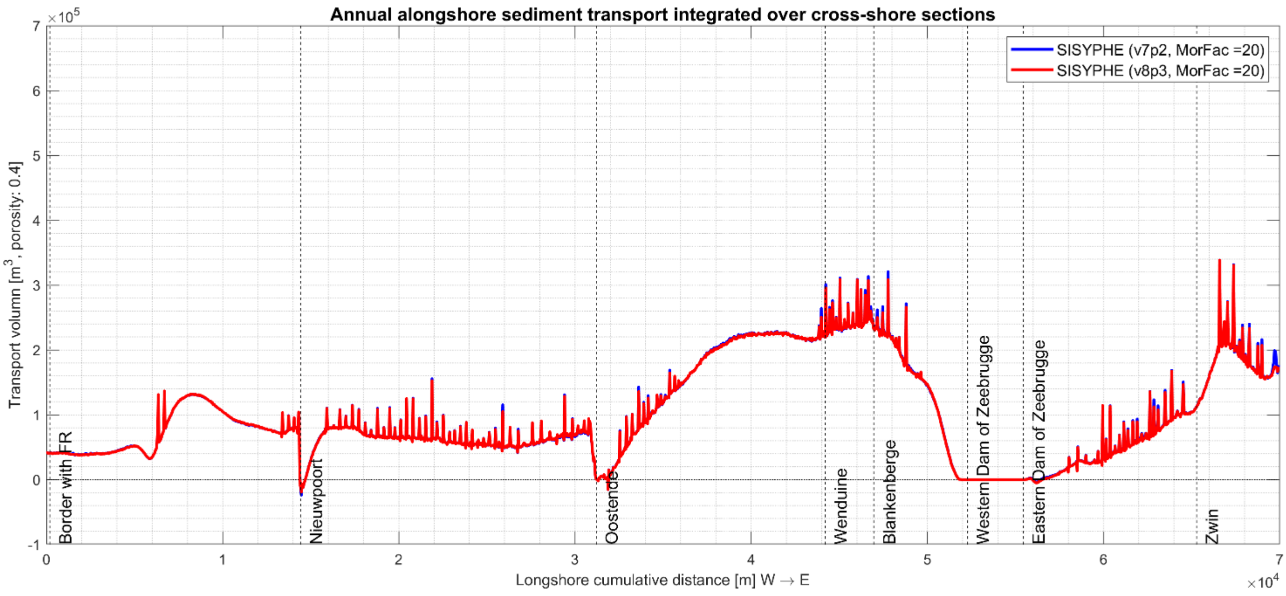

Figure 30 – Comparision of modelled net longshore sediment transport between v7p2 and v8p3 of SISYPHE.

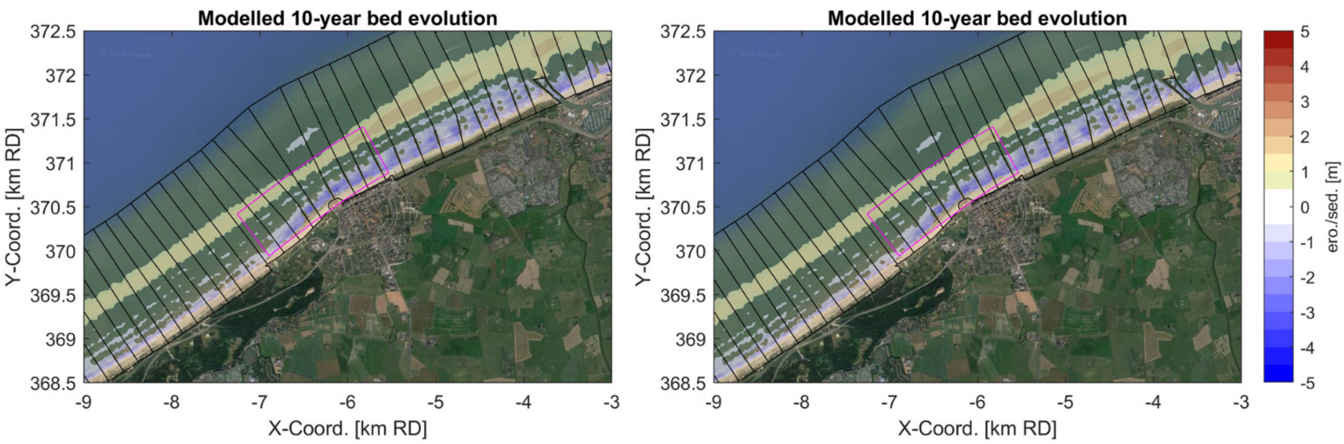

Figure 31 – 10-year bed evolution around Wenduine (left: SISYPHE, v7p2; right: SISYPHE, v8p3).

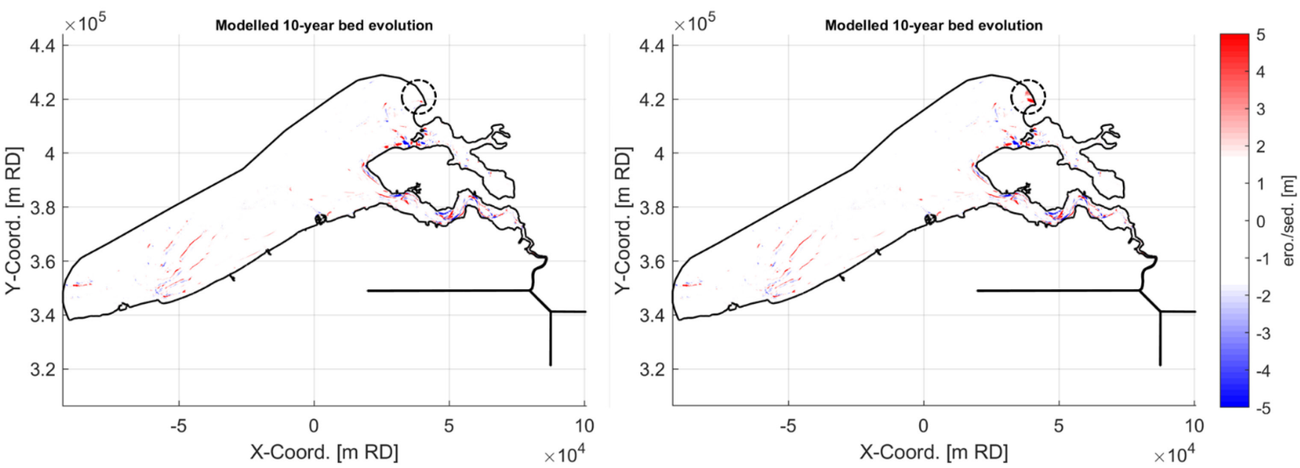

Figure 32 – 10-year bed evolution in the full domain of the model (left: SISYPHE, v7p2; right: SISYPHE, v8p3).

3.2 GAIA run with v8p3

Except the significant sedimentation at the northeast boundary, the new version of SISYPHE appears to sufficiently reproduce the results of the old version. Furthermore, a comparison was performed between SISYPHE and GAIA using the new version v8p3.

SISYPHE and GAIA show nearly identical morphological results in the Belgian coastal zone (Figure 33). Moreover, GAIA has demonstrated an excellent agreement with SISYPHE in estimating longshore transport although its fluctuations around groynes are less stronger than SISYPHE (Figure 34). A detailed comparison is also performed in the vicinity of Wenduine (Figure 35). GAIA is found to produce visually same results as SISYPHE. A calculation of net erosion within the magenta box suggests a value of 236,000 m^3 for GAIA, only 3.8% larger than 227,300 m^3 obtained from SISYPHE.

However, like the new version of SISYPHE, GAIA has also shown a significant sedimentation at the northeast boundary (Figure 36). More investigation is required to find the cause for this issue, or a workaround is needed to fix this issue. But this issue is not considered to impact the results in the area of our interest for the model which is currently being used.

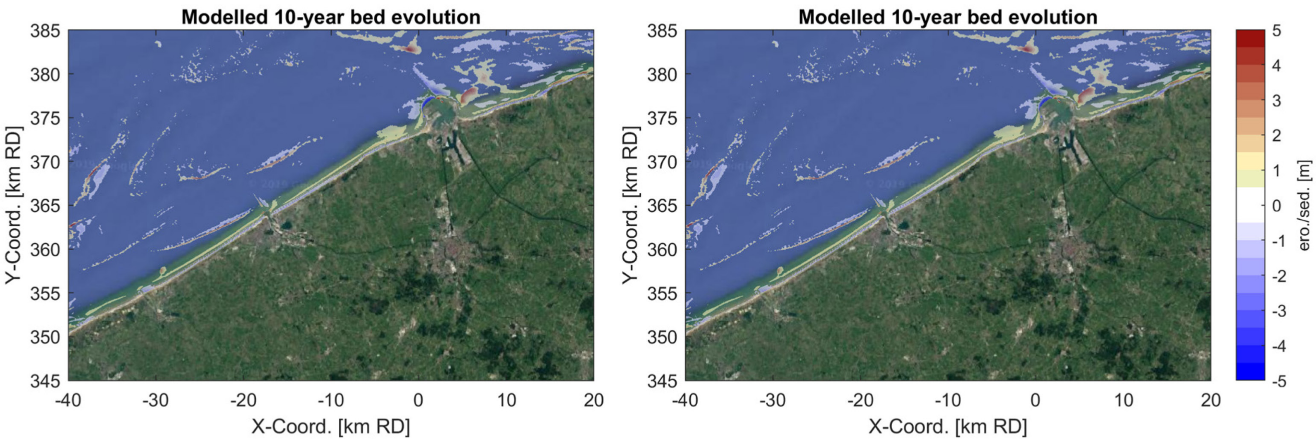

Figure 33 – 10-year bed evolution along the Belgian Coast (left: SISYPHE, v8p3; right: GAIA, v8p3).

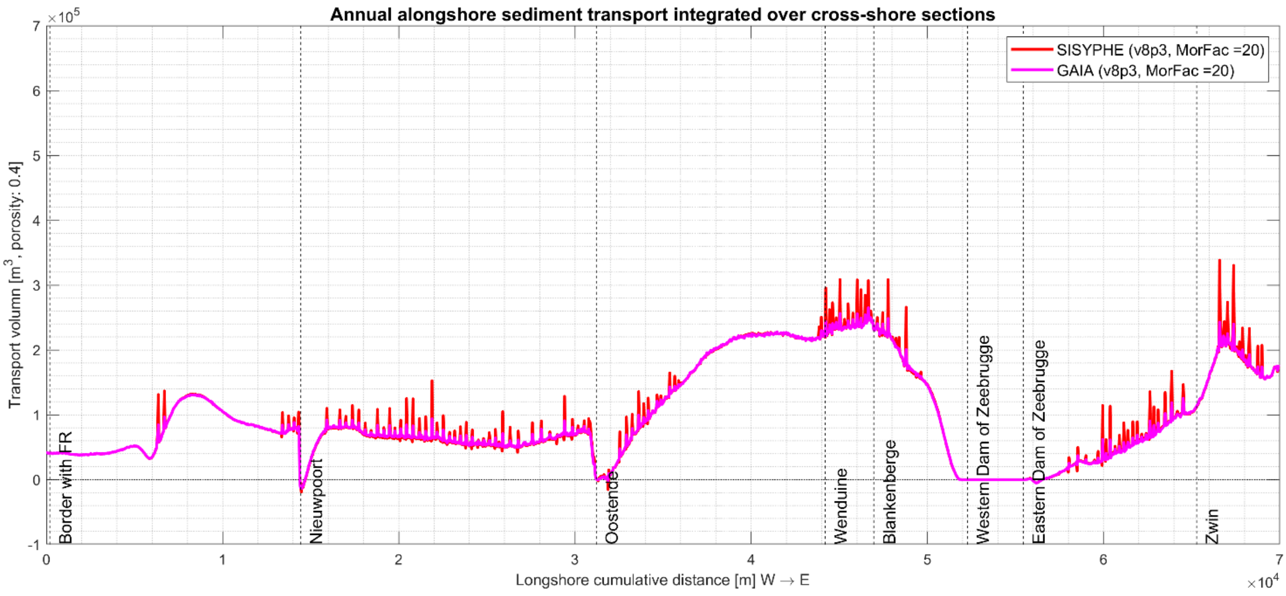

Figure 34 – Comparision of modelled net longshore sediment transport between SISYPHE and GAIA on v8p3.

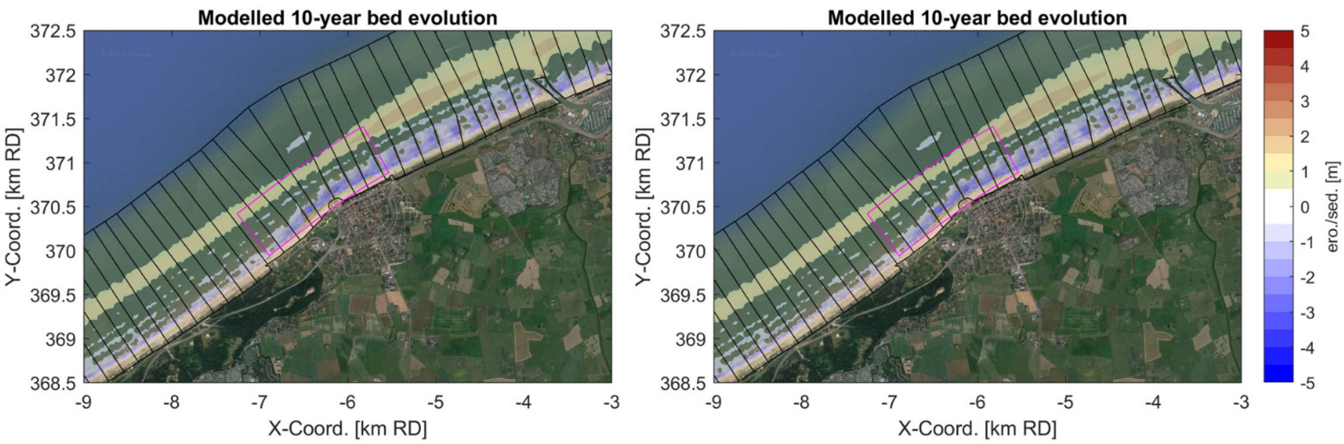

Figure 35 – 10-year bed evolution around Wenduine (left: SISYPHE, v8p3; right: GAIA, v8p3).

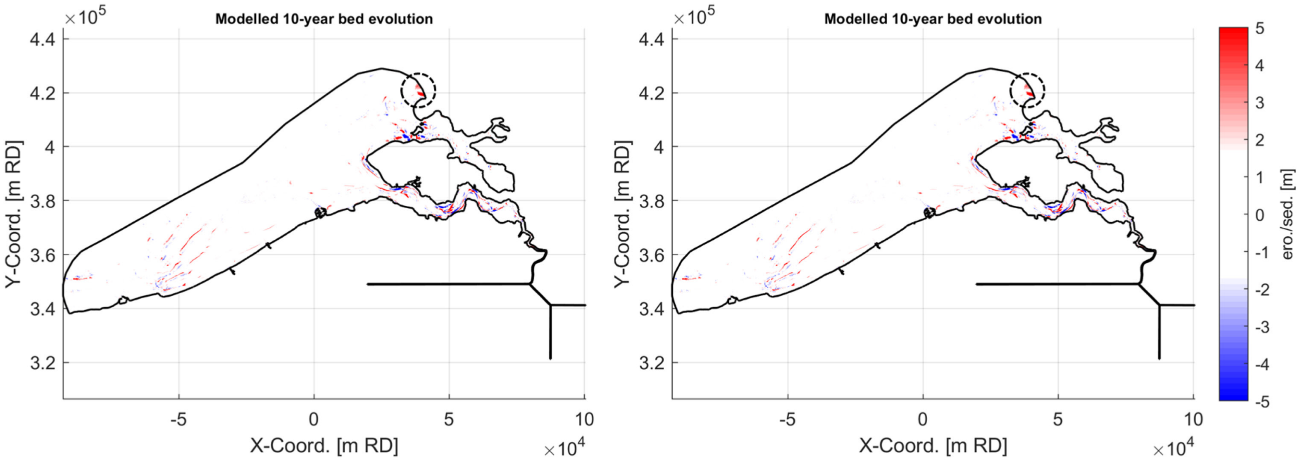

Figure 36 – 10-year bed evolution in the full domain of the model (left: SISYPHE, v8p3; right: GAIA, v8p3).

3.3 Conclusions and next steps

The different versions v7p2 and v8p3 of SISYPHE exhibits very consistent results on the 10-year morphological change of the Belgian coastal zone.

With the same version v8p3, GAIA has also demonstrated an excellent agreement with SISYPHE on the 10-year morphological change of the Belgian coastal zone.

However, in the new version of both SISYPHE and GAIA a substantial sedimentation occurs at the northeast boundary of the model. This issue requires more investigation, or a workaround is needed to resolve this issue.

References

Kolokythas, G.; De Maerschalck, B.; Wang, L.; Fonias, S.; Breugem, A.; Vanlede, J.; Mostaert, F. (2021). Modelling Belgian Coastal zone and Scheldt mouth area Modelling Belgian Coastal zone and Scheldt mouth area: Sub report 12: Scaldis-Coast model – Model setup and validation of the 2D hydrodynamic model. Version 4.0. FHR Reports, 15_068_12. Flanders Hydraulics Research: Antwerp

Kolokythas, G.; Fonias, S.; Wang, L.; De Maerschalck, B.; Vanlede, J. (2023). Modelling Belgian Coastal zone and Scheldt mouth area: Sub report 14: Scaldis-Coast model – Model setup and validation of the morphodynamic model. Version 4.0. FH Reports, 15_068_14. Flanders Hydraulics: Antwerp.

Maximova, T.; Vanlede, J.; Verwaest, T.; Mostaert, F. (2016). Vervolgonderzoek bevaarbaarheid Bovenzeeschelde: subreport 4 – Modelling Train CSM – ZUNO: validation 2013. WL Rapporten, 13_131. Waterbouwkundig Laboratorium: Antwerp

Studieteam Hoogtij(d) IMDC, Arcadis, ORG, Econopolis, Common Ground, An Luyten, Connect, LDR en Jeroen Bryon (2023) Synthese hydromorfologische analyses geoptimaliseerde alternatieven, I/RA/11630/23.051/ABO. Opgesteld in opdracht van Vlaamse Overheid- Departement Mobiliteit en Openbare Werken i.s.m. Agentschap Maritieme Dienstverlening en Kust MT/02401

Wang, L.; Kolokythas, G.; Fonias, S.; De Maerschalck, B.; Vanlede, J.; Mostaert, F. (2021). Modelling Belgian Coastal zone and Scheldt mouth area: Sub report 13: Scaldis-Coast model – Model setup and validation of the wave propagation model. Version 4.0. FHR Reports, 15_068_13. Flanders Hydraulics Research: Antwerp

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