NICOLAIDES
& Associates
Civil and Environmental
Engineers & Scientists

NUMERICAL COASTAL INVESTIGATION FOR THE CONSTRUCTION OF TWO BREAKWATERS AT PYRGOS LIMASSOL, CYPRUS.

MAY 2020

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BASIC DATA

Purpose of the report	Numerical coastal investigation related to the construction of two breakwaters in Pyrgos Limassol coastal area
Area of the project	Coastal area of Pyrgos - District of Limassol
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1 INTRODUCTION

1.1 General

This report details the results of the coastal analysis study undertaken for the installation of two breakwaters at the coast of Pyrgos, Limassol. The analysis assessed the sediment transportation, bed level change rate, wave currents and the wave agitation of the site for the following two scenarios:

- Current condition - no new breakwaters;
- Proposed works – Installation of two new breakwaters.

In addition, for the purpose of this report, a desk-based study was undertaken to further investigate the relevant environmental conditions of the site based on available information.

This assessment is a supplementary addition of the coastal study report undertaken by Spyros M. Gouloumis and issued by Nicolaides & Associates on November 2019. The coastal study undertook an in-depth investigation regarding the characteristics of the site and the design basis of the breakwaters. Therefore, only a brief description of the site and breakwater characteristics will be provided within this report.

1.2 Sources of Information

Reports and Source Database

Several sources of information have been reviewed to determine the environmental characteristics at Pyrgos, Limassol and are as follows:

- Coastal Zone Management for Cyprus: Nearshore Wave Climate Analysis by Xenia Loizidou and John Dekker, March 1994.
- Beach Evolution Caused by Littoral Drift Barrier by Deva K. Borah & Armando Ballofet. January 1986.

- Ακτομηχανική Μελέτη Έργων Προστασίας Ακτής Πύργου Λεμεσού, Σπύρος Μ. Γουλουμής & Νικολαΐδης και Συνεργάτες, Νοέμβριος 2019. This includes sources mentioned within the report that are relevant to the current study.
- ΜΕΕΠ για την κατασκευή έργων προστασίας και βελτίωσης της παραλίας παρά το ξενοδοχείο LE MERIDIEN της εταιρείας L΄ UNION NATIONALE TOURISM AND SEA RESORTS LTD, στην περιοχή Πύργου Λεμεσού, Παράρτημα 3.

1.3 Location of Site

The site is located on the South coast of Cyprus, on the east side of Saint Rafael Marina, Limassol (see Figure 1.1).

Figure 1.1. Site location. Source: Google Earth.

1.4 Project Background

The plot shown in Figure 1.2, is situated to the east of Saint Rafael Marina and is planned to be converted into a residential development.

Figure 1.2: Project area

The coastline is approximately 150m long and reefs located adjacent to the shore provide a lesser protection to the coastline. Three breakwaters were recently constructed near the shore to the West of the plot and provide protection to the coastline in front of an existing Hotel.

Two new breakwaters are proposed to be constructed immediately adjacent to the east of the three breakwaters in order to provide shelter to the coastline indicated in Figure 1.2. The new breakwaters are to protect potential users of the beach from incoming wave and to possibly reduce erosion caused to the coastline.

1.5 Scope of Study

The scope of the study is to assess the following listed below, before and after the installation of the breakwaters:

- mean and maximum wave conditions;
- the characteristic wave currents;
- the sediment transport;
- bed level change rate.

The results are then reviewed and compared, to assess the performance of the breakwaters and to discuss any potential impacts caused to the coast West and East of the plot. The study aims to address the following requests made by the Department of Environment Cyprus for the construction of the breakwaters (see Appendix E):

- Based on the results of the analysis, discuss and critical review the coastal impacts caused by the breakwaters to the coast situated shoreward, west and east of the proposed works.
- Examine the wave action and the wave currents of the surrounding coastal area before and after the construction of the breakwaters.
- Examine the sediment transport of the area and in particular to the coastline shoreward, east and west of the proposed works. In addition, assess any potential impacts to the sediment transportation around the reefs and to the posidonia oceanica and discuss any erosion or deposition of sediments during and after the construction of the breakwaters.

The above request that are related to the scenarios before and after the construction of the breakwaters are to be assessed through the coastal analysis platform Mike 21/3. Preventing measures are to be proposed in order to minimise potential impacts during the construction of the breakwaters

2 ENVIRONMETAL CONDITIONS REVIEW

2.1 General

This section presents a summary of key information used within the study to determine the environmental conditions at study area.

2.2 Bathymetry and Topography

The water depth nearshore is shallow, with water levels ranging between 0 to 5m. The water depth south of the coast is also relatively shallow. An extended and a close-up view of the modelled bathymetry is shown in Figure 2.1.

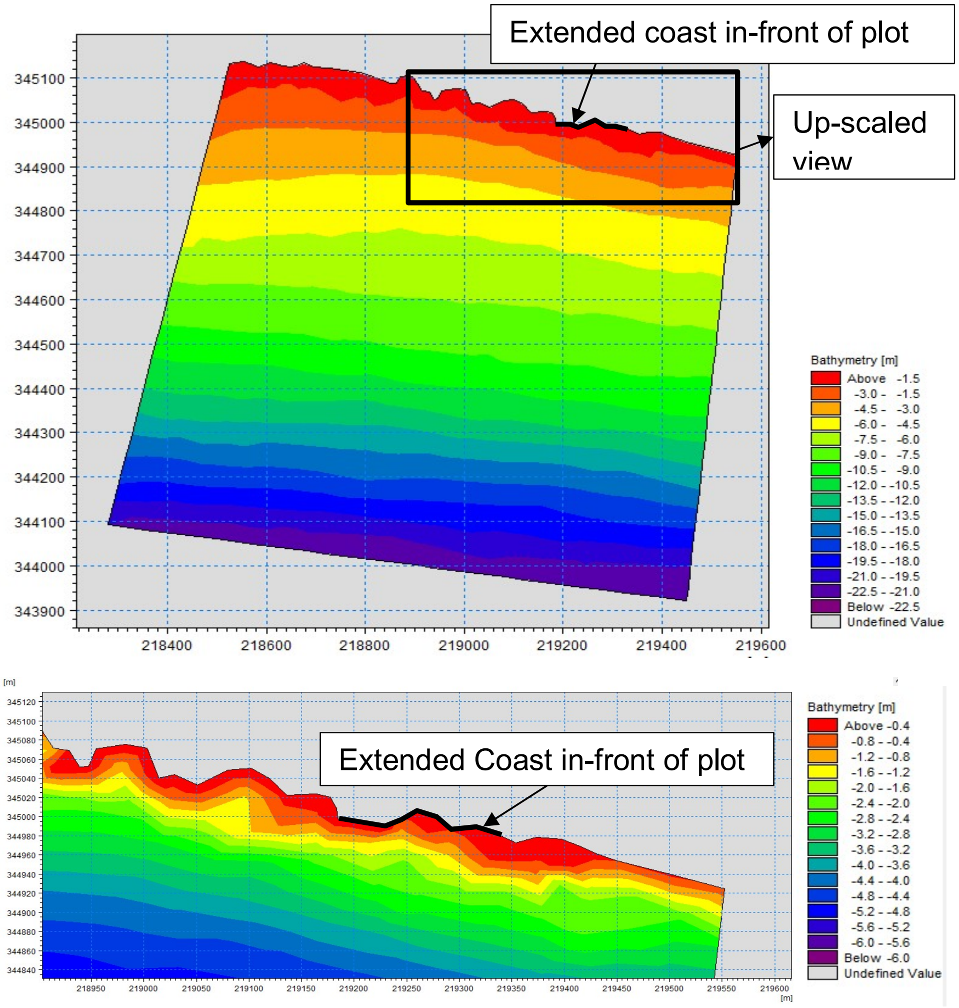


Figure 2.1: Bathymetry of modelled area

The proposed breakwaters are situated in close proximity to the coastline, at a water depth approximately equal to 4m. The model covers an area equal to 1200x1100m. The total length of the analysed coastline is approximately 1200m in length. The influence of the breakwaters to the coast is not expected to extend further than that examined in this study (shown in Figure 2.1) due to their relatively close position to the coastline.

2.3 Wind & Wave climate

The data of wave and wind frequency and intensity distribution of the area were collected from the study, “Coastal Zone Management for Cyprus: Nearshore Wave Climate Analysis - Xenia Loizidou”. Wind and waves characteristics were derived from ship observations to the South of Cyprus by KNMI (Royal Netherlands Meteorological Institute). The statistical analysis of wind data was performed by Harbours, Coasts and Offshore Technology Division, Delft Hydraulics (de Vroost) and provides the 1-year average wind direction and intensity. Relevant information is presented in Appendix G.

The most persistent wind direction is from the southwest and west with angles between 195°-285° and has a total frequency of 50.54%.

According to the statistical wave database mentioned above, the characteristics of the incoming maximum wave conditions selected for this study are presented in Table 2.1. The direction and intensity of the four cases are considered to have the biggest impact to the coastal morphology of the area of study.

Table 2.1: Maximum wave conditions at a water depth equal to 20m.

Direction (deg)	Significant Wave Height (m)	Peak period (s)
150	2.75	7.14
180	3.75	8.34
210	3.75	8.34
240	2.25	6.46

2.4 Yearly equivalent Wave climate

The yearly equivalent wave conditions were calculated based on the four cases shown above. The representative wave period was calculated using Equation 1 and the representative significant wave height using Equation 2, according to Borahand Bolloffet (1985).

$$T_e = \frac{\sum H_i^2 * T_i * f_i}{\sum f_i} \qquad (\mathbf{1})$$

$$H_e^2 * T_e = \frac{\sum H_i^2 * T_i * f_i}{\sum f_i} \qquad (\mathbf{2})$$

Where:

$H_i, T_i, f_i,$ are the wave height, wave period and frequency of occurrence of waves that correspond to the various intensity levels of wind of each direction.

The calculated equivalent yearly wave conditions are presented in Table 2.2.

Table 2.2: Calculated equivalent yearly wave conditions used for the analysis

Direction (deg)	Equivalent Wave Height H_e (m)	Equivalent wave period T_e (s)
150	0.90	4.73
180	0.89	4.76
210	1.16	4.84
240	1.13	4.89

2.5 Sediment Characteristics

The sediment characteristics were derived from previous sediment investigations performed for the construction of the three breakwaters that are currently situated adjacent to the location of the proposed works (refer to ΜΕΕΠ για την κατασκευή έργων προστασίας και βελτίωσης της παραλίας παρά το ξενοδοχείο LE MERIDIEN της εταιρείας L΄ UNION NATIONALE TOURISM AND SEA RESORTS LTD, στην περιοχή Πύργου Λεμεσού, Παράρτημα 3).

During the above indicated investigations samples of the sediments were collected from the seabed at depths of 4-5.5m and 7-8.5m. The samples were analysed and the characteristic mean grain diameter d_{50} was established. The analysis concluded that the mean grain diameter of the site equals to 0.2mm.

3 METHODOLOGY OF ANALYSIS

3.1 Introduction

The model used within the study is MIKE 21/3 CM (coupled model) powered by DHI group. MIKE 21/3 is a software package for modelling of hydrodynamics, waves & sediment dynamics. The software solves the equations for the conservation of mass and momentum based on Reynolds averaged Navier-stokes and assesses the hydrographic conditions for design and operation of structures in stratified and non-stratified waters. The Spectral Wave Module simulates the growth, decay and transformation of wind-generated waves in coastal areas and can be used to study the morphological evolution of the coast. Basic information on the MIKE 21 software is included in Appendix F.

3.2 Model Set Up

The analysis has examined the following:

- Hydrodynamic Module – Calculate the flow, current and forces generated by the wave conditions;
- Spectal Wave module – Calculate the sea state characteristics of the mean and maximum wave conditions;
- Sediment Transport Module – Calculate the statistical mean sediment transport and bed level change rate of the site using input data and information calculated from the Hydrodynamic and Spectral Wave module.

The analysis involved the following two scenarios:

- Current condition - no new breakwaters;
- Proposed works – Installed two new breakwaters.

The changes to the wave conditions due to shoaling were calculated at a water depth equal to 6m and the results were used to the final model area shown in Figure 3.1.

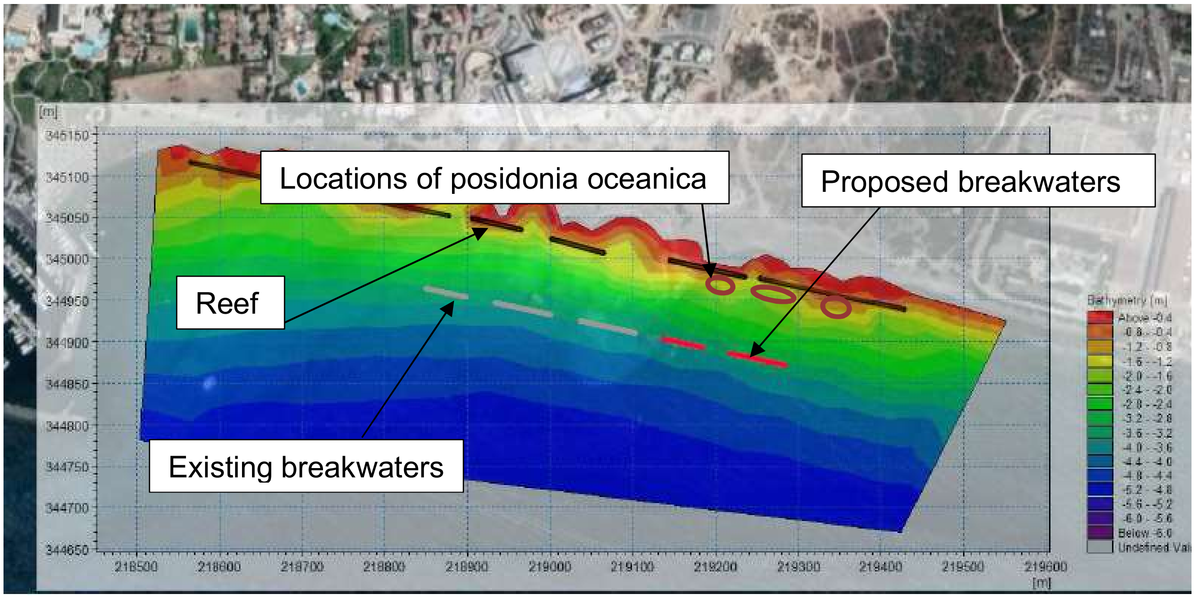


Figure 3.1: Model area used for the analysis.

It should be noted that the location of the posidonia oceanica were established from a site survey carried out during the preparation of the Environmental Impact Assessment report of the proposed breakwaters. Figure 3.2 below indicates the results of this site survey.

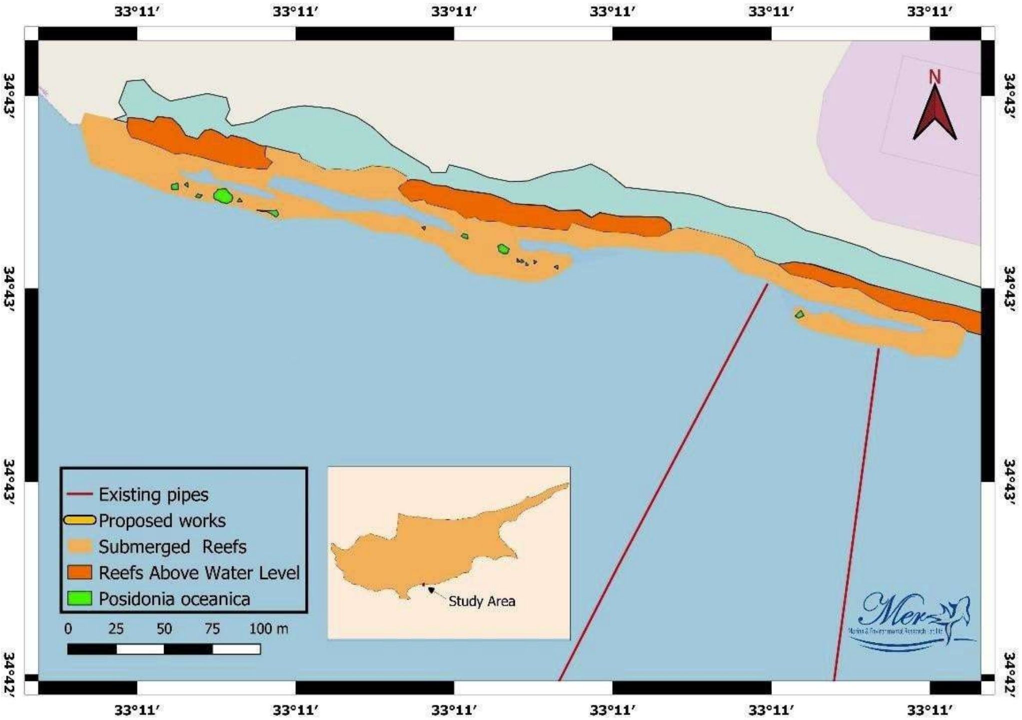


Figure 3.2: Results of the Posedonia oceanica site survey

3.3 Inputs of the model

Model runs have been undertaken assuming random waves based on a JONSWAP wave spectra with a spectral shape parameter of $\gamma = 3.3$.

Wave parameters (Hs, Tp and direction) have been selected for different scenarios based on the information review discussed in Section 2. Wave breaking, diffraction, reflection, bottom friction, refraction, etc. are all taken into account by the software calculations.

The input height of the breakwaters was set to extend 0.5m above the water level, as originally proposed. The length of the west breakwater was set to 60m and the length of the east to 75m.

The wave input parameters are shown in Table 2. Scenario A relates to the scenario that includes both the existing and proposed breakwaters and Scenario B to the scenario that includes only the existing breakwaters.

Table 3.1: Input wave parameters analysed

Scenario A – With Proposed Breakwaters			
Name	**Direction**	**Hs (m)**	**Tp (s)**
A – D150.Hs0.9.T4.73s	150	0.90	4.73
A – D150.Hs2.75.T7.14s	150	2.75	7.14
A – D180.Hs0.89.T4.76s	180	0.89	4.76
A – D180.Hs3.75.T8.34s	180	3.75	8.34
A – D210.Hs1.16.T4.84s	210	1.16	4.84
A – D210.Hs3.75.T8.34s	210	3.75	8.34
A – D240.Hs1.13.T4.89s	240	1.13	4.89
A – D240.Hs2.25.T6.46s	240	2.25	6.46
Scenario B – Without Proposed Breakwaters			
Name	**Direction**	**Hs (m)**	**Tp (s)**
B – D150.Hs0.9.T4.73s	150	0.90	4.73
B – D150.Hs2.75.T7.14s	150	2.75	7.14
B – D180.Hs0.89.T4.76s	180	0.89	4.76
B – D180.Hs3.75.T8.34s	180	3.75	8.34
B – D210.Hs1.16.T4.84s	210	1.16	4.84
B – D210.Hs3.75.T8.34s	210	3.75	8.34
B – D240.Hs1.13.T4.89s	240	1.13	4.89
B – D240.Hs2.25.T6.46s	240	2.25	6.46

4 RESULTS & DISCUSSION BEFORE AND AFTER THE CONSTRUCTION OF BREAKWATERS

4.1 General

This section details the main findings of the analysis for all scenarios indicated in Section 3.3. This includes discussion and critical review of the results and concentrates on the performance of the proposed breakwater and their impact compared to the current condition of the site. The following four categories of coastal parameters are discussed:

- Wave conditions;
- Sediment transport;
- Bed level change rate;
- Hydrodynamic behaviour.

The observations and differences between the two scenarios (with and without proposed breakwaters) were consistent, therefore, the analysis of some results were omitted within this section. However, all detailed results are presented in the Appendices A through D. Two figures are provided in the Appendices for each case (refer to Table 3.1). One figure shows an extended view of the total modelled area and a second figure a close up view that focuses on the area behind the proposed breakwaters.

For the purpose of this report the term “area behind” the breakwaters or “behind the reefs” will be used to refer to the area situated to the shoreward side. The term “site area” describes the area and coastline shoreward of the proposed breakwaters.

The analysis of the model did not consider the influence of the marina situated to the west of the modelled area. This is a conservative approach and incoming waves from the southwest would normally have smaller impact to the sediment transportation of modelled area.

4.2 Wave Conditions

The wave conditions were analysed for all cases with mean wave directions of 150°, 180°, 210° and 240°. Figures presented in Appendix A show the mean significant wave height.

The output trend among the analysed cases was similar, therefore, only one case for both scenarios is presented in this section for illustrative purposes. The following figures indicate the wave conditions for the case with wave direction 180°, wave height 0.89m and wave period 4.76s.

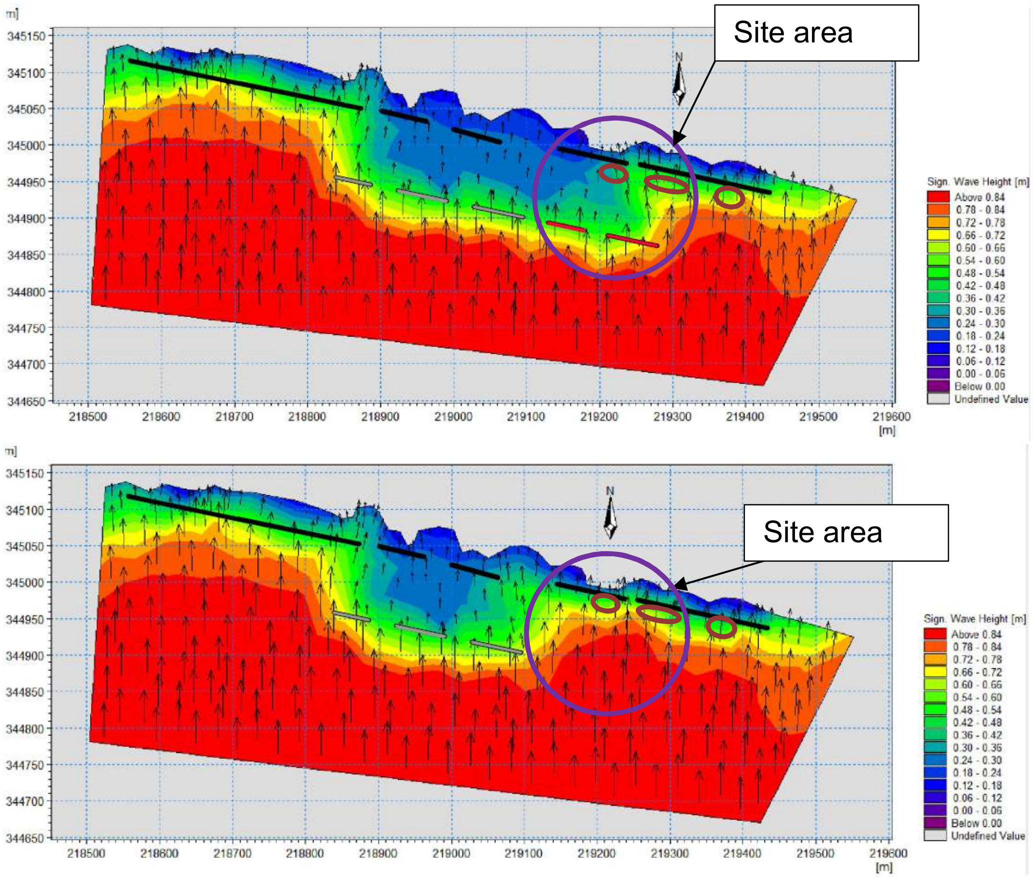


Figure 4.1: Significant wave height for the case with wave direction 180°, H_e=0.89m and T_e=4.76s. (Proposed breakwaters (red —), Existing breakwaters (grey —), reefs (black —), location of posidonia oceanica (○))

As expected, a reduction of the wave energy is observed to the area protected by the existing breakwater and as a result the magnitude of the wave action is lower compared to other areas.

In addition, areas that are situated behind the natural reefs are also protected by the wave action creating safe areas for swimmers. However, those areas are considered to be relatively small in capacity and have shallow water depths. Therefore, these areas are mostly suitable for the young swimmers.

Referring to the results of Scenario B (without proposed breakwaters), the cases with wave directions between 180° to 240°, show to cause the most severe wave conditions.

Cases with input of the equivalent yearly average (H_e), show values of significant wave heights up-to 0.8m, within a 25m radius from the coastline of the site. These wave conditions can generate large wave heights in excess of 1m and are not recommended for public beaches with amateur swimmers. Cases with extreme wave conditions, significant wave heights can reach up-to 1.25m within 25m radius from the coast, however, the frequency of these is low.

With the installation of the proposed breakwaters (refer to figures in Appendix A), the significant wave heights behind the breakwaters are considerably reduced. The significant wave height for cases simulating H_e conditions, is mostly constraint at values up-to 0.40m within 25m radius from the coast of the site. Only a small area to the east of the site reaches values up-to 0.66m. The same behaviour is observed for the cases with extreme wave conditions, where significant wave heights are reduced and reach up-to 0.5m, apart from a small area to the east of the coast reaching up-to 0.75m. The intensity of waves that pass through the gaps of the proposed breakwaters is also reduced. As observed in Figure 4.1 and in figures presented in Appendix A, some part of the wave energy is diffracted by the breakwater gaps to the protected area. However, a large percentage of the energy is efficiently dissipated by the breakwaters and still reduce the wave field amplitude to the areas immediately behind the breakwaters and between their gaps. Significant wave heights reach up-to 0.72m at a number of small areas situated between the gaps and immediately behind the breakwaters

These levels of significant wave height are considered satisfactory for the public use of the beach as they only occur locally to small areas and are situated in close proximity to the breakwaters. The same behaviour and levels are observed to the areas immediately behind the existing breakwaters.

With the installation of the breakwaters, no significant changes are observed to the wave action at the coasts to the east coast of the area of study. The values remain almost unchanged with significant wave heights to reach up-to 0.75m. The impact of the proposed breakwaters to the area west of the site is also insignificant and incident waves remain low due to the protection of the existing structures. In some cases, the proposed breakwaters enhance the protection west coast adjacent to the site and the incoming wave action is reduced to a lesser degree. This increases the safety of the existing beach and creates a more suitable environment for the public use of the beach.

4.3 Sediment Transport & Bed Level Change Rate

The statistical mean sediment transport and bed level change rate was analysed for all cases that had as initial input the wave equivalent yearly average H_e and T_e. The main inputs of the analysis were the mean grain diameter and the output results of the hydrodynamic and wave analysis. Figures presented in Appendix B show the volumetric sediment transport per year per metre for all examined cases. Figures presented in Appendix C show the bed level change in meters per day. The trend of the output between cases of the two scenarios was similar, therefore, only one case for both scenarios is presented in this section for illustrative purposes.

The following figures indicate the sediment transport and bed level change rate for the case with wave direction 180°, wave height 0.89m and wave period 4.76s.

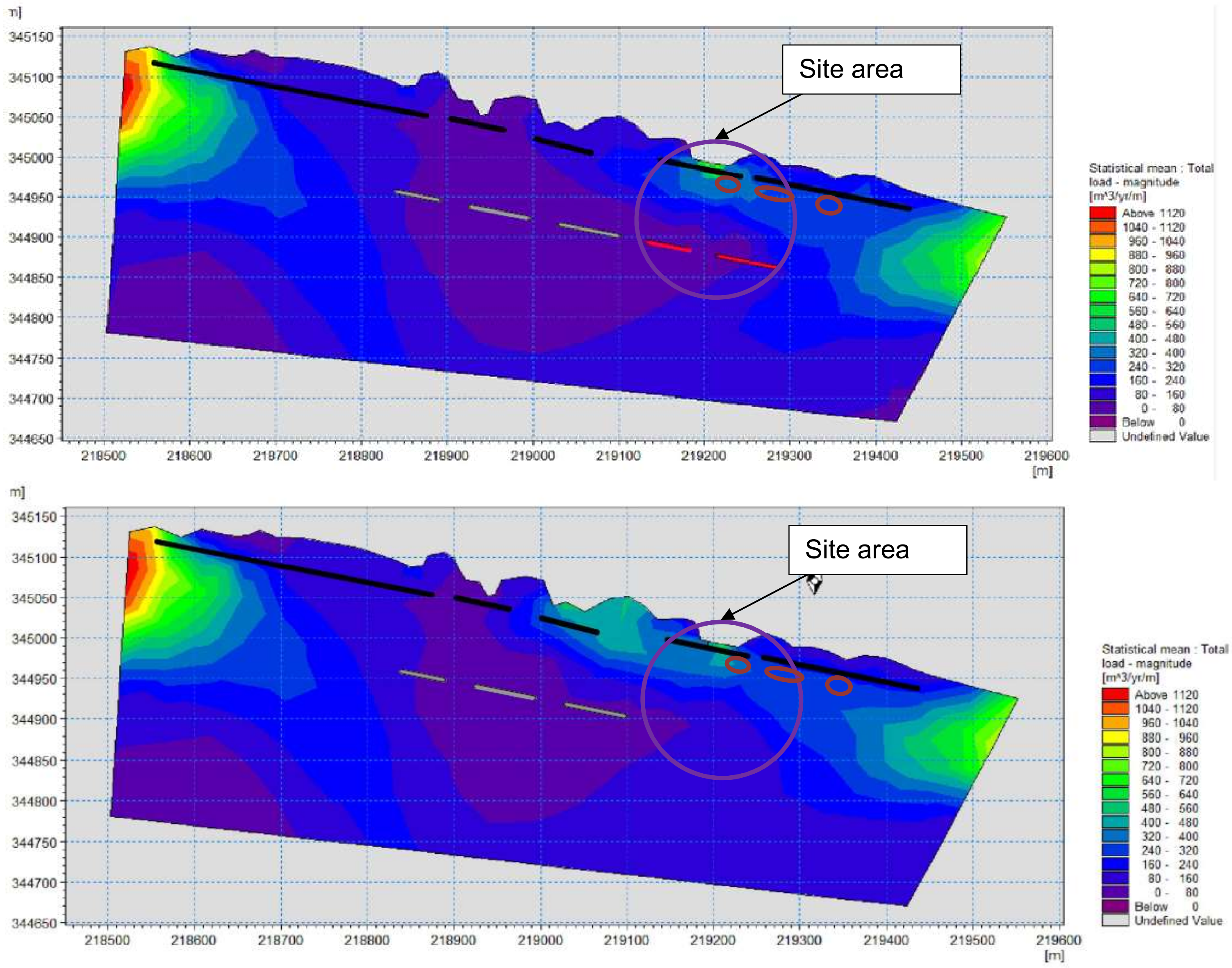


Figure 4.2: Sediment transport for the case with wave direction 180°, H_e=0.89m and T_e=4.76s. (Proposed breakwaters (red —), Existing breakwaters (grey —), reefs (black —), location of posidonia oceanica (○)

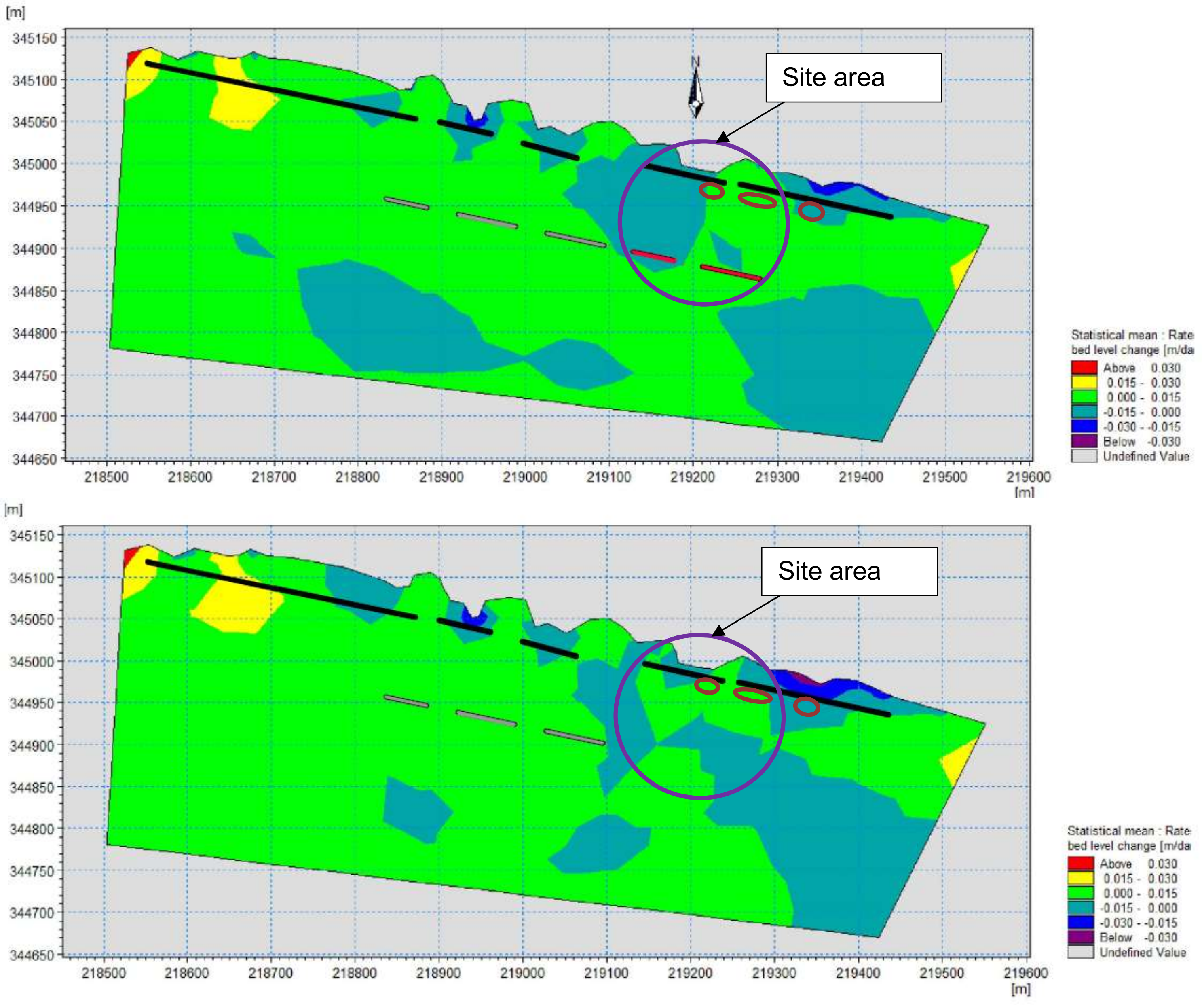


Figure 4.3 Bed level change rate for the case with wave direction 180°, H_e=0.89m and T_e=4.76s. (Proposed breakwaters (red —), Existing breakwaters (grey —), reefs (black —), location of posidonia oceanica (○)

As expected, the sediment transport was greatly influenced by the direction of the wave action. Cases with waves propagating from the southwest, have sediments transportation from east to west, parallel to the coastline. The same trend was observed for the cases with waves propagating from the south east, with sediments being transported from west to east. Similar behaviour was observed for both scenarios (with and without the proposed breakwaters).

Referring to the results of Scenario B (without proposed breakwaters), it is observed that the sediment transport is reduced to the protected shore behind the currently installed breakwaters. The coastline that is situated behind the reefs is also protected and therefore, a reduced transport exists to those. However, the analytical results indicate that the magnitude of the morphological changes experienced by the overall modelled area is minor. The bed level change rate to the majority of the total area ranges between 0.015 to -0.015m/day. Erosion to the bed and to the shoreline is mainly observed to areas behind the reefs. Erosion is more profound to the shoreward area behind the western reef which agrees with the current formation of the coastline where small bays have currently formed behind them. A small area of deposition is observed shoreward of the existing breakwaters for the case with wave direction 150°. The bed level change rate ranges between 0.015m/day to 0.03m/day.

An increased sediment transportation is observed to the western and eastern areas in front of the reefs. This is believed to be caused by the relatively strong incoming currents that propagate from the western and eastern directions and possibly from the waves reflected by the reefs.

With the construction of the proposed breakwaters, the sediment transport is slightly reduced to the coast situated to the shoreward area. The breakwaters reduce the incident wave energy and therefore reduce the erosion of the coastline to a lesser degree. Breakwaters can trap wave currents that are being reflected by the coast and carry suspended sediments. This restricts the escape of sediment transport from the protected shoreline. Evident of the trap currents is shown to the hydrodynamic results and are discussed in more detail in the subsection further below.

Calm hydrodynamic conditions and suspended sediment concentrations can cause sediment deposition to the area. In other areas situated shoreward of the breakwaters a minor reduction of sediment deposition is observed. This is believed to be caused by the alternation of the wave current path developed to the area and the prevention of suspended sediment carried by these currents entering the protected area. However, due to the small magnitude of the morphological evolution of the area, the sediment deposition caused by the breakwaters is minor and insignificant. This is evident by the small changes of the bed level rates which remain within the range of 0.015 to -0.015m/day as with the scenario without the proposed breakwaters.

The coastal areas situated to the shore west and east of the proposed breakwaters show minor or no differences to the morphological evolution of the area between the two scenarios. The bed level change rates show minor or no changes and the magnitude of bed erosion/deposition remains the same as with the scenario without the proposed breakwaters. This shows that the influence of the proposed breakwaters to the morphology of the area is insignificant.

The same conclusions are drawn to the areas where posidonia oceanica are located. The sediment transport and bed level change rates remain unchanged and range between 0.015m/day to -0.015m/day. Therefore, this concludes that the proposed breakwaters do not influence the morphological evolution of posidonia oceanica ecosystem.

4.4 Hydrodynamic behaviour

The hydrodynamic behaviour of the area was analysed for all cases that had as initial input the wave equivalent yearly average H_e and T_e. The wave conditions of this analysis used the analytical output derived from the wave module. Figures presented in Appendix D, show the wave current velocity with the directional vectors for all the examined cases. The trend of the output between cases of the two scenarios was similar, therefore, only one case for both scenarios is presented in this section for illustrative purposes.

The following figures show the current output for the case with wave direction 180°, wave height 0.89m and wave period 4.76s.

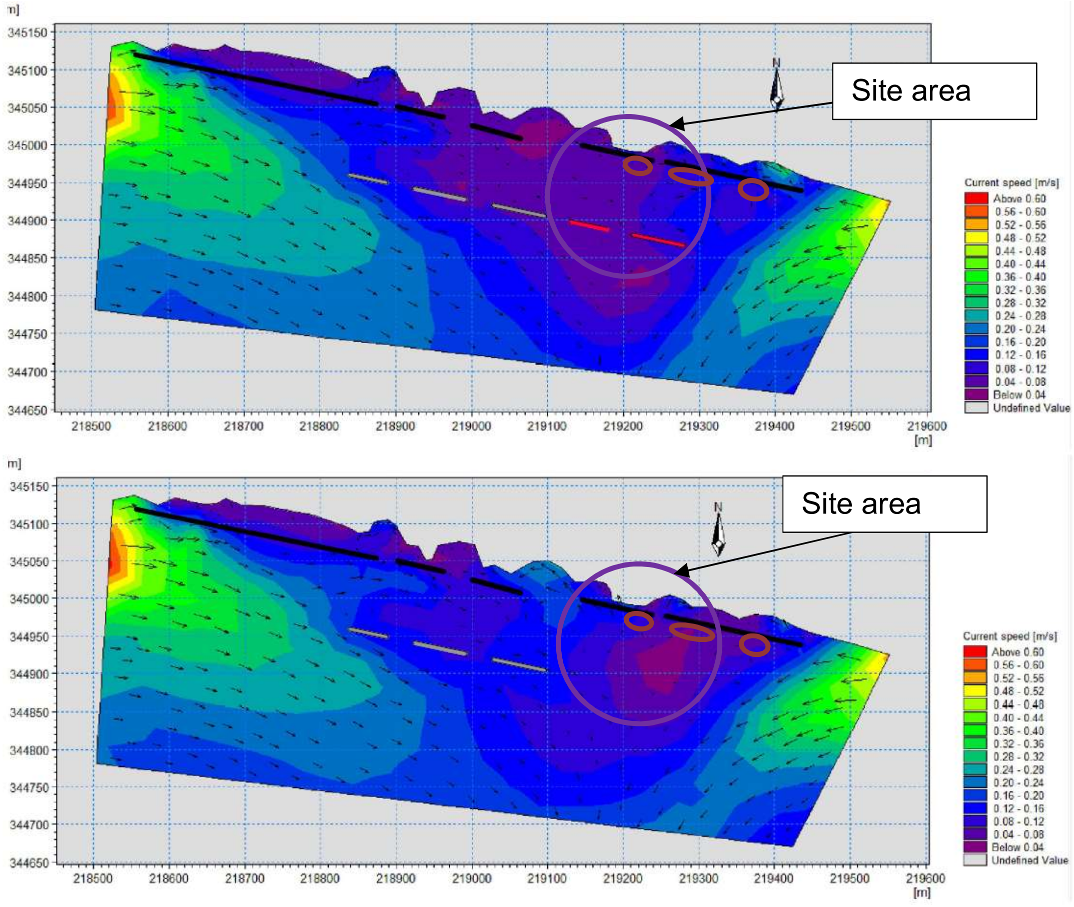


Figure 4.4: Wave currents for the case with wave direction 180°, H_e=0.89m and T_e=4.76s. Proposed breakwaters (red —), Existing breakwaters (grey —), reefs (black —), location of posidonia oceanica (○)

East and west of the model, the currents propagate parallel to the coast with a direction inwards to the model. Moving towards the centre of the model, the direction of the currents shift and continue to propagate to the offshore. This indicates that suspended sediment is transported to the offshore. Higher speeds are mostly observed to the western and eastern area of the model. These areas are not protected by breakwaters or reefs.

Referring to the analysis of Scenario B (without proposed breakwaters), it is observed that areas situated shoreward of the current breakwaters, show a reduction of the current speeds. This creates a safer and more suitable environment for the public use of the beach.

With the absence of the proposed works, the current breakwaters show to provide a degree of protection to the site area, however, still in some cases the current speeds reach values up-to 0.45 m/s in close proximity to the coastal bay. These levels of current speed are considered strong and may cause safety issues to the public using the beach.

A circulation pattern of flow is observed inside the protected area, shoreward of the breakwaters. This prevents to a lesser degree, suspended sediments to be transported away or in from the protected coast, as discussed in Sub-section 0.

Referring to the analysis of Scenario A (with proposed breakwaters), a reduction of the current speeds is observed within the area of study. The current speed to the majority part of the site area values reach up-to 0.15m/s. The speed of the currents to the eastern and western coast of the model remain almost unchanged and show a similar behaviour with the analysis of Scenario B. The speeds are reduced to a lesser degree to the east of the area of study, however, as similarly indicated in the sediment transport analysis, the magnitude of change is insignificant.

The results show that with the installation of the proposed breakwaters, the protected area has reduced wave current speeds which creates a suitable environment for swimmers to use the beach. No high current speeds are observed to be generated between the gaps of the breakwaters. Current speed levels to areas situated between the gaps or immediately behind the breakwaters are similar to the rest of the protected areas and reach up-to a maximum of 0.08m/s.

The proposed breakwaters do not show to cause any significant changes to the currents of the surrounding area or to the area where posidonia oceanica are located, but only to the protected areas shoreward of the breakwaters.

5 PREVENTION MEASURES DURING CONSTRUCTION OF BREAKWATERS

5.1 General

Suspended sediments caused by the breakwater construction may be transferred to the water column. The volume of excavation that will take place during the construction of the two breakwaters is very small and therefore the potential negative impact to the aquatic organisms or to posedonia oceanica beds situated north of the construction, near the shore can be considered as negligible. However the following section details preventing measures that can be used during the construction of the works in order to eliminate any small potential impact to the surrounding area from suspended material and deposition.

5.2 Discussion on Preventing Measures

The construction of breakwaters requires excavation and levelling of the seabed. During the construction of numerous and long breakwaters this excavation and levelling can cause suspension of sediment to enter the water column and can have negative impacts to the aquatic organisms or to posedonia oceanica beds situated to the surrounding area.

As discussed in Section 4, the wave currents in most cases have low speeds around the location of the proposed location breakwaters and their direction is towards the offshore, which is to the opposite direction of the posidonia oceanica beds. This considerably reduces the risk of suspended sediments transferred to the posidonia oceanica beds since suspended sediments are more likely to be transferred to the offshore and follow the direction of the currents. However, there is still a very small risk that a small amount of suspended sediment can be transferred to those areas. Therefore, a silt screen can be installed during the levelling of the seabed, to mitigate against the suspended sediments.

Silt screens are floating geo-textile barriers used in the marine construction to control silt and sediment in a body of water.

The silt screens will enclose the area of construction and will provide a barrier extending from the water surface to an appropriate depth that will prevent suspended sediments to be transferred by the water column. The screen will contain and capture the suspended sediments within a limited area and provide enough residence time so that sediments settle back to the seabed within the contained area.

Furthermore, during the construction, excavation activities should take into account the direction of the water movement. If water currents are relatively strong or propagate towards the shore then the excavation activities should be stopped to avoid the disturbance of the seabed and movement of sediments.

6 CONCLUSION

6.1 General

A coastal analysis has been undertaken for the two proposed breakwaters at Pyrgos, Limassol. The breakwaters extend 0.5m above mean water level and have a length of 60m and 75m. Refer to Ακτομηχανική Μελέτη Έργων Προστασίας Ακτής Πύργου Λεμεσού for more details about the breakwaters design, location and other.

This study analyzed the hydrodynamic behaviour, the wave action, sediment transport and bed level change rates of the coastal area before and after the construction of the breakwaters. The study aimed to examine the performance of the two breakwaters and to identify any potential environmental impacts caused to the surrounding area and in particular to the coast west and east of the site area.

The performance of the breakwaters was examined by conservatively assuming the area to the west of the model is an open coast and has not considered the presence of St. Rafael marina. However, in reality the marina would considerably reduce the incoming wave energy propagating from the southwest. This would result in lower wave currents and sediment transportation levels of the model.

In addition, preventing measures were proposed that will be used during the construction of the works in order to minimize any potential impact to the surrounding area from suspended material and deposition.

A discussion and a critical review of the results was undertaken, and a summary of the main findings is presented below.

6.2 Summary

- Without the presence of the proposed breakwaters, the incident wave heights to the site area are considered to be high for the public use of the beach. The mean wave heights can reach up-to 0.8m within 25m radius from the coastline. The proposed breakwaters considerably reduce the wave action to the site area and provides a satisfactory protection for the public use of the beach.
- The construction of the two proposed breakwaters show to have no or insignificant impact to the wave conditions at the coasts situated west and east of the protected area.
- The erosion of the coastline shoreward of the proposed breakwaters is reduced and the magnitude of the sediment transportation of the sea bed is lowered.
- The proposed works cause insignificant impacts to the sediment transportation to the sea-bed and the area around the natural reefs to the east or to the west coast. A minor reduction of suspended sediments is observed and a reduction of sediment erosion to the coastline protected by the breakwaters.
- The change caused to the deposition and erosion rates at areas in close proximity of the proposed breakwaters is insignificant and in some parts it remains unchanged. The magnitude of the bed level change rate remains insignificant and majority ranges between 0.015m/day to -0.015m/day for both scenarios. The deposition/erosion of areas situated further west, east and south of the breakwater remain unchanged.
- The bed level change rate to areas with posidonia oceanica beds range between 0.015m/day to -0.015m/day and remains unchanged with the construction of the breakwaters. This is evident that the proposed breakwaters do not influence the current morphological evolution to those areas.

- The proposed works provide an additional protection to the beach situated west of the site area and slightly reduce the current velocities. The speed of the wave current within the protected area is reduced and creates a safer and suitable environment to public users of the beach.
- For the reasons summarized below, it is concluded that during the construction of the proposed breakwaters there will be no negative impacts to the surrounding area or to the areas where posidonia oceanica beds are located.
    - During the construction of the breakwaters the area can be enclosed by silt screens that will contain the sediments suspended by the works. This will prevent any potential transport of the sediments to the surrounding areas.
    - If the speed of the currents is relatively high and the direction is towards the shore, then works that cause excessive disturbance to the seabed will be minimized.
    - The hydrodynamic analysis of the area shows the wave currents at the location of the proposed breakwater have low speeds and, in most cases, propagate towards the offshore and therefore opposite of the posidonia oceanica bed locations. This shows that suspended sediments are more likely to be transferred to the offshore and follow the direction of the currents. In addition, the low speed of the currents will possibly lead to the majority of sediments to settle without being transferred far from the location of the disturbance.

APPENDICES

APPENDIX A	**WAVE CONDITIONS RESULTS**
APPENDIX B	**SEDIMENT TRANSPORT RESULTS**
APPENDIX C	**BED LEVEL CHANGE RATE RESULTS**
APPENDIX D	**HYDRODYNAMIC RESULTS**
APPENDIX E	**REQUEST OF ADDITIONAL INFORMATION BY THE DEPARTMENT OF ENVIRONMENT CYPRUS**
APPENDIX F	**MIKE 21/3 ADDITIONAL MODEL PACKAGE INFORMATION**
APPENDIX G	**WAVE AND WIND CONTIONS**

APPENDIX A WAVE CONDITIONS RESULTS

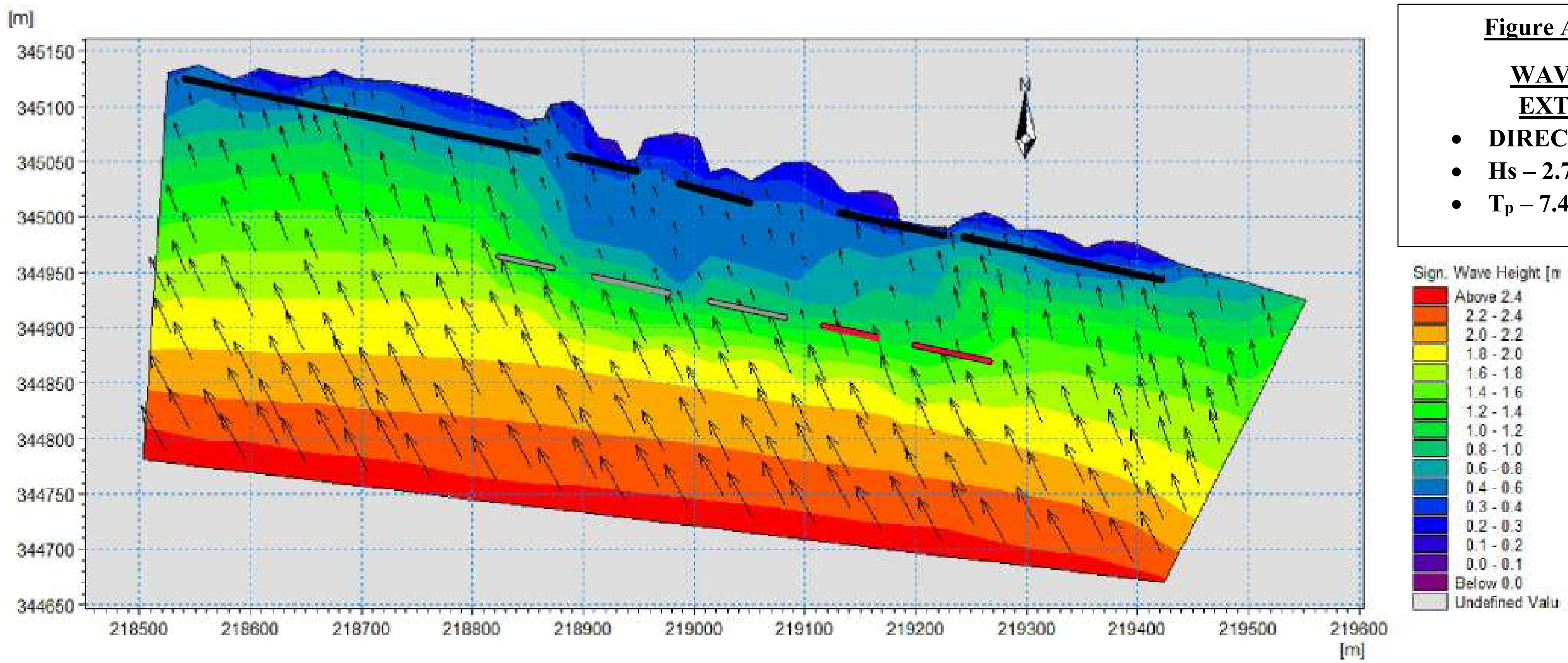


Figure A1 - SCENARIO A

WAVE CONDITION
EXTENDED VIEW

- **DIRECTION - 150°**
- **Hs – 2.75m**
- **T_p – 7.41s**

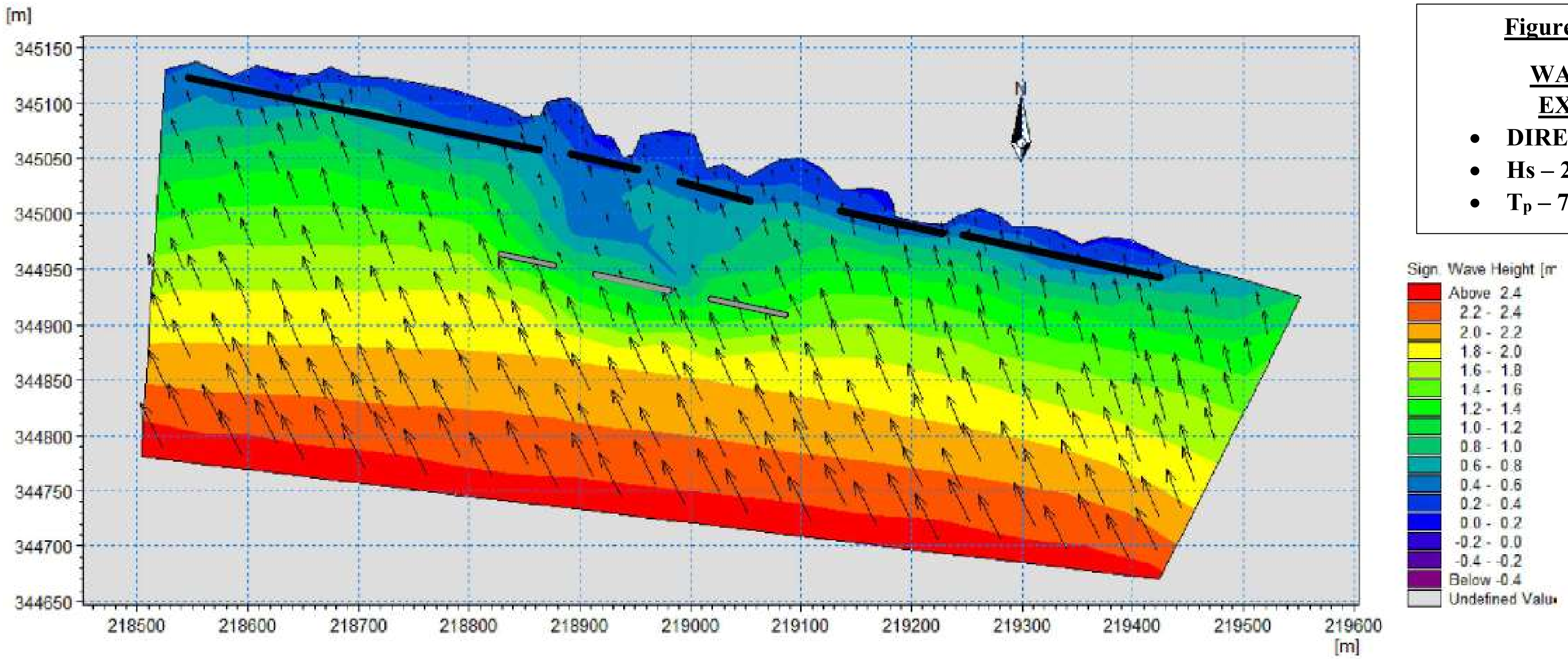


Figure A2 - SCENARIO B

WAVE CONDITION
EXTENDED VIEW

- **DIRECTION - 150°**
- **Hs – 2.75m**
- **T_p – 7.41s**

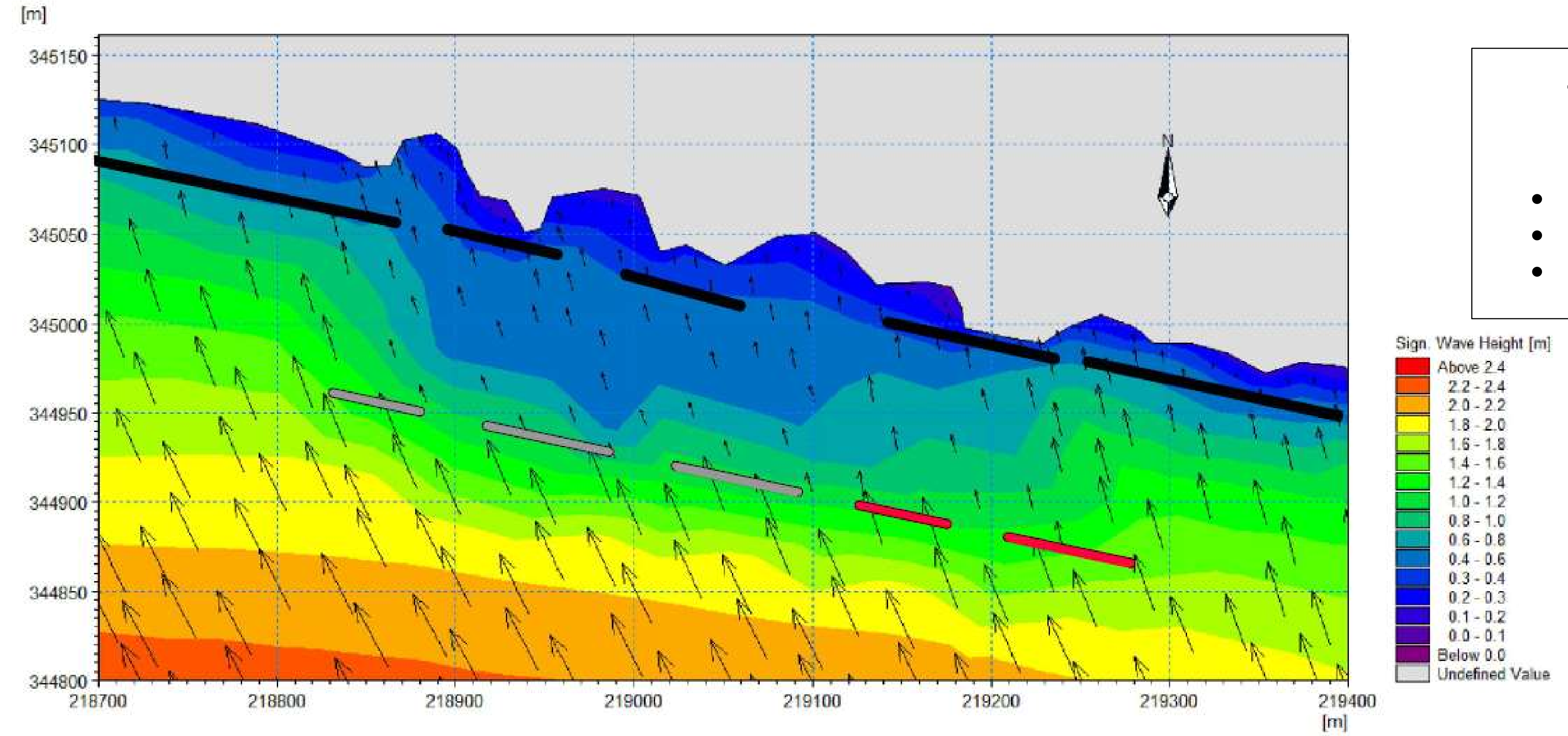


Figure A3 - SCENARIO A

WAVE CONDITION
CLOSE UP VIEW

- **DIRECTION - 150°**
- **Hs – 2.75m**
- **T_p – 7.41s**

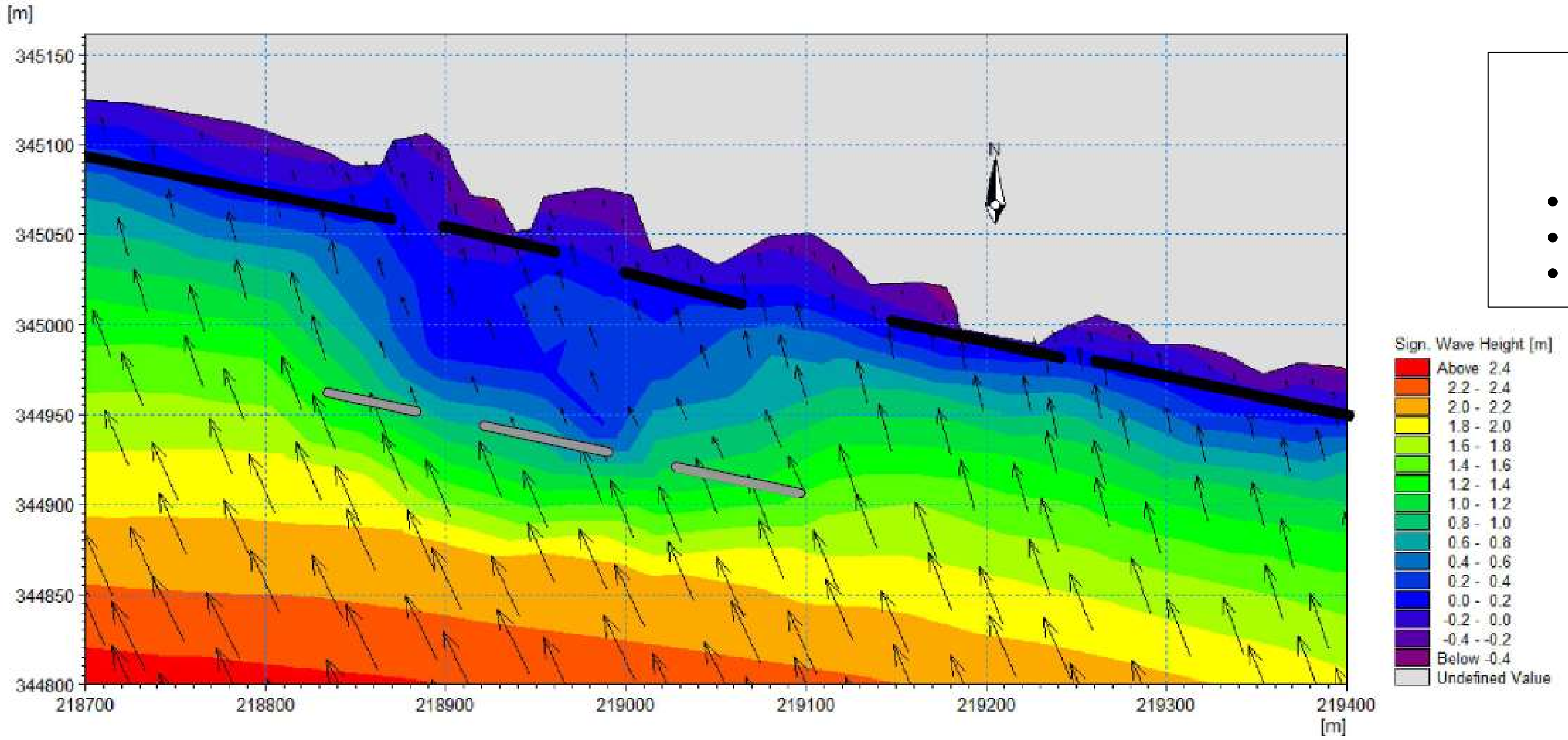


Figure A4 - SCENARIO B

WAVE CONDITION
CLOSE UP VIEW

- **DIRECTION - 150°**
- **Hs – 2.75m**
- **T_p – 7.41s**

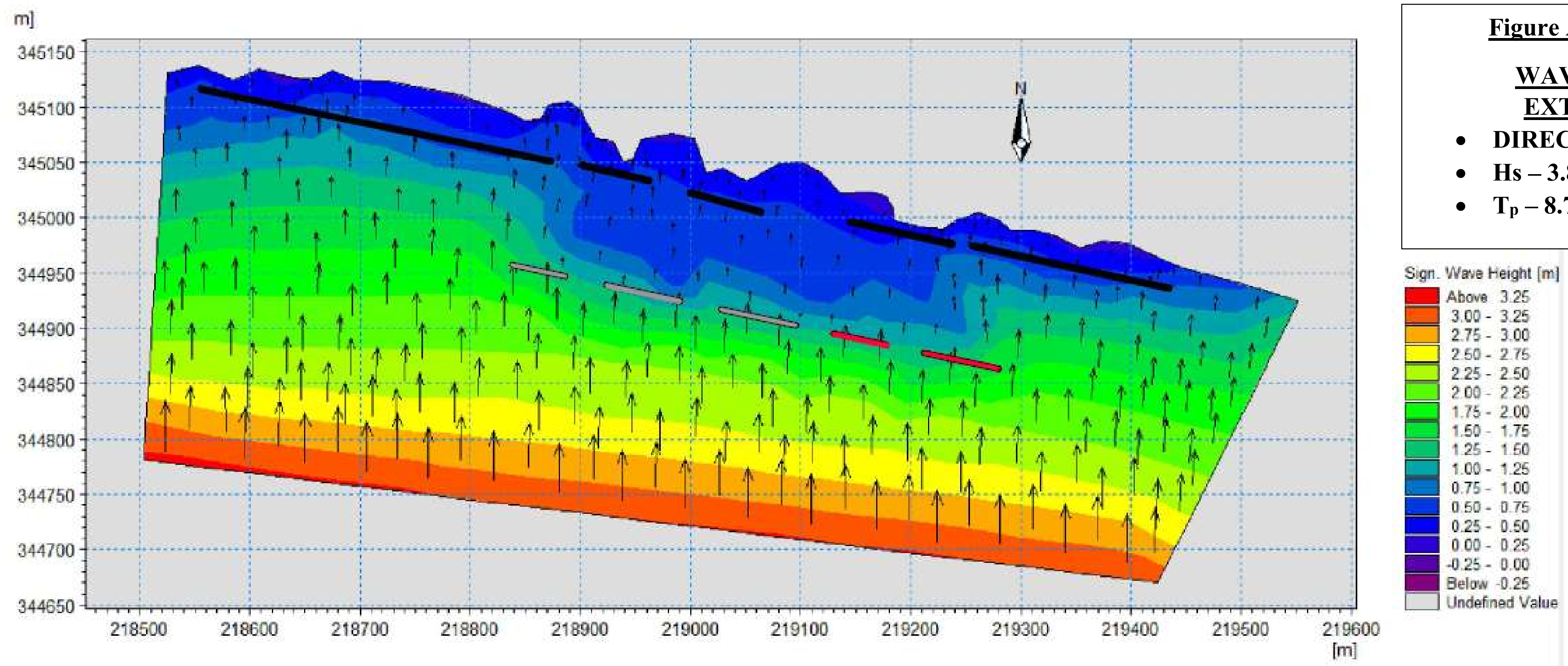


Figure A5 - SCENARIO A

WAVE CONDITION
EXTENDED VIEW

- **DIRECTION - 180°**
- **Hs – 3.85m**
- **T_p – 8.72s**

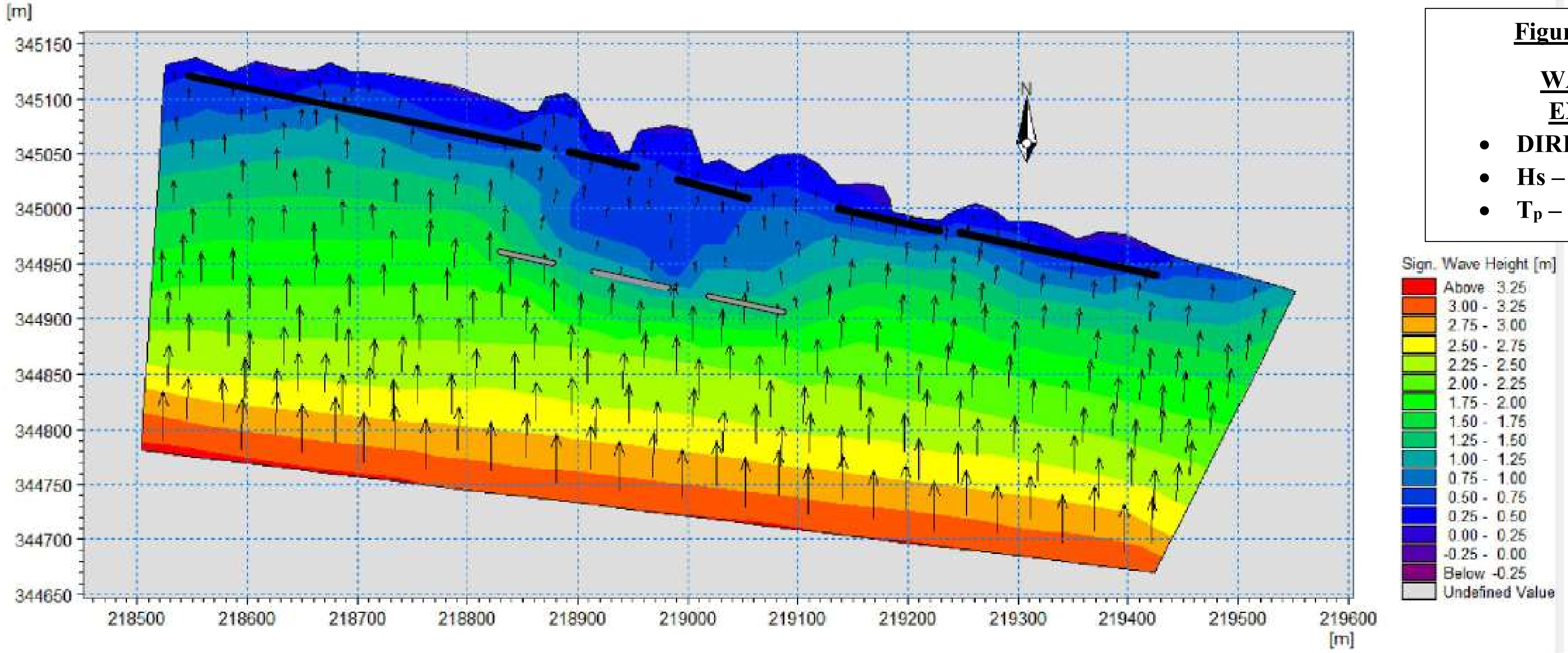


Figure A6 - SCENARIO B

WAVE CONDITION
EXTENDED VIEW

- **DIRECTION - 180°**
- **Hs – 3.85m**
- **T_p – 8.72s**

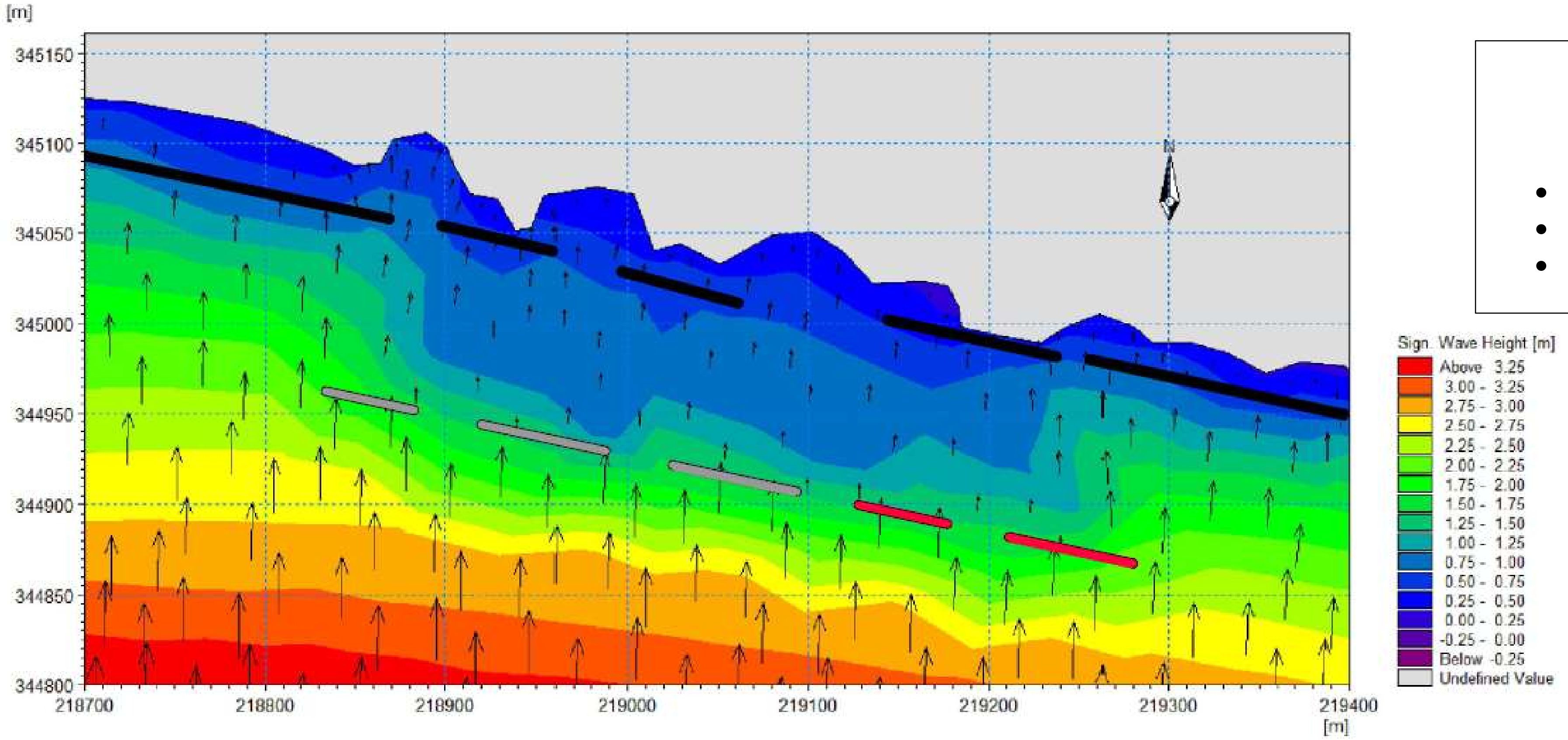


Figure A7 - SCENARIO A

WAVE CONDITION
CLOSE UP VIEW

- **DIRECTION - 180°**
- **Hs – 3.85m**
- **T_p – 8.72s**

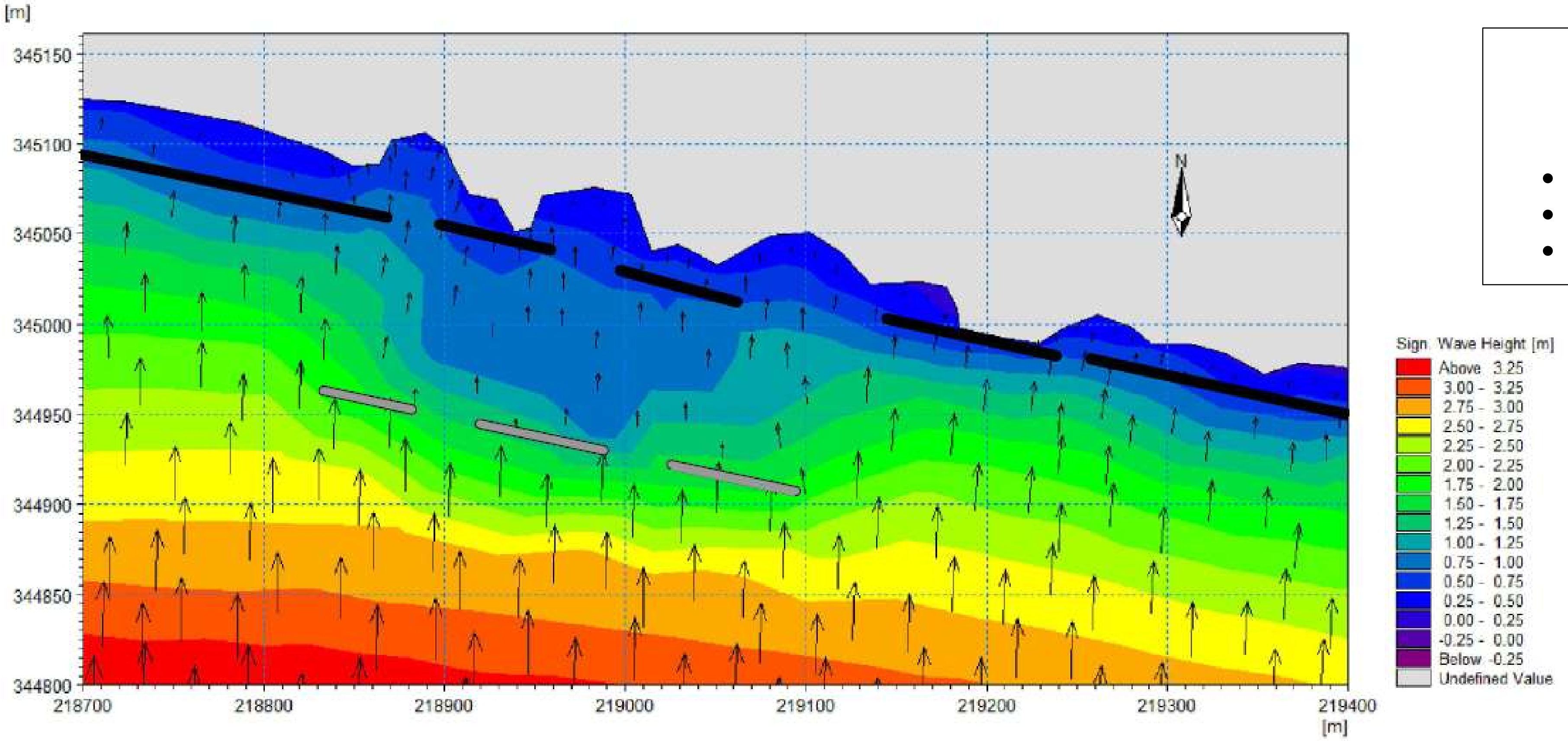


Figure A8 - SCENARIO B

WAVE CONDITION
CLOSE UP VIEW

- **DIRECTION - 180°**
- **Hs – 3.85m**
- **T_p – 8.72s**

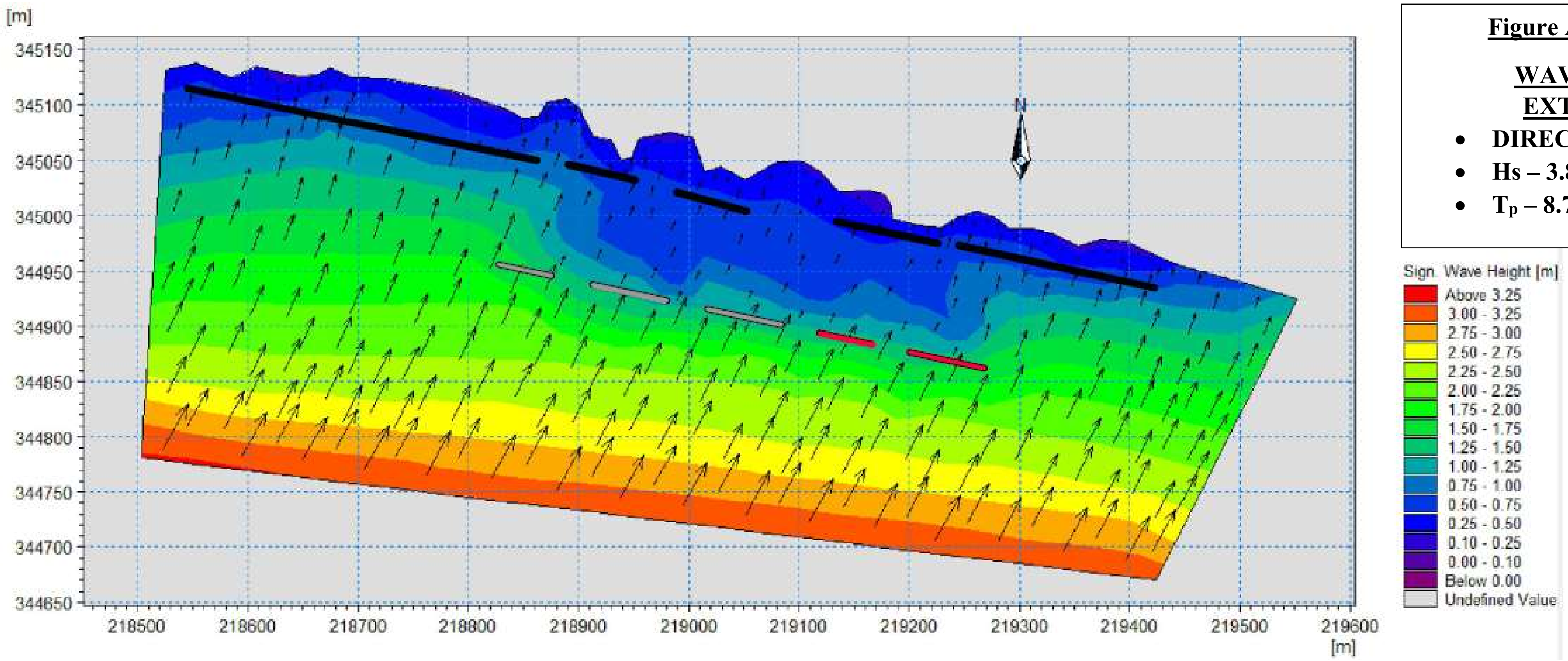


Figure A8 - SCENARIO A

WAVE CONDITION
EXTENDED VIEW

- **DIRECTION - 210°**
- **Hs – 3.85m**
- **T_p – 8.72s**

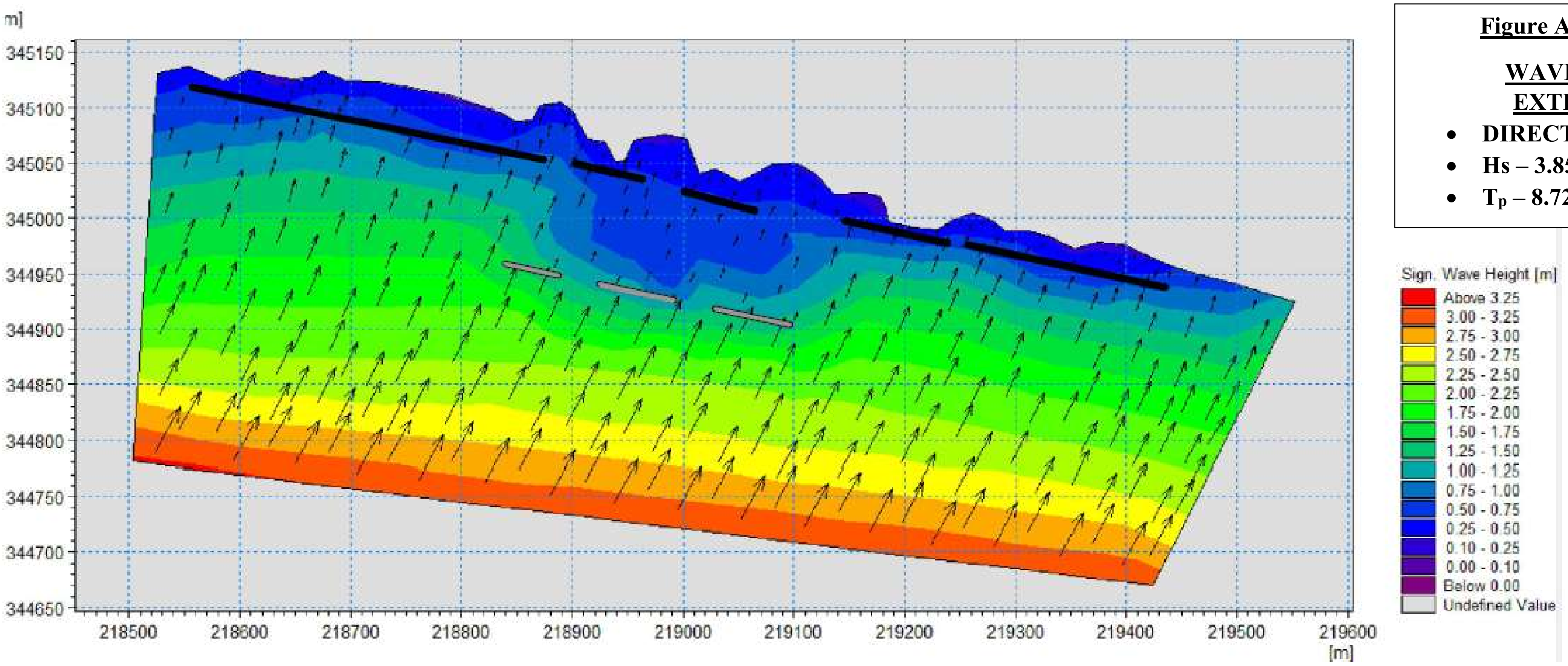


Figure A9 - SCENARIO B

WAVE CONDITION
EXTENDED VIEW

- **DIRECTION - 210°**
- **Hs – 3.85m**
- **T_p – 8.72s**

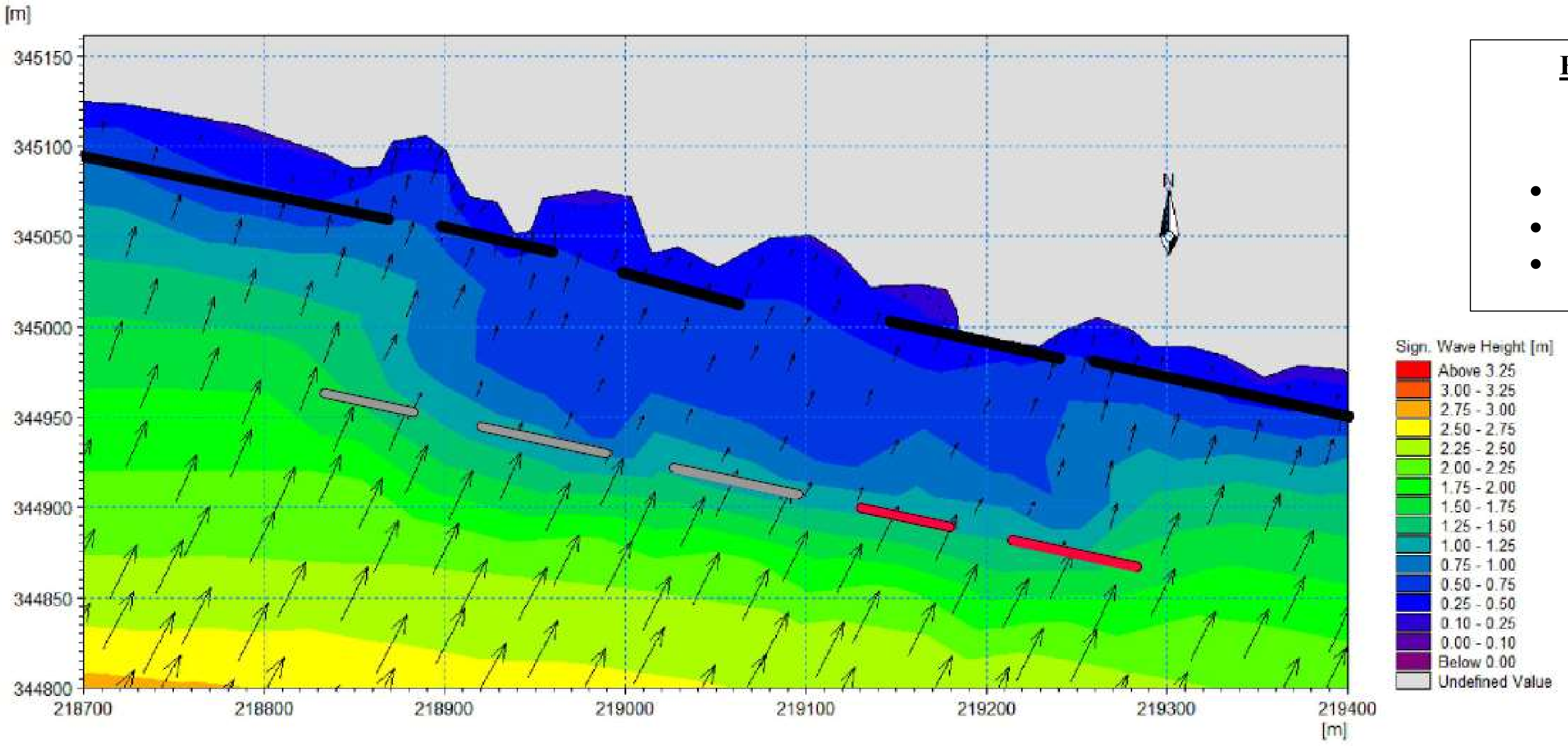


Figure A10 - SCENARIO A

WAVE CONDITION
CLOSE UP VIEW

- **DIRECTION - 210°**
- **Hs – 3.85m**
- **T_p – 8.72s**

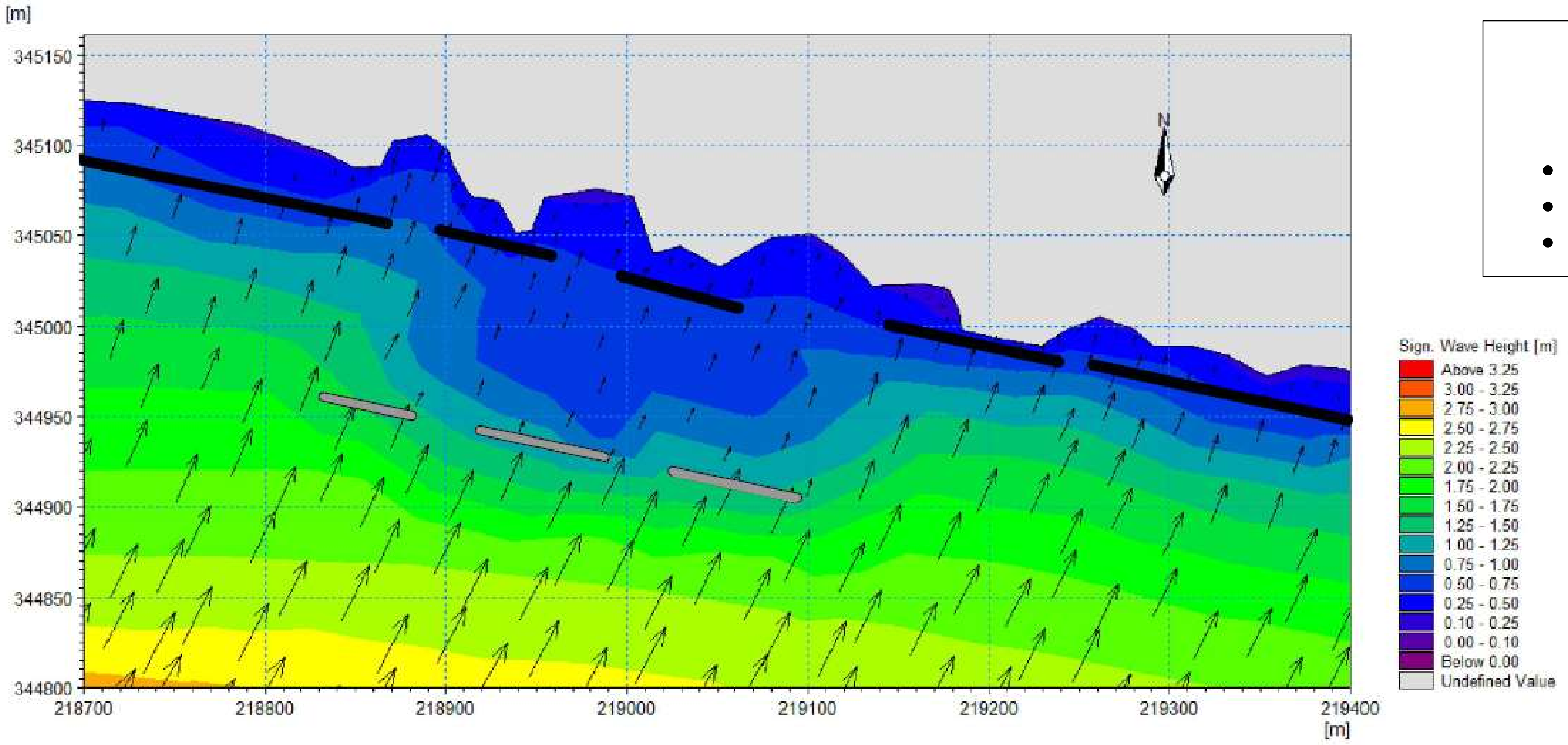


Figure A11 - SCENARIO B

WAVE CONDITION
CLOSE UP VIEW

- **DIRECTION - 210°**
- **Hs – 3.85m**
- **T_p – 8.72s**

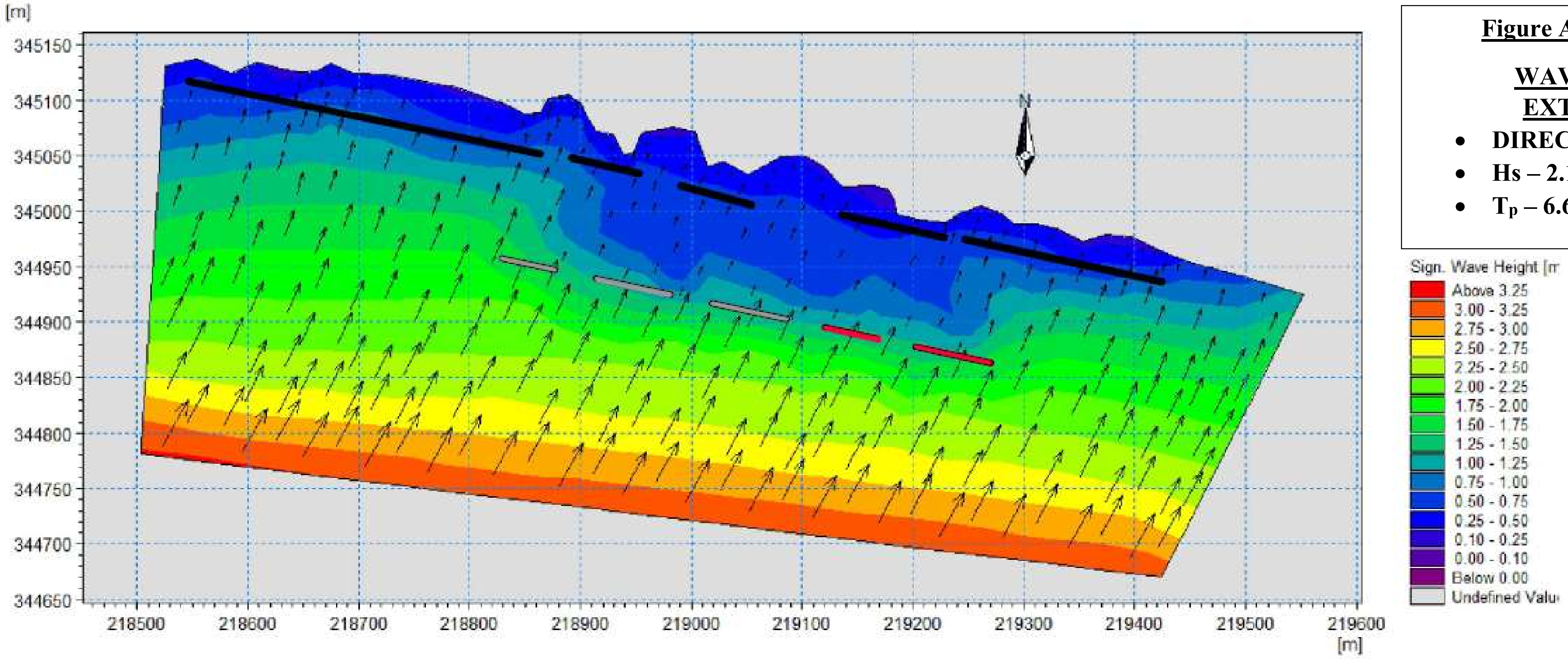


Figure A12 - SCENARIO A

WAVE CONDITION
EXTENDED VIEW

- **DIRECTION - 240°**
- **Hs – 2.17m**
- **T_p – 6.64s**

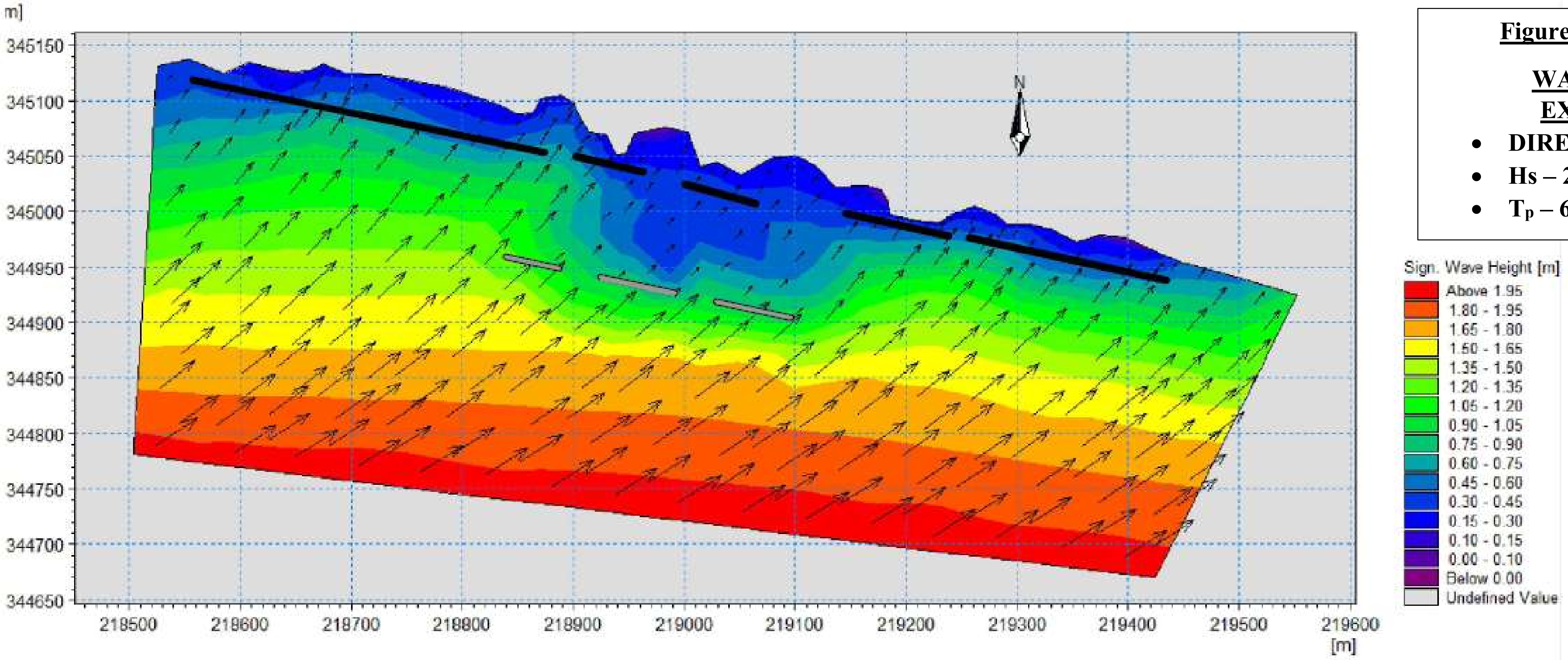


Figure A13 - SCENARIO B

WAVE CONDITION
EXTENDED VIEW

- **DIRECTION - 240°**
- **Hs – 2.17m**
- **T_p – 6.64s**

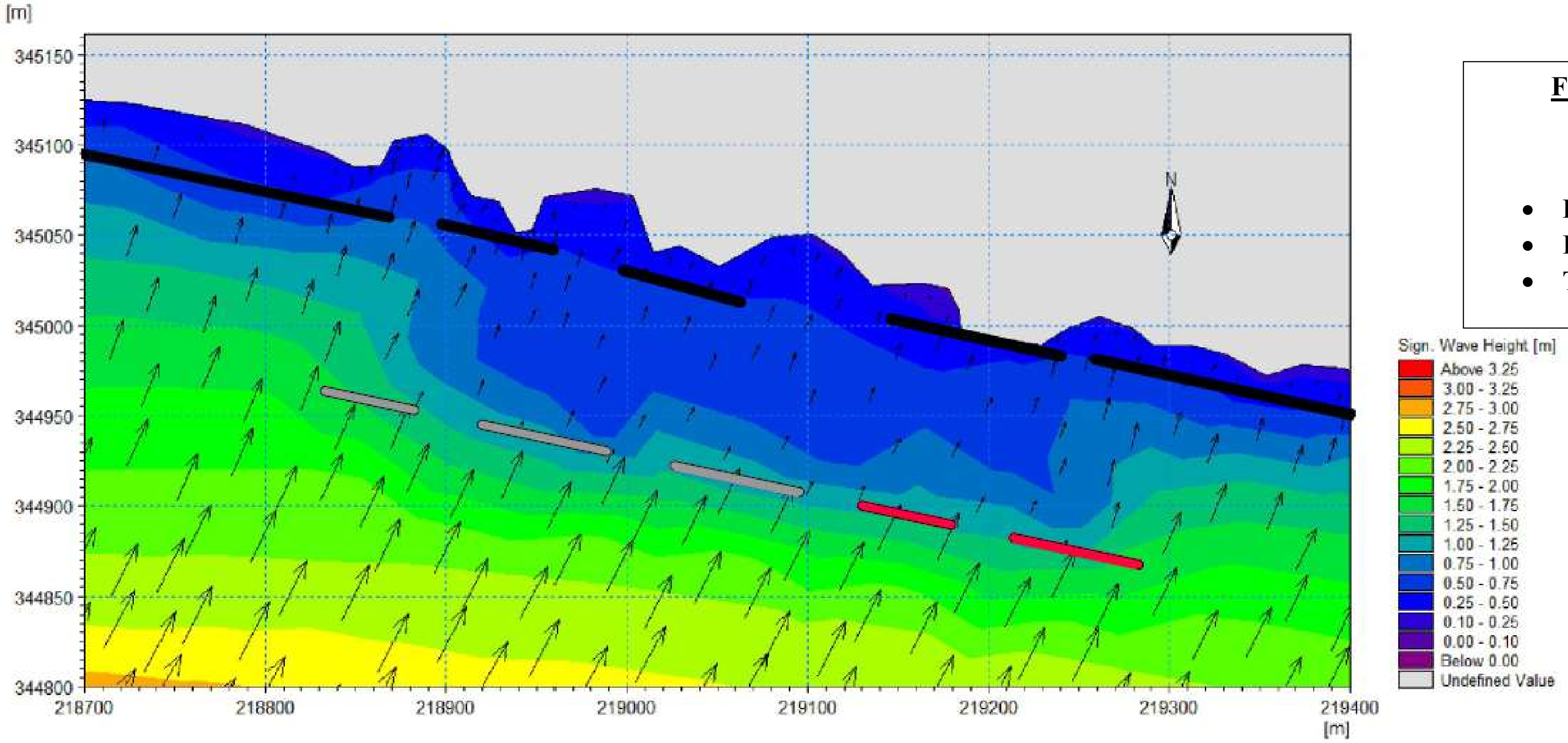


Figure A14 - SCENARIO A

WAVE CONDITION
CLOSE UP VIEW

- **DIRECTION - 240°**
- **Hs – 2.17m**
- **T_p – 6.64s**

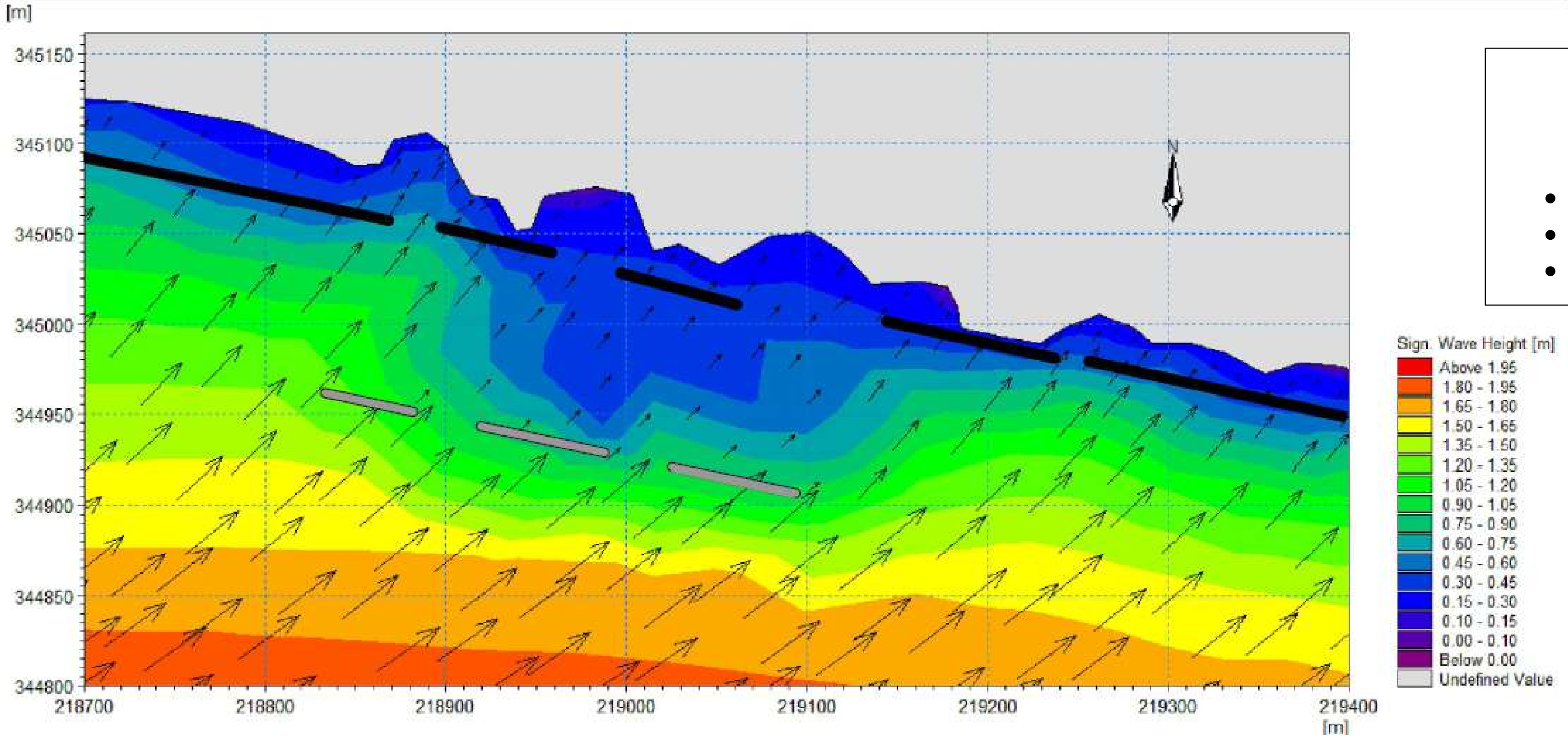


Figure A15 - SCENARIO B

WAVE CONDITION
CLOSE UP VIEW

- **DIRECTION - 240°**
- **Hs – 2.17m**
- **T_p – 6.64s**

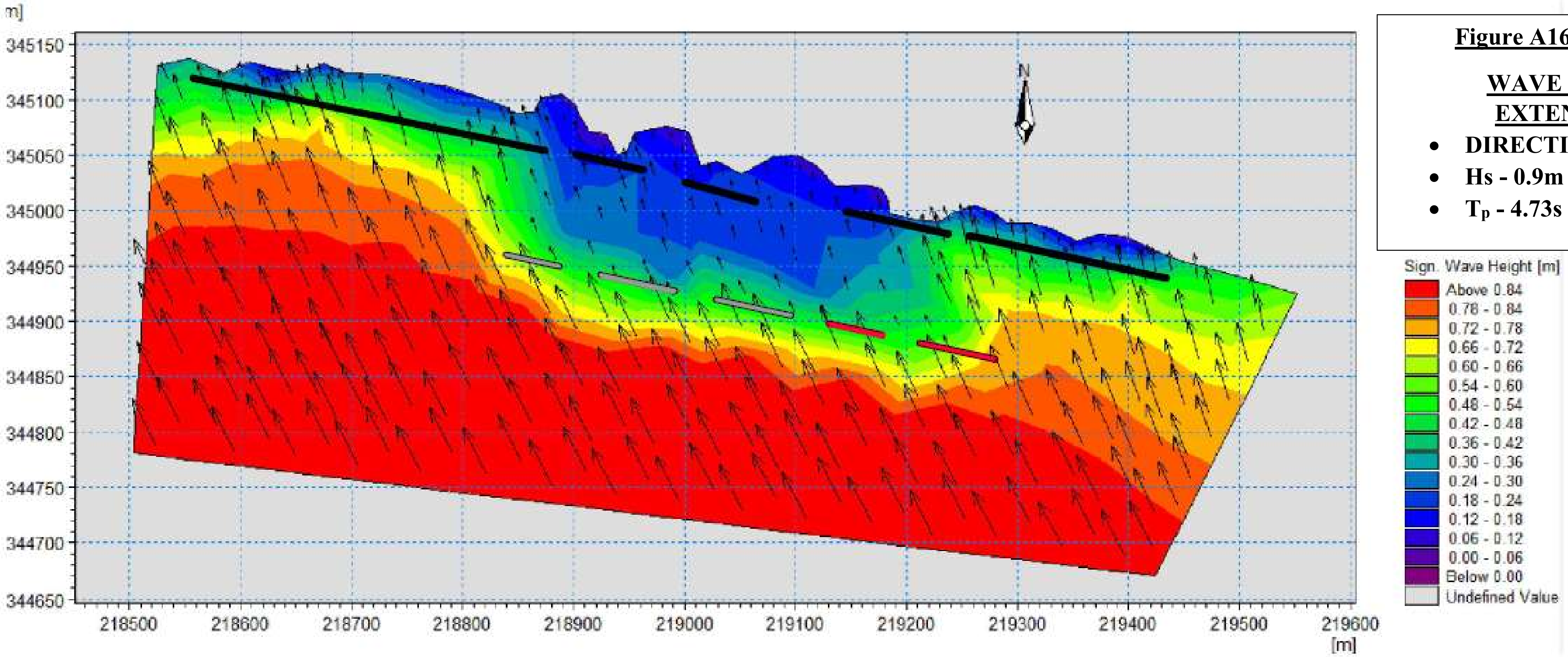


Figure A16 - SCENARIO A

WAVE CONDITION
EXTENDED VIEW

- **DIRECTION - 150°**
- **Hs - 0.9m**
- **T_p - 4.73s**

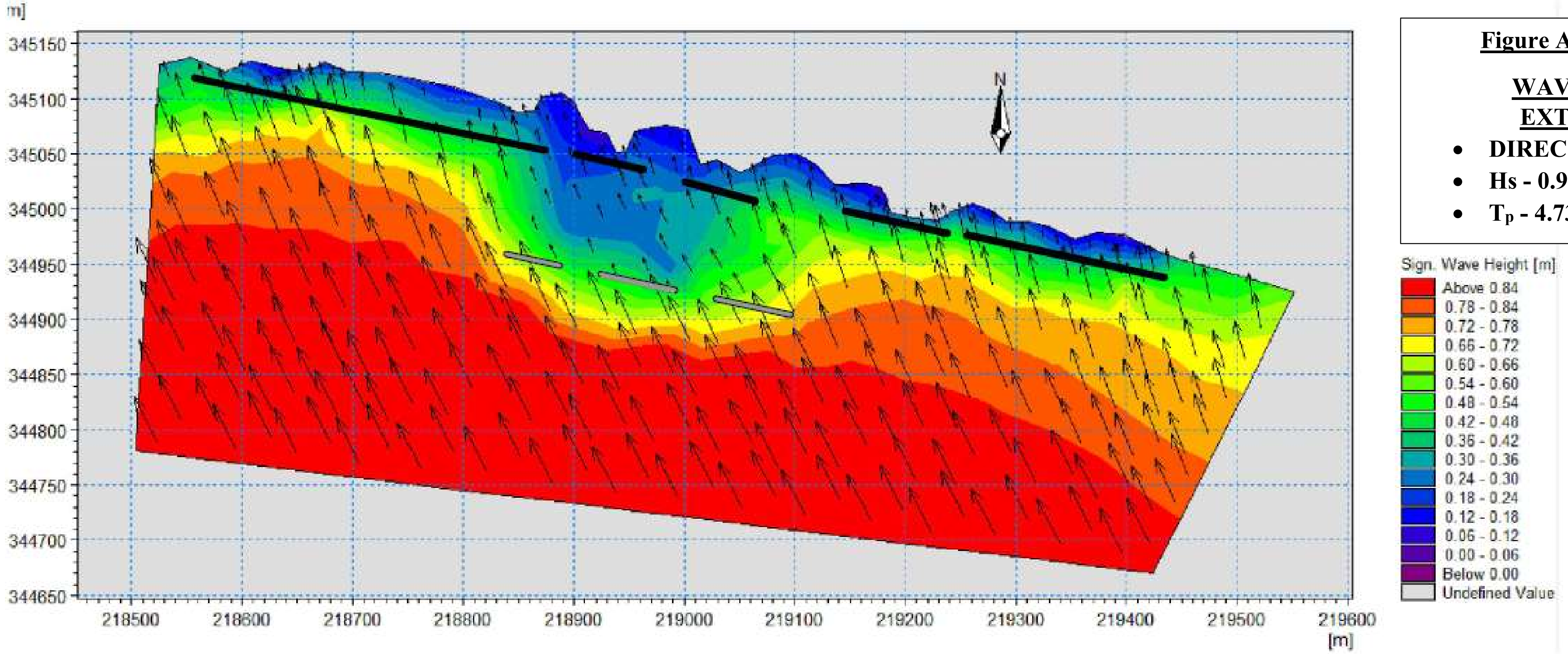


Figure A17 - SCENARIO B

WAVE CONDITION
EXTENDED VIEW

- **DIRECTION - 150°**
- **Hs - 0.9m**
- **T_p - 4.73s**

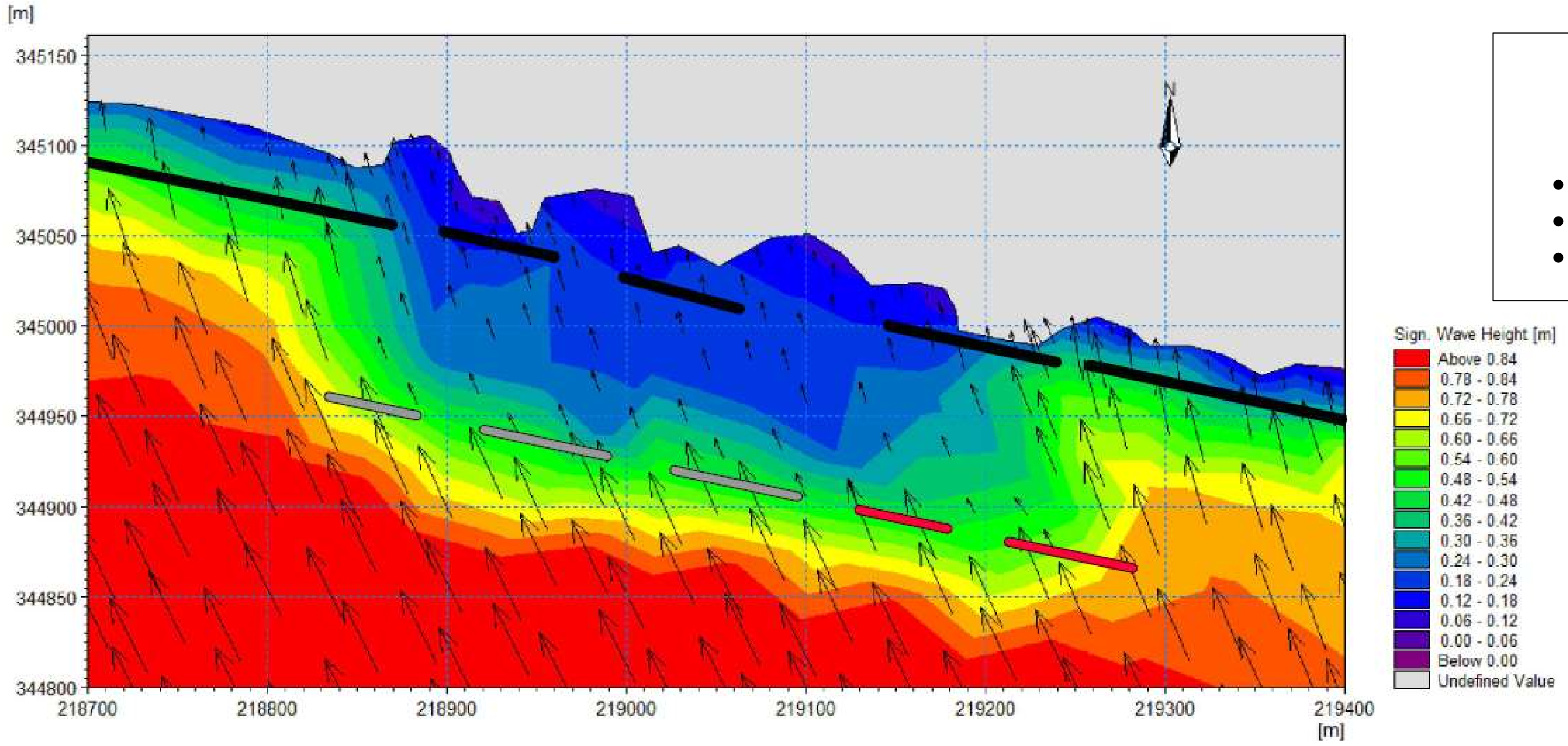


Figure A18 - SCENARIO A

WAVE CONDITION
CLOSE UP VIEW

- **DIRECTION - 150°**
- **Hs - 0.9m**
- **T_p - 4.73s**

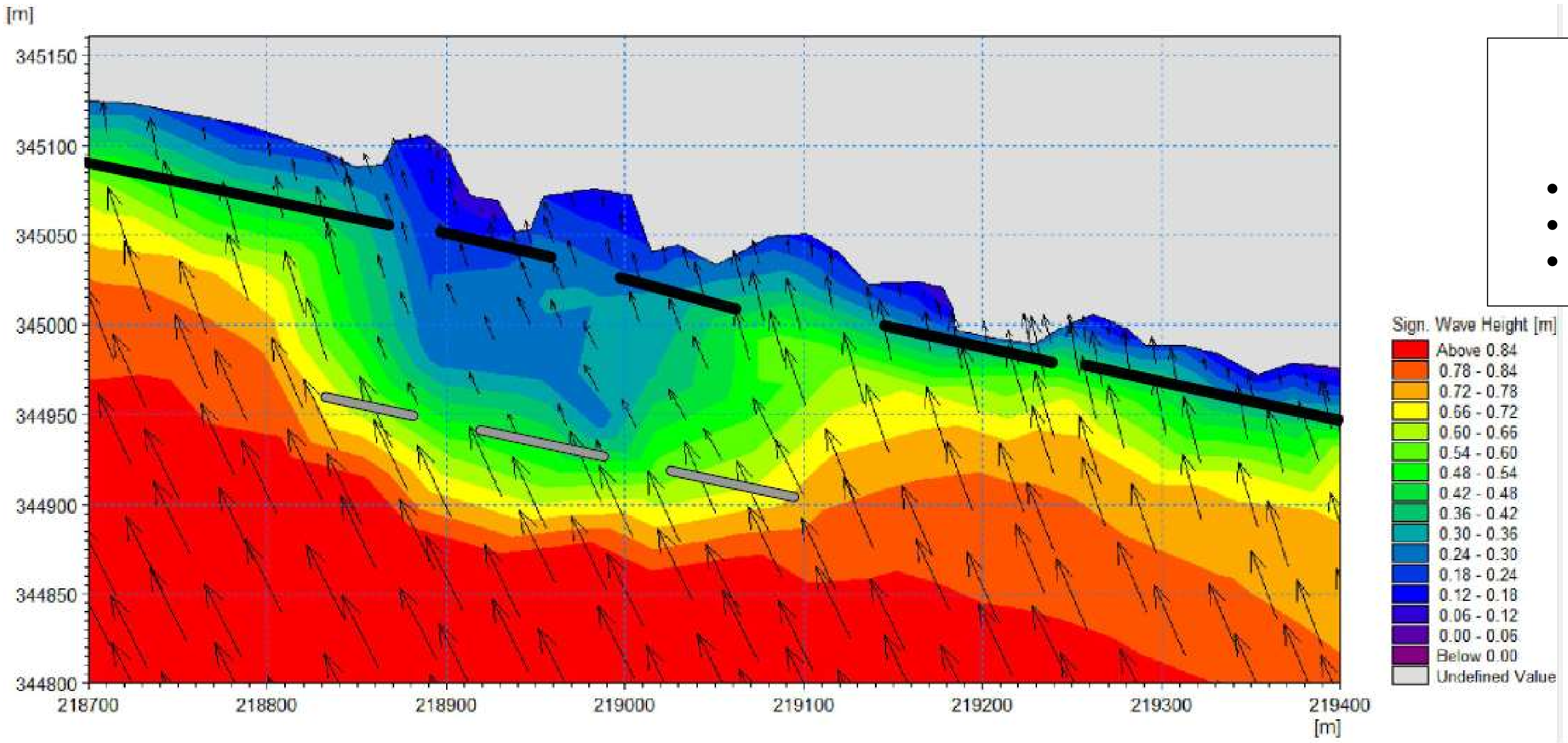


Figure A19 - SCENARIO B

WAVE CONDITION
CLOSE UP VIEW

- **DIRECTION - 150°**
- **Hs - 0.9m**
- **T_p - 4.73s**

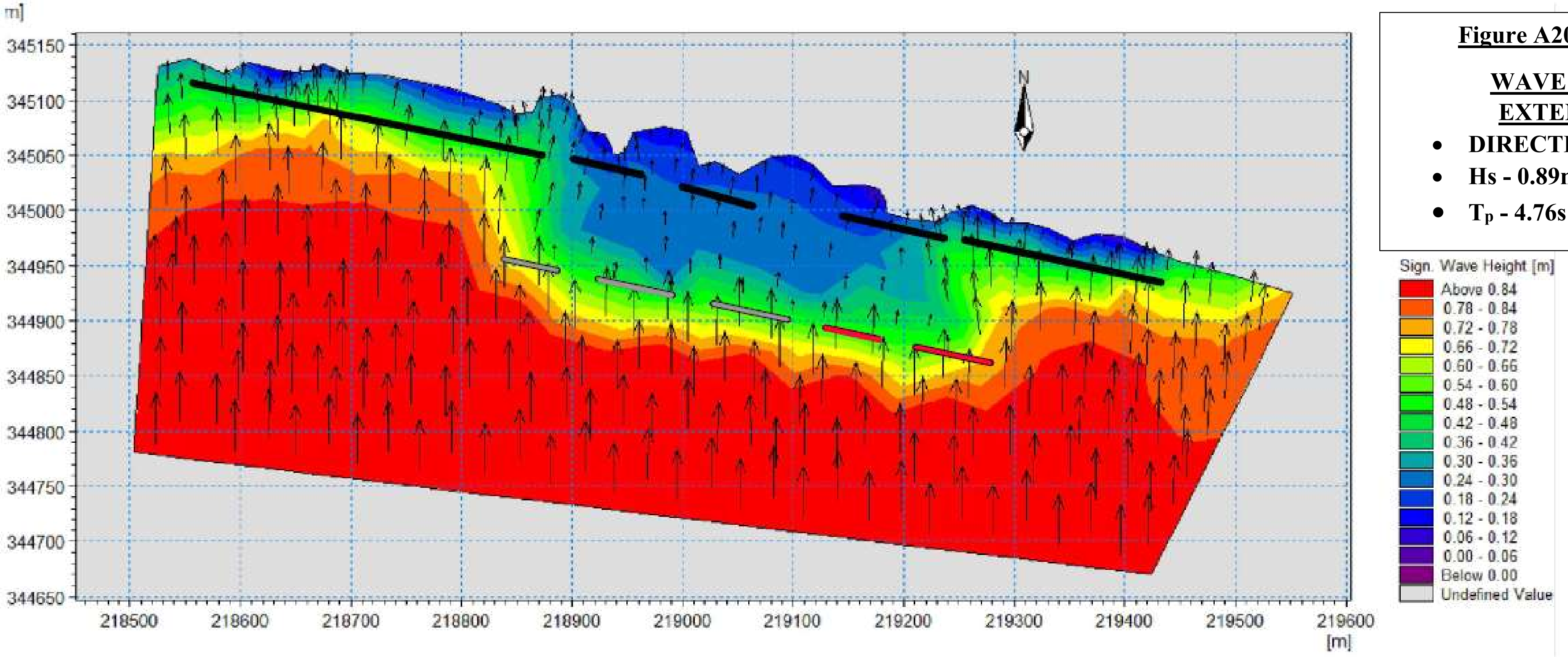


Figure A20 - SCENARIO A

WAVE CONDITION
EXTENDED VIEW

- **DIRECTION - 180°**
- **Hs - 0.89m**
- **T_p - 4.76s**

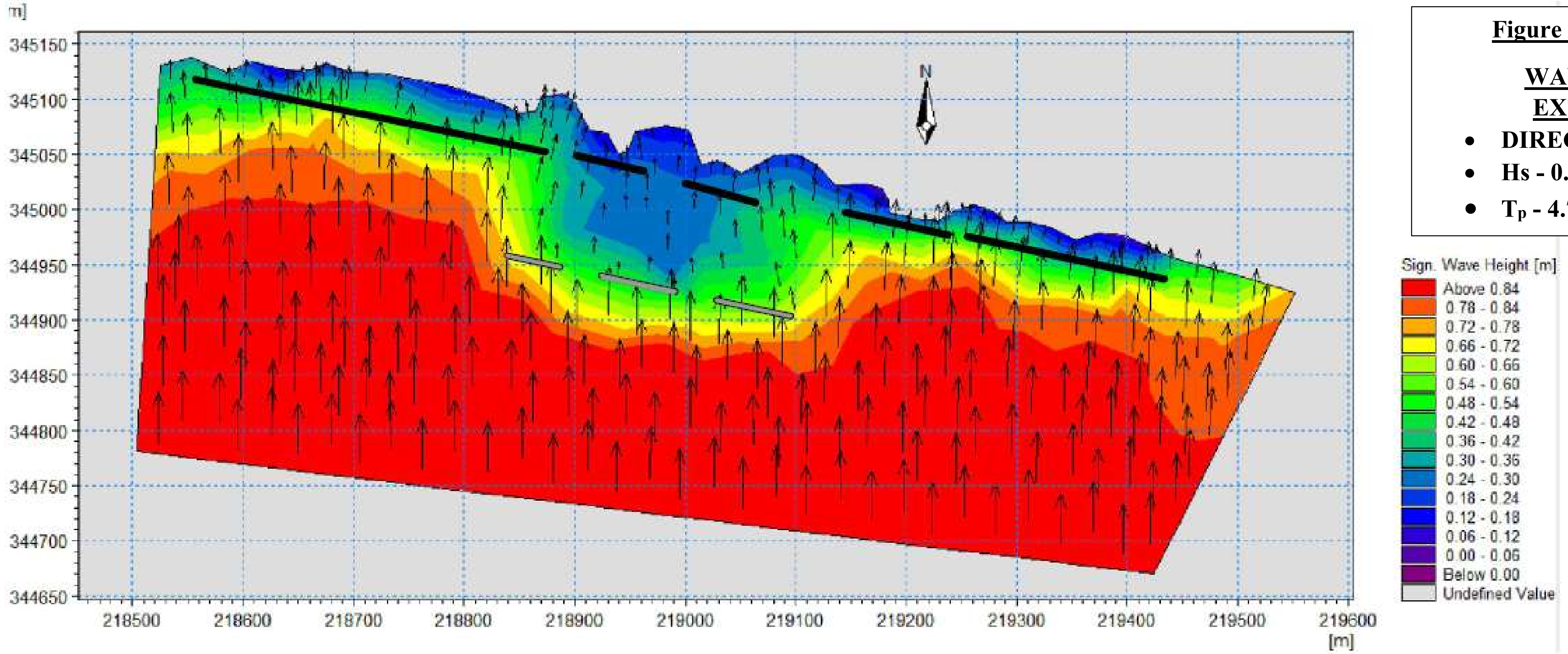


Figure A21 - SCENARIO A

WAVE CONDITION
EXTENDED VIEW

- **DIRECTION - 180°**
- **Hs - 0.89m**
- **T_p - 4.76s**

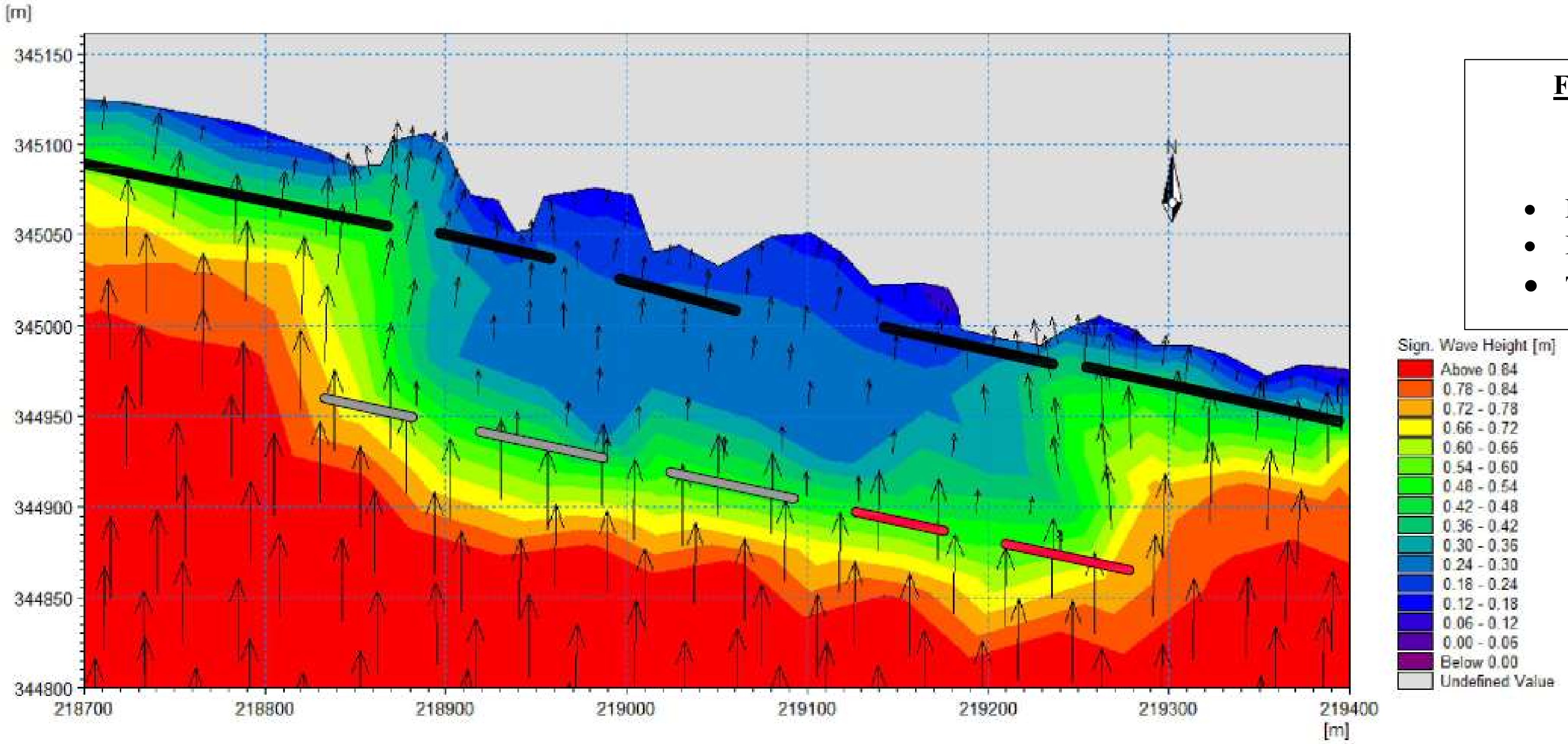


Figure A22 - SCENARIO A

WAVE CONDITION
CLOSE UP VIEW

- **DIRECTION - 180°**
- **Hs - 0.89m**
- **T_p - 4.76s**

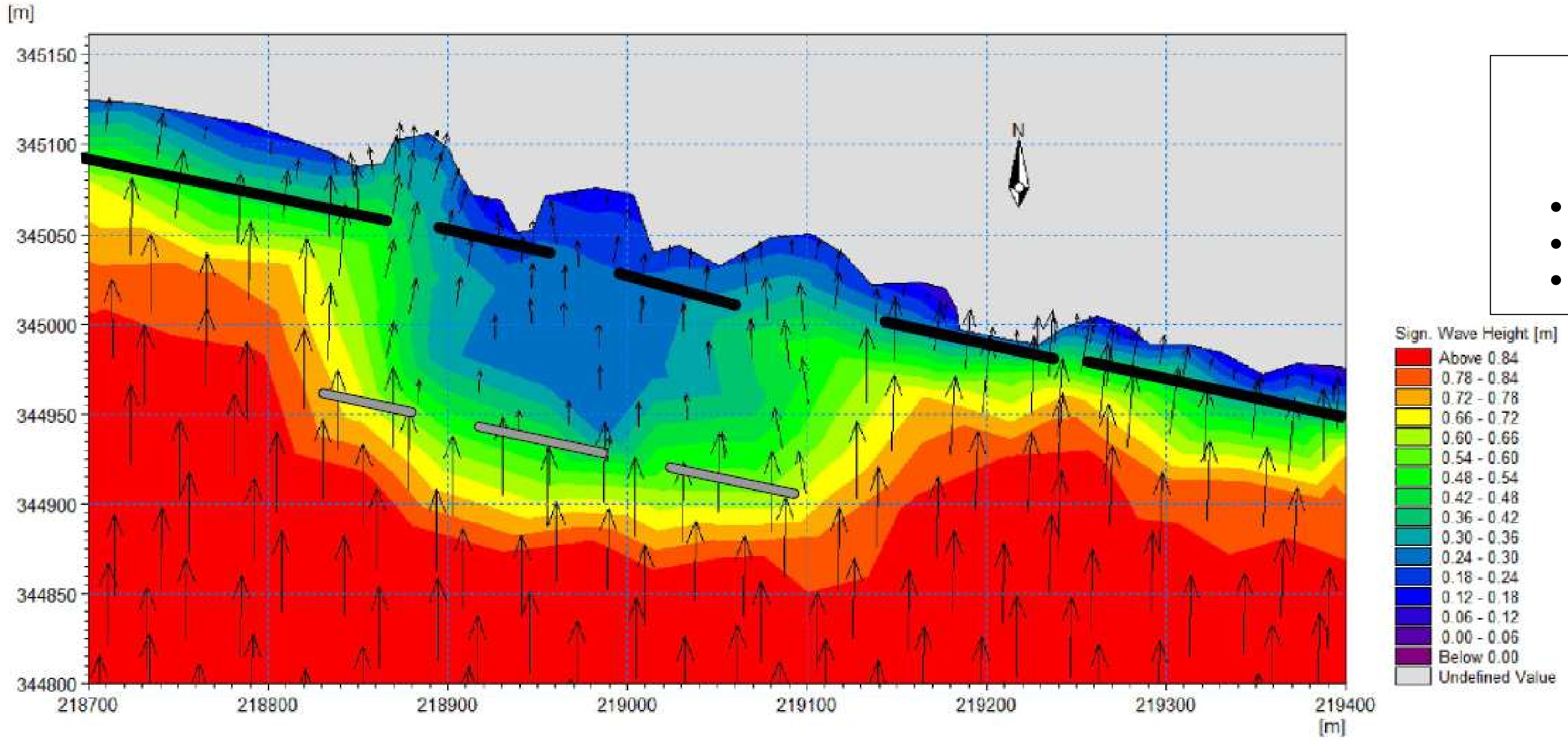


Figure A23 - SCENARIO B

WAVE CONDITION
CLOSE UP VIEW

- **DIRECTION - 180°**
- **Hs - 0.89m**
- **T_p - 4.76s**

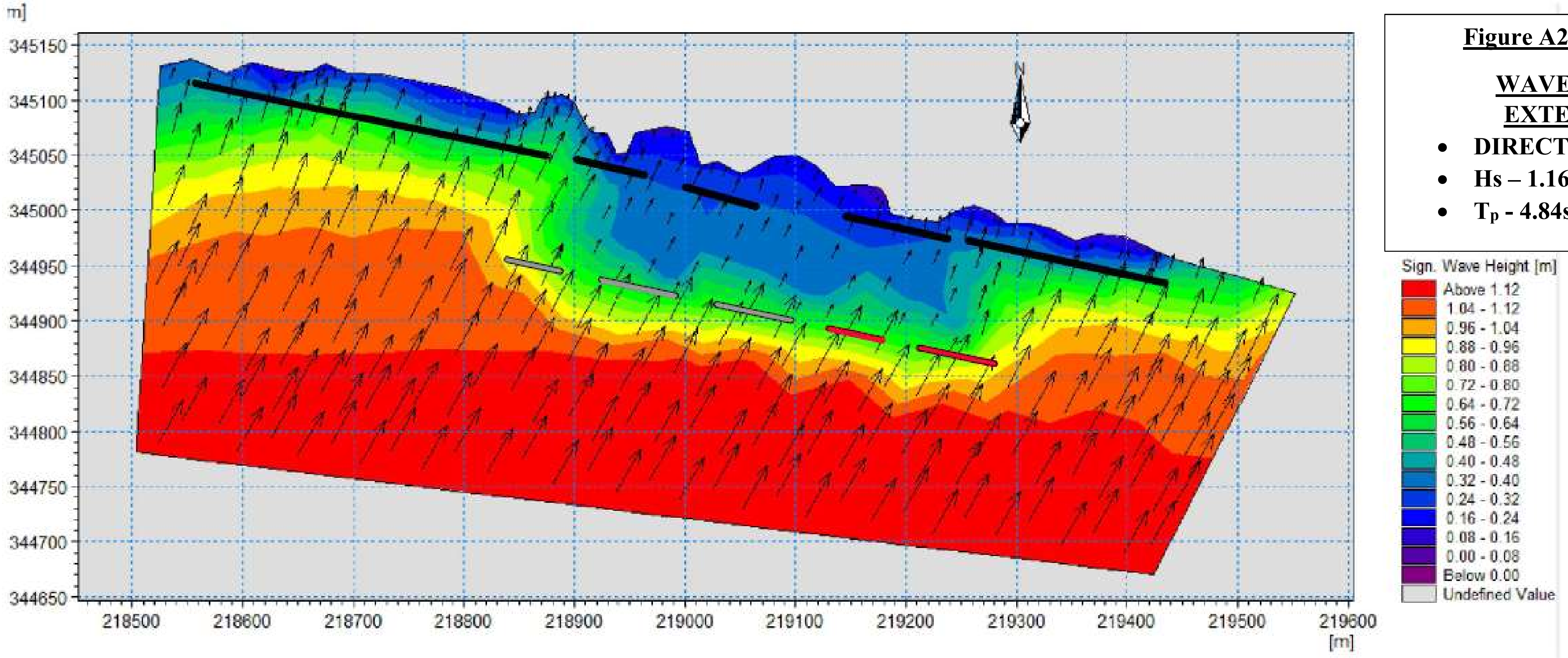


Figure A24 - SCENARIO A

WAVE CONDITION EXTENDED VIEW

- **DIRECTION - 210°**
- **Hs – 1.16m**
- **T_p - 4.84s**

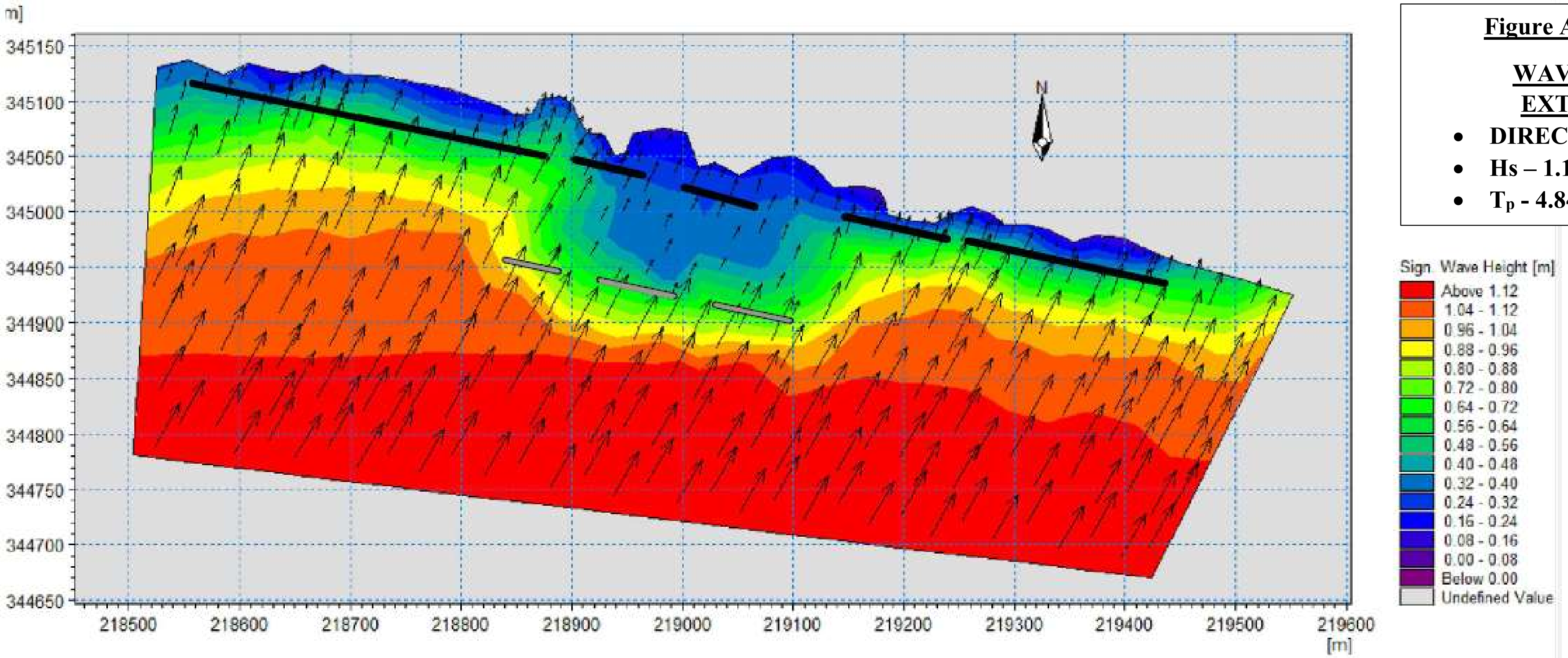


Figure A25- SCENARIO B

WAVE CONDITION EXTENDED VIEW

- **DIRECTION - 210°**
- **Hs – 1.16m**
- **T_p - 4.84s**

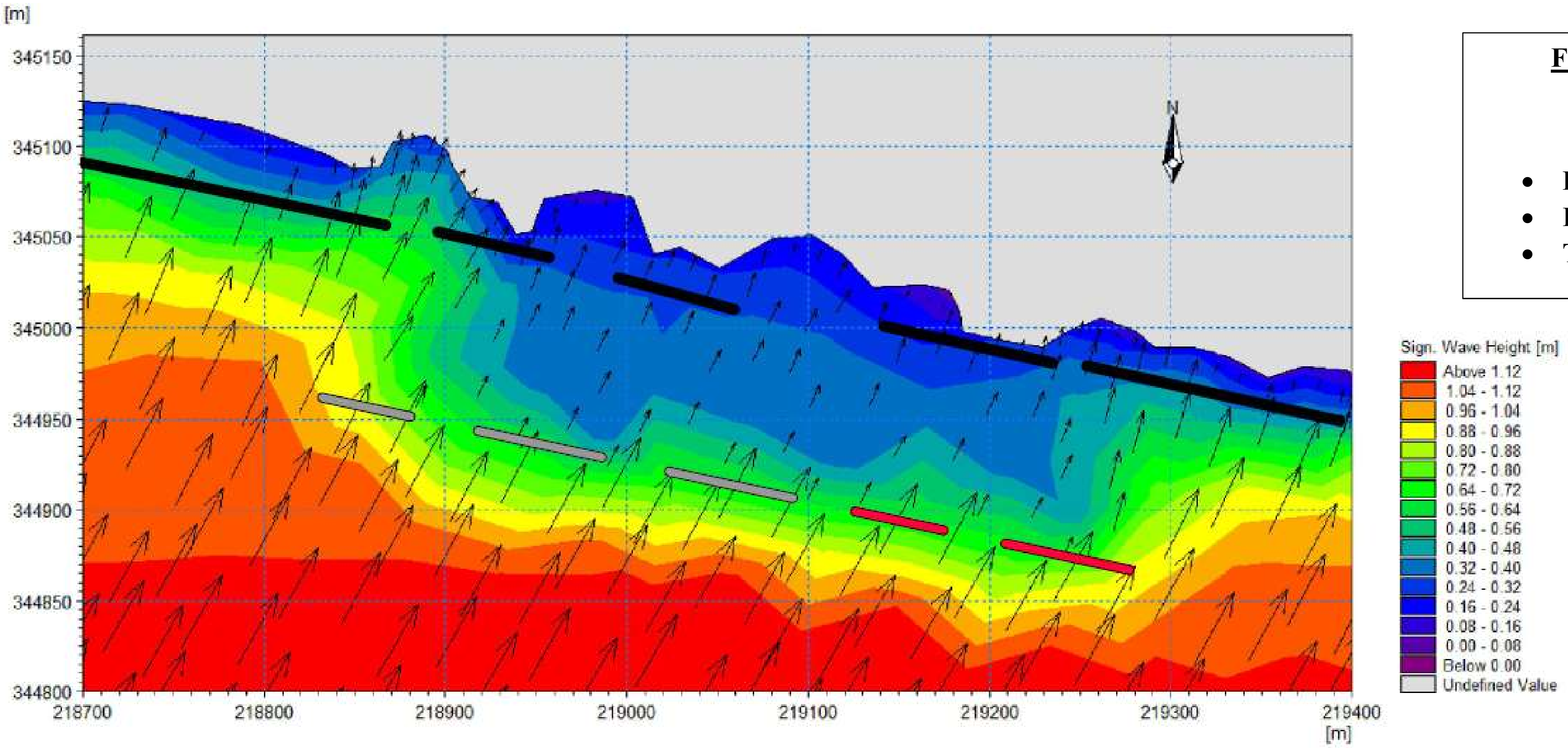


Figure A26 - SCENARIO A

WAVE CONDITION
CLOSE UP VIEW

- **DIRECTION - 210°**
- **Hs – 1.16m**
- **T_p - 4.84s**

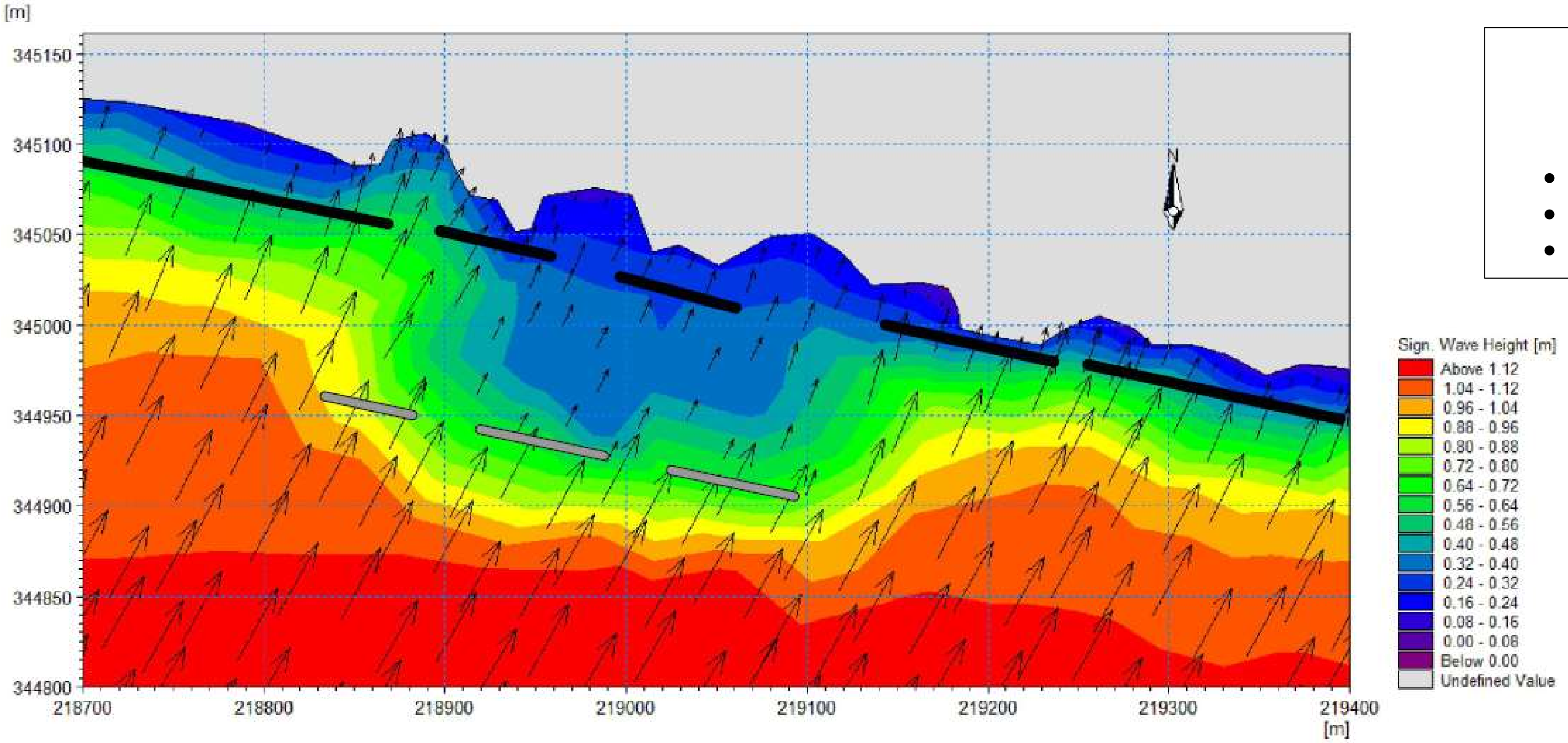


Figure A27- SCENARIO B

WAVE CONDITION
CLOSE UP VIEW

- **DIRECTION - 210°**
- **Hs – 1.16m**
- **T_p - 4.84s**

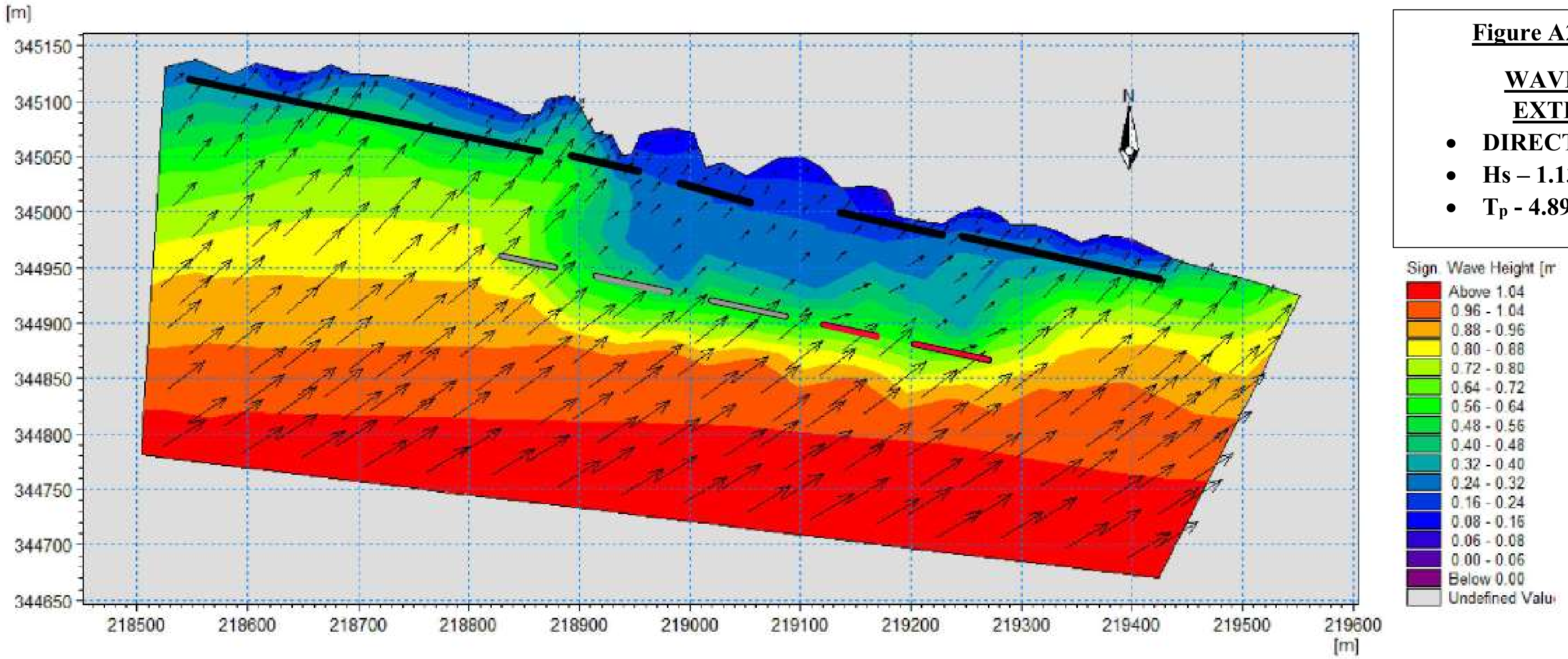


Figure A28 - SCENARIO A

WAVE CONDITION EXTENDED VIEW

- **DIRECTION - 240°**
- **Hs – 1.13m**
- **T_p - 4.89s**

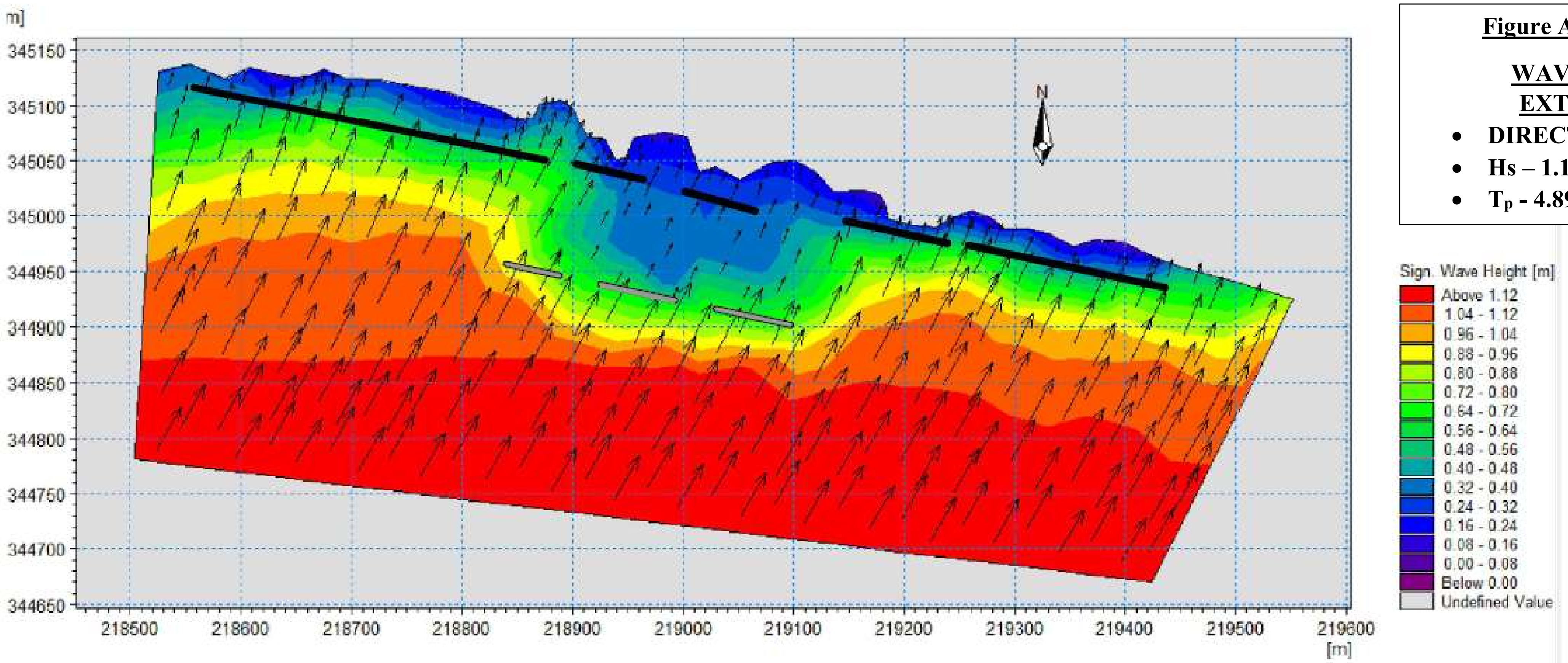


Figure A29- SCENARIO B

WAVE CONDITION EXTENDED VIEW

- **DIRECTION - 240°**
- **Hs – 1.13m**
- **T_p - 4.89s**

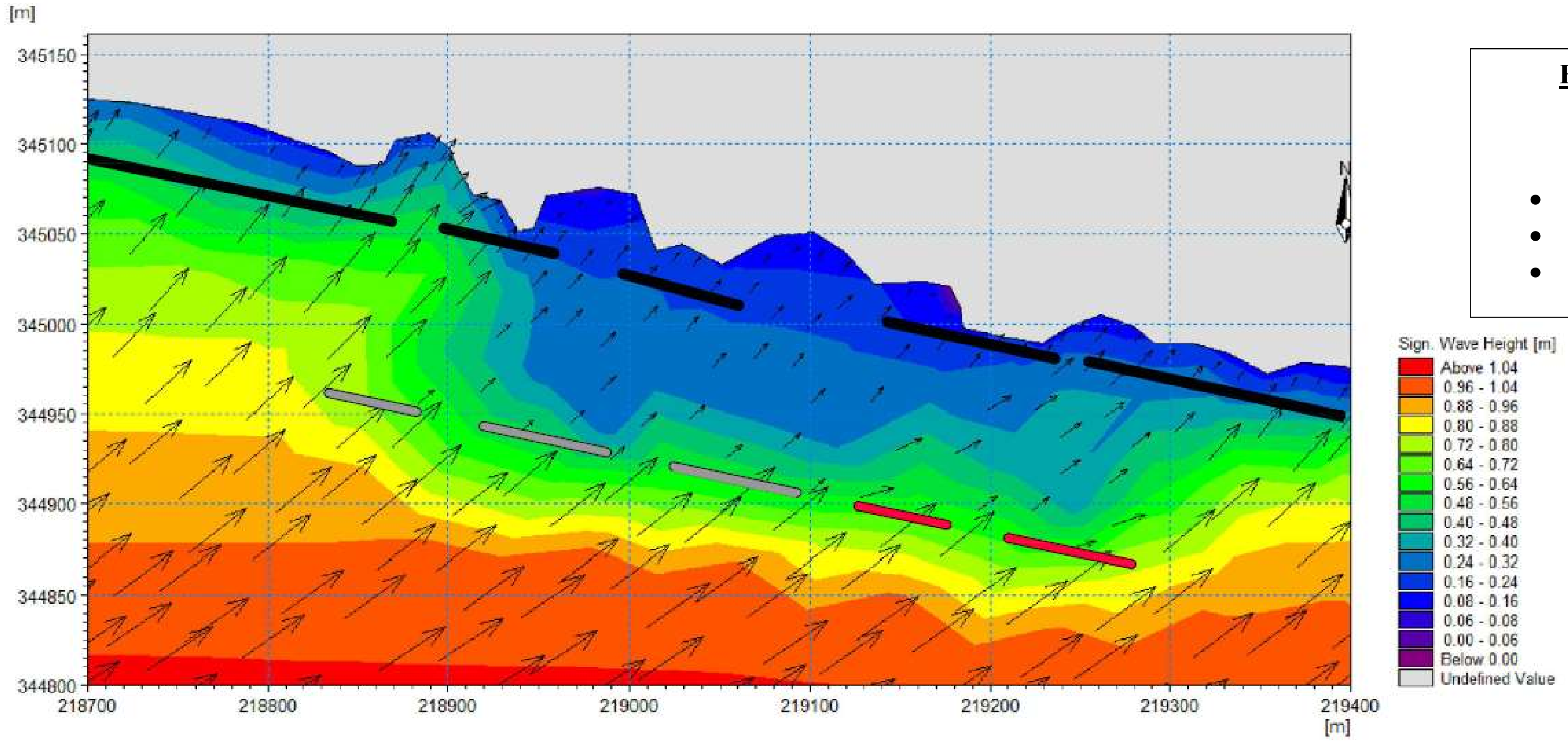


Figure A30 - SCENARIO A

WAVE CONDITION
CLOSE UP VIEW

- **DIRECTION - 240°**
- **Hs – 1.13m**
- **T_p - 4.89s**

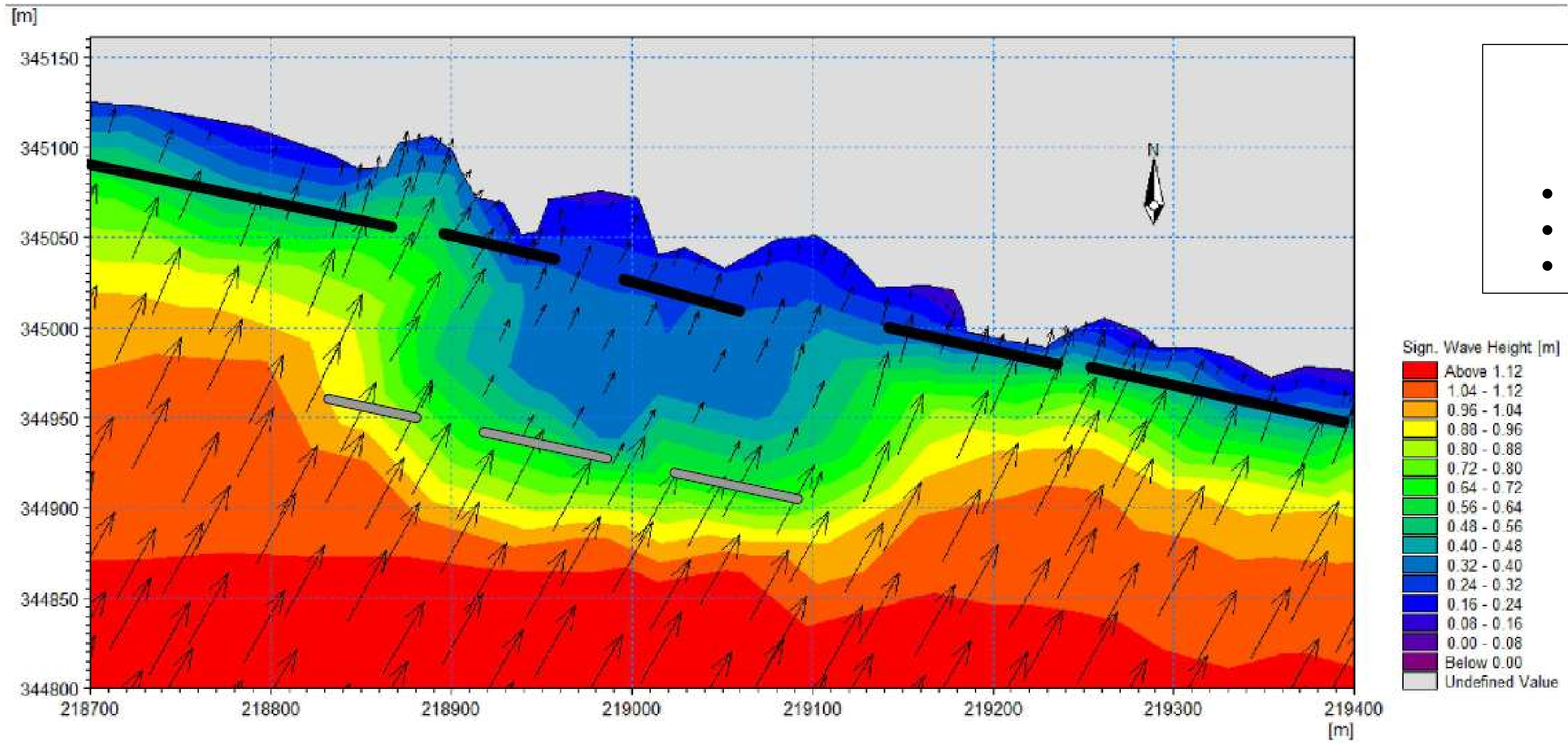


Figure A31- SCENARIO B

WAVE CONDITION
CLOSE UP VIEW

- **DIRECTION - 240°**
- **Hs – 1.13m**
- **T_p - 4.89s**

APPENDIX B SEDIMENT TRANSPORT RESULTS

Figure B1 - SCENARIO A

SEDIMENT TRANSPORT EXTENDED VIEW

- **DIRECTION - 150°**
- **Hs - 0.9m**
- **T_p - 4.73s**

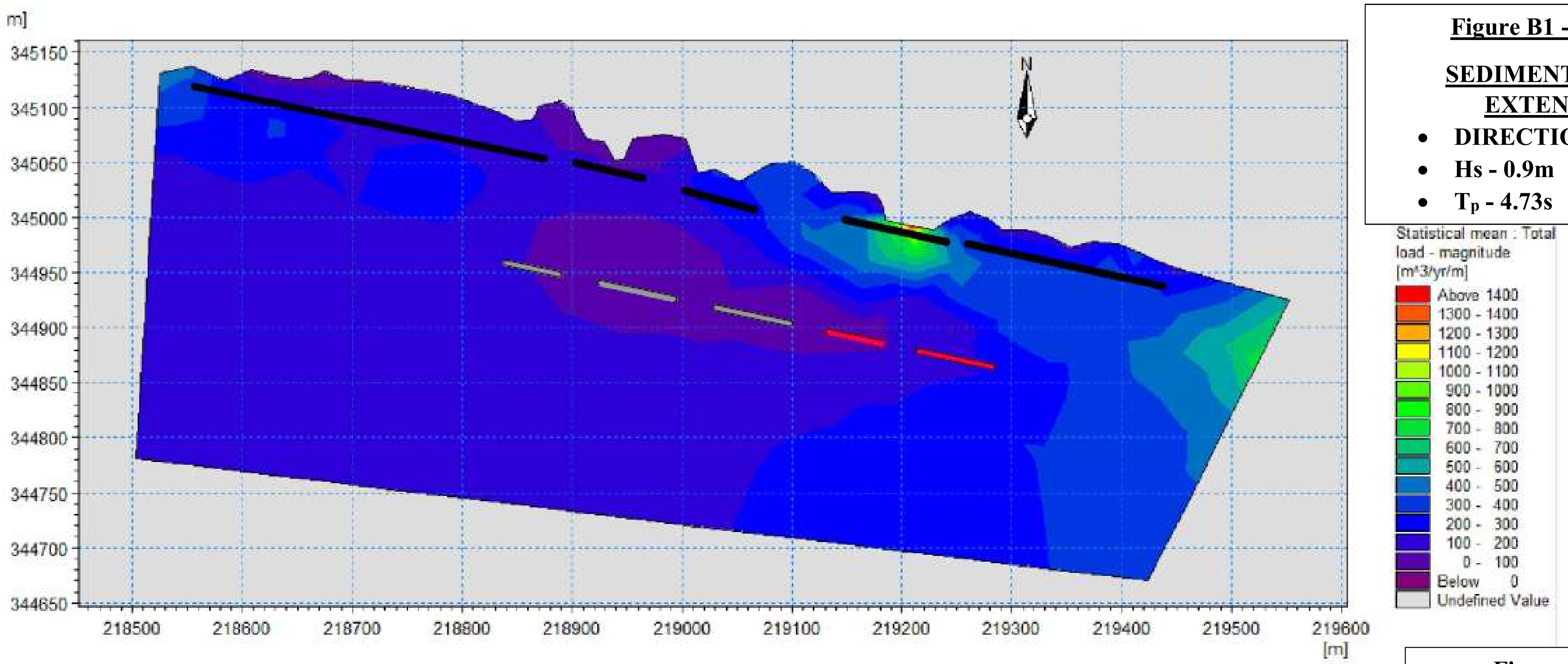
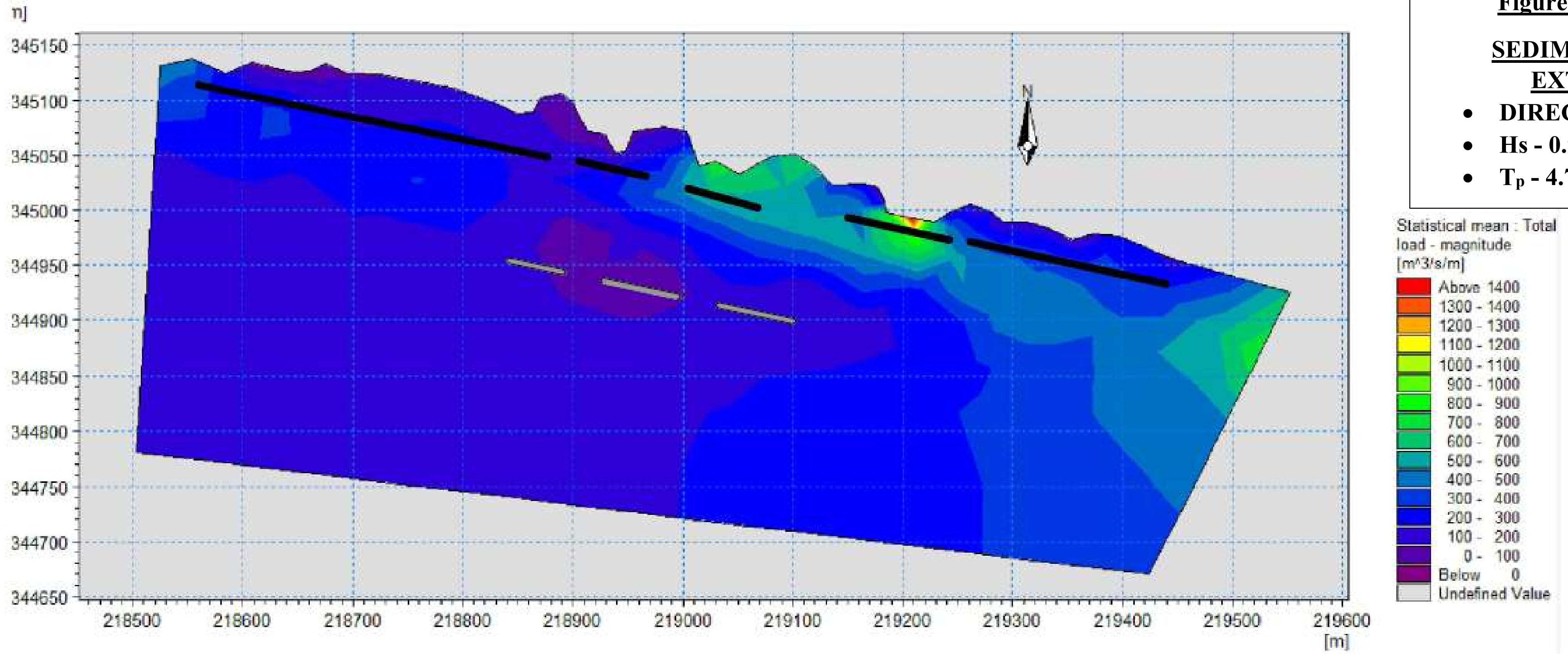


Figure B2 - SCENARIO B

SEDIMENT TRANSPORT EXTENDED VIEW

- **DIRECTION - 150°**
- **Hs - 0.9m**
- **T_p - 4.73s**



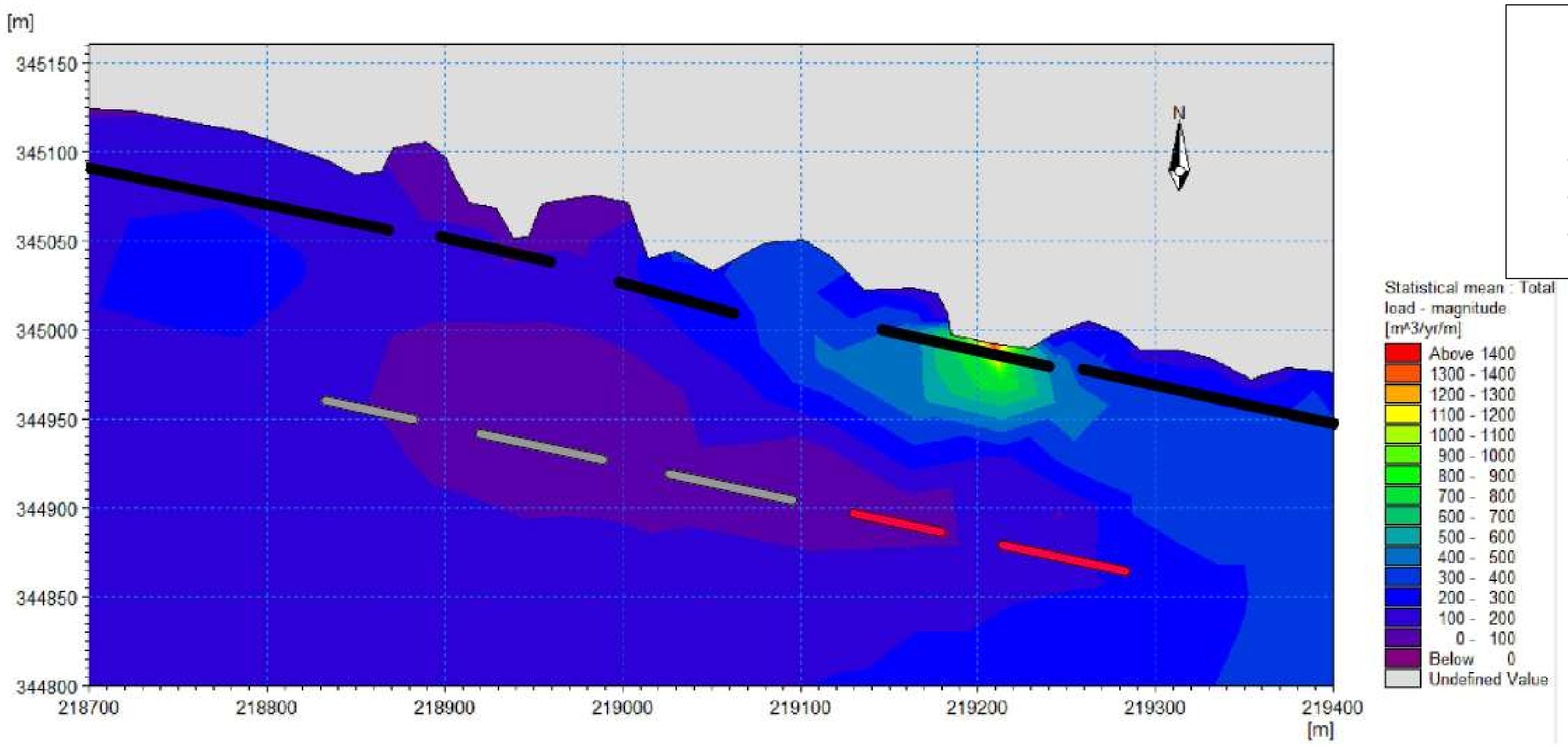


Figure B3 - SCENARIO A

SEDIMENT TRANSPORT
CLOSE UP VIEW

- **DIRECTION - 150°**
- **Hs - 0.9m**
- **T_p - 4.73s**

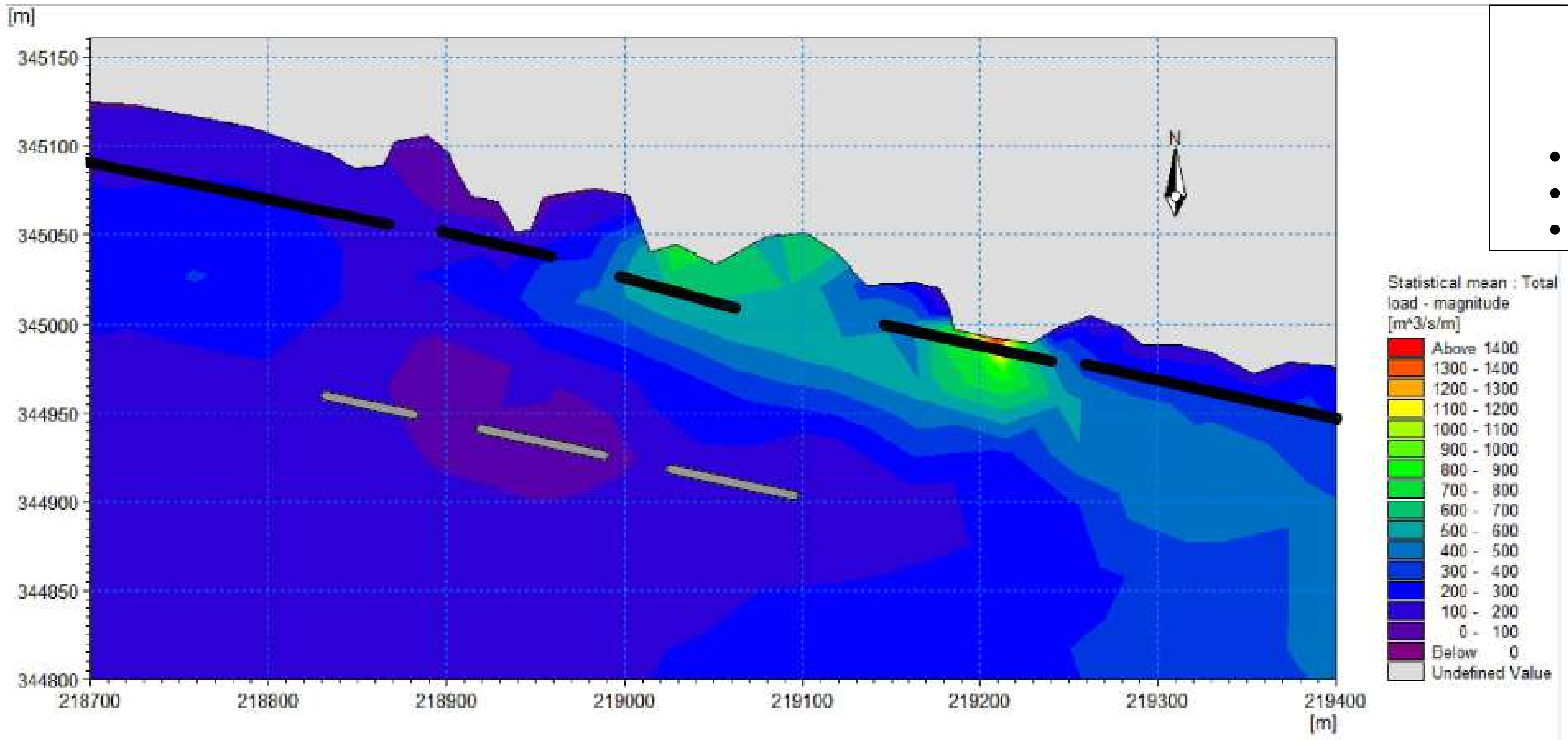


Figure B4 - SCENARIO B

SEDIMENT TRASPORT
CLOSE UP VIEW

- **DIRECTION - 150°**
- **Hs - 0.9m**
- **T_p - 4.73s**

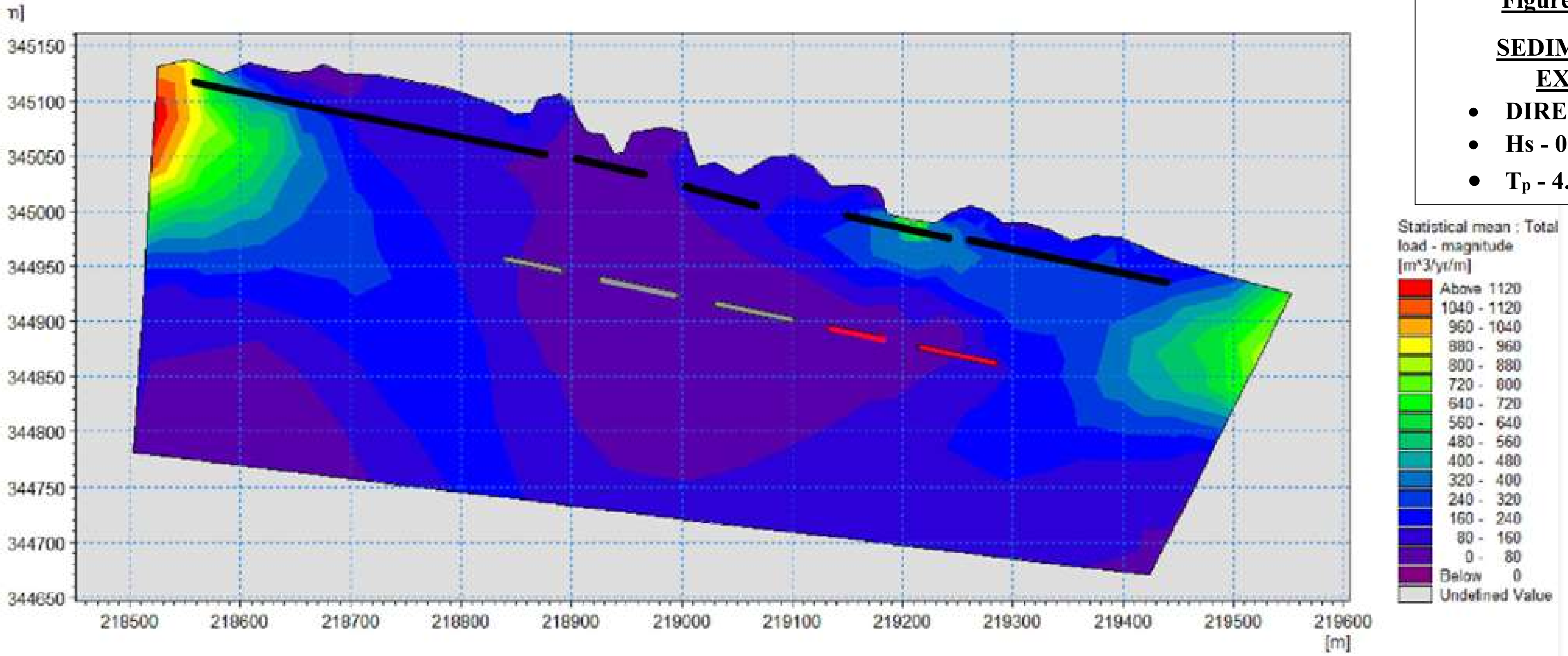


Figure B5 - SCENARIO A

SEDIMENT TRANSPORT EXTENDED VIEW

- **DIRECTION - 180°**
- **Hs - 0.89m**
- **T_p - 4.76s**

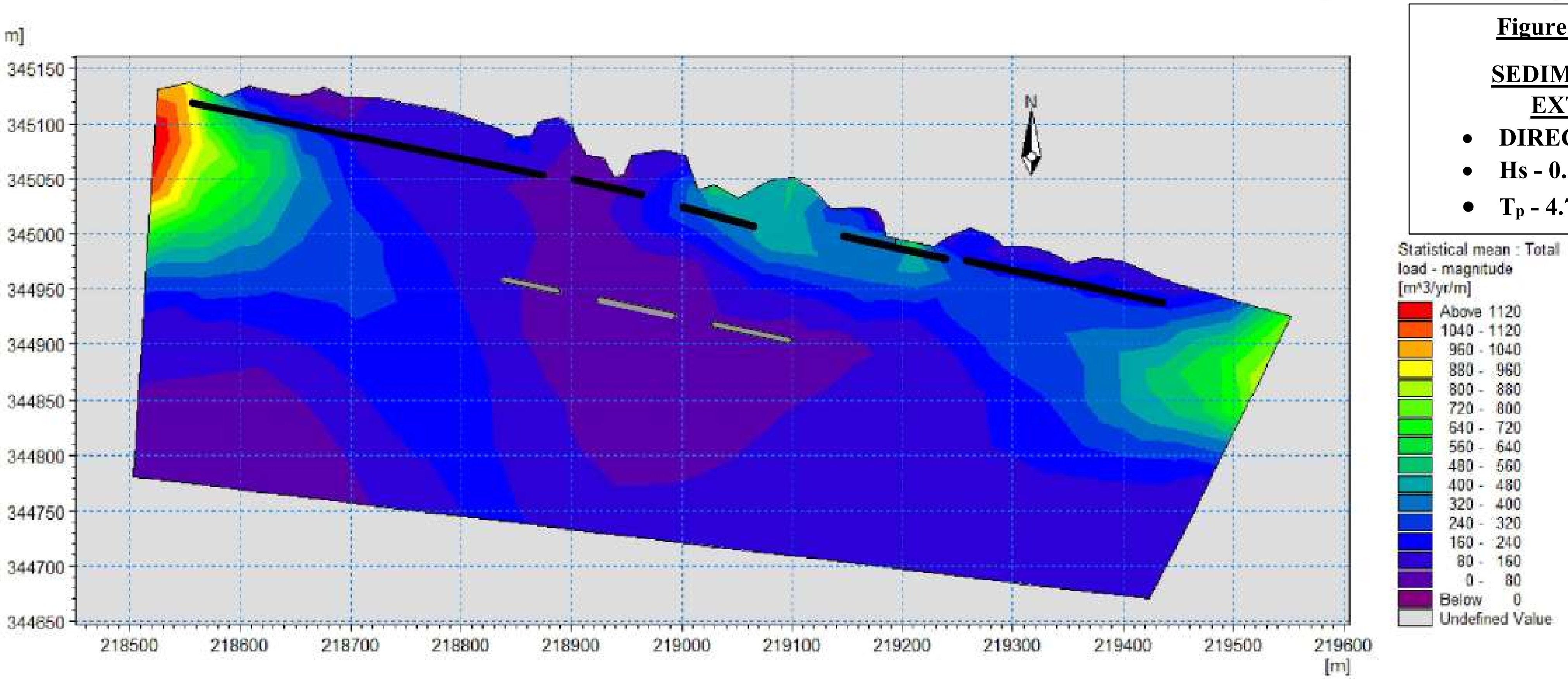


Figure B6 - SCENARIO A

SEDIMENT TRANSPORT EXTENDED VIEW

- **DIRECTION - 180°**
- **Hs - 0.89m**
- **T_p - 4.76s**

Figure B7 - SCENARIO A

SEDIMENT TRANSPORT CLOSE UP VIEW

- **DIRECTION - 180°**
- **Hs - 0.89m**
- **T_p - 4.76s**

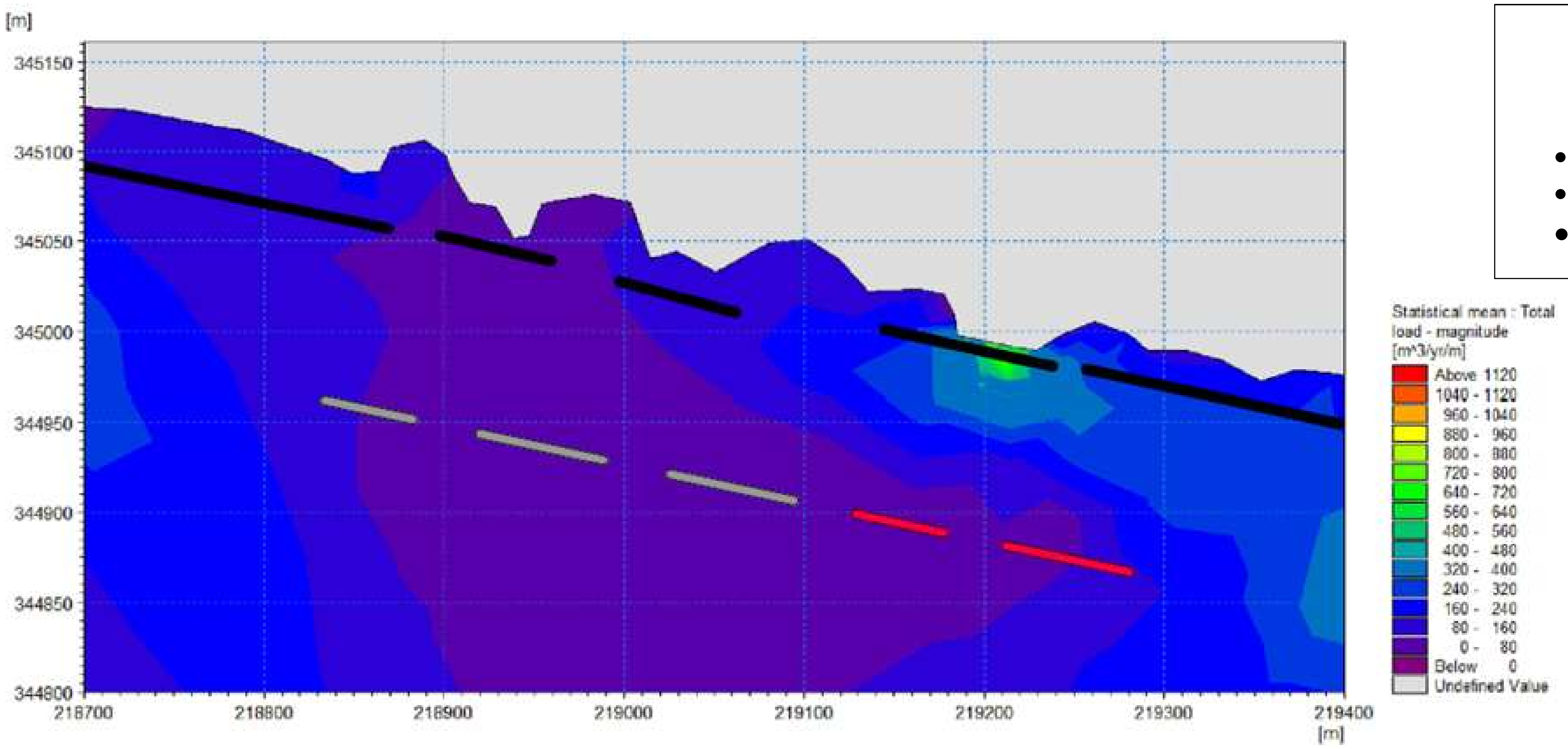
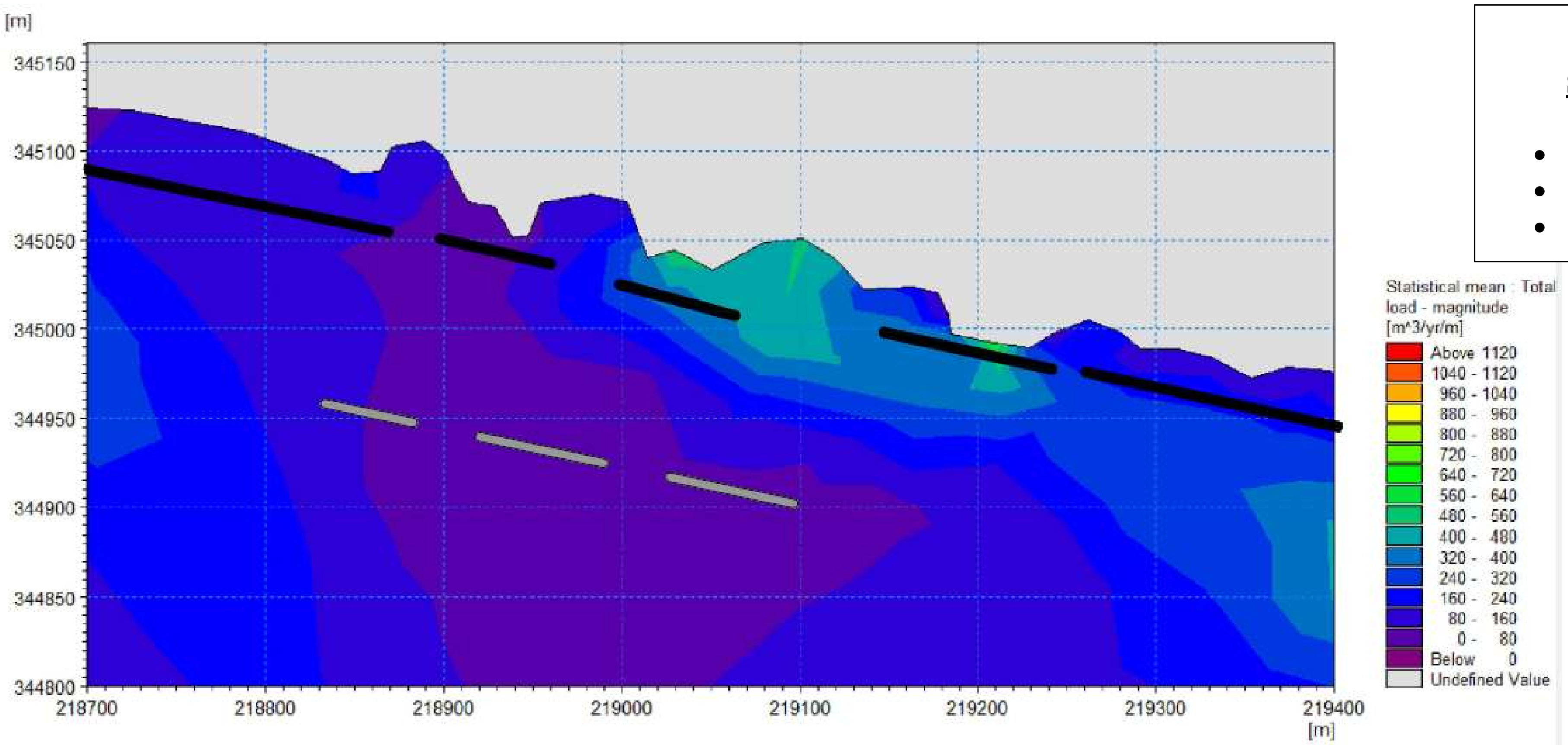


Figure B8 - SCENARIO B

SEDIMENT TRANSPORT CLOSE UP VIEW

- **DIRECTION - 180°**
- **Hs - 0.89m**
- **T_p - 4.76s**



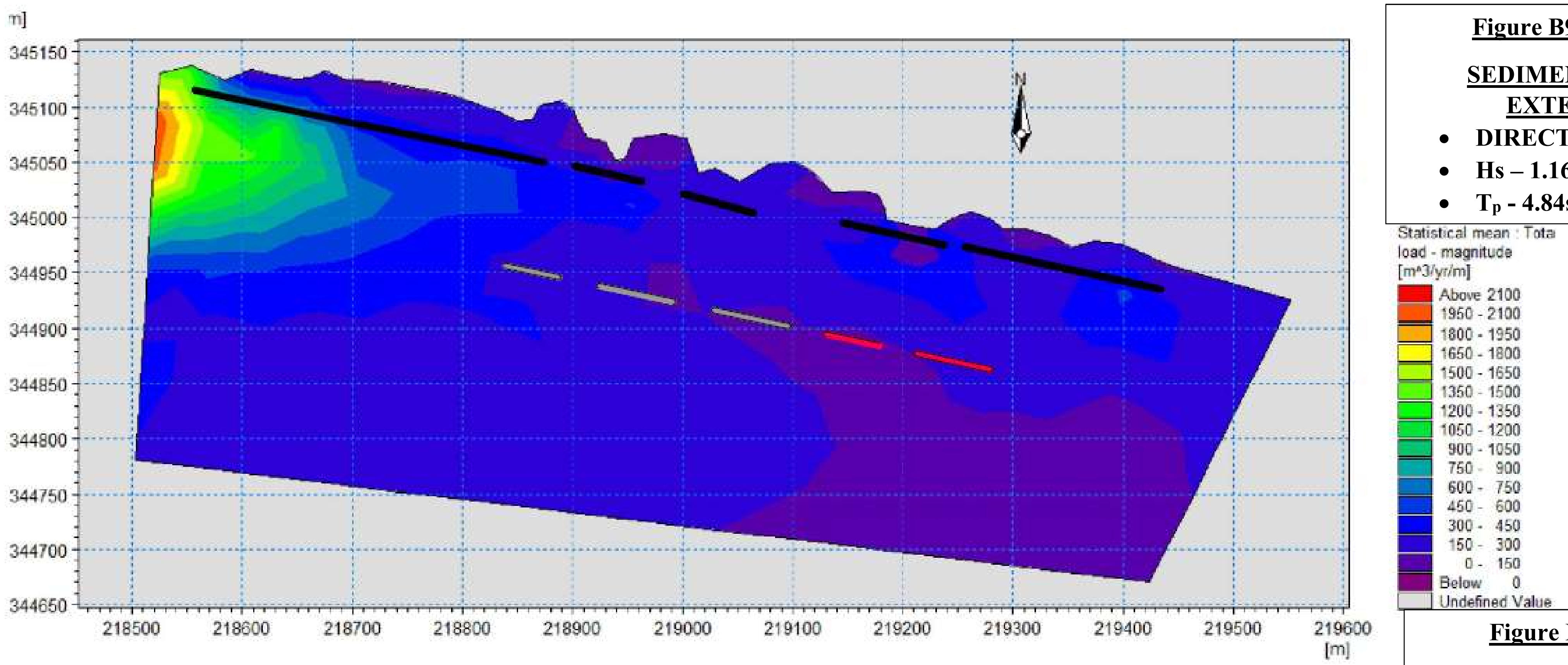


Figure B9 - SCENARIO A

SEDIMENT TRANSPORT EXTENDED VIEW

- **DIRECTION - 210°**
- **Hs – 1.16m**
- **T_p - 4.84s**

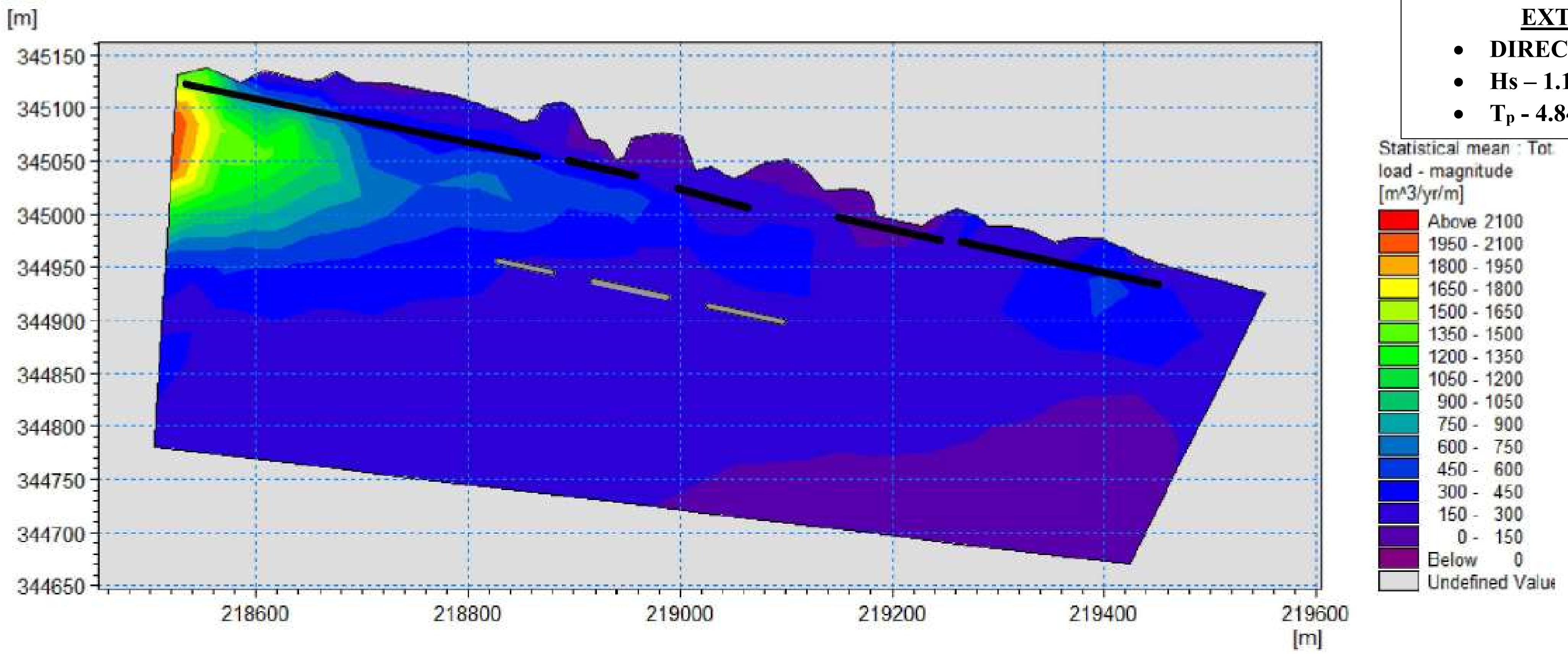


Figure B10- SCENARIO B

SEDIMENT TRANSPORT EXTENDED VIEW

- **DIRECTION - 210°**
- **Hs – 1.16m**
- **T_p - 4.84s**

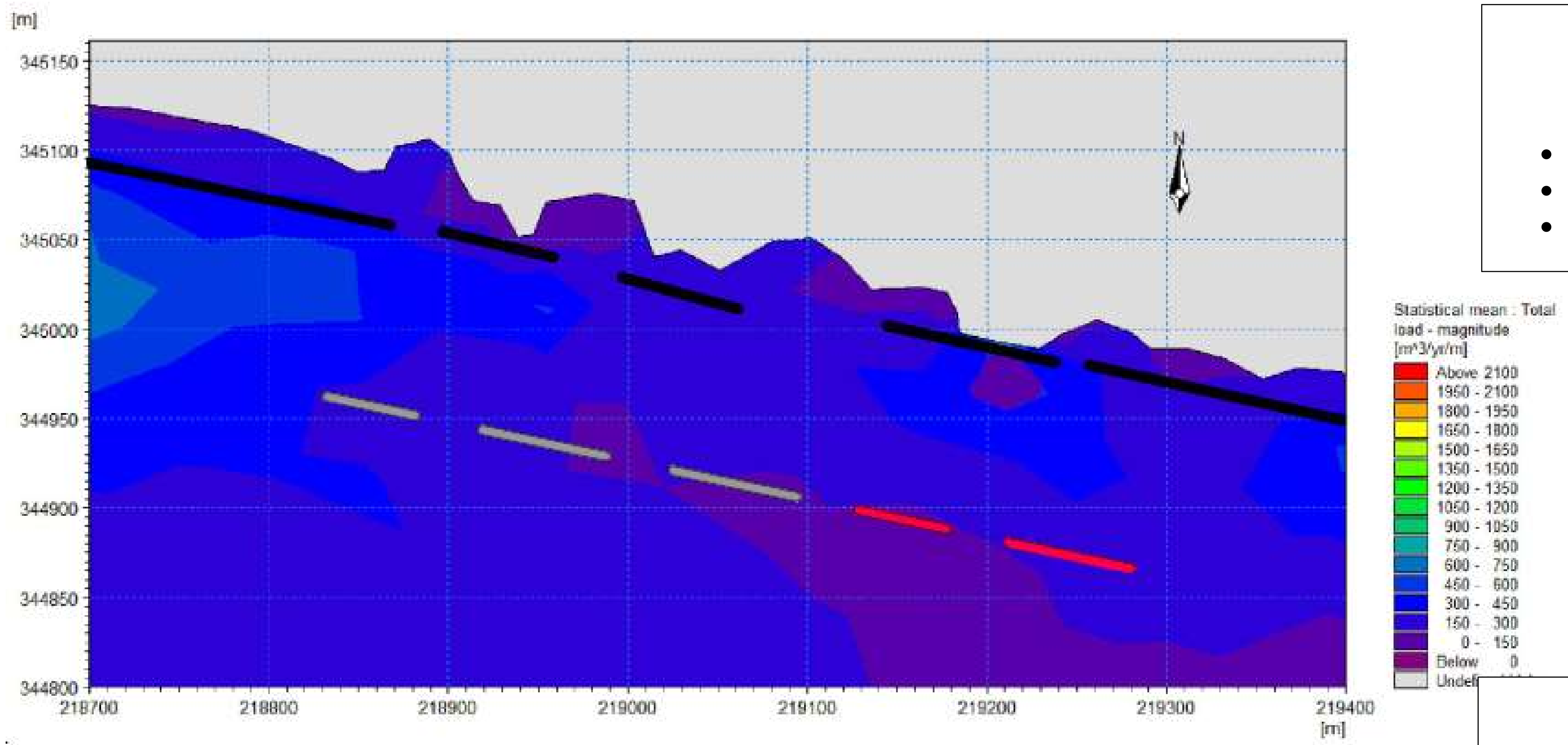


Figure B11 - SCENARIO A

SEDIMENT TRANSPORT
CLOSE UP VIEW

- **DIRECTION - 210°**
- **Hs – 1.16m**
- **T_p - 4.84s**

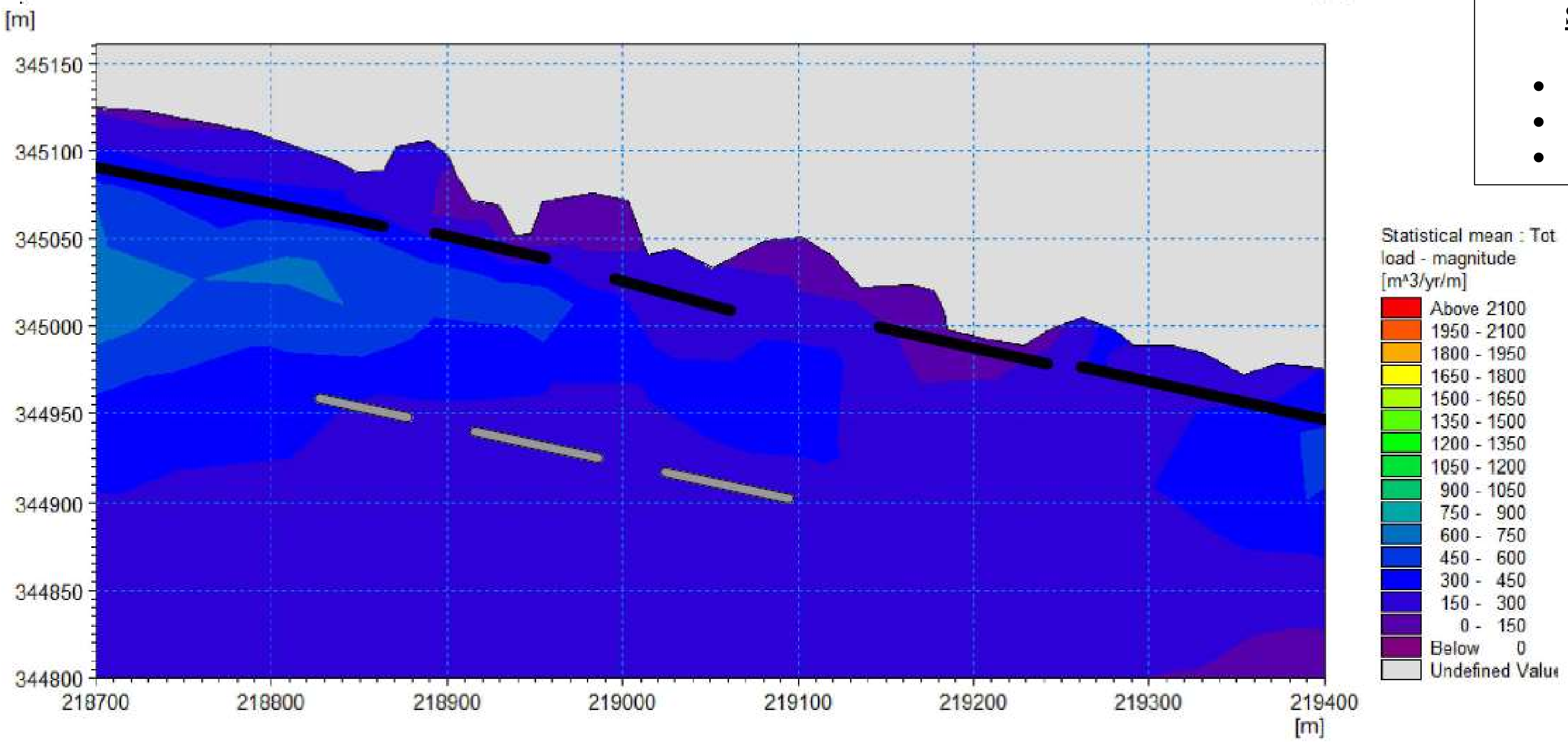


Figure B12- SCENARIO B

SEDIMENT TRANSPORT
CLOSE UP VIEW

- **DIRECTION - 210°**
- **Hs – 1.16m**
- **T_p - 4.84s**

Figure B13 - SCENARIO A

SEDIMENT TRANSPORT EXTENDED VIEW

- **DIRECTION - 240°**
- **Hs – 1.13m**
- **T_p - 4.89s**

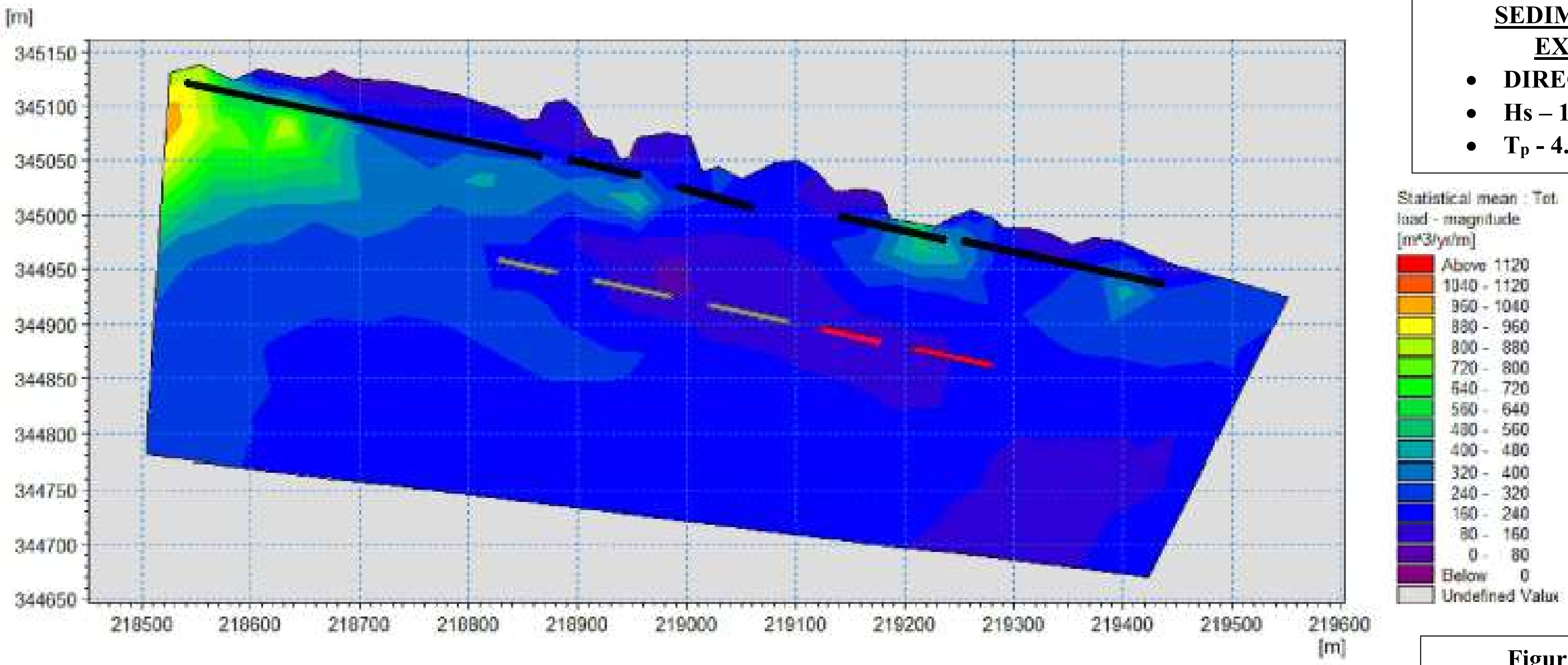
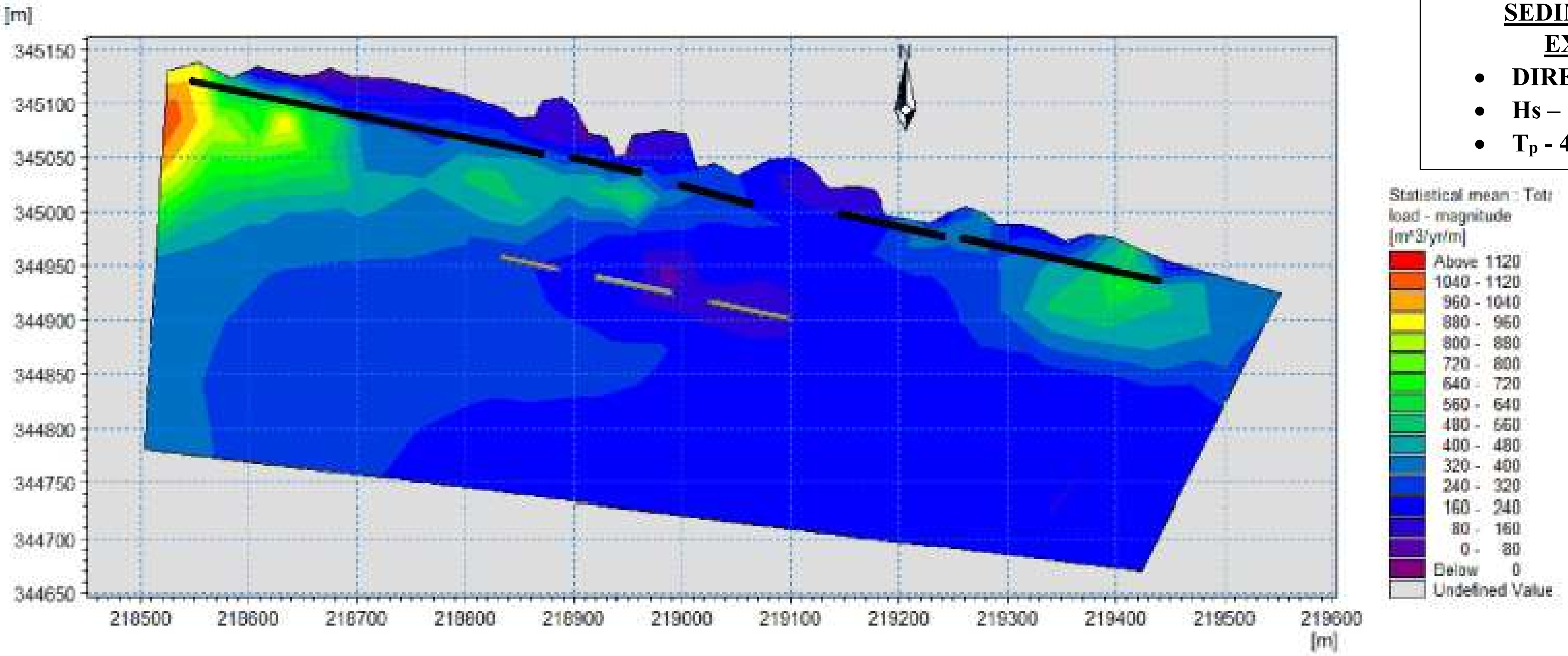


Figure B14- SCENARIO B

SEDIMENT TRANSPORT EXTENDED VIEW

- **DIRECTION - 240°**
- **Hs – 1.13m**
- **T_p - 4.89s**



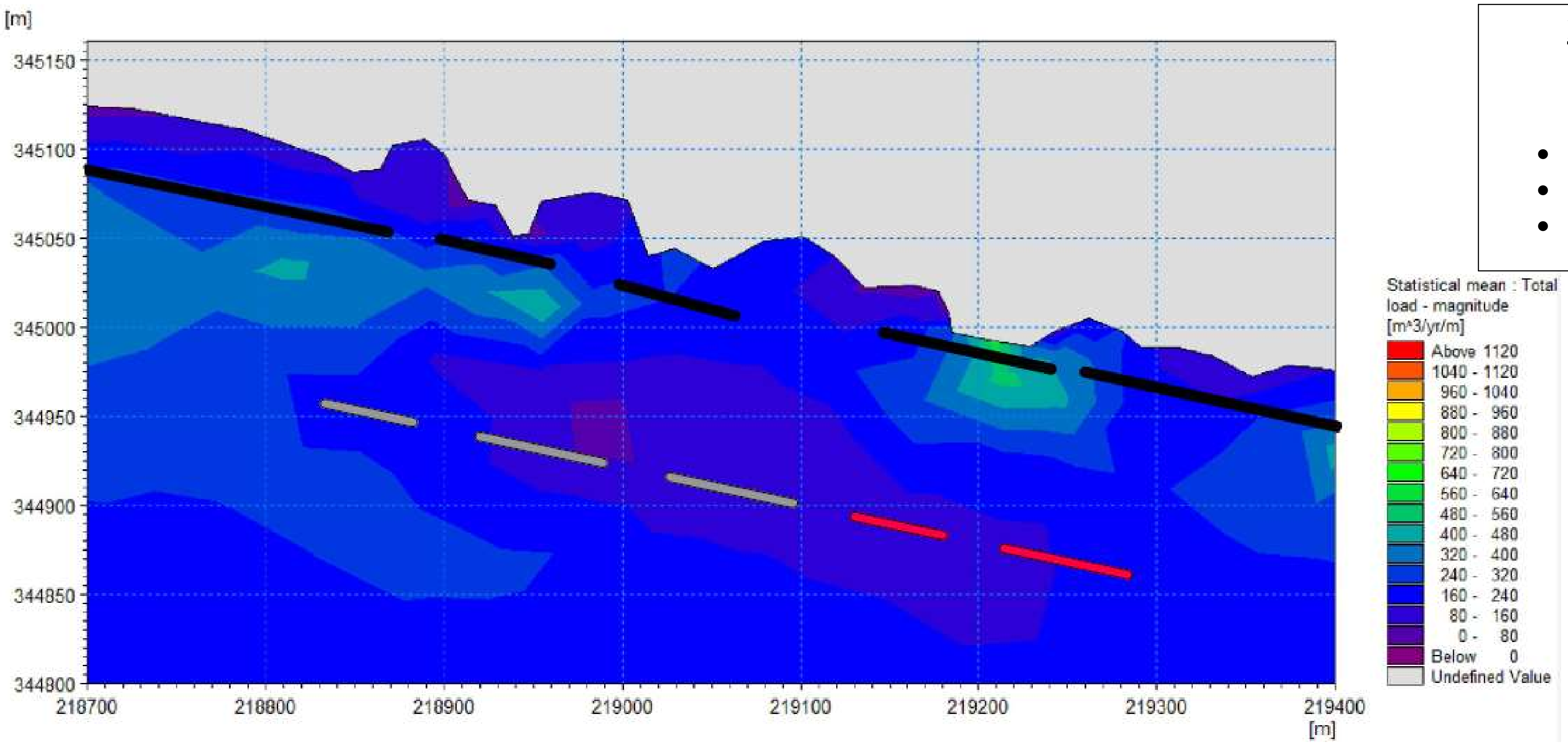


Figure B15 - SCENARIO A

SEDIMENT TRANSPORT CLOSE UP VIEW

- **DIRECTION - 240°**
- **Hs – 1.13m**
- **T_p - 4.89s**

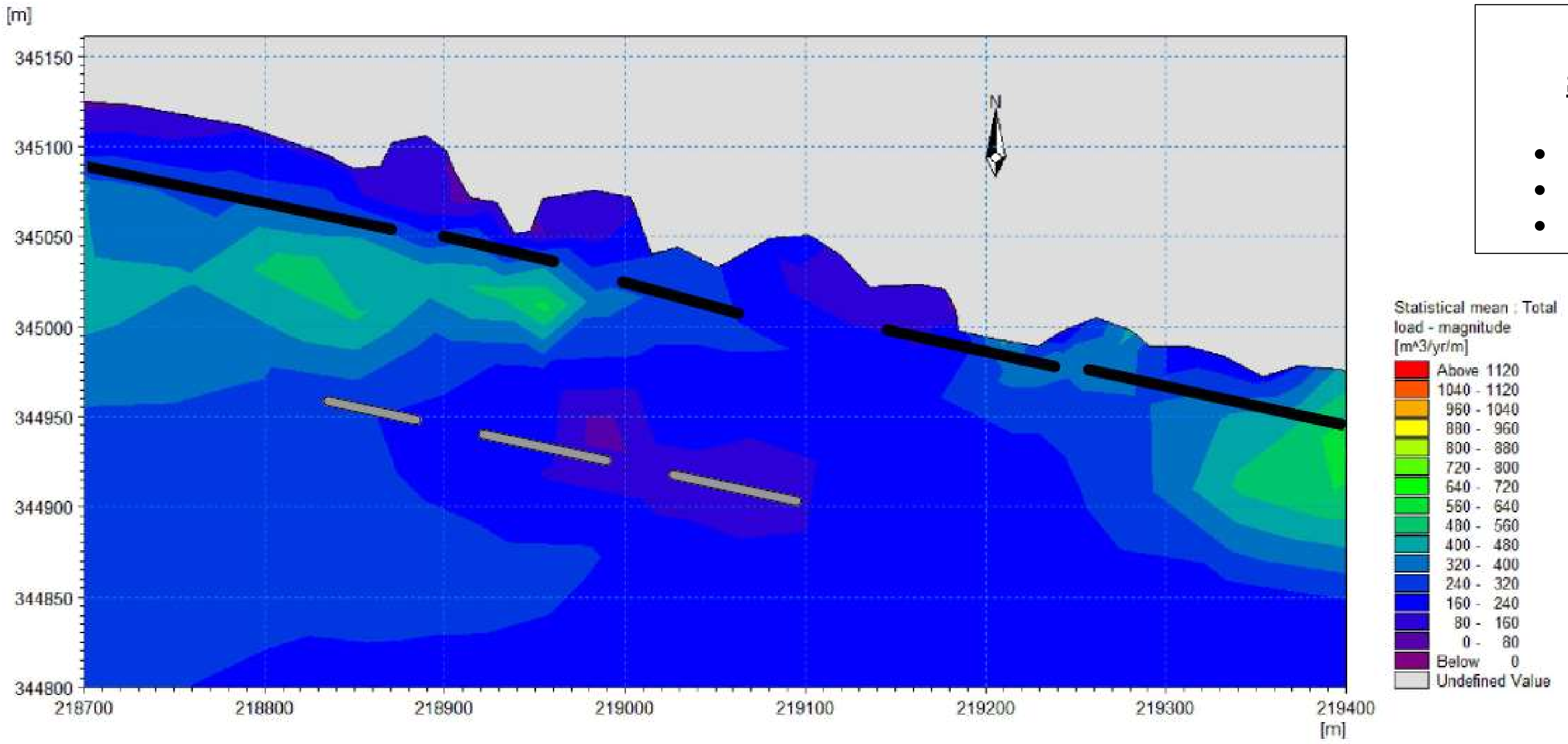


Figure B16- SCENARIO B

SEDIMENT TRANSPORT CLOSE UP VIEW

- **DIRECTION - 240°**
- **Hs – 1.13m**
- **T_p - 4.89s**

APPENDIX C BED LEVEL CHANGE RATE RESULTS

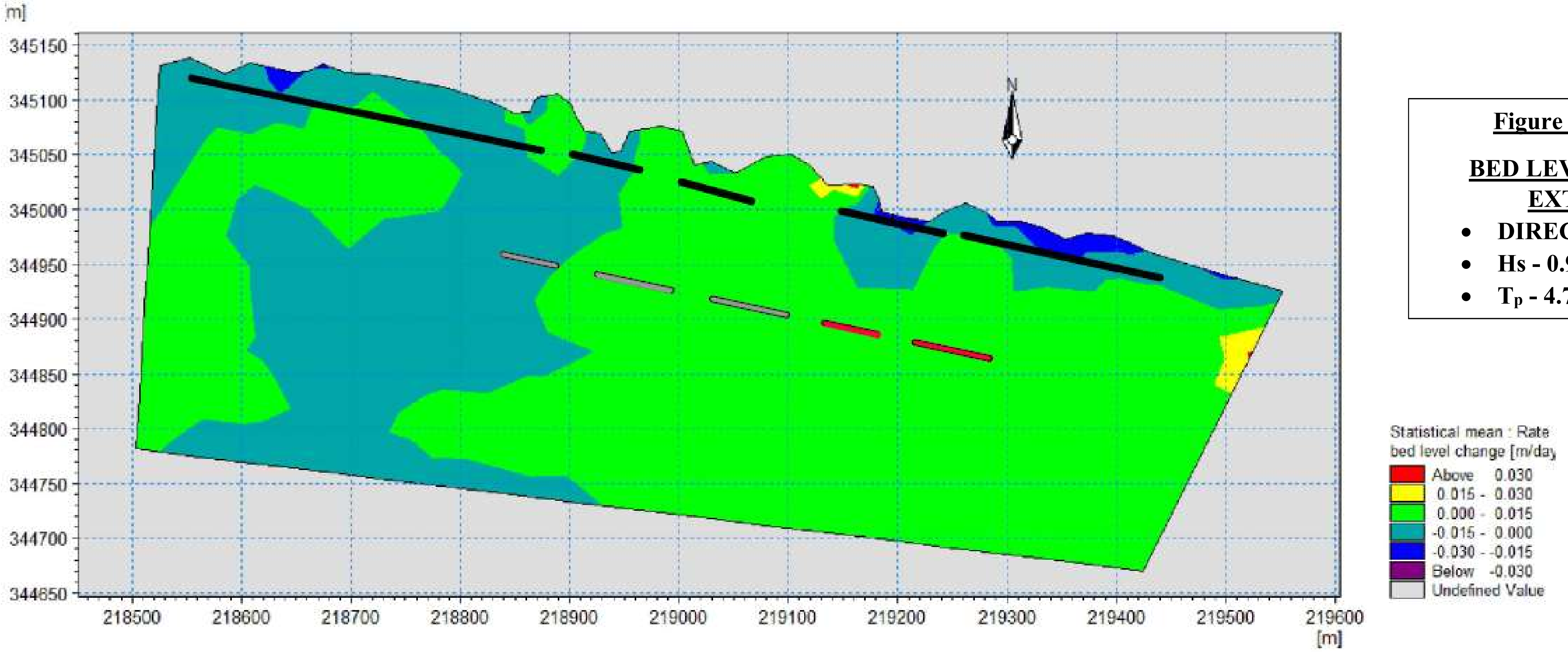


Figure C1 - SCENARIO A

BED LEVEL RATE CHANGE EXTENDED VIEW

- **DIRECTION - 150°**
- **Hs - 0.9m**
- **T_p - 4.73s**

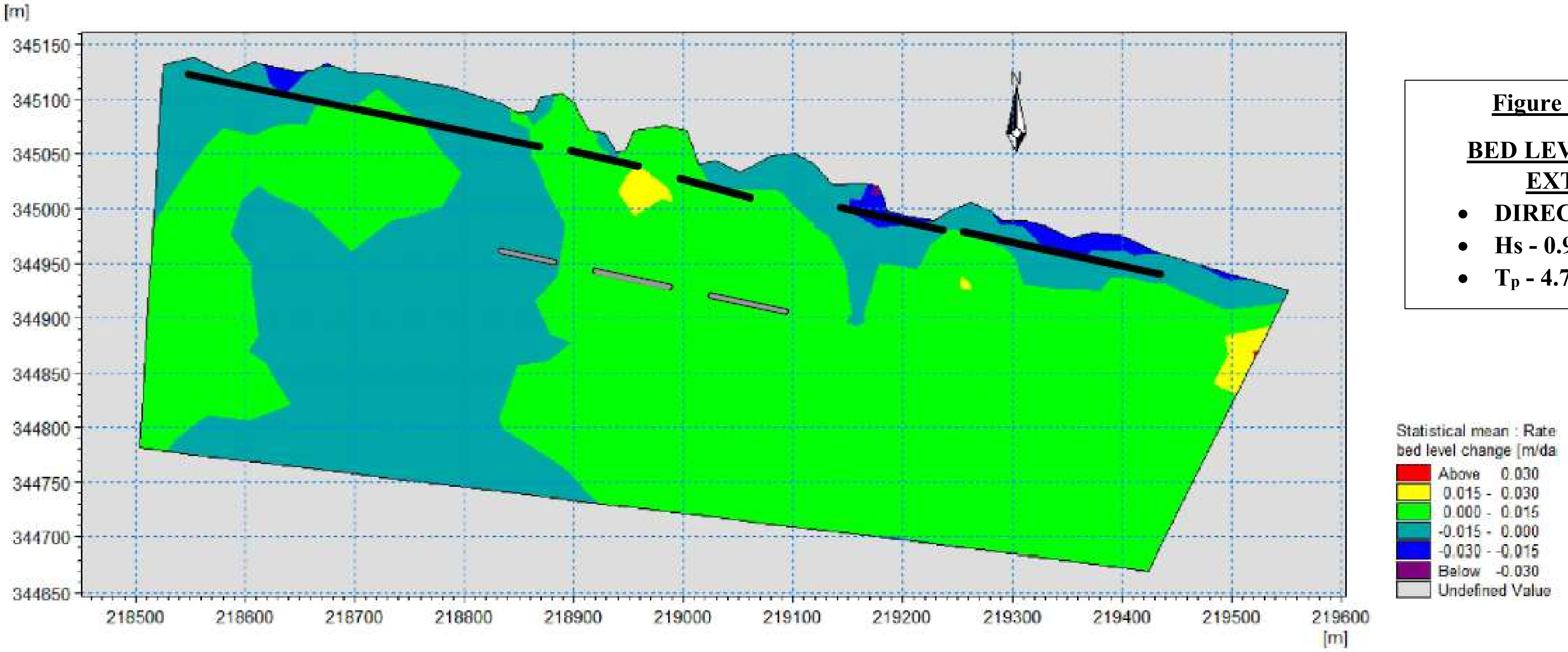


Figure C2 - SCENARIO B

BED LEVEL RATE CHANGE EXTENDED VIEW

- **DIRECTION - 150°**
- **Hs - 0.9m**
- **T_p - 4.73s**

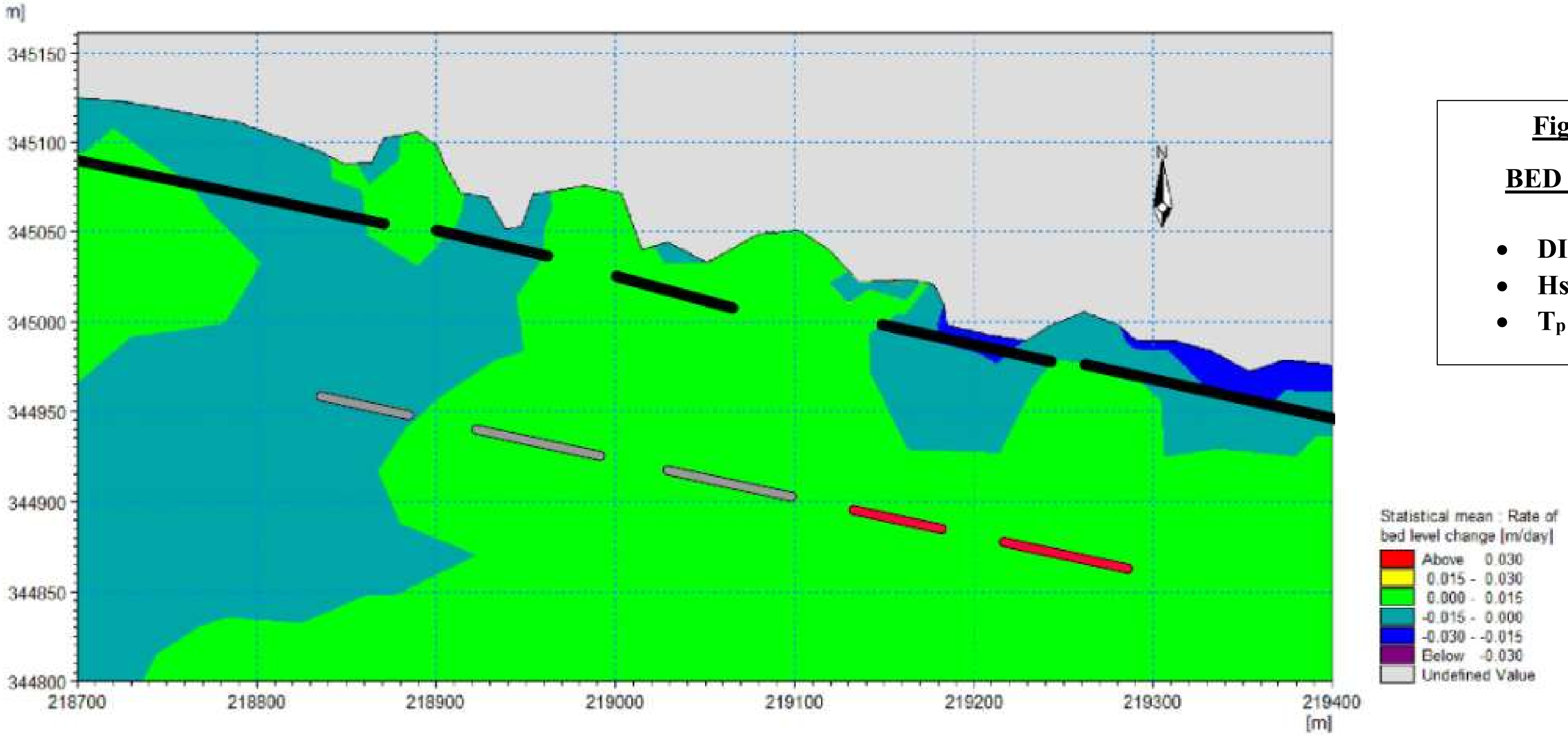


Figure C3 - SCENARIO A

BED LEVEL RATE CHANGE CLOSE UP VIEW

- **DIRECTION - 150°**
- **Hs - 0.9m**
- **T_p - 4.73s**

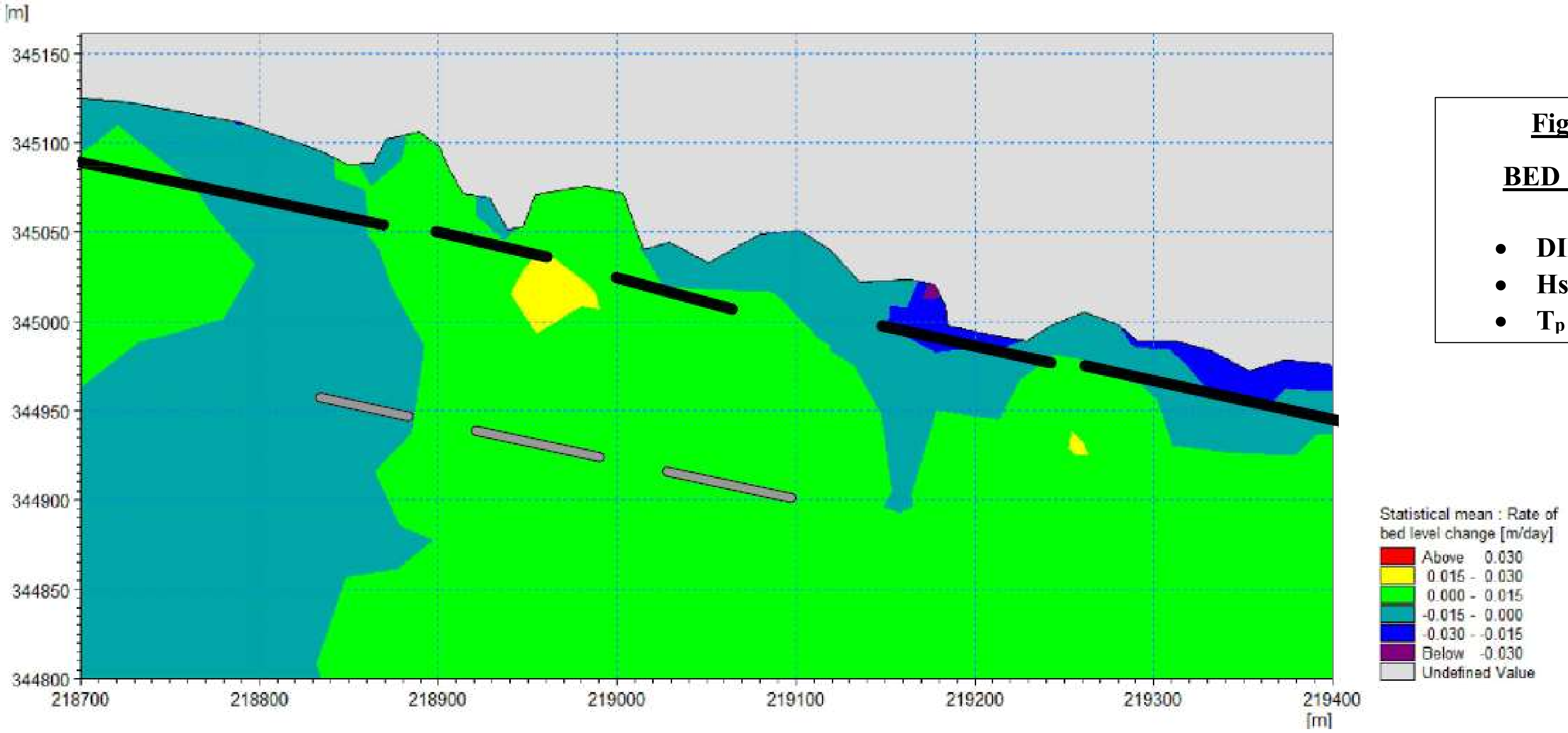


Figure C4 - SCENARIO B

BED LEVEL RATE CHANGE CLOSE UP VIEW

- **DIRECTION - 150°**
- **Hs - 0.9m**
- **T_p - 4.73s**

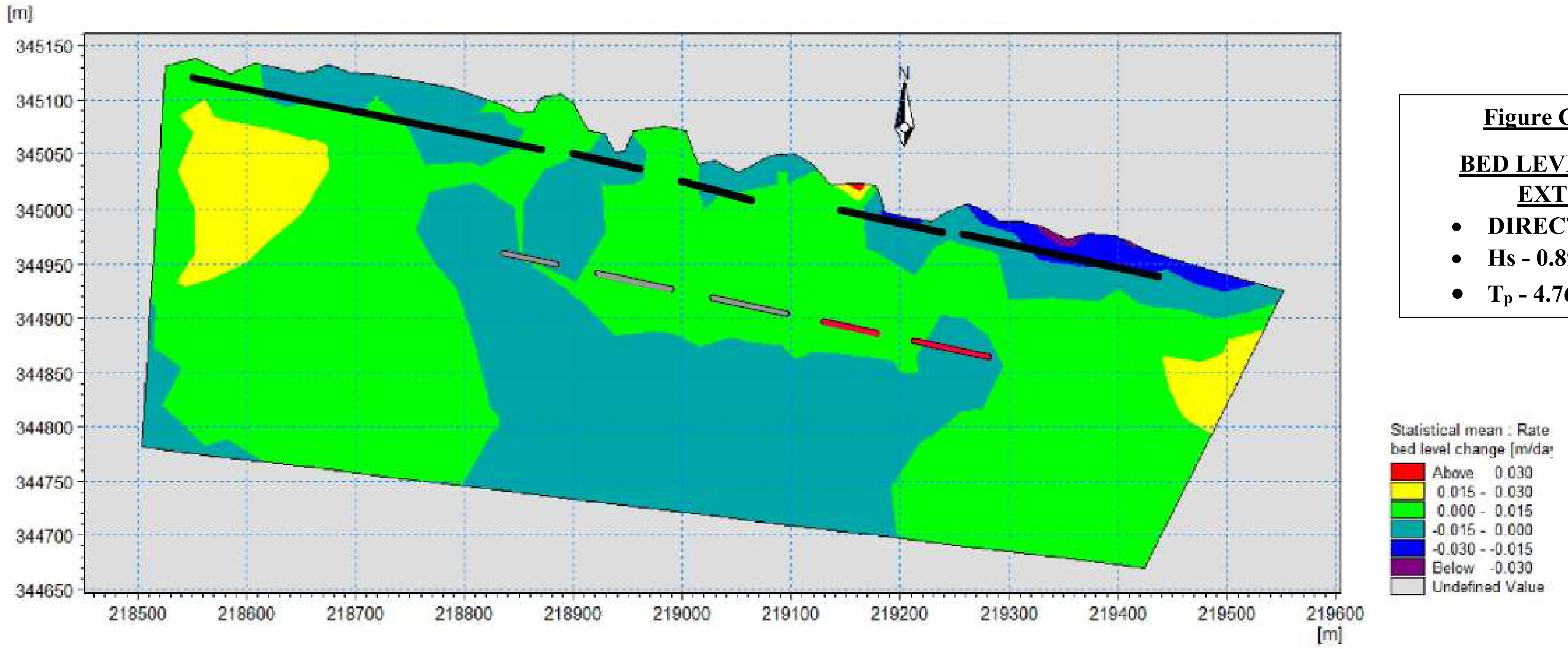


Figure C5 - SCENARIO A

BED LEVEL RATE CHANGE EXTENDED VIEW

- **DIRECTION - 180°**
- **Hs - 0.89m**
- **T_p - 4.76s**

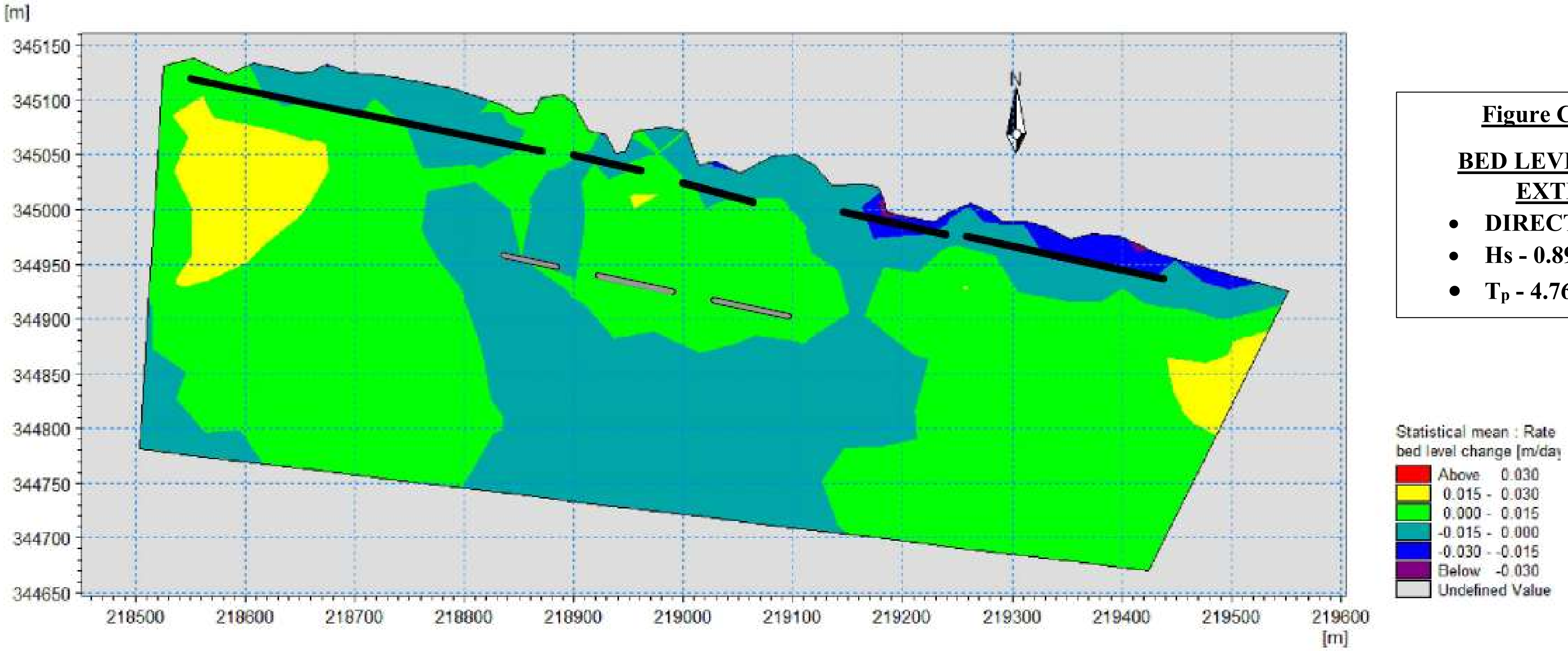


Figure C6 - SCENARIO A

BED LEVEL RATE CHANGE EXTENDED VIEW

- **DIRECTION - 180°**
- **Hs - 0.89m**
- **T_p - 4.76s**

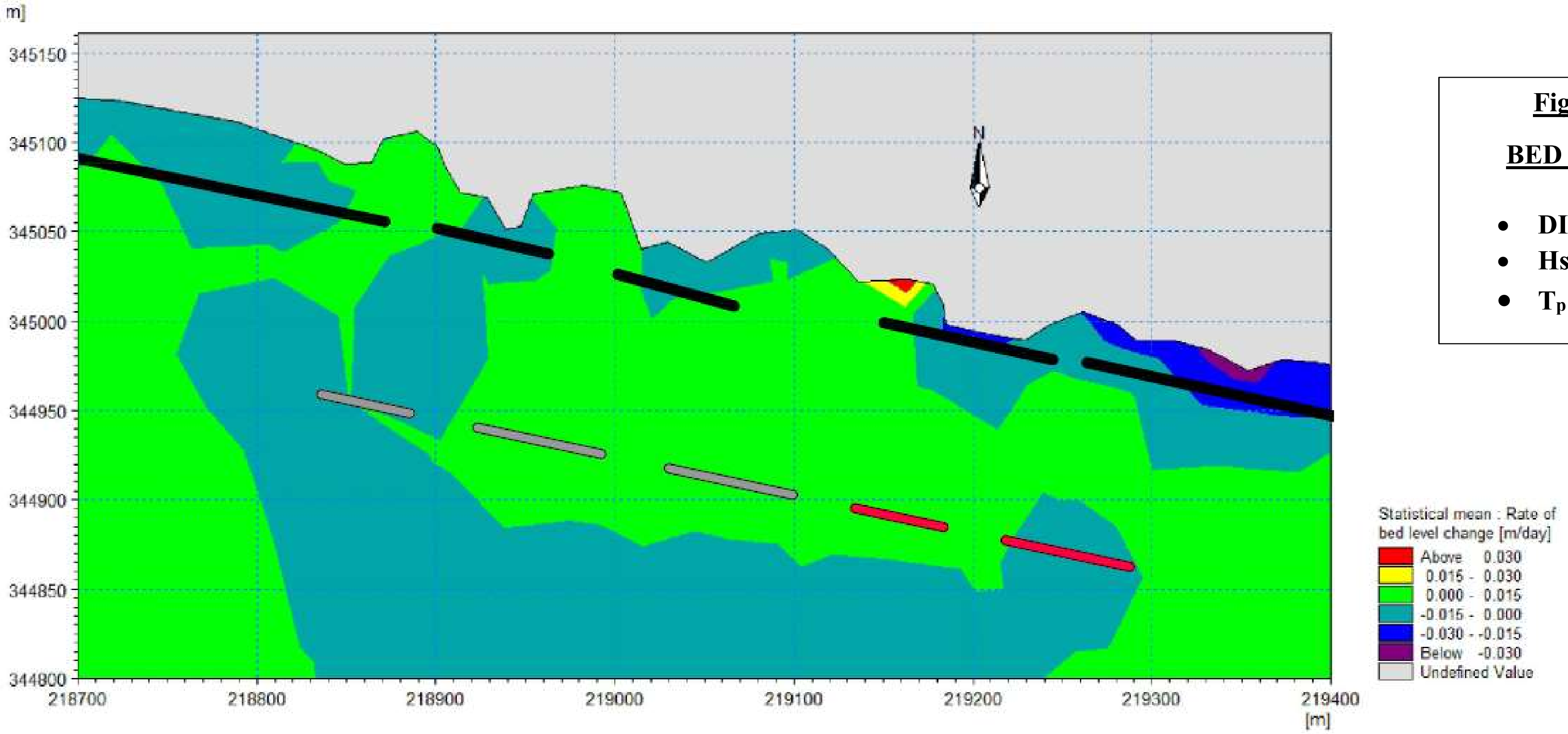


Figure C7 - SCENARIO A

BED LEVEL RATE CHANGE CLOSE UP VIEW

- **DIRECTION - 180°**
- **Hs - 0.89m**
- **T_p - 4.76s**

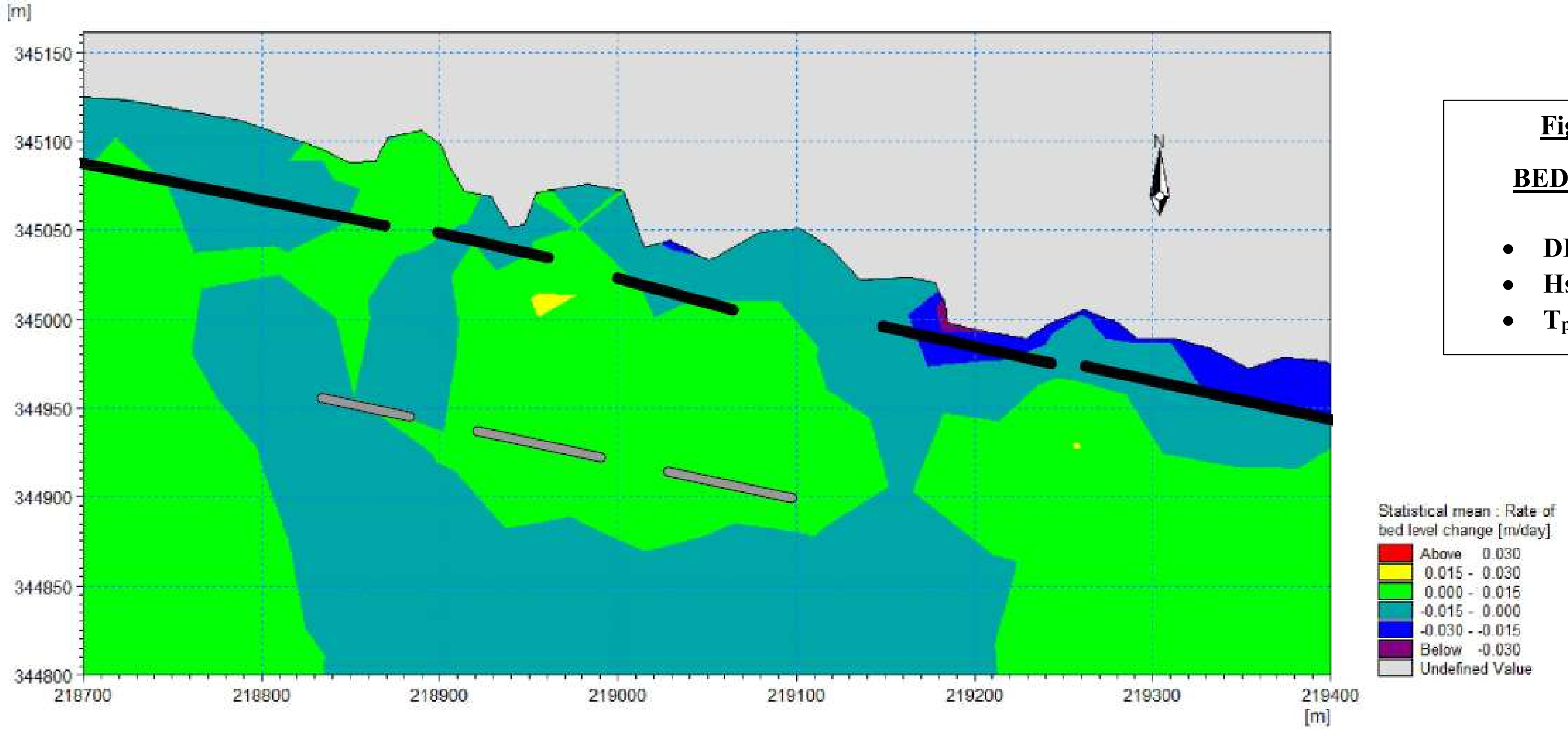


Figure C8 - SCENARIO B

BED LEVEL RATE CHANGE CLOSE UP VIEW

- **DIRECTION - 180°**
- **Hs - 0.89m**
- **T_p - 4.76s**

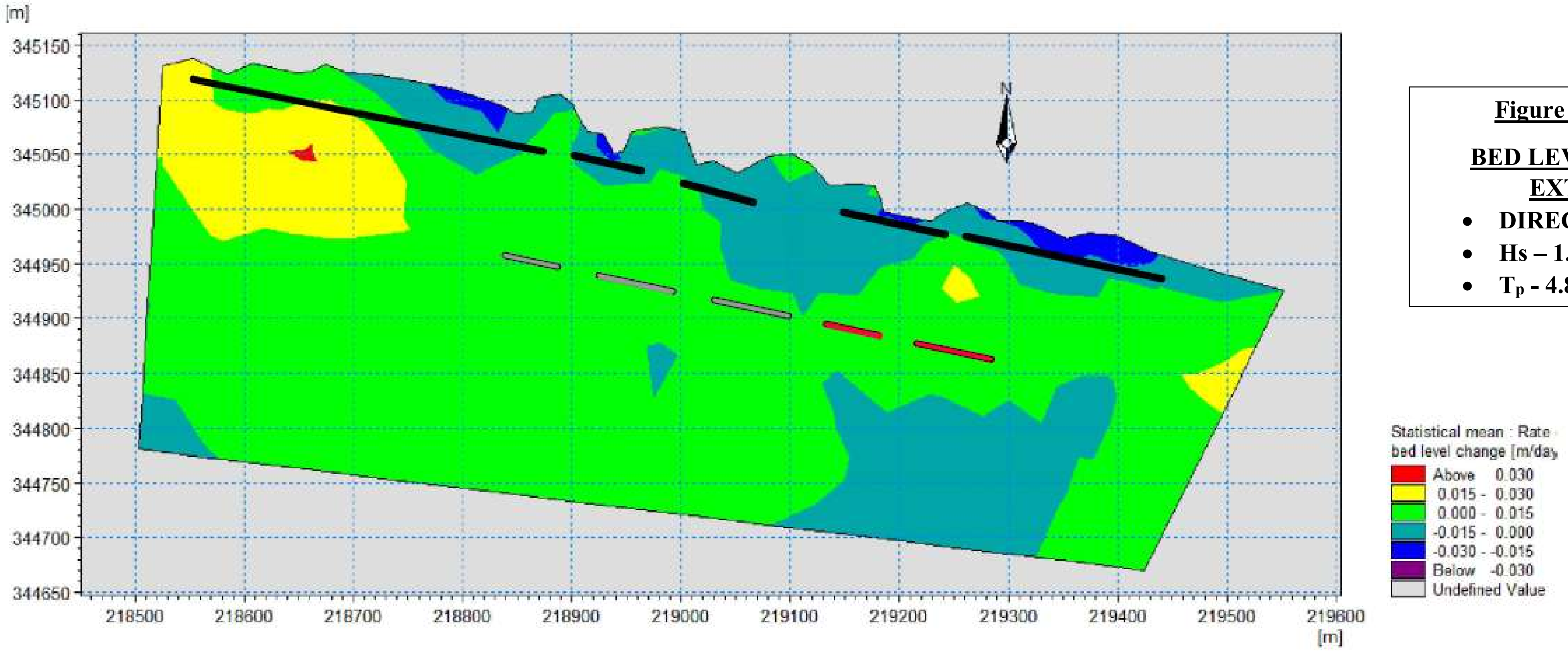


Figure C9 - SCENARIO A

BED LEVEL RATE CHANGE
EXTENDED VIEW

- **DIRECTION - 210°**
- **Hs – 1.16m**
- **T_p - 4.84s**

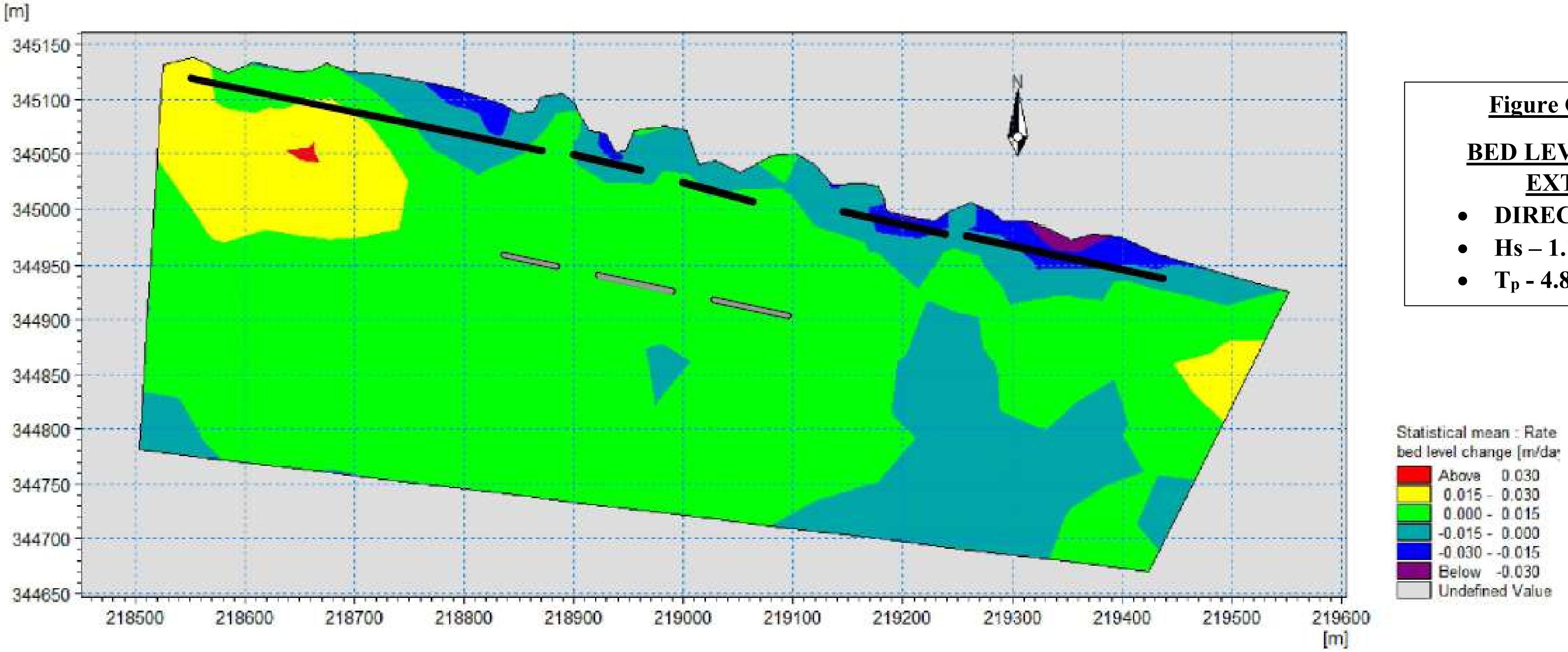


Figure C10- SCENARIO B

BED LEVEL RATE CHANGE
EXTENDED VIEW

- **DIRECTION - 210°**
- **Hs – 1.16m**
- **T_p - 4.84s**

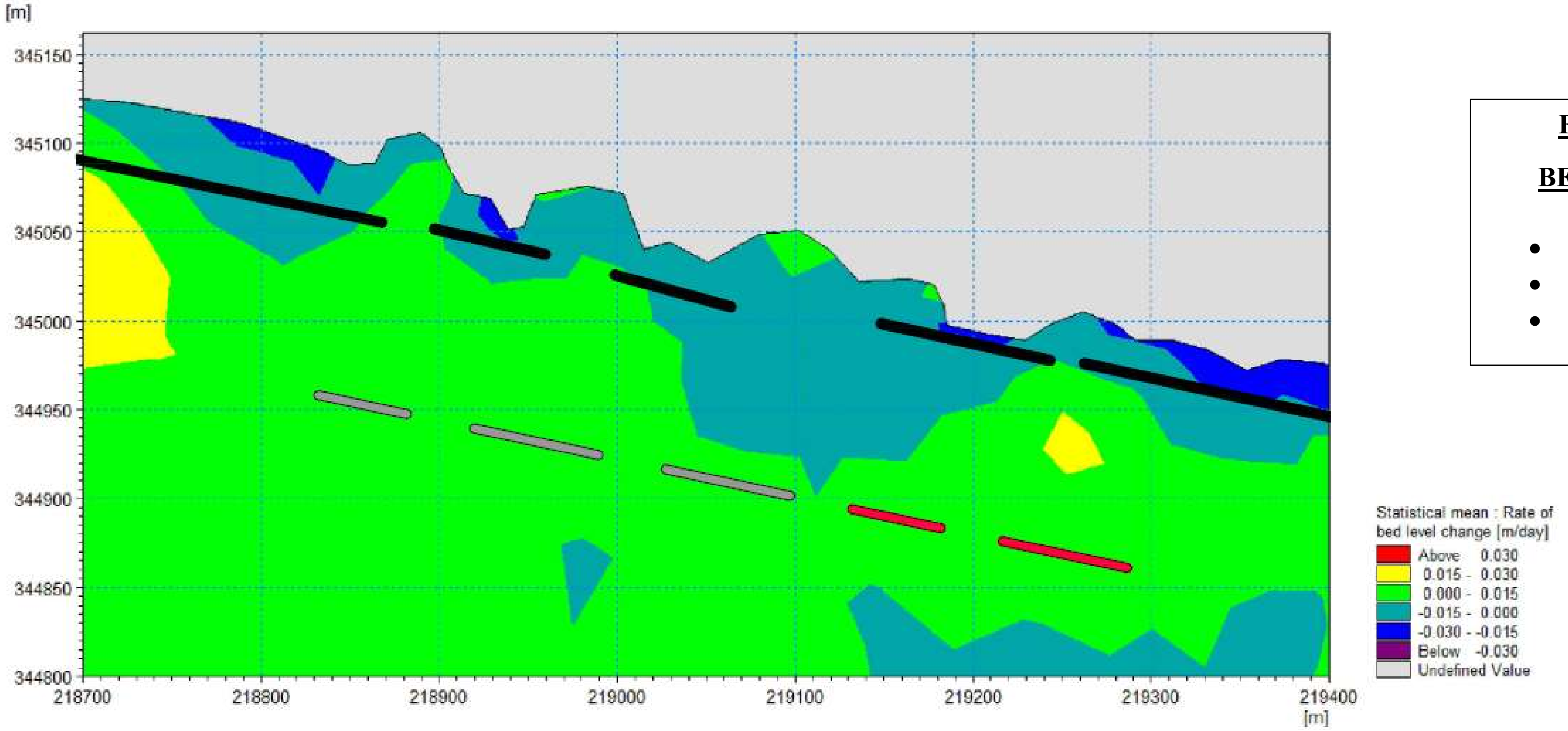


Figure C11 - SCENARIO A

BED LEVEL RATE CHANGE CLOSE UP VIEW

- **DIRECTION - 210°**
- **Hs – 1.16m**
- **T_p - 4.84s**

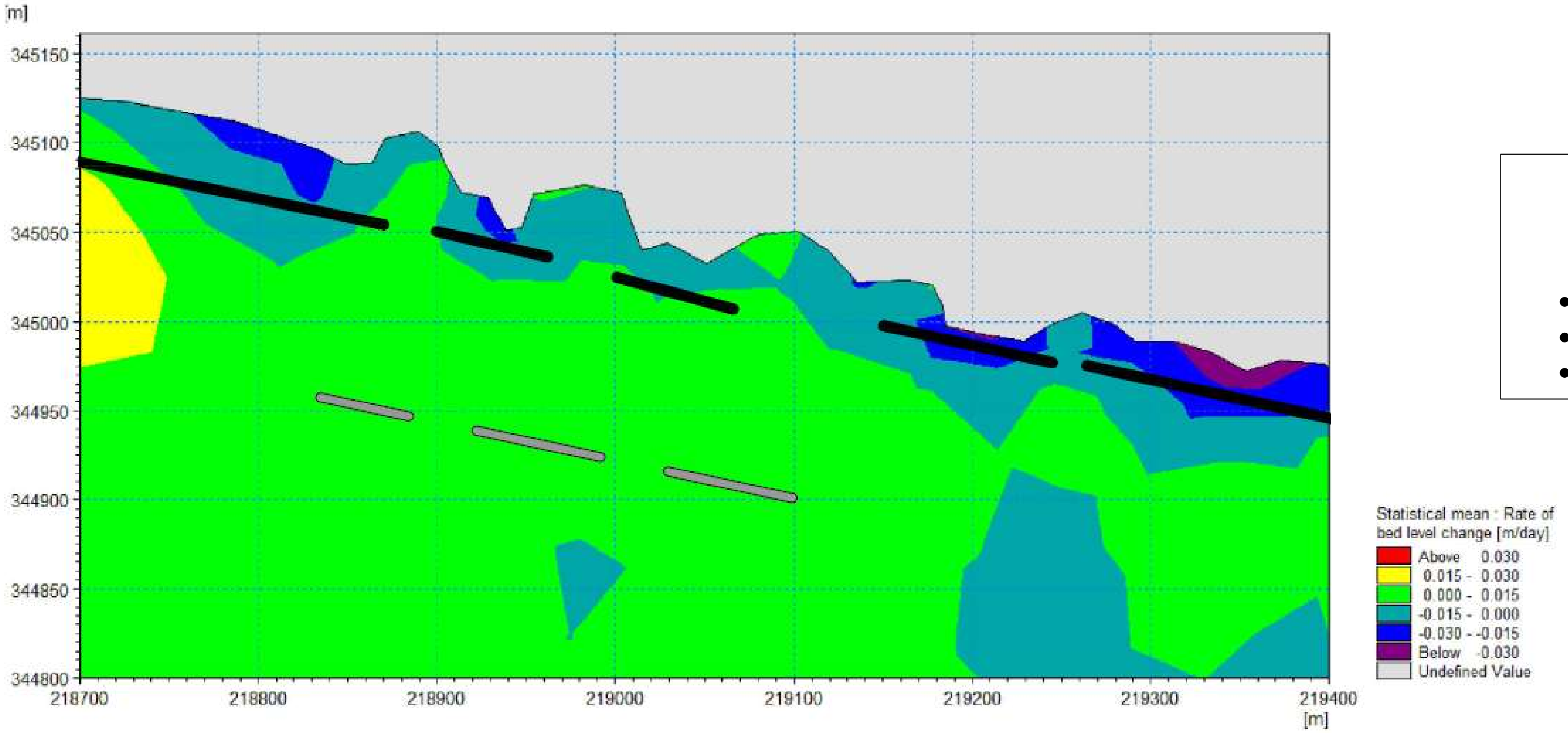


Figure C12- SCENARIO B

BED LEVEL RATE CHANGE CLOSE UP VIEW

- **DIRECTION - 210°**
- **Hs – 1.16m**
- **T_p - 4.84s**

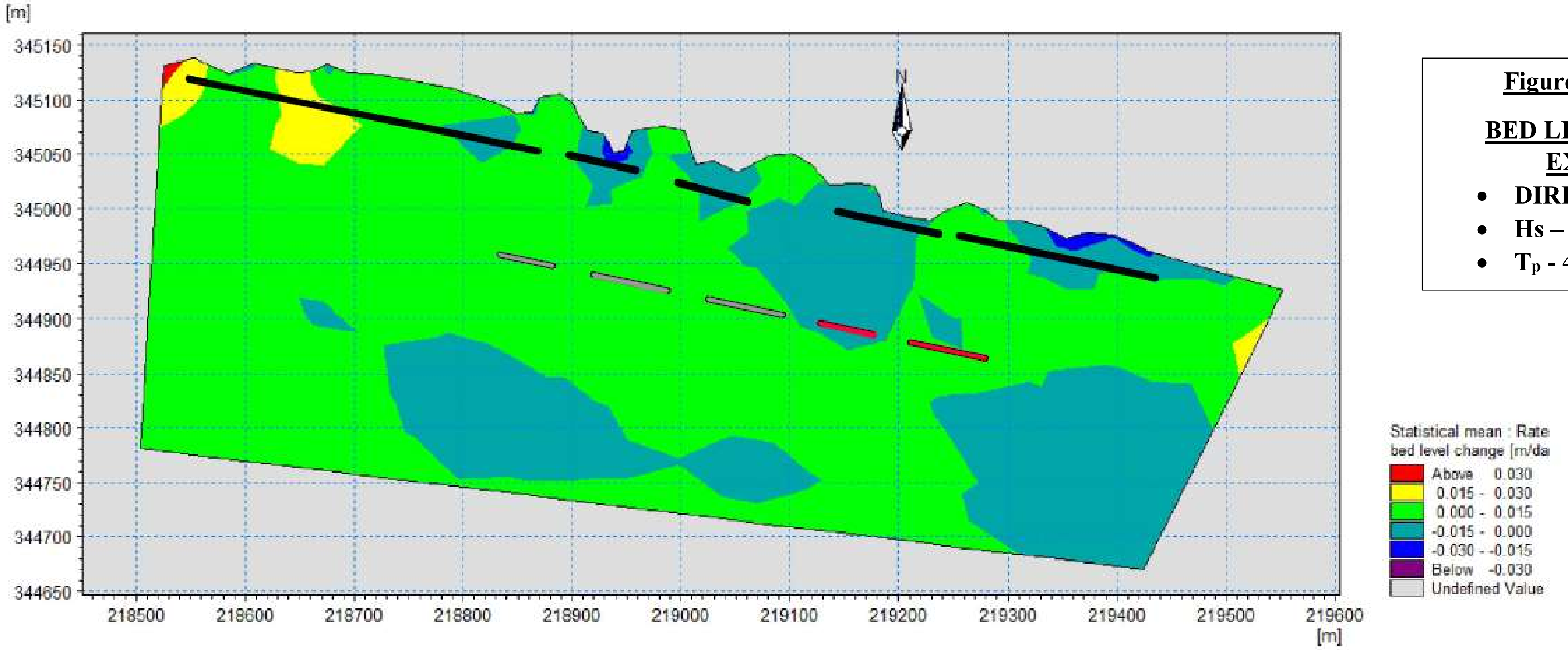


Figure C13 - SCENARIO A

BED LEVEL RATE CHANGE EXTENDED VIEW

- **DIRECTION - 240°**
- **Hs – 1.13m**
- **T_p - 4.89s**

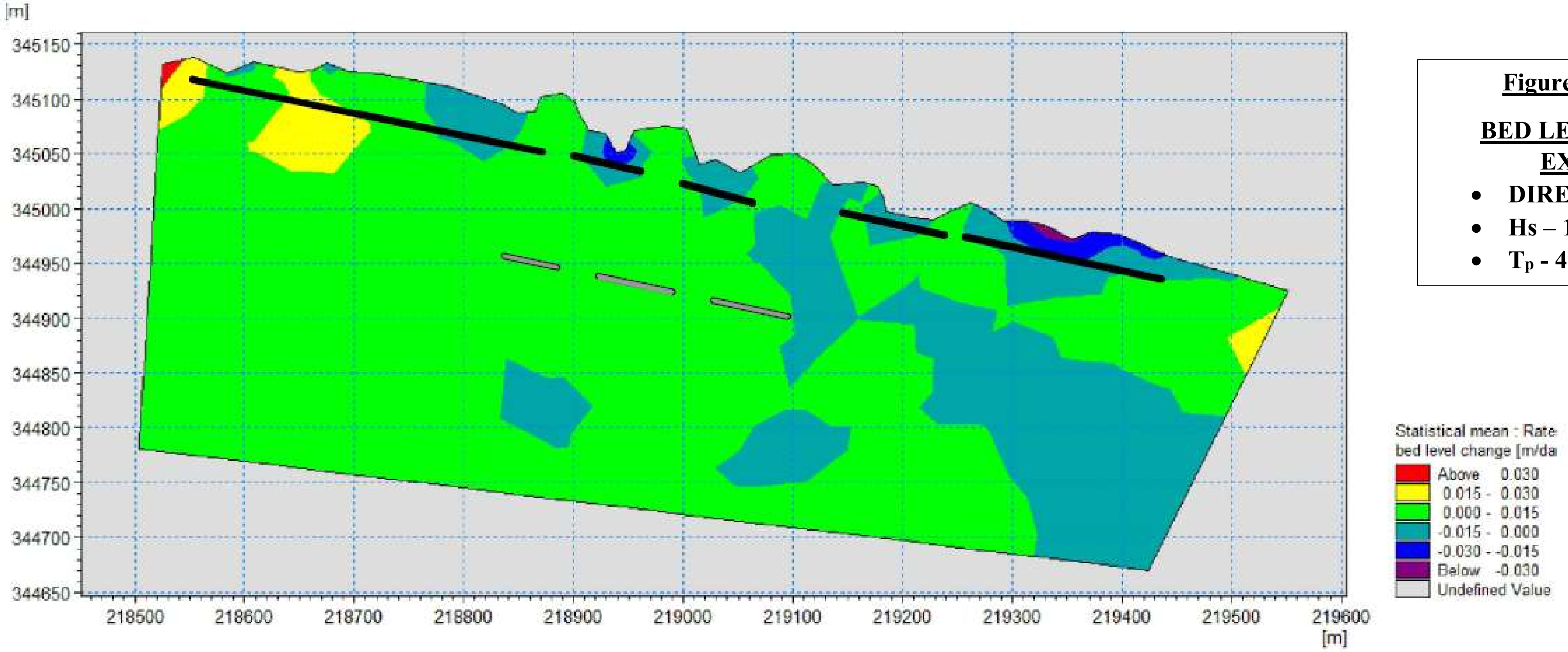
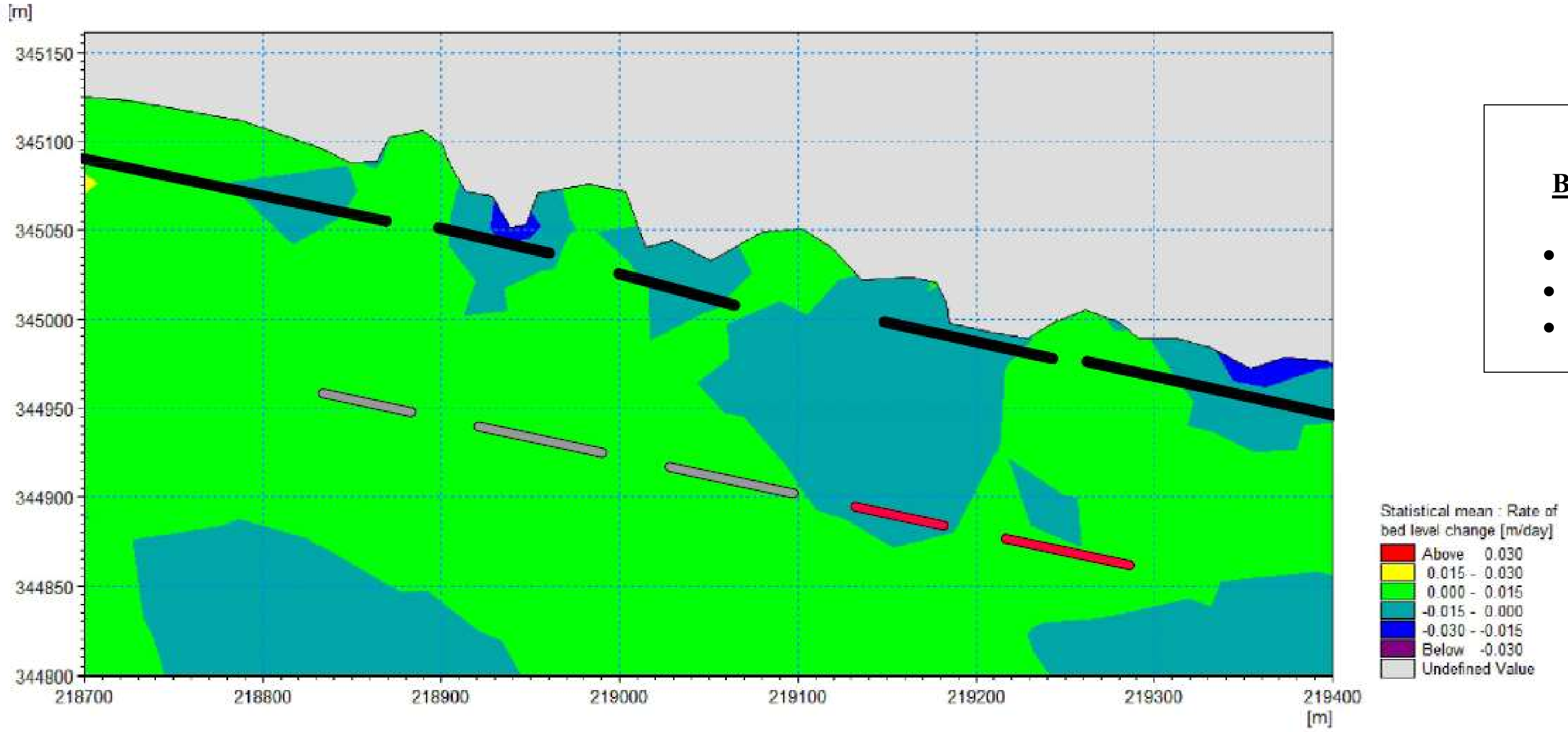


Figure C14- SCENARIO B

BED LEVEL RATE CHANGE EXTENDED VIEW

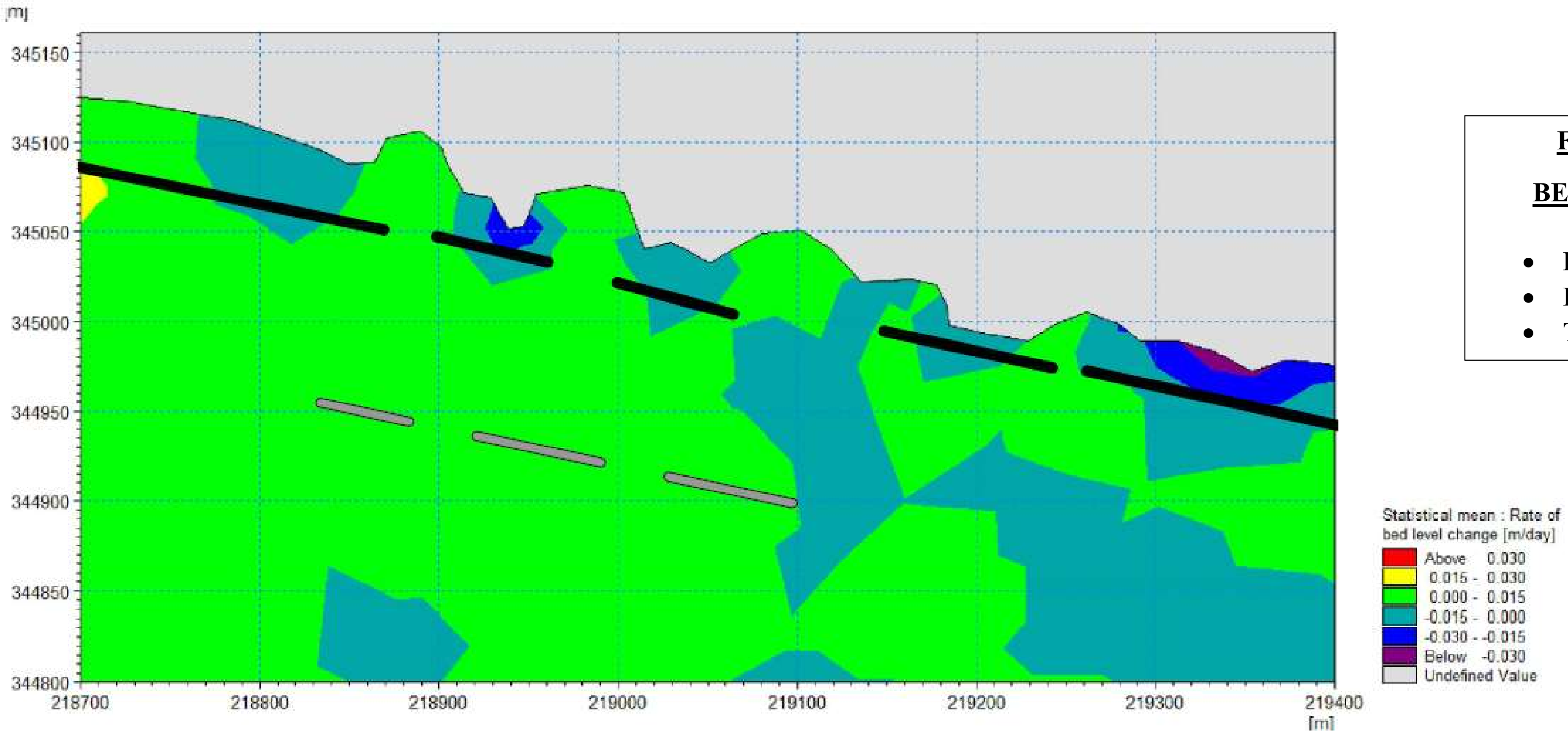
- **DIRECTION - 240°**
- **Hs – 1.13m**
- **T_p - 4.89s**



<u>Figure C15 - SCENARIO A</u>

<u>BED LEVEL RATE CHANGE CLOSE UP VIEW</u>

- **DIRECTION - 240°**
- **Hs – 1.13m**
- **T_p - 4.89s**



<u>Figure C16- SCENARIO B</u>

<u>BED LEVEL RATE CHANGE CLOSE UP VIEW</u>

- **DIRECTION - 240°**
- **Hs – 1.13m**
- **T_p - 4.89s**

APPENDIX D HYDRODYNAMIC RESULTS

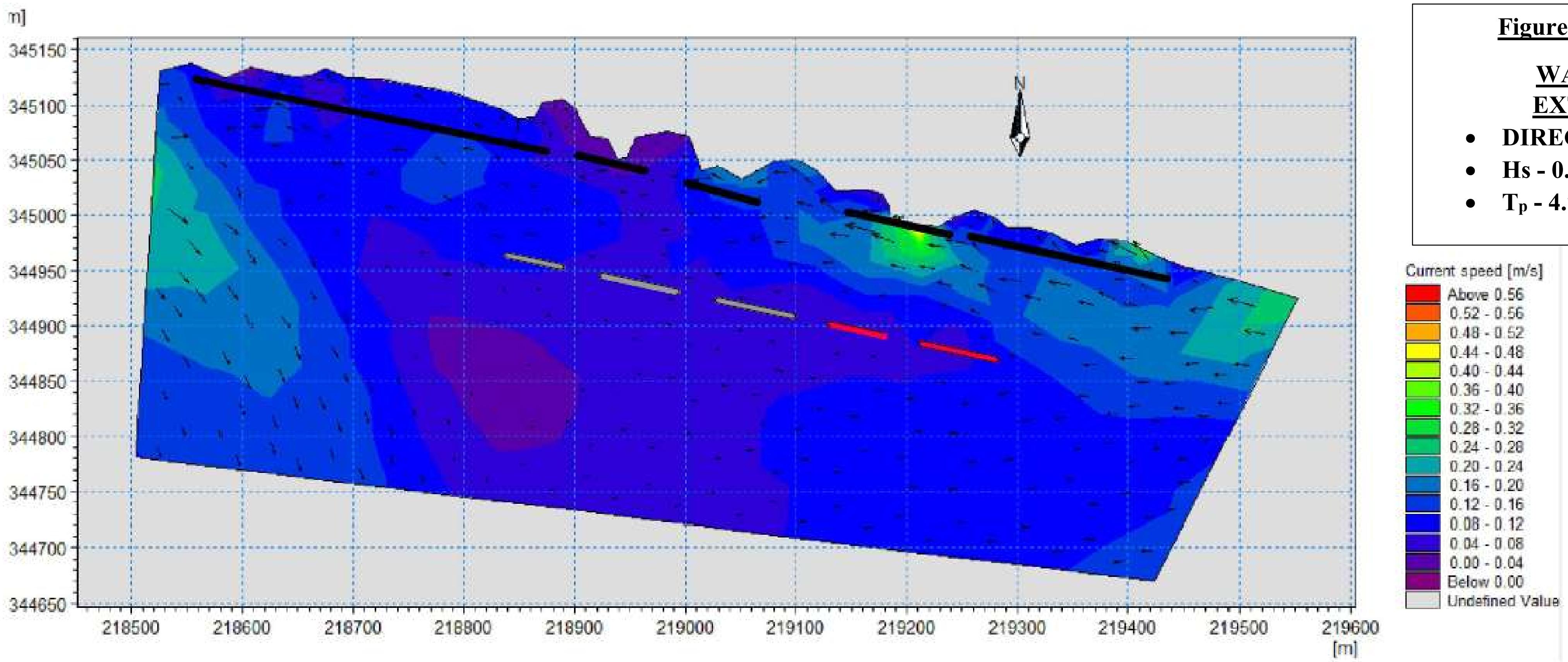


Figure D1 - SCENARIO A

WAVE CURRENT
EXTENDED VIEW

- **DIRECTION - 150°**
- **Hs - 0.9m**
- **T_p - 4.73s**

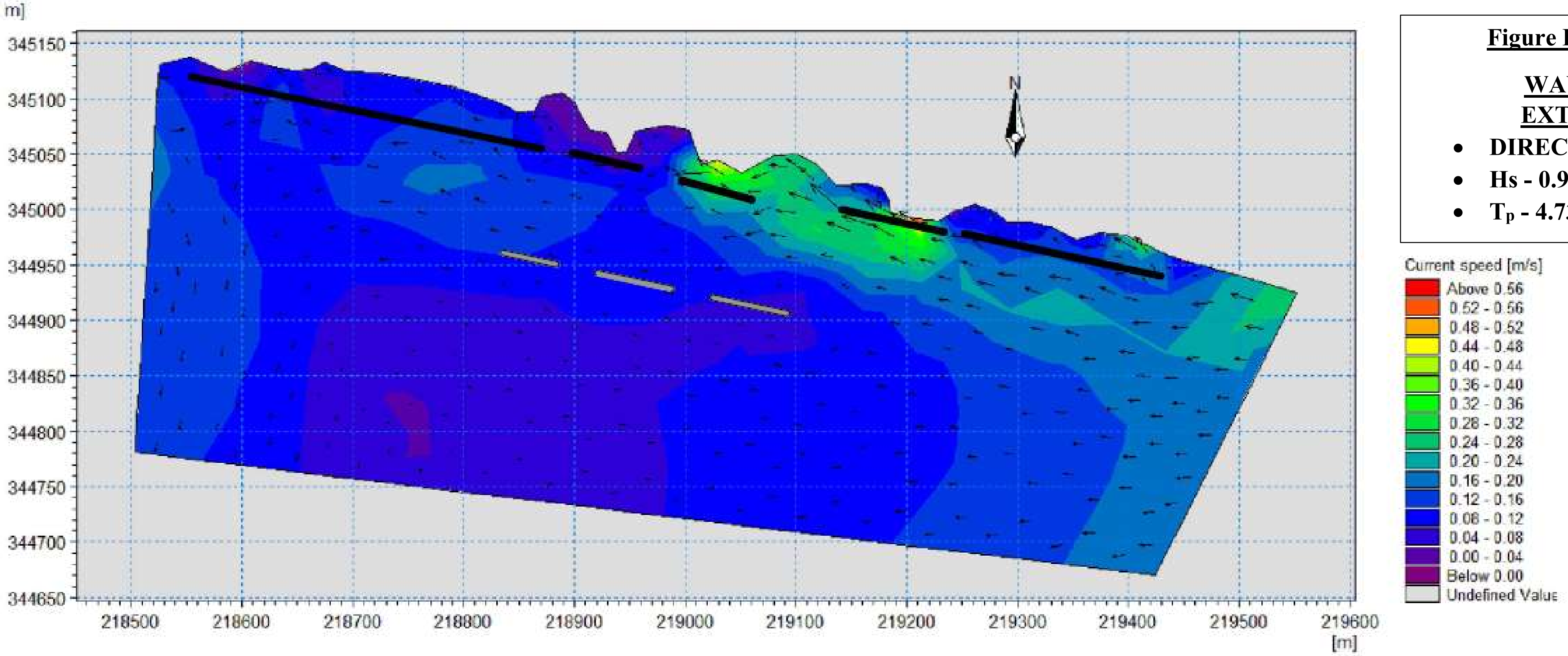


Figure D2 - SCENARIO B

WAVE CURRENT
EXTENDED VIEW

- **DIRECTION - 150°**
- **Hs - 0.9m**
- **T_p - 4.73s**

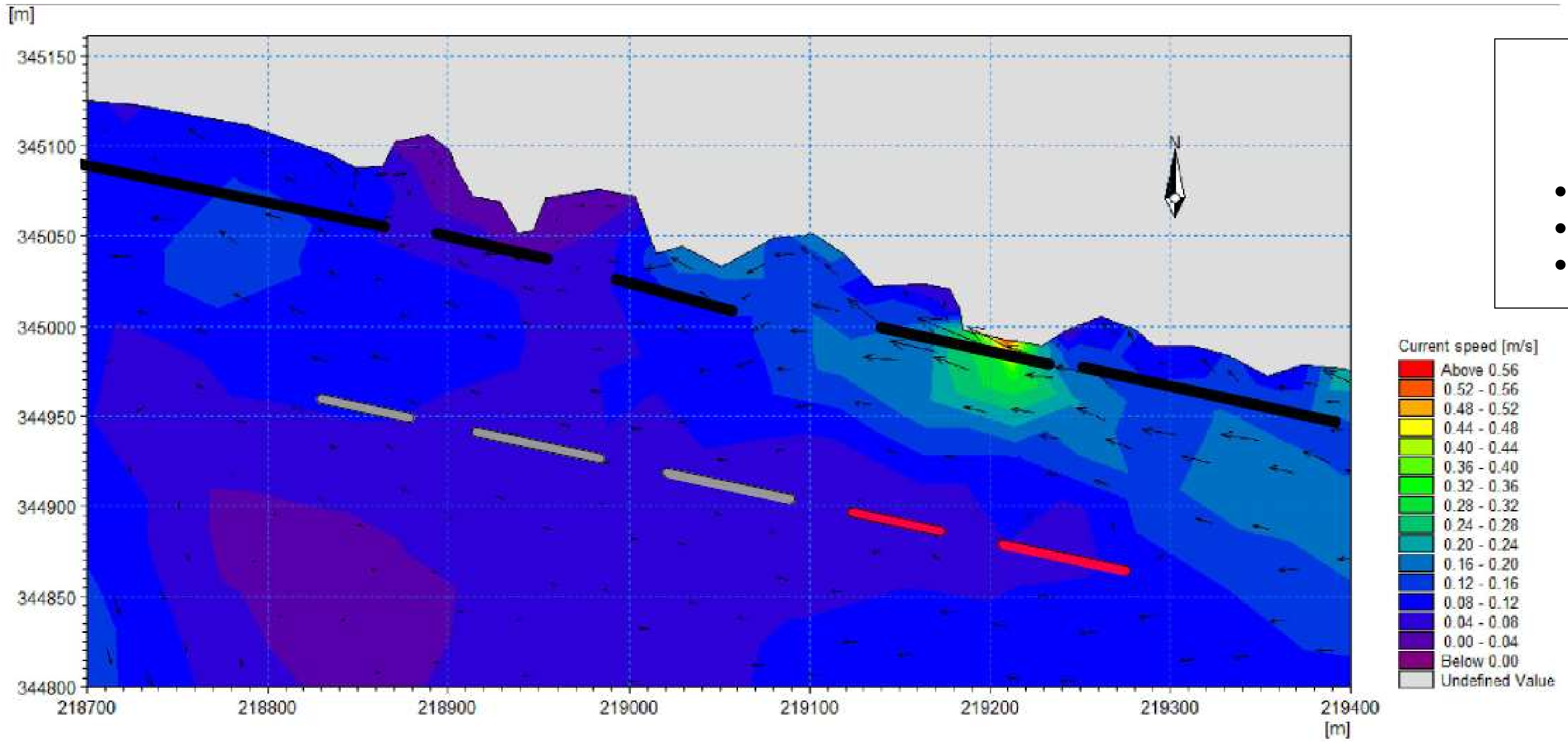


Figure D3 - SCENARIO A

WAVE CURRENT
CLOSE UP VIEW

- **DIRECTION - 150°**
- **Hs - 0.9m**
- **T_p - 4.73s**

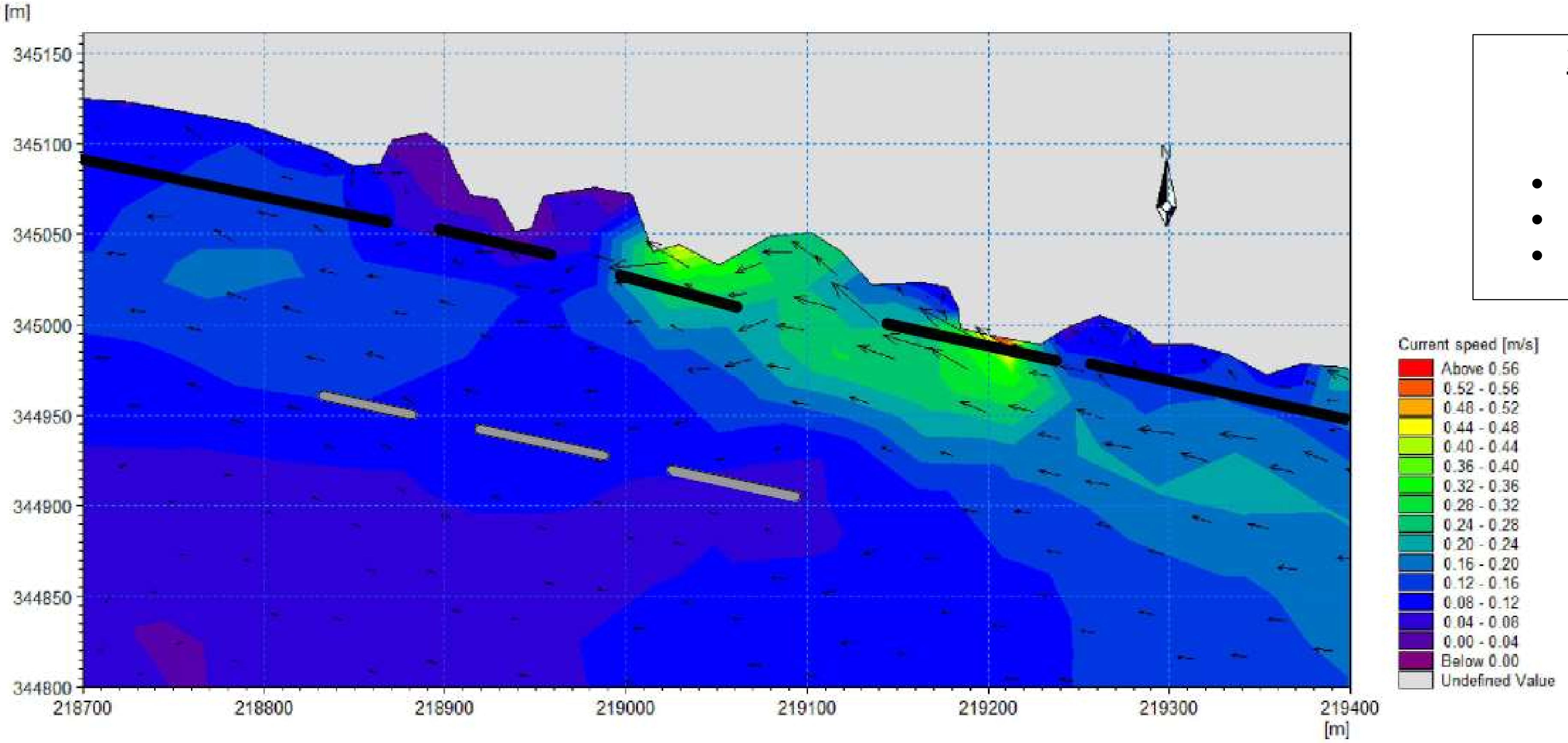


Figure D4 - SCENARIO B

WAVE CURRENT
CLOSE UP VIEW

- **DIRECTION - 150°**
- **Hs - 0.9m**
- **T_p - 4.73s**

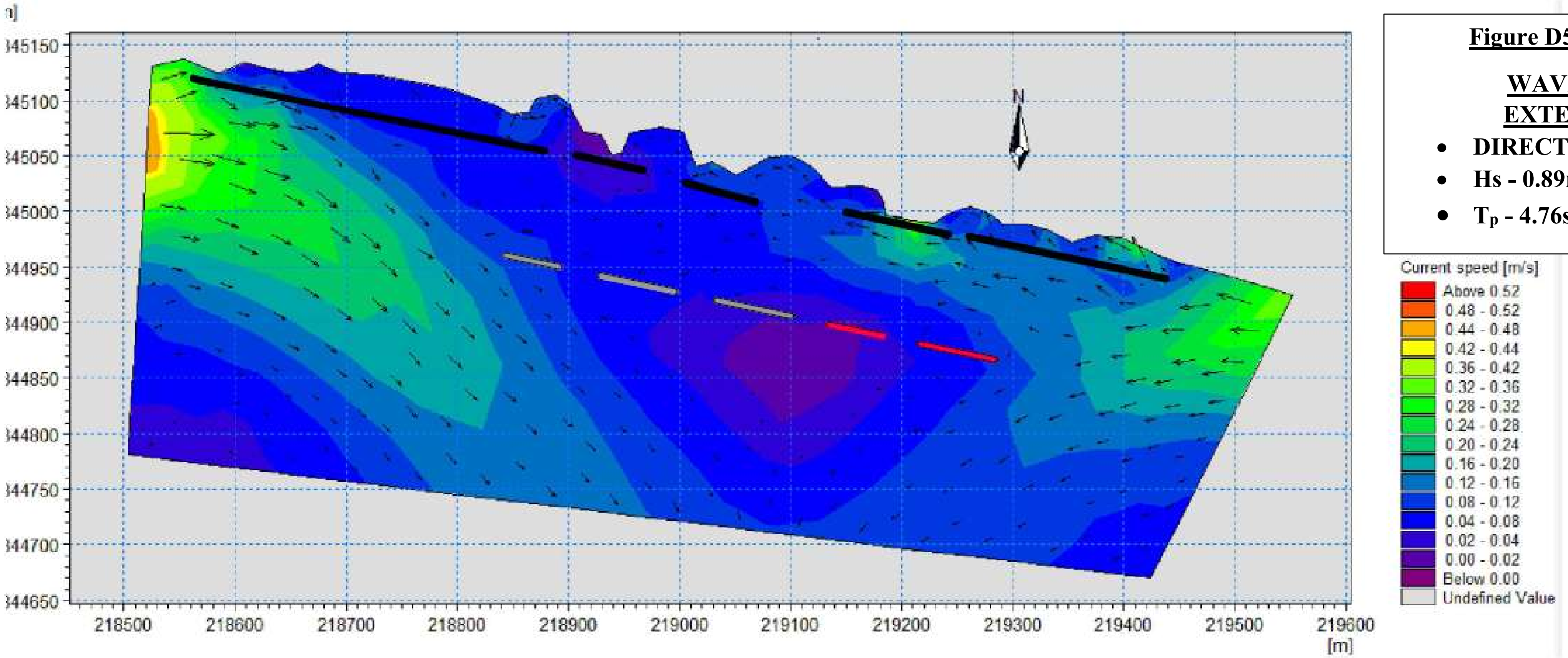


Figure D5 - SCENARIO A

WAVE CURRENT
EXTENDED VIEW

- **DIRECTION - 180°**
- **Hs - 0.89m**
- **T_p - 4.76s**

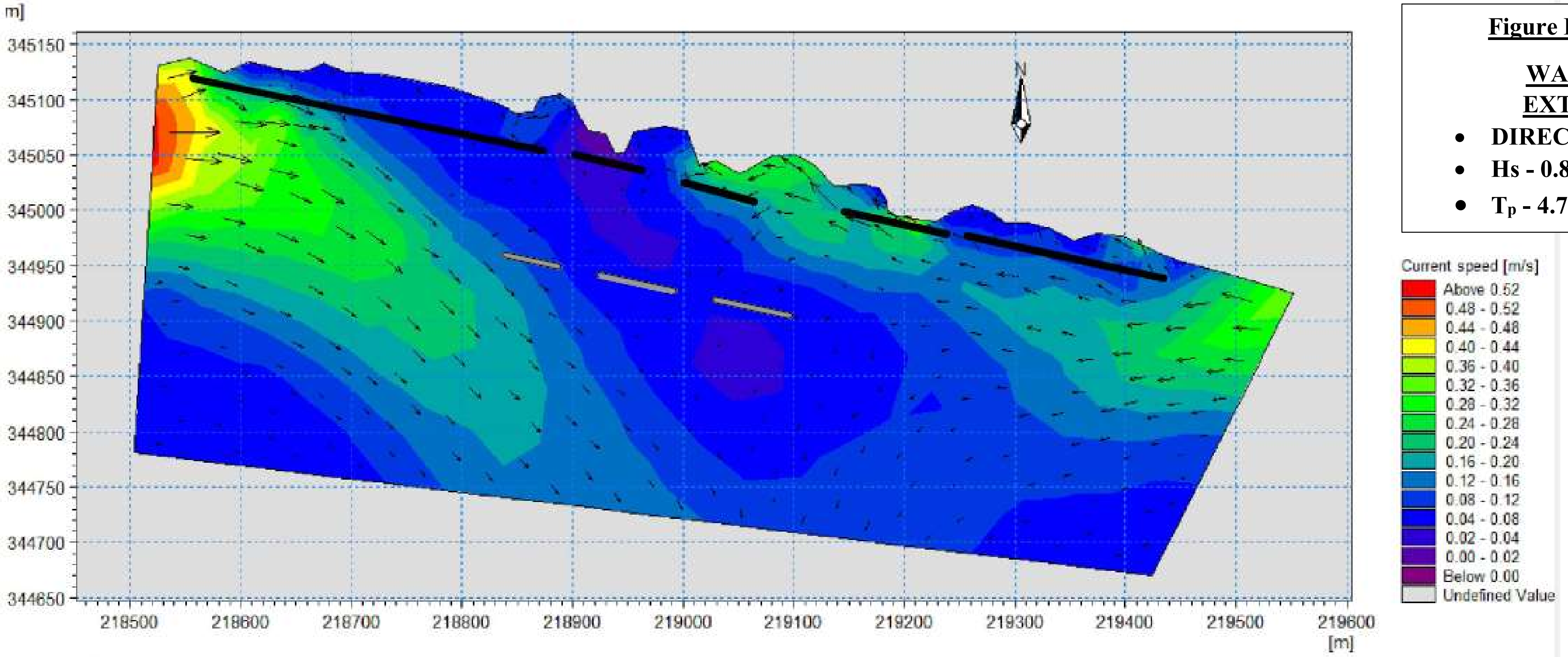


Figure D6 - SCENARIO A

WAVE CURRENT
EXTENDED VIEW

- **DIRECTION - 180°**
- **Hs - 0.89m**
- **T_p - 4.76s**

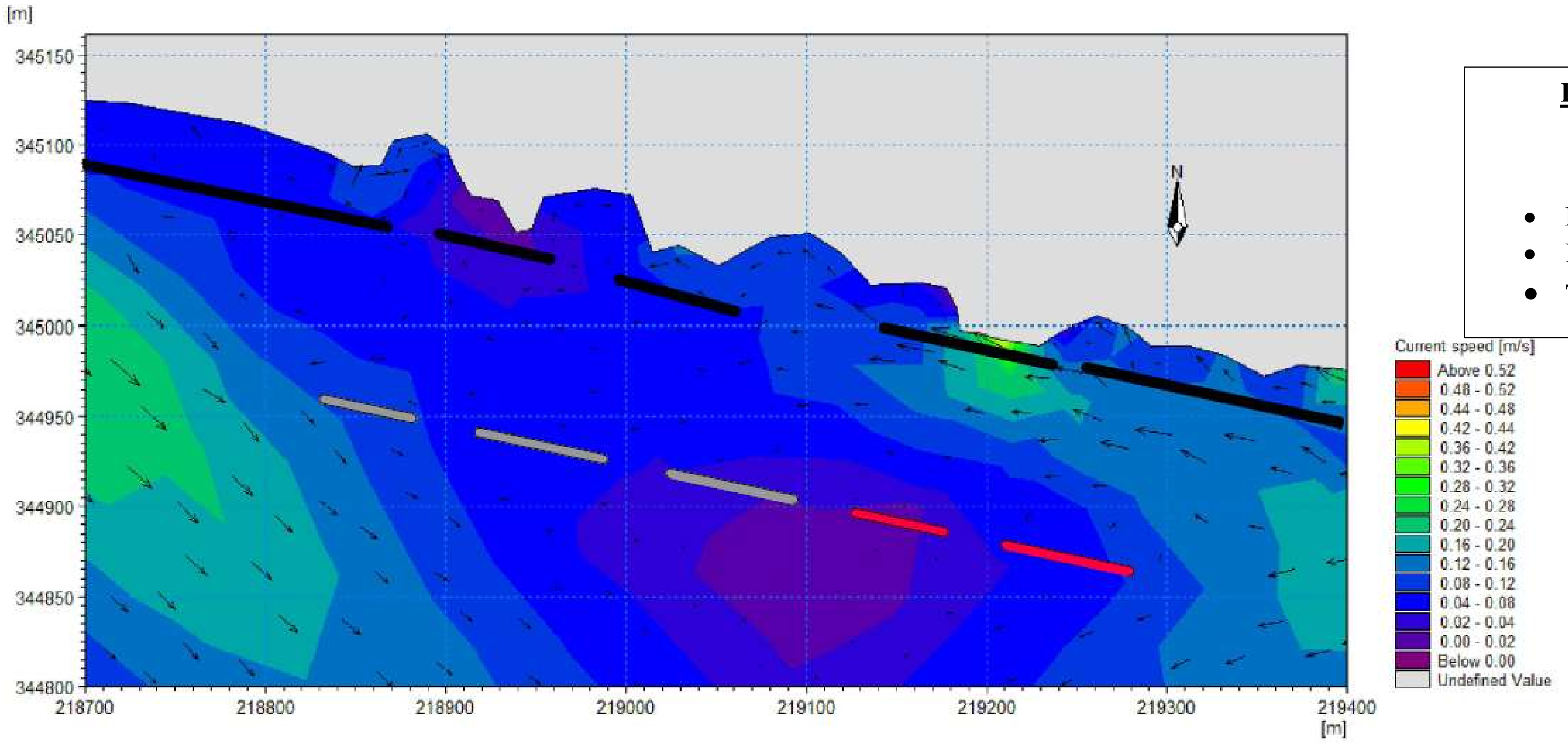


Figure D7 - SCENARIO A

WAVE CURRENT
CLOSE UP VIEW

- **DIRECTION - 180°**
- **Hs - 0.89m**
- **T_p - 4.76s**

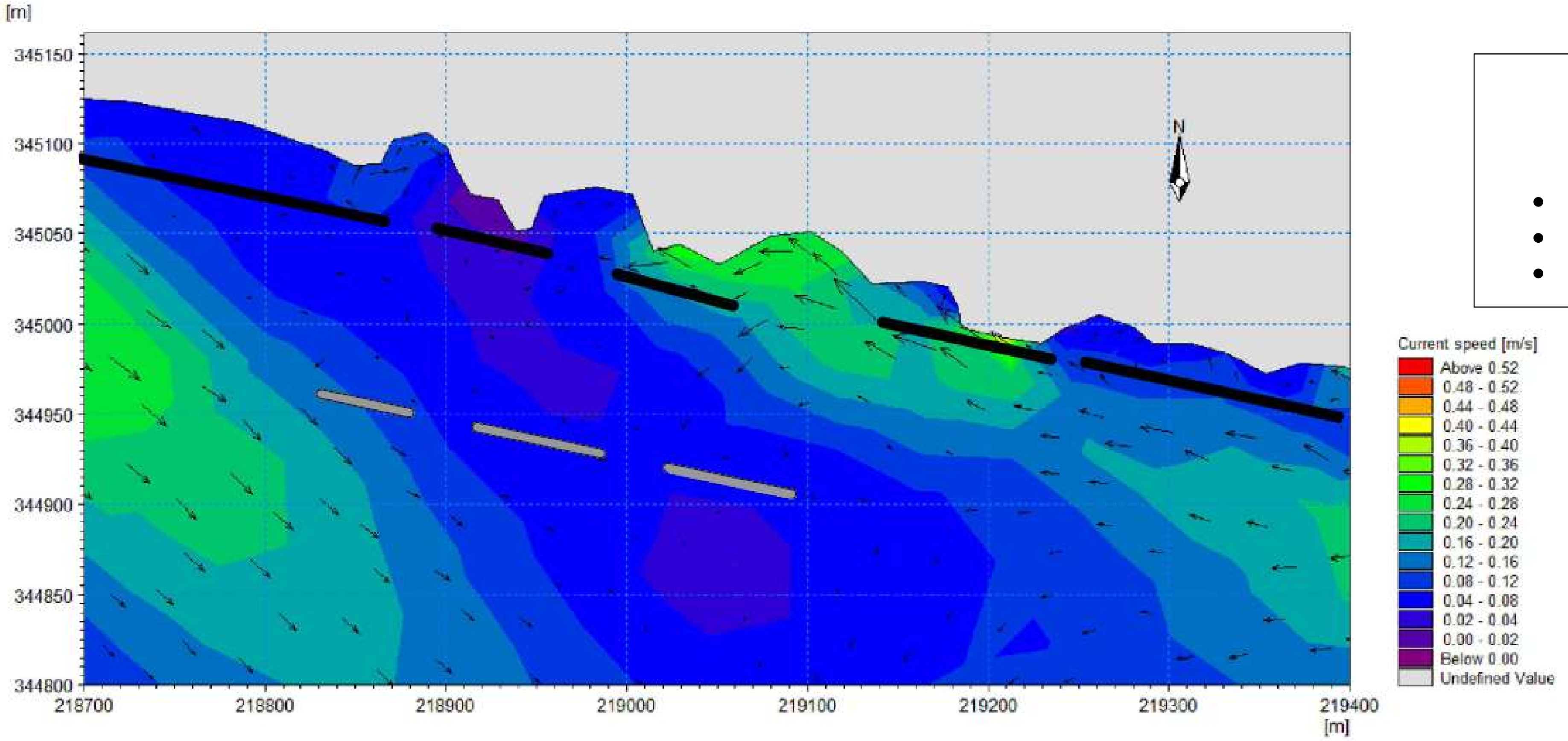


Figure D8 - SCENARIO B

WAVE CURRENT
CLOSE UP VIEW

- **DIRECTION - 180°**
- **Hs - 0.89m**
- **T_p - 4.76s**

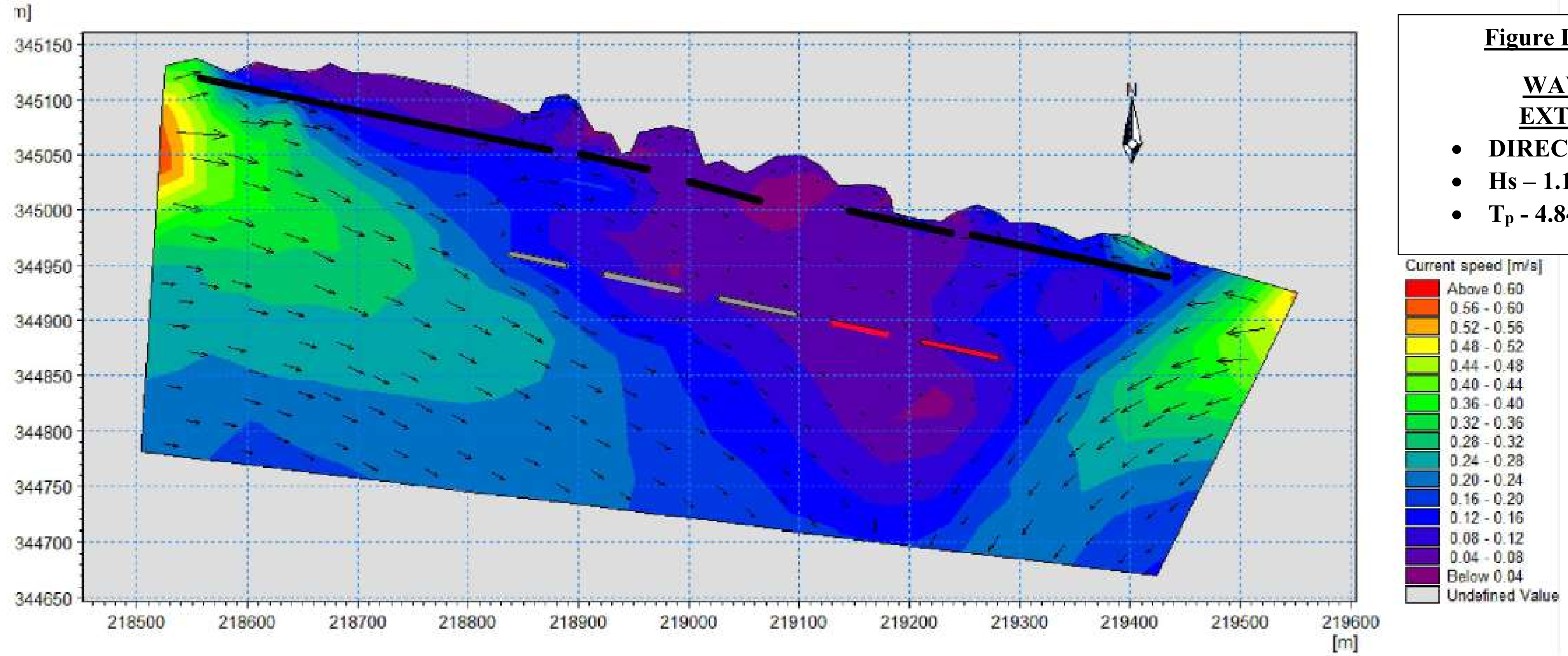


Figure D9 - SCENARIO A

WAVE CURRENT
EXTENDED VIEW

- **DIRECTION - 210°**
- **Hs – 1.16m**
- **T_p - 4.84s**

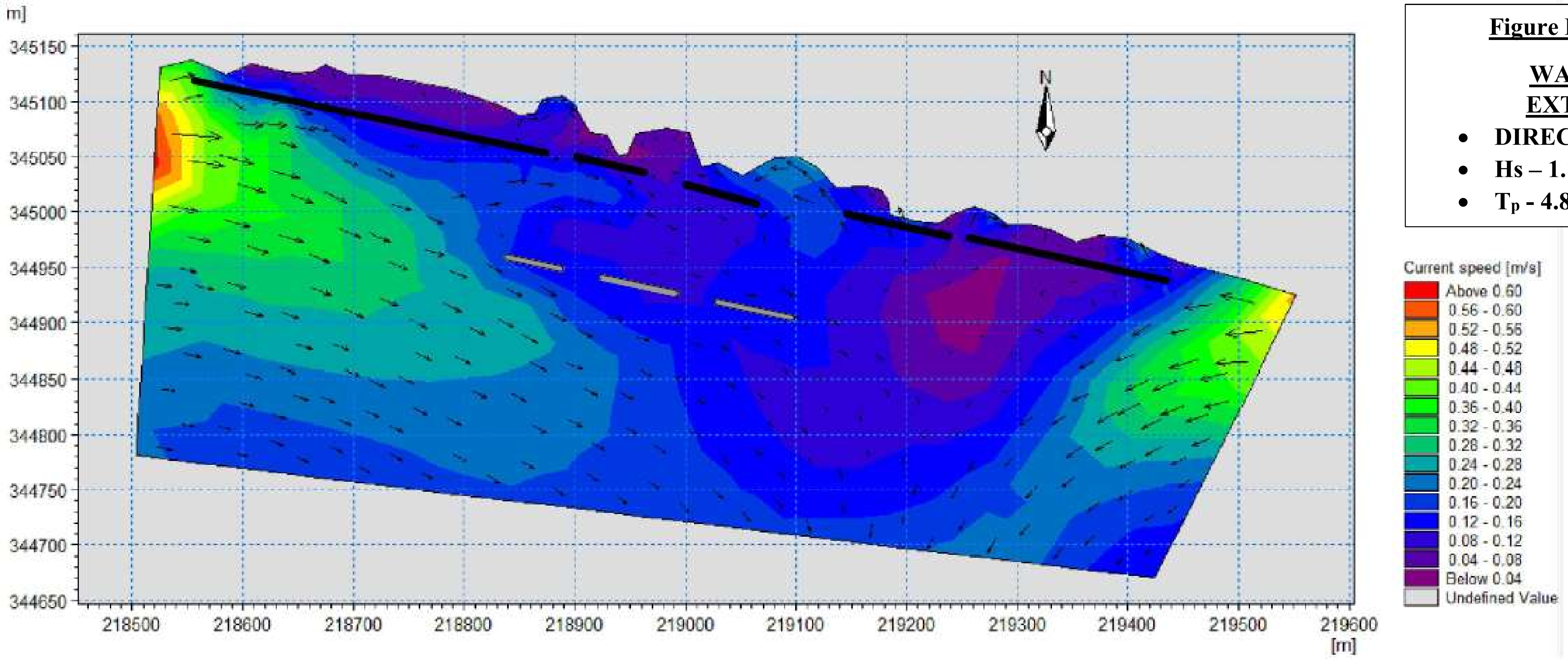


Figure D10- SCENARIO B

WAVE CURRENT
EXTENDED VIEW

- **DIRECTION - 210°**
- **Hs – 1.16m**
- **T_p - 4.84s**

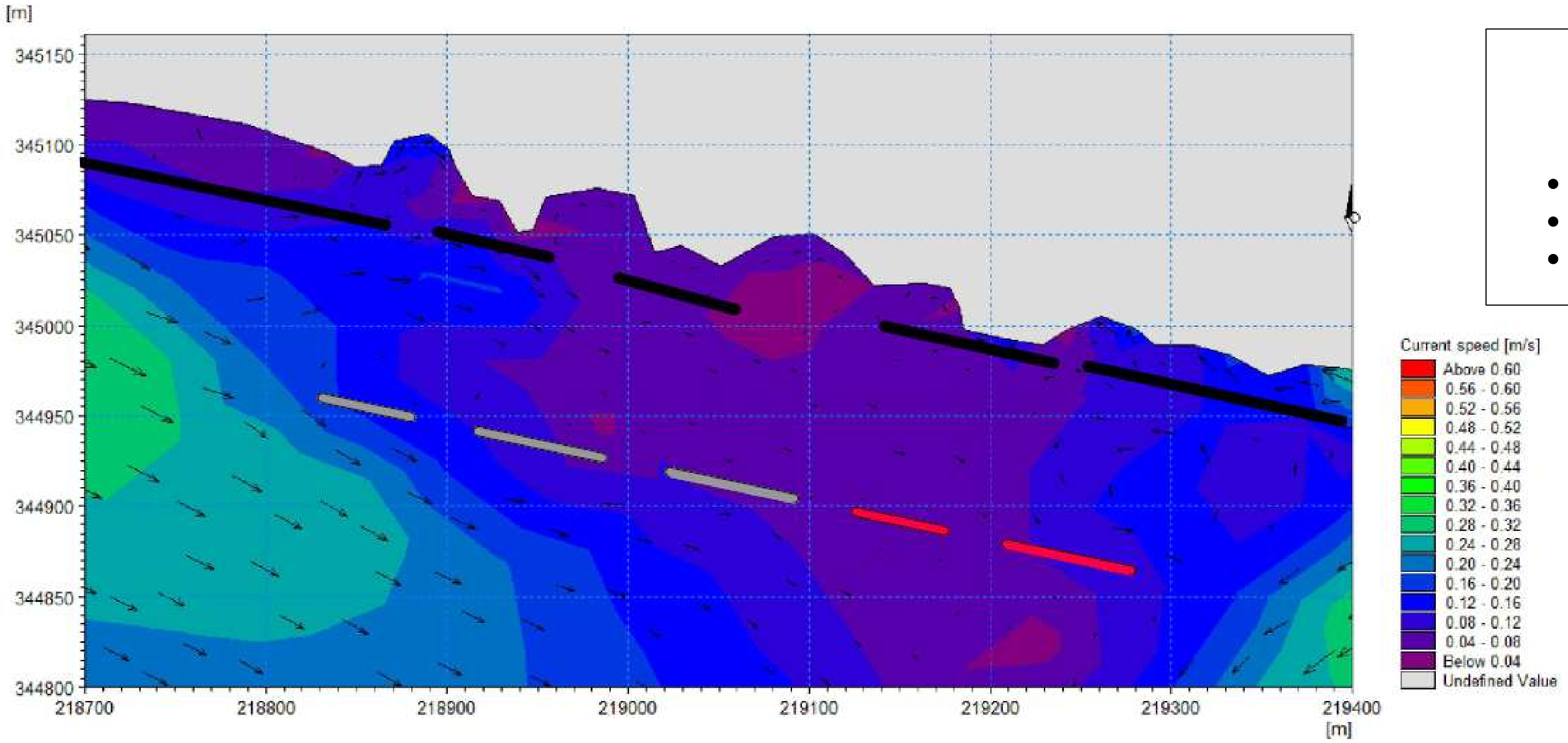


Figure D11 - SCENARIO A

WAVE CURRENT
CLOSE UP VIEW

- **DIRECTION - 210°**
- **Hs – 1.16m**
- **T_p - 4.84s**

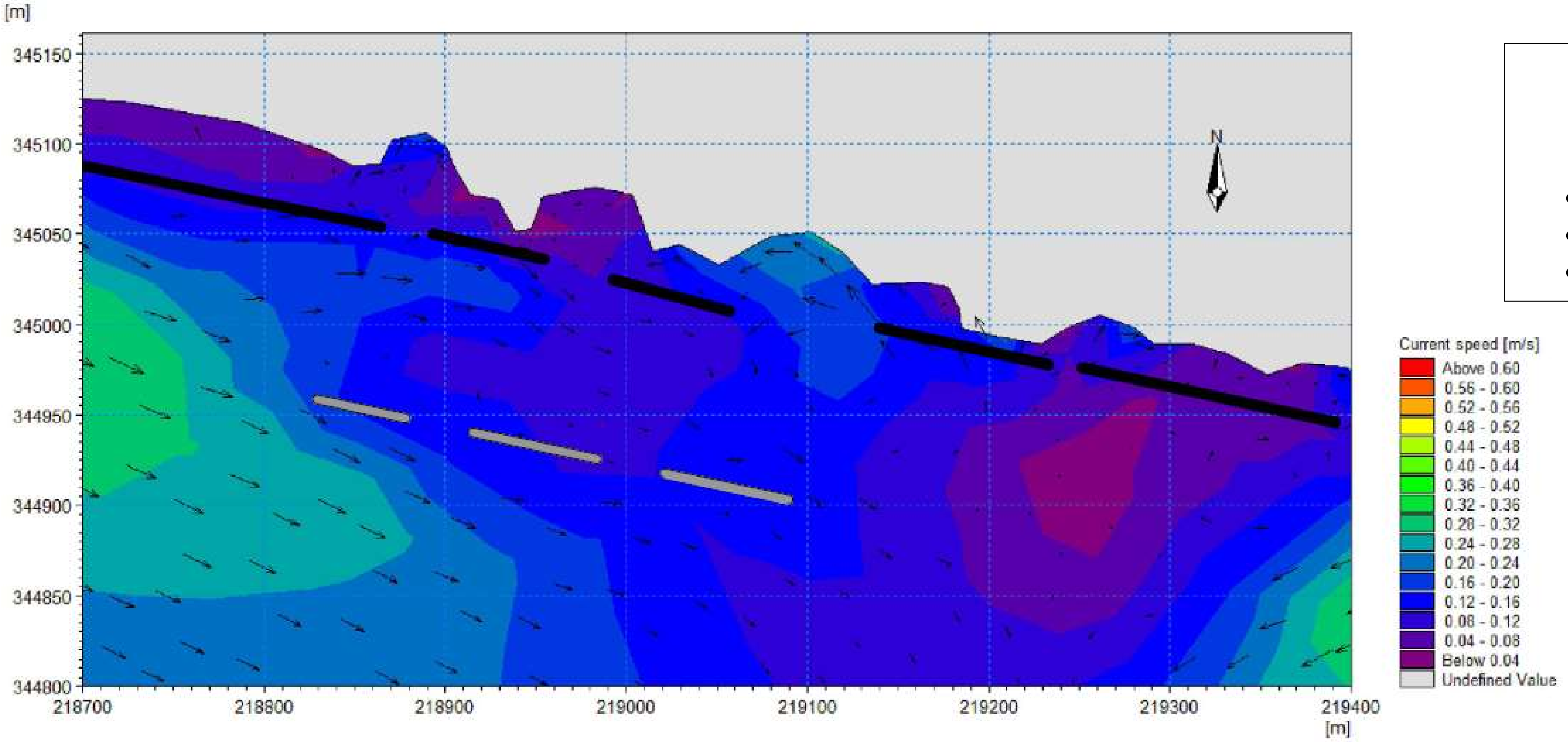


Figure D12- SCENARIO B

WAVE CURRENT
CLOSE UP VIEW

- **DIRECTION - 210°**
- **Hs – 1.16m**
- **T_p - 4.84s**

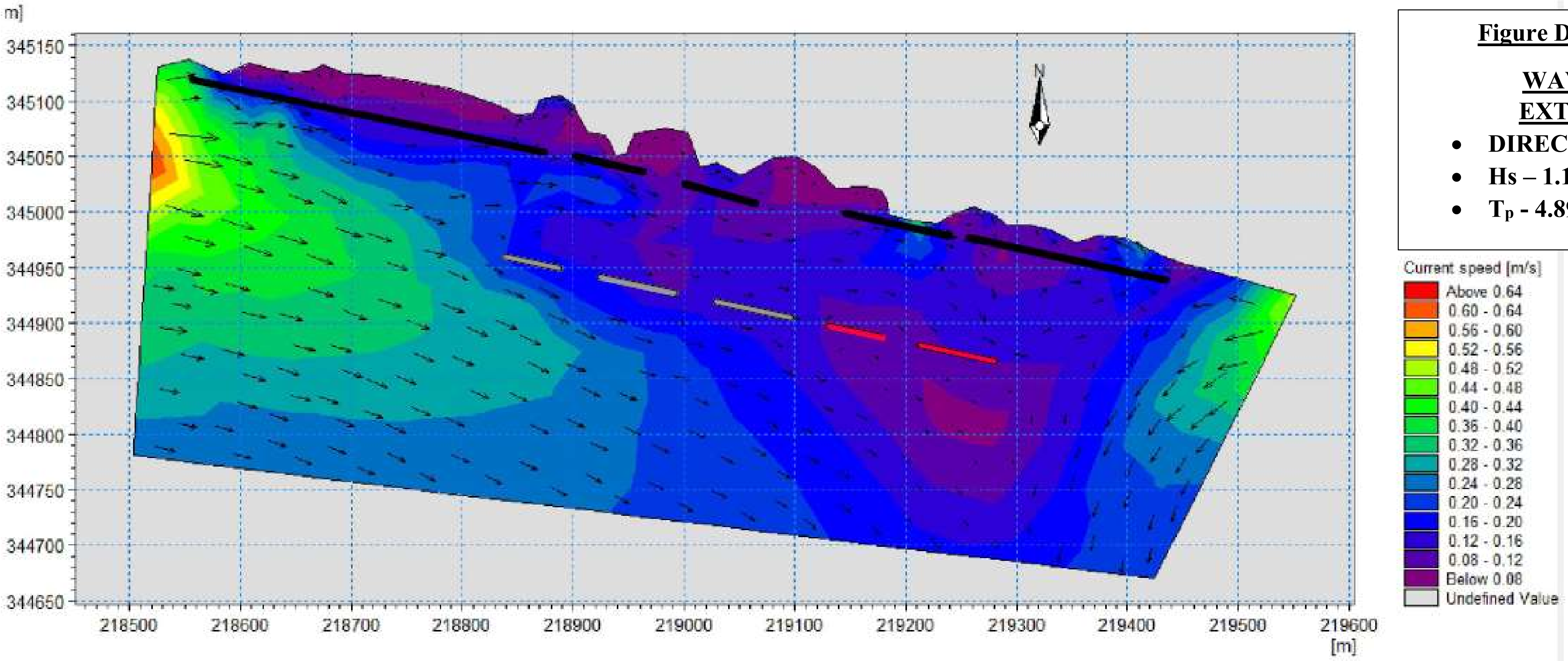


Figure D13 - SCENARIO A

WAVE CURRENT
EXTENDED VIEW

- **DIRECTION - 240°**
- **Hs – 1.13m**
- **T_p - 4.89s**

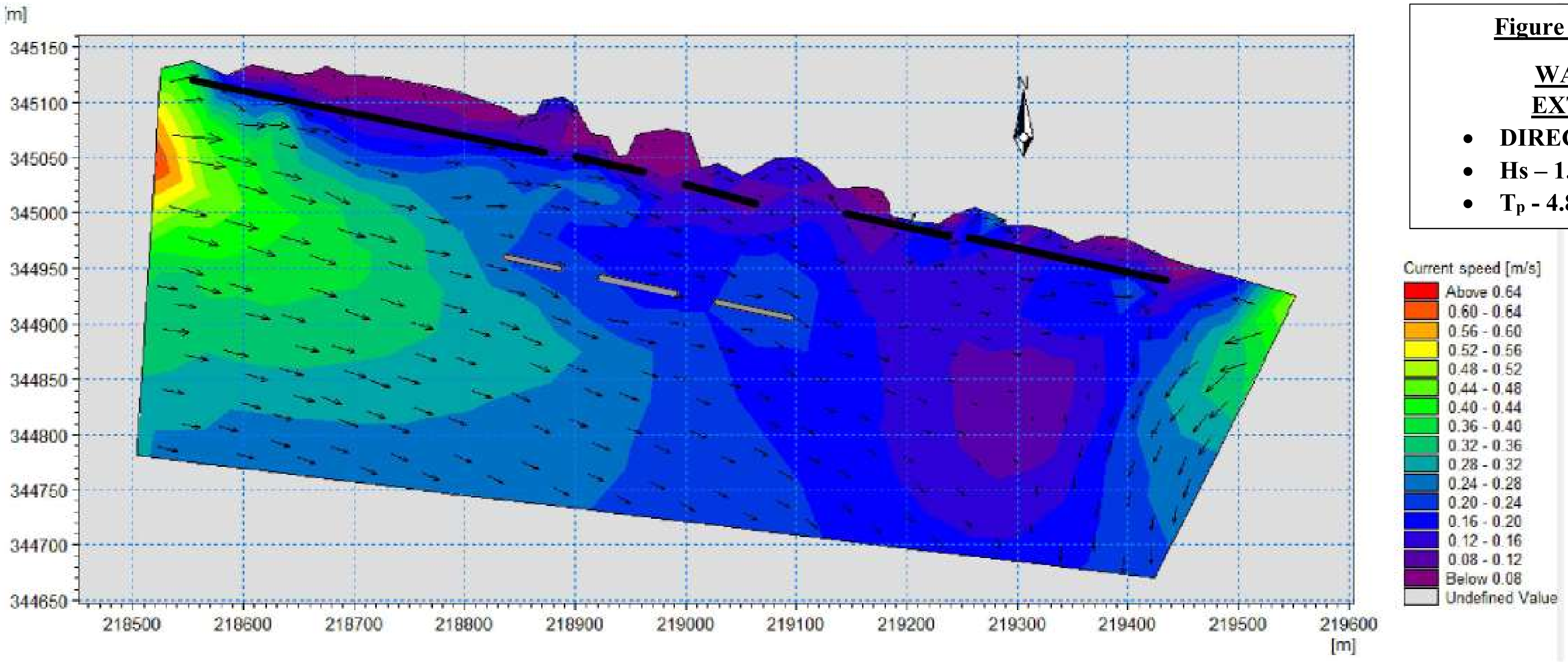
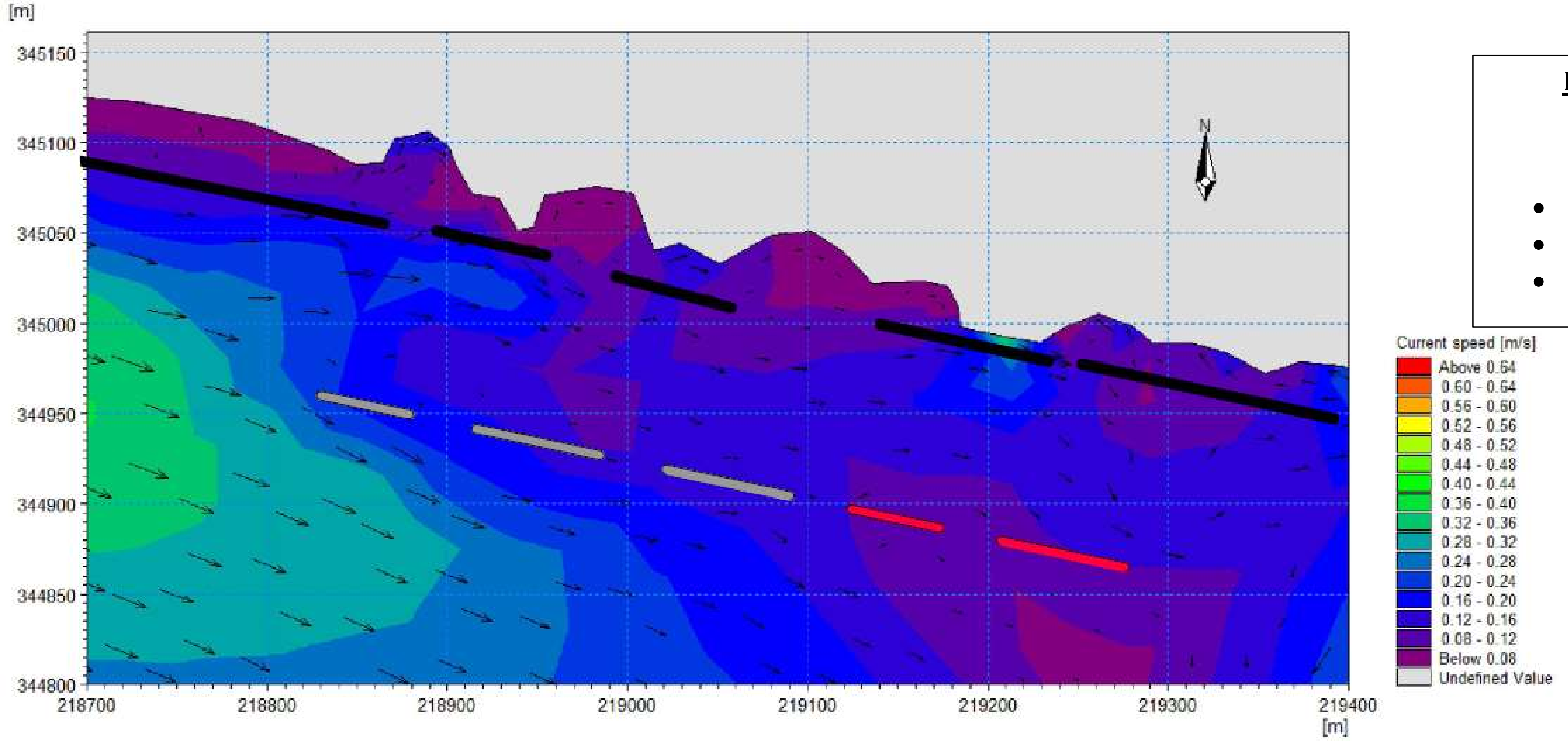


Figure D14- SCENARIO B

WAVE CURRENT
EXTENDED VIEW

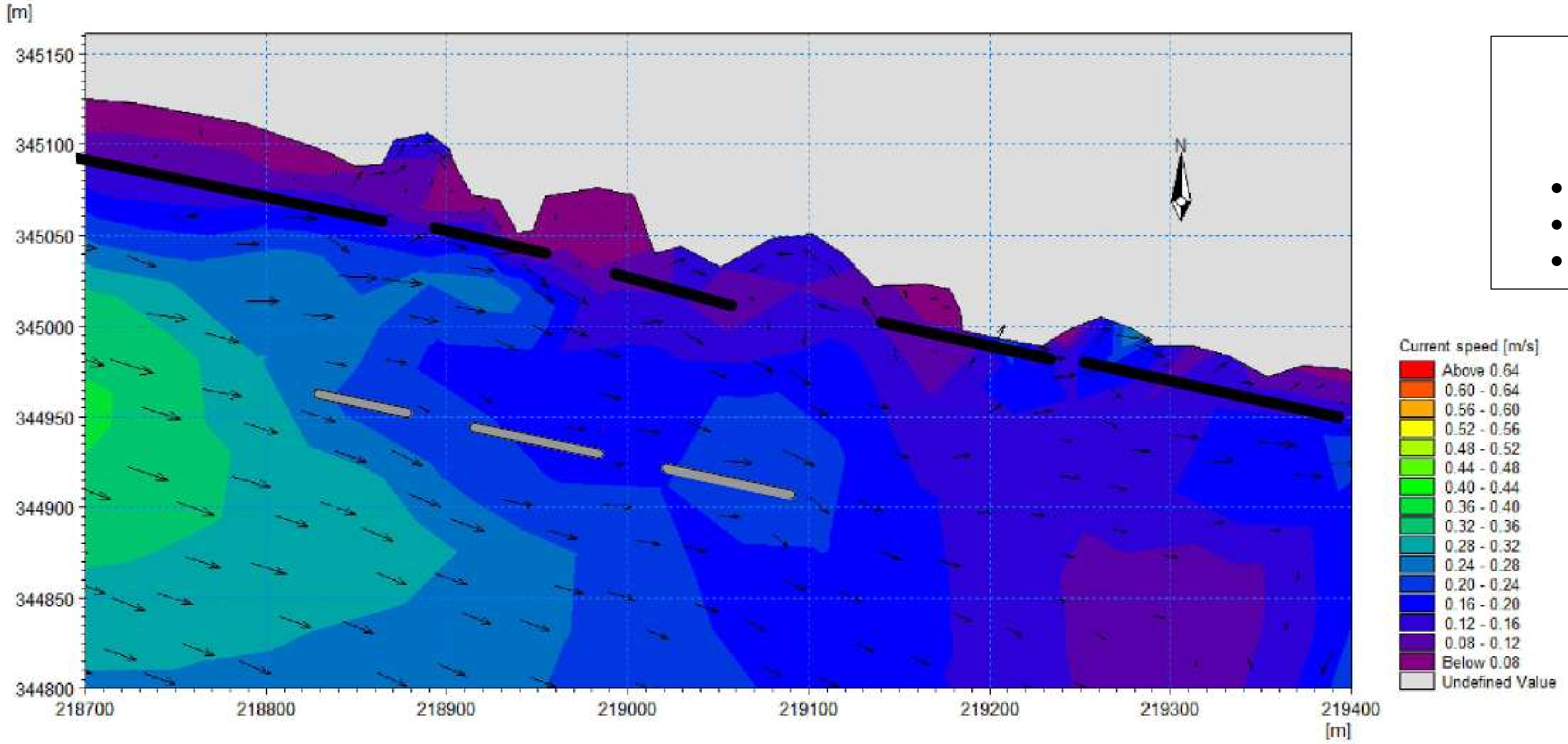
- **DIRECTION - 240°**
- **Hs – 1.13m**
- **T_p - 4.89s**



<u>Figure D15 - SCENARIO A</u>

<u>WAVE CURRENT</u>
<u>CLOSE UP VIEW</u>

- **DIRECTION - 240°**
- **Hs – 1.13m**
- **T_p - 4.89s**

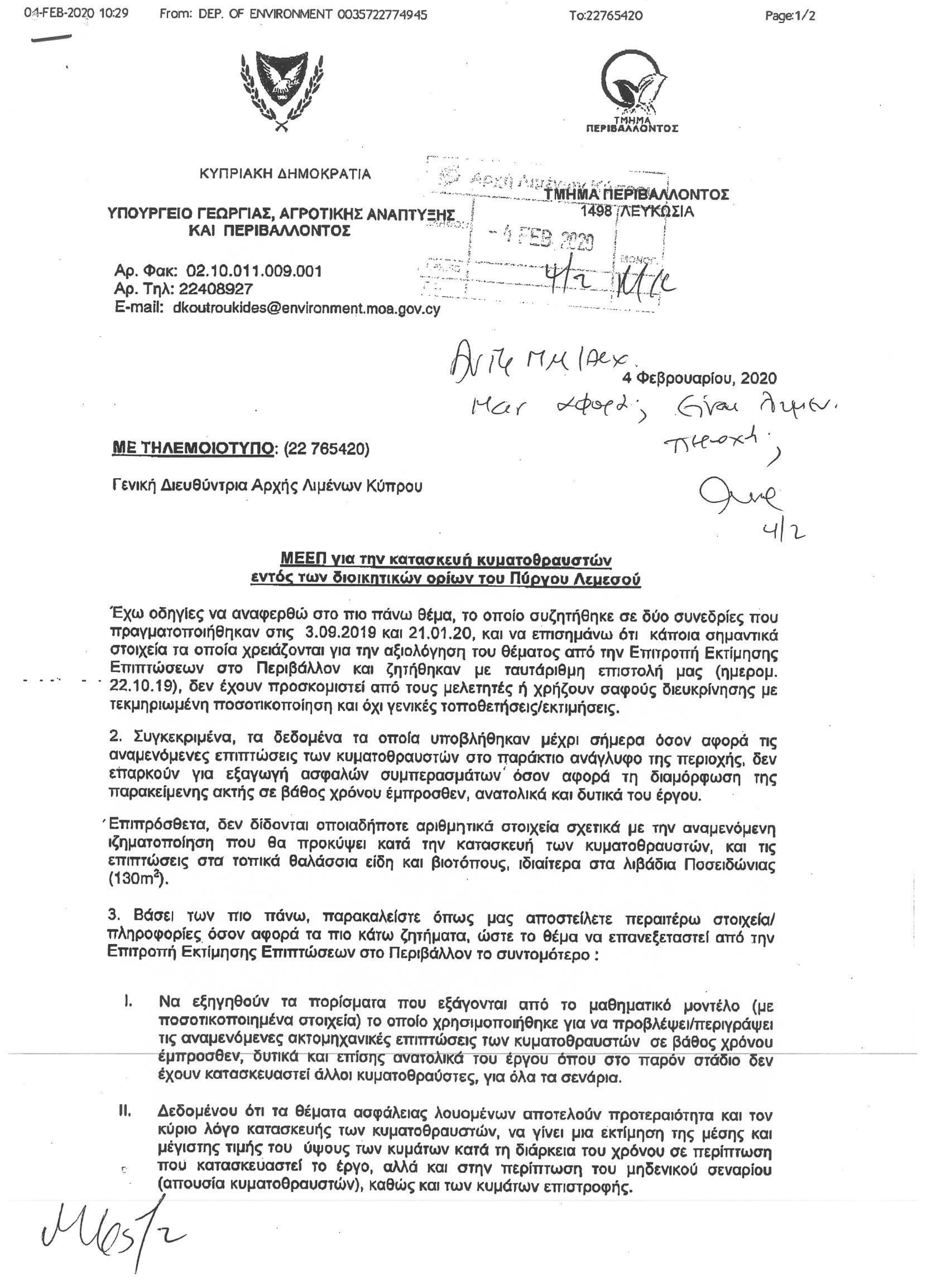


<u>Figure D16- SCENARIO B</u>

<u>WAVE CURRENT</u>
<u>CLOSE UP VIEW</u>

- **DIRECTION - 240°**
- **Hs – 1.13m**
- **T_p - 4.89s**

APPENDIX E REQUEST OF ADDITIONAL INFORMATION BY THE DEPARTMENT OF ENVIRONMENT CYPRUS



04-FEB-2020 10:29 From: DEP. OF ENVIRONMENT 0035722774945 To:22765420 Page:1/2

ΤΜΗΜΑ ΠΕΡΙΒΑΛΛΟΝΤΟΣ

ΚΥΠΡΙΑΚΗ ΔΗΜΟΚΡΑΤΙΑ

ΥΠΟΥΡΓΕΙΟ ΓΕΩΡΓΙΑΣ, ΑΓΡΟΤΙΚΗΣ ΑΝΑΠΤΥΞΗΣ
ΚΑΙ ΠΕΡΙΒΑΛΛΟΝΤΟΣ

ΤΜΗΜΑ ΠΕΡΙΒΑΛΛΟΝΤΟΣ
1498 ΛΕΥΚΩΣΙΑ

Αρ. Φακ: 02.10.011.009.001
Αρ. Τηλ: 22408927
E-mail: dkoutroukides@environment.moa.gov.cy

Αρχή Λιμένων Κύπρου
- 4 FEB 2020
4/2

Αντ/ζ ΜΜ/Αεχ.

4 Φεβρουαρίου, 2020

Μας αφορά; Είναι λιμεν. περιοχή;

4/2

ΜΕ ΤΗΛΕΜΟΙΟΤΥΠΟ: (22 765420)

Γενική Διευθύντρια Αρχής Λιμένων Κύπρου

ΜΕΕΠ για την κατασκευή κυματοθραυστών εντός των διοικητικών ορίων του Πύργου Λεμεσού

Έχω οδηγίες να αναφερθώ στο πιο πάνω θέμα, το οποίο συζητήθηκε σε δύο συνεδρίες που πραγματοποιήθηκαν στις 3.09.2019 και 21.01.20, και να επισημάνω ότι κάποια σημαντικά στοιχεία τα οποία χρειάζονται για την αξιολόγηση του θέματος από την Επιτροπή Εκτίμησης Επιπτώσεων στο Περιβάλλον και ζητήθηκαν με ταυτάριθμη επιστολή μας (ημερομ. 22.10.19), δεν έχουν προσκομιστεί από τους μελετητές ή χρήζουν σαφούς διευκρίνησης με τεκμηριωμένη ποσοτικοποίηση και όχι γενικές τοποθετήσεις/εκτιμήσεις.

2. Συγκεκριμένα, τα δεδομένα τα οποία υποβλήθηκαν μέχρι σήμερα όσον αφορά τις αναμενόμενες επιπτώσεις των κυματοθραυστών στο παράκτιο ανάγλυφο της περιοχής, δεν επαρκούν για εξαγωγή ασφαλών συμπερασμάτων όσον αφορά τη διαμόρφωση της παρακείμενης ακτής σε βάθος χρόνου έμπροσθεν, ανατολικά και δυτικά του έργου.

Επιπρόσθετα, δεν δίδονται οποιαδήποτε αριθμητικά στοιχεία σχετικά με την αναμενόμενη ιζηματοποίηση που θα προκύψει κατά την κατασκευή των κυματοθραυστών, και τις επιπτώσεις στα τοπικά θαλάσσια είδη και βιοτόπους, ιδιαίτερα στα λιβάδια Ποσειδώνιας (130m^2).

3. Βάσει των πιο πάνω, παρακαλείστε όπως μας αποστείλετε περαιτέρω στοιχεία/πληροφορίες όσον αφορά τα πιο κάτω ζητήματα, ώστε το θέμα να επανεξεταστεί από την Επιτροπή Εκτίμησης Επιπτώσεων στο Περιβάλλον το συντομότερο :

I. Να εξηγηθούν τα πορίσματα που εξάγονται από το μαθηματικό μοντέλο (με ποσοτικοποιημένα στοιχεία) το οποίο χρησιμοποιήθηκε για να προβλέψει/περιγράψει τις αναμενόμενες ακτομηχανικές επιπτώσεις των κυματοθραυστών σε βάθος χρόνου έμπροσθεν, δυτικά και επίσης ανατολικά του έργου όπου στο παρόν στάδιο δεν έχουν κατασκευαστεί άλλοι κυματοθραύστες, για όλα τα σενάρια.

II. Δεδομένου ότι τα θέματα ασφάλειας λουομένων αποτελούν προτεραιότητα και τον κύριο λόγο κατασκευής των κυματοθραυστών, να γίνει μια εκτίμηση της μέσης και μέγιστης τιμής του ύψους των κυμάτων κατά τη διάρκεια του χρόνου σε περίπτωση που κατασκευαστεί το έργο, αλλά και στην περίπτωση του μηδενικού σεναρίου (απουσία κυματοθραυστών), καθώς και των κυμάτων επιστροφής.

Μ(05/2

III. Να διενεργηθεί υποθαλάσσια αρχαιολογική επισκόπηση, ώστε να διαφανεί κατά πόσο υπάρχουν αρχαιότητες στην θαλάσσια περιοχή η οποία θα καλύπτεται από τους κυματοθραύστες. Σε περίπτωση εύρεσης αρχαιοτήτων, να εκτιμηθούν οι επιπτώσεις των κυματοθραυστών στις αρχαιότητες.

IV. Να εκπονηθεί μοντέλο διασποράς ιζήματος και να εξηγηθούν τα σχετικά πορίσματα τόσο κατά την κατασκευή όσο και για τη λειτουργία του έργου. Βάσει των (μετρήσιμων) αποτελεσμάτων, να εξηγηθεί η αναμενόμενη στερεομεταφορά εντός της θάλασσας αλλά και επί της ακτής, ιδιαίτερα στα ανατολικά, και να εκτιμηθούν οι επιπτώσεις στο οικοσύστημα του θαλάσσιου υφάλου και στα λειβάδια ποσειδωνίας απο τυχόν συσσώρευση άμμου και εμπλουτισμό παραλίας. Να γίνει και σχετική εκτίμηση στην περίπτωση εναπόθεσης / εμπλουτισμού της παραλίας με άμμο όπως στην εισήγηση της μελέτης.

Δ. Κουτρουκίδης
για Διευθυντή

Κοιν. : Διευθύντρια Τμήματος Αλιείας και Θαλασσίων Ερευνών (22 781226)
Διευθύντρια Τμήματος Δημοσίων Έργων (22 498910)
Διευθυντή Τμήματος Αρχαιοτήτων (22 303148)
Νικολαΐδης και Συνεργάτες (22 312519)

APPENDIX F MIKE 21/3 ADDITIONAL MODEL PACKAGE INFORMATION

MIKE 21

2D modelling
of coast and sea

MIKE 21 is by far **the most versatile tool for coastal modelling**. If you need to **simulate physical, chemical or biological processes** in coastal or marine areas, MIKE 21 has the tools you need.

APPLICATIONS

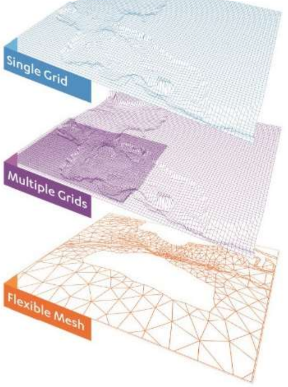
The following is a small subset of the almost endless list of possible MIKE 21 applications.

TYPICAL APPLICATIONS

MIKE 21 is the ideal software for:

- Design assessment for coastal and offshore structures
- Optimisation of port layouts and coastal protection measures
- Cooling water, desalination and recirculation analysis
- Optimisation of coastal outfalls
- Environmental impact assessment of marine infrastructures
- Ecological modelling including optimisation of aquaculture systems
- Optimisation of renewable energy systems
- Water forecast for safe marine operations and navigation
- Coastal flooding and storm surge warnings
- Inland river, flooding and overland flow modelling

3-in-1



© DHI

The unique 3-in-1 package includes all three engines in one great package deal.

ENGINES

MIKE 21 comprises the following simulation engines:

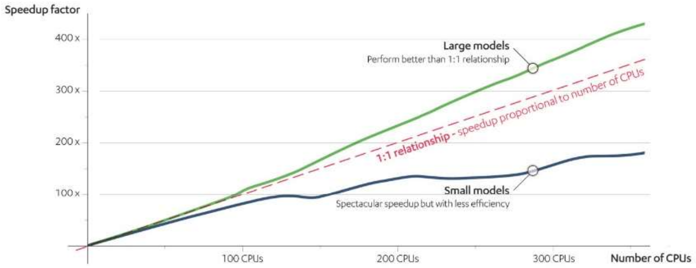
- **Single Grid**, which is a classic rectilinear model that is easy to set up and with easy I/O exchange
- **Multiple Grids**, which is a dynamically nested rectilinear model with the ability to focus the grid resolution
- **Flexible Mesh**, which allows maximum flexibility for adapting grid resolution of the model domain

PARALLEL PROCESSING (CPU)

All Flexible Mesh and Single Grid engines support parallel processing. The Flexible Mesh (FM) engines show excellent performance when parallel processing is undertaken - also on a large number of computational cores. On multicore Windows computers, parallelisation is menu-driven and straightforward. The FM engines are also available for Linux, which gives the possibility to utilise High Performance Computing (HPC) systems.

GRAPHICAL PROCESSING UNITS (GPU)

For the FM engines, the use of graphical processing units (GPU) is also supported and gives easy access to spectacular increases in simulation speed.



Example of CPU-based speedup tests.

MODULES

MIKE 21 is modular. You buy what you need and nothing more. It includes a wide range of modules, allowing you to create your own tailored modelling framework for your coastal and marine studies.

PP - PREPROCESSING AND POSTPROCESSING

This module offers an integrated work environment which provides convenient and compatible routines to ease the tasks of data input, analysis and presentation of simulation results.

HD - HYDRODYNAMICS

This module simulates water level variations and flows in response to a variety of forcing functions.

AD - ADVECTION-DISPERSION

This simulates the transport, dispersion and decay of dissolved or suspended substances. It is typically used in cooling water and wastewater discharge studies.

COUPLED MODELLING

The FM series include a powerful, integrated system which, in a surprisingly easy manner, combines wave, flow and sediment transport models into a fully dynamic morphological model.

MODULES

MIKE 21 includes the following modules specifically for sediment transport and water quality modelling.

ST - SAND TRANSPORT

This is an advanced sand transport model with several formulations for current as well as current-wave generated transport, including 3D description of sediment transport rates. It is, for example, used for morphological optimisation of port layouts, impact of shore protection schemes and stability of tidal inlets.

MT - MUD TRANSPORT

This is a combined multi-fraction and multi-layered model that describes erosion, transport and deposition of mud (cohesive sediment) or mixtures of sand and mud.

PT - PARTICLE TRACKING

This module simulates transport and fate of dissolved and suspended substances, including sediments.

SM - SHORELINE MORPHOLOGY

This module combines detailed 2D modelling of currents and waves with a constrained morphological model, making it possible to undertake fast, stable and robust modelling of shoreline evolution in 2D environments.

OS - OIL SPILL

This module simulates the spreading and weathering of hydrocarbons and is used for oil spill modelling.

MIKE ECO LAB - ECOLOGICAL MODELLING

This is a complete numerical laboratory for water quality and ecological modelling. See page 18.

MODULES

MIKE 21 includes the following modules specifically for wave modelling.

SW - SPECTRAL WAVES

This is a spectral wind-wave model that simulates the growth, decay and transformation of wind-generated waves and swell.

BW - BOUSSINESQ WAVES

The state-of-the-art tool for studies and analyses of wave disturbance in ports, harbours and coastal areas. It includes full surf and swash zone dynamics.

MA – MOORING ANALYSIS

This module simulates the motions of single or multiple vessels subject to winds, waves and currents. It also calculates the forces in fenders and mooring lines and can directly use results from MIKE 21 BW, MIKE 3 Wave FM and MIKE 21 HD as input.

SELECTED TOOLS IN MIKE 21

In addition to its variety of modules, MIKE 21 also includes a number of tools to optimise your work. Here is a subset of tools:

- Global tide data and tools for tidal analysis and prediction
- MIKE's Climate Change Editor
- Cyclone wind generation and wind generation from pressure maps
- Advanced mesh and grid generators and editors
- Advanced tools for generation of graphical output
- An interface (API) for reading and modifying files in MIKE 21's internal, binary format

BENEFITS

MIKE 21 is proven technology. No other modelling package has been used for as many coastal and marine engineering projects around the world as MIKE 21.

The recipe for the unique success of MIKE 21 is simple. It gives you maximum flexibility, higher productivity and full confidence in the results.

Also, MIKE 21 is much more than just the right tool for your project. It also gives access to other benefits of MIKE software products, including unparalleled technical support, training courses and access to DHI's expertise and know-how regardless of where you are in the world.

MIKE 21 also comes with a wealth of first class tools that enhance and ease modelling possibilities.

MIKE C-MAP and MIKE ANIMATOR PLUS

MIKE C-Map offers model bathymetries generated fast and easy from an electronic chart database. MIKE ANIMATOR PLUS turns model results into amazing 3D video presentations. Both applications are free and available if you hold a valid Service and Maintenance Agreement (SMA) for Professional License.

Contact: mike@dhigroup.com

For more information, visit:
www.mikepoweredbydhi.com

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MIKE 21 Wave Modelling

MIKE 21 Spectral Waves FM

Short Description

The expert in WATER ENVIRONMENTS

MIKE 21 SW - SPECTRAL WAVE MODEL FM

MIKE 21 SW is a state-of-the-art third generation spectral wind-wave model developed by DHI. The model simulates the growth, decay and transformation of wind-generated waves and swells in offshore and coastal areas.

MIKE 21 SW includes two different formulations:

- Fully spectral formulation
- Directional decoupled parametric formulation

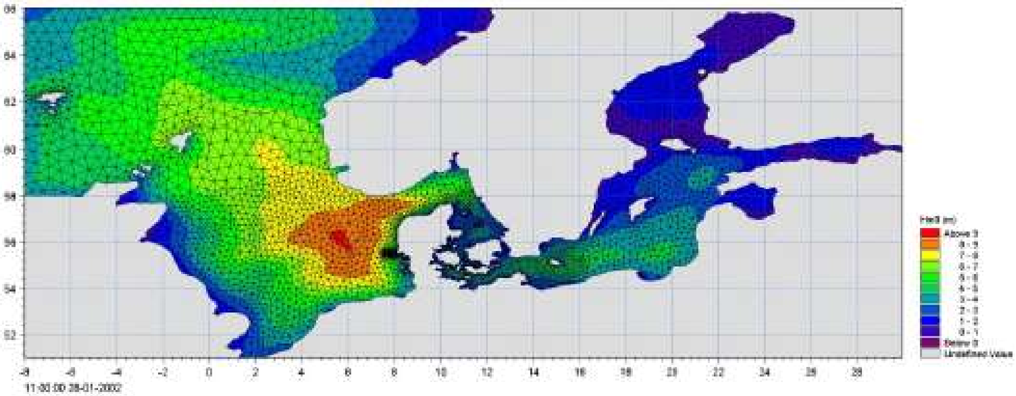
The fully spectral formulation is based on the wave action conservation equation, as described in e.g. Komen et al (1994) and Young (1999). The directional decoupled parametric formulation is based on a parameterisation of the wave action conservation equation. The parameterisation is made in the frequency domain by introducing the zeroth and first moment of the wave action spectrum. The basic conservation equations are formulated in either Cartesian co-ordinates for small-scale applications and polar spherical co-ordinates for large-scale applications.

The fully spectral model includes the following physical phenomena:

- Wave growth by action of wind
- Non-linear wave-wave interaction
- Dissipation due to white-capping
- Dissipation due to bottom friction
- Dissipation due to depth-induced wave breaking
- Refraction and shoaling due to depth variations
- Wave-current interaction
- Effect of time-varying water depth
- Effect of ice coverage on the wave field

The discretisation of the governing equation in geographical and spectral space is performed using cell-centred finite volume method. In the geographical domain, an unstructured mesh technique is used. The time integration is performed using a fractional step approach where a multi-sequence explicit method is applied for the propagation of wave action.

MIKE 21 SW is a state-of-the-art numerical modelling tool for prediction and analysis of wave climates in offshore and coastal areas. © BIOFOTO/Klaus K. Bentzen



A MIKE 21 SW forecast application in the North Sea and Baltic Sea. The chart shows a wave field (from the NSBS model) illustrated by the significant wave height in top of the computational mesh. See also www.waterforecast.com

Computational Features

The main computational features of MIKE 21 SW - Spectral Wave Model FM are as follows:

- Fully spectral and directionally decoupled parametric formulations
- Source functions based on state-of-the-art 3rd generation formulations
- Instationary and quasi-stationary solutions
- Optimal degree of flexibility in describing bathymetry and ambient flow conditions using depth-adaptive and boundary-fitted unstructured mesh
- Coupling with hydrodynamic flow model for modelling of wave-current interaction and time-varying water depth
- Flooding and drying in connection with time-varying water depths
- Cell-centred finite volume technique
- Fractional step time-integration with an multi-sequence explicit method for the propagation
- Extensive range of model output parameters (wave, swell, air-sea interaction parameters, radiation stress tensor, spectra, etc.)

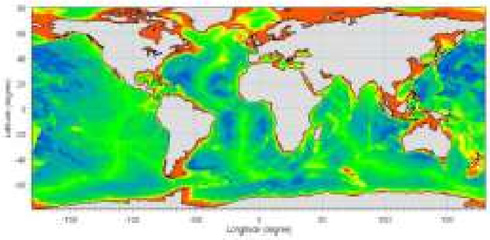
Application Areas

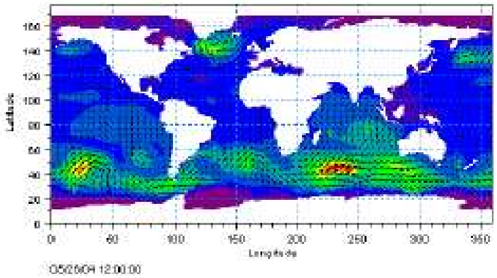
MIKE 21 SW is used for the assessment of wave climates in offshore and coastal areas - in hindcast and forecast mode.

A major application area is the design of offshore, coastal and port structures where accurate assessment of wave loads is of utmost importance to the safe and economic design of these structures.

Illustrations of typical application areas of DHI's MIKE 21 SW – Spectral Wave Model FM

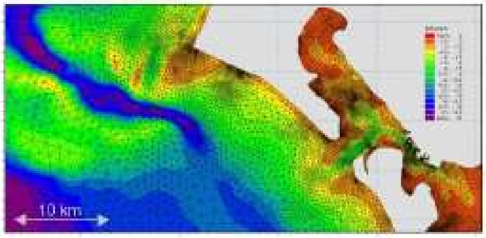
Measured data are often not available during periods long enough to allow for the establishment of sufficiently accurate estimates of extreme sea states. In this case, the measured data can then be supplemented with hindcast data through the simulation of wave conditions during historical storms using MIKE 21 SW.





Example of a global application of MIKE 21 SW. The upper panel shows the bathymetry. Results from such a model (cf. lower panel) can be used as boundary conditions for regional scale forecast or hindcast models. See http://www.waterforecast.com for more details on regional and global modelling

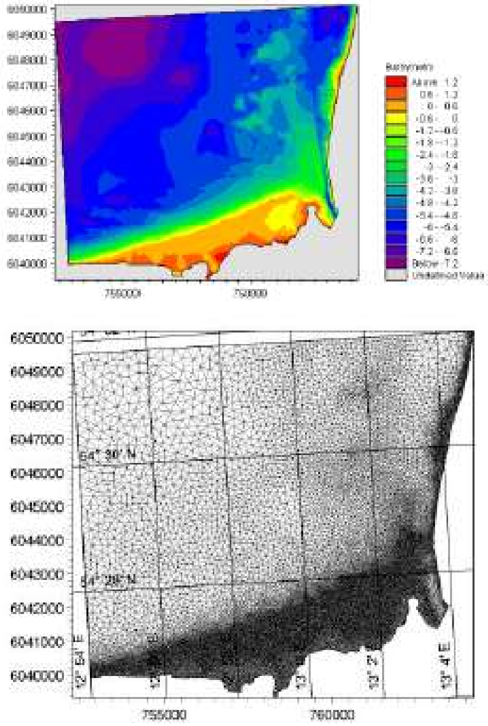
MIKE 21 SW is particularly applicable for simultaneous wave prediction and analysis on regional scale and local scale. Coarse spatial and temporal resolution is used for the regional part of the mesh and a high-resolution boundary and depth-adaptive mesh is describing the shallow water environment at the coastline.



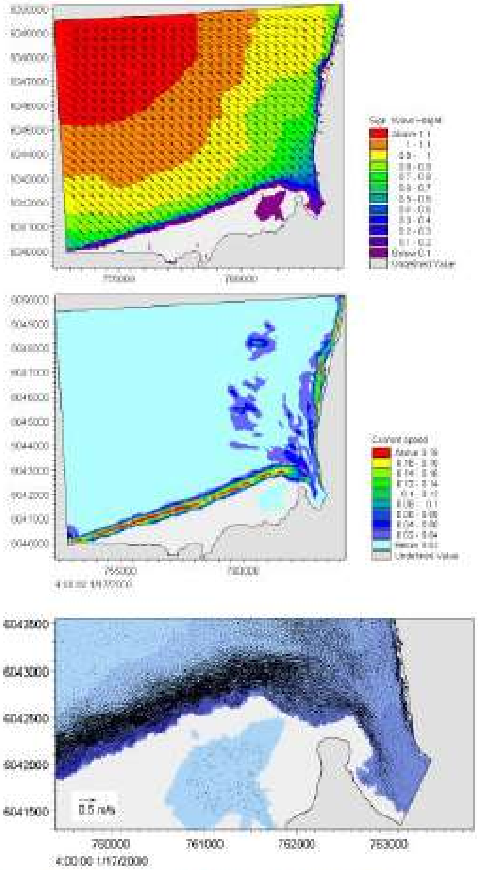
Example of a computational mesh used for transformation of offshore wave statistics using the directionally decoupled parametric formulation

MIKE 21 SW is also used for the calculation of the sediment transport, which for a large part is determined by wave conditions and associated wave-induced currents. The wave-induced current is generated by the gradients in radiation stresses that occur in the surf zone.

MIKE 21 SW can be used to calculate the wave conditions and associated radiation stresses. The long-shore currents and sediment transport are then calculated using the flow and sediment transport models available in the MIKE 21 package. For such type of applications, the directional decoupled parametric formulation of MIKE 21 SW is an excellent compromise between the computational effort and accuracy.



Bathymetry (upper) and computational mesh (lower) used in a MIKE 21 SW application on wave induced currents in Gellen Bay, Germany



Map of significant wave height (upper), current field (middle) and vector field (lower). The flow field is simulated by DHI's MIKE 21 Flow Model FM, which is dynamically coupled to MIKE 21 SW

Model Equations

In MIKE 21 SW, the wind waves are represented by the wave action density spectrum $N(\sigma,\theta)$. The independent phase parameters have been chosen as the relative (intrinsic) angular frequency, $\sigma = 2\pi f$ and the direction of wave propagation, θ. The relation between the relative angular frequency and the absolute angular frequency, ω, is given by the linear dispersion relationship

$$\sigma = \sqrt{gk\tanh(kd)} = \omega - \bar{k}\cdot\bar{U}$$

where g is the acceleration of gravity, d is the water depth and $\bar{U}$ is the current velocity vector and $\bar{k}$ is the wave number vector with magnitude k and direction θ. The action density, $N(\sigma,\theta)$, is related to the energy density $E(\sigma,\theta)$ by

$$N = \frac{E}{\sigma}$$

Fully Spectral Formulation

The governing equation in MIKE 21 SW is the wave action balance equation formulated in either Cartesian or spherical co-ordinates. In horizontal Cartesian co-ordinates, the conservation equation for wave action reads

$$\frac{\partial N}{\partial t} + \nabla\cdot(\bar{v}N) = \frac{S}{\sigma}$$

where $N(\bar{x},\sigma,\theta,t)$ is the action density, t is the time, $\bar{x} = (x,y)$ is the Cartesian co-ordinates, $\bar{v} = (c_x, c_y, c_\sigma, c_\theta)$ is the propagation velocity of a wave group in the four-dimensional phase space $\bar{x}$, σ and θ. S is the source term for energy balance equation. ∇ is the four-dimensional differential operator in the $\bar{x}$, σ, θ-space. The characteristic propagation speeds are given by the linear kinematic relationships

$$(c_x, c_y) = \frac{d\bar{x}}{dt} = \bar{c}_g + \bar{U} = \frac{1}{2}\left(1 + \frac{2kd}{\sinh(2kd)}\right)\frac{\sigma}{k} + \bar{U}$$

$$c_\sigma = \frac{d\sigma}{dt} = \frac{\partial\sigma}{\partial d}\left[\frac{\partial d}{\partial t} + \bar{U}\cdot\nabla_{\bar{x}} d\right] - c_g \bar{k}\cdot\frac{\partial\bar{U}}{\partial s}$$

$$c_\theta = \frac{d\theta}{dt} = -\frac{1}{k}\left[\frac{\partial\sigma}{\partial d}\frac{\partial d}{\partial m} + \bar{k}\cdot\frac{\partial\bar{U}}{\partial m}\right]$$

Here, s is the space co-ordinate in wave direction θ and m is a co-ordinate perpendicular to s. $\nabla_{\bar{x}}$ is the two-dimensional differential operator in the $\bar{x}$-space.

Source Functions

The source function term, S, on the right hand side of the wave action conservation equation is given by

$$S = S_{in} + S_{nl} + S_{ds} + S_{bot} + S_{surf}$$

Here S_{in} represents the momentum transfer of wind energy to wave generation, S_{nl} the energy transfer due non-linear wave-wave interaction, S_{ds} the dissipation of wave energy due to white-capping (deep water wave breaking), S_{bot} the dissipation due to bottom friction and S_{surf} the dissipation of wave energy due to depth-induced breaking.

The default source functions S_{in}, S_{nl} and S_{ds} in MIKE 21 SW are similar to the source functions implemented in the WAM Cycle 4 model, see Komen et al (1994).

The wind input is based on Janssen's (1989, 1991) quasi-linear theory of wind-wave generation, where the momentum transfer from the wind to the sea not only depends on the wind stress, but also the sea state itself. The non-linear energy transfer (through the resonant four-wave interaction) is approximated by the DIA approach, Hasselmann et al (1985). The source function describing the dissipation due to white-capping is based on the theory of Hasselmann (1974) and Janssen (1989). The bottom friction dissipation is modelled using the approach by Johnson and Kofoed-Hansen (2000), which depends on the wave and sediment properties. The source function describing the bottom-induced wave breaking is based on the well-proven approach of Battjes and Janssen (1978) and Eldeberky and Battjes (1996).

A detailed description of the various source functions is available in Komen et al (1994) and Sørensen et al (2003), which also includes the references listed above.

Directional Decoupled Parametric Formulation

The directionally decoupled parametric formulation is based on a parameterisation of the wave action conservation equation. Following Holthuijsen et al (1989), the parameterisation is made in the frequency domain by introducing the zeroth and first moment of the wave action spectrum as dependent variables.

A similar formulation is used in the MIKE 21 NSW Near-shore Spectral Wind-Wave Model, which is one of the most popular models for wave transformation in coastal and shallow water environment. However, with MIKE 21 SW it is not necessary to set up a number of different orientated bathymetries to cover varying wind and wave directions.

The parameterisation leads to the following coupled equations

$$\frac{\partial(m_0)}{\partial t}+\frac{\partial(c_x m_0)}{\partial x}+\frac{\partial(c_y m_0)}{\partial y}+\frac{\partial(c_\theta m_0)}{\partial \theta}=T_0$$

$$\frac{\partial(m_1)}{\partial t}+\frac{\partial(c_x m_1)}{\partial x}+\frac{\partial(c_y m_1)}{\partial y}+\frac{\partial(c_\theta m_1)}{\partial \theta}=T_1$$

where $m_0(x, y, \theta)$ and $m_1(x, y, \theta)$ are the zeroth and first moment of the action spectrum $N(x, y, \sigma, \theta)$, respectively. $T_0(x, y, \theta)$ and $T_1(x, y, \theta)$ are source functions based on the action spectrum. The moments $m_n(x, y, \theta)$ are defined as

$$m_n(x,y,\theta)=\int_0^\infty \omega^n N(x,y,\omega,\theta)d\omega$$

The source functions T_0 and T_1 take into account the effect of local wind generation (stationary solution mode only) and energy dissipation due to bottom friction and wave breaking. The effects of wave-current interaction are also included. The source functions for the local wind generation are derived from empirical growth relations, see Johnson (1998) for details.

Numerical Methods

The frequency spectrum (fully spectral model only) is split into a prognostic part for frequencies lower than a cut-off frequency σ_{max} and an analytical diagnostic tail for the high-frequency part of the spectrum

$$E(\sigma,\theta)=E(\sigma_{max},\theta)\left(\frac{\sigma}{\sigma_{max}}\right)^{-m}$$

where m is a constant (= 5) as proposed by Komen et al (1994).

The directional decoupled parametric formulation in MIKE 21 SW is used extensively for calculation of the wave transformation from deep-water to the shoreline and for wind-wave generation in local areas

Space Discretisation

The discretisation in geographical and spectral space is performed using cell-centred finite volume method. In the geographical domain an unstructured mesh is used. The spatial domain is discretised by subdivision of the continuum into non-overlapping elements. Triangle and quadrilateral shaped polygons are presently supported in MIKE 21 SW. The action density, $N(\sigma,\theta)$ is represented as a piecewise constant over the elements and stored at the geometric centres.

In frequency space either an equidistant or a logarithmic discretisation is used. In the directional space, an equidistant discretisation is used for both types of models. The action density is represented as piecewise constant over the discrete intervals, $\Delta\sigma$ and $\Delta\theta$, in the frequency and directional space.

Integrating the wave action conservation over an area A_i, the frequency interval $\Delta\sigma_l$ and the directional interval $\Delta\theta_m$ gives

$$\frac{\partial}{\partial t}\int_{\Delta\theta_m}\int_{\Delta\sigma_l}\int_{A_i} N d\Omega d\sigma d\theta - \int_{\Delta\theta_m}\int_{\Delta\sigma_l}\int_{A_i}\frac{S}{\sigma}d\Omega d\sigma d\theta$$
$$= \int_{\Delta\theta_m}\int_{\Delta\sigma_l}\int_{A_i}\nabla\cdot(\bar{v}N)d\Omega d\sigma d\theta$$

where Ω is the integration variable defined on A_i. Using the divergence theorem and introducing the convective flux $\overline{F} = \bar{v}N$, we obtain

$$\frac{\partial N_{i,l,m}}{\partial t} = -\frac{1}{A_i}\left[\sum_{p=1}^{NE}(F_n)_{p,l,m}\Delta l_p\right]$$
$$-\frac{1}{\Delta\sigma_l}\left[(F_\sigma)_{i,l+1/2,m} - (F_\sigma)_{i,l-1/2,m}\right]$$
$$-\frac{1}{\Delta\theta_m}\left[(F_\theta)_{i,l,m+1/2} - (F_\theta)_{i,l,m-1/2}\right] + \frac{S_{i,l,m}}{\sigma_l}$$

where NE is the total number of edges in the cell, $(F_n)_{p,l,m} = (F_x n_x + F_y n_y)_{p,l,m}$ is the normal flux trough the edge p in geographical space with length Δl_p. $(F_\sigma)_{i,l+1/2,m}$ and $(F_\theta)_{i,l,m+1/2}$ is the flux through the face in the frequency and directional space, respectively.

The convective flux is derived using a first-order upwinding scheme. In that

$$F_n = c_n\left(\frac{1}{2}(N_i + N_j) - \frac{1}{2}\frac{c}{|c|}(N_i - N_j)\right)$$

where c_n is the propagation speed normal to the element cell face.

Time Integration

The integration in time is based on a fractional step approach. Firstly, a propagation step is performed calculating an approximate solution N^* at the new time level (n+1) by solving the homogenous wave action conservation equation, i.e. without the source terms. Secondly, a source terms step is performed calculating the new solution N^{n+1} from the estimated solution taking into account only the effect of the source terms.

The propagation step is carried out by an explicit Euler scheme

$$N^*_{i,l,m} = N^n_{i,l,m} + \Delta t\left(\frac{\partial N_{i,l,m}}{\partial t}\right)^n$$

To overcome the severe stability restriction, a multi-sequence integration scheme is employed. The maximum allowed time step is increased by employing a sequence of integration steps locally, where the number of steps may vary from point to point.

A source term step is performed using an implicit method (see Komen et al, 1994)

$$N^{n+1}_{i,l,m} = N^*_{i,l,m} + \Delta t\left[\frac{(1-\alpha)S^*_{i,l,m} + \alpha S^{n+1}_{i,l,m}}{\sigma_l}\right]$$

where α is a weighting coefficient that determines the type of finite difference method. Using a Taylor series to approximate S^{n+1} and assuming the off-diagonal terms in $\partial S/\partial E = \gamma$ are negligible, this equation can be simplified as

$$N^{n+1}_{i,l,m} = N^n_{i,l,m} + \frac{(S^*_{i,l,m}/\sigma_l)\Delta t}{(1-\alpha\gamma\Delta t)}$$

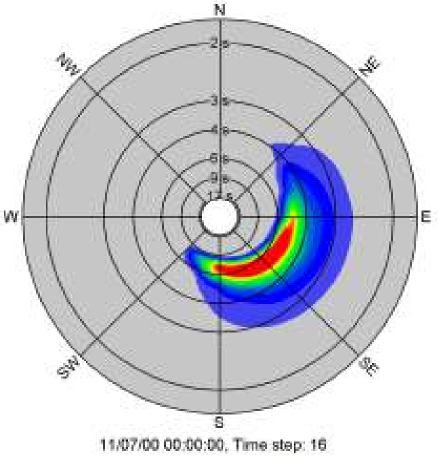
For growing waves ($\gamma > 0$) an explicit forward difference is used ($\alpha = 0$), while for decaying waves ($\gamma < 0$) an implicit backward difference ($\alpha = 1$) is applied.

MIKE 21 SW is also applied for wave forecasts in ship route planning and improved service for conventional and fast ferry operators

Model Output

At each mesh point and for each time step four types of output can be obtained from MIKE 21 SW:

- Integral wave parameters divided into wind sea and swell such as
    - significant wave height, H_{m0}
    - peak wave period, T_p
    - averaged wave period, T_{01}
    - zero-crossing wave period, T_{02}
    - wave energy period, T_{-10}
    - peak wave direction, θ_p
    - mean wave direction, θ_m
    - directional standard deviation, σ
    - wave height with dir., $H_{m0} \cos\theta_m$, $H_{m0} \sin\theta_m$
    - radiation stress tensor, S_{xx}, S_{xy} and S_{yy}
    - particle velocities, *horizontal/vertical*
    - wave power, P, P_x and P_y



Example of model output (directional-frequency wave spectrum) processed using the Polar Plot control in the MIKE Zero Plot Composer

The distinction between wind-sea and swell can be calculated using either a constant threshold frequency or a dynamic threshold frequency with an upper frequency limit.

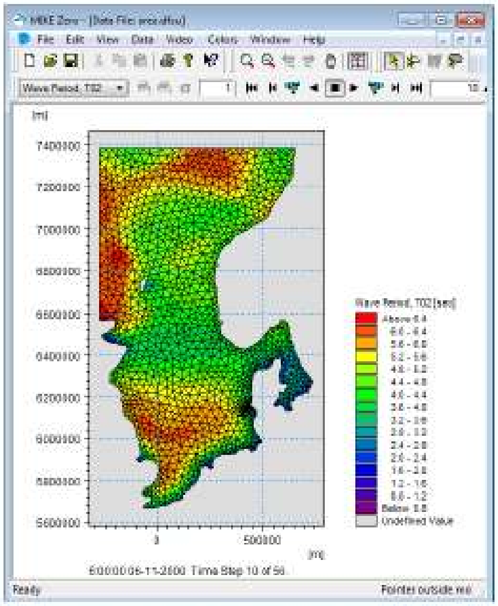
- Input parameters
    - water level, WL
    - water depth, h
    - current velocity, $\overline{U}$
    - wind speed, U_{10}
    - wind direction, θ_w
    - Ice concentration

- Model parameters
    - bottom friction coefficient, C_f
    - breaking parameter, γ
    - Courant number, Cr
    - time step factor, α
    - characteristic edge length, Δl
    - area of element, a
    - wind friction speed, u_*
    - roughness length, z_0
    - drag coefficient, C_D
    - Charnock parameter, z_{ch}

- Directional-frequency wave spectra at selected grid points and or areas as well as direction spectra and frequency spectra

Output from MIKE 21 SW is typically post-processed using the Data Viewer available in the common MIKE Zero shell. The Data Viewer is a tool for analysis and visualisation of unstructured data, e.g. to view meshes, spectra, bathymetries, results files of different format with graphical extraction of time series and line series from plan view and import of graphical overlays.

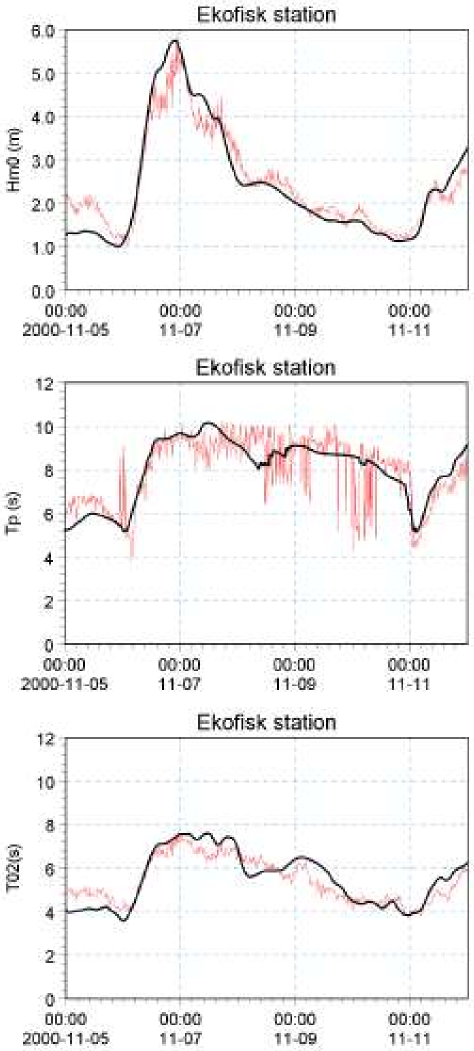
Various other editors and plot controls in the MIKE Zero Composer (e.g. Time Series Plot, Polar Plot, etc.) can be used for analysis and visualisation.



The Data Viewer in MIKE Zero – an efficient tool for analysis and visualisation of unstructured data including processing of animations

Validation

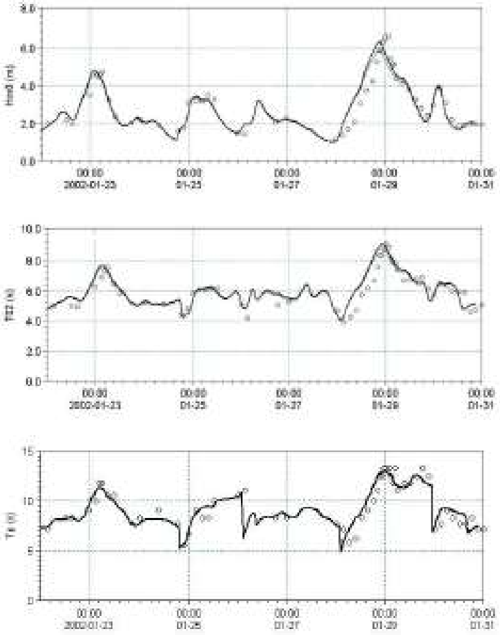
The model has successfully been applied to a number of rather basic idealised situations for which the results can be compared with analytical solutions or information from the literature. The basic tests covered fundamental processes such as wave propagation, depth-induced and current-induced shoaling and refraction, wind-wave generation and dissipation.



Comparison between measured and simulated significant wave height, peak wave period and mean wave period at the Ekofisk offshore platform (water depth 70 m) in the North Sea). (——) calculations and (——) measurements

A major application area of MIKE 21 SW is in connection with design and maintenance of offshore structures

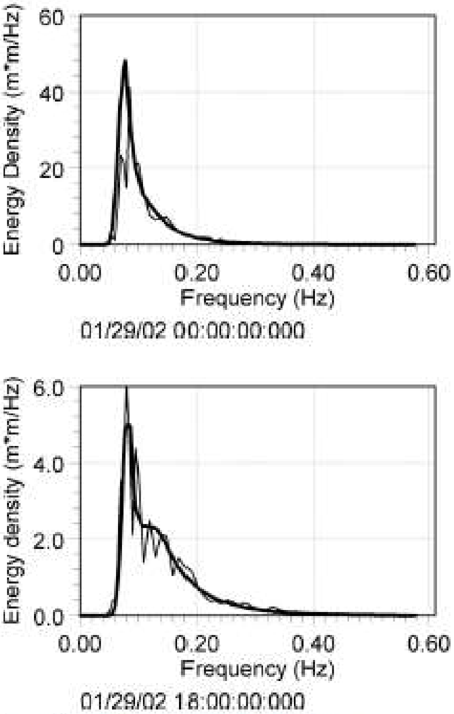
The model has also been tested in natural geophysical conditions (e.g. in the North Sea, the Danish West Coast and the Baltic Sea), which are more realistic and complicated than the academic test and laboratory tests mentioned above.



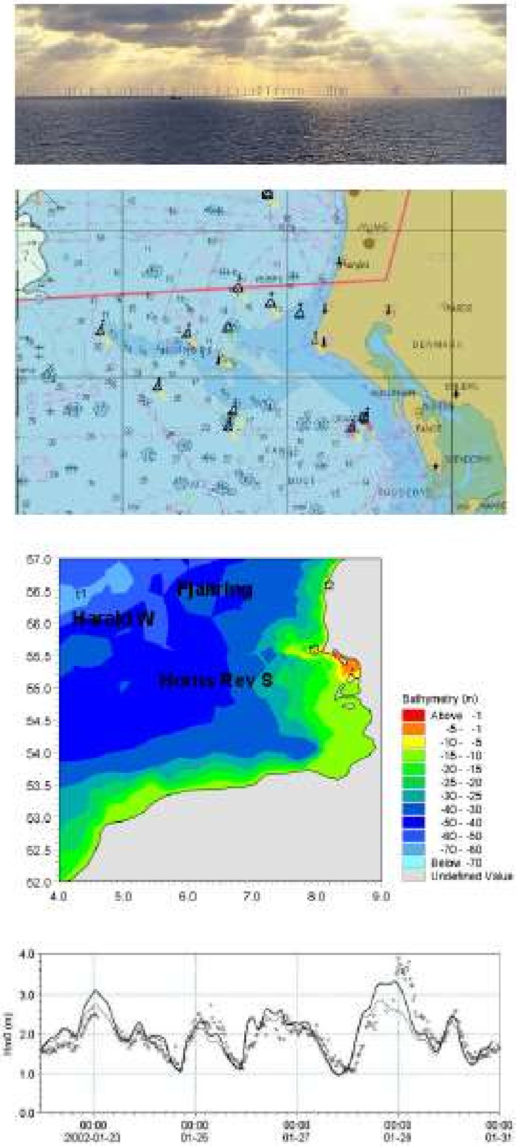
Comparison between measured and simulated significant wave height, peak wave period and mean wave period at Fjaltring located at the Danish west coast (water depth 17.5 m).(——) calculations and (o) measurements

The Fjaltring directional wave rider buoy is located offshore relative to the depicted arrow

MIKE 21 SW is used for prediction of the wave conditions at the complex Horns Rev (reef) in the southeastern part of the North Sea. At this site, a 168 MW offshore wind farm with 80 turbines has been established in water depths between 6.5 and 13.5 m.

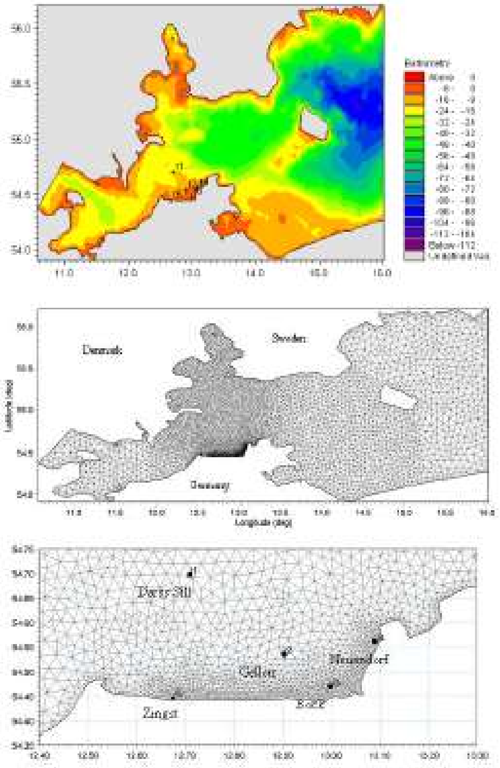


Comparison of frequency spectra at Fjaltring. (——) calculations and (—·—)measurements

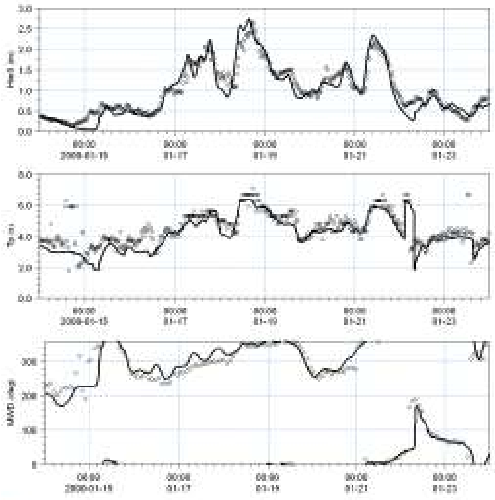


The upper panels show the Horns Rev offshore wind farm and MIKE C-map chart. 'The middle panel shows a close-up of the mesh near the Horns Rev S wave rider buoy (t3, 10 m water depth. The lower panel shows a comparison between measured and simulated significant wave height at Horns Rev S, (——) calculations including tide and surge and (—·—) calculations excluding including tide and surge, (o) measurements

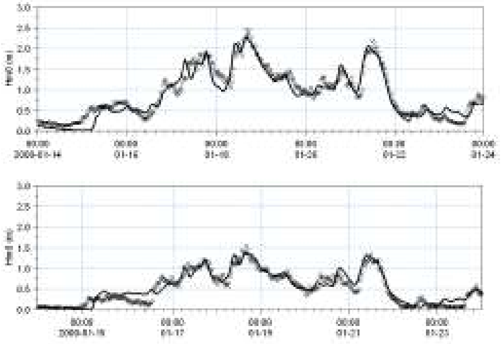
The predicted nearshore wave climate along the island of Hiddensee and the coastline of Zingst located in the micro-tidal Gellen Bay, Germany have been compared to field measurements (Sørensen et al, 2004) provided by the MORWIN project. From the illustrations it can be seen that the wave conditions are well reproduced both offshore and in more shallow water near the shore. The RMS values (on significant wave height) are less than 0.25m at all five stations.



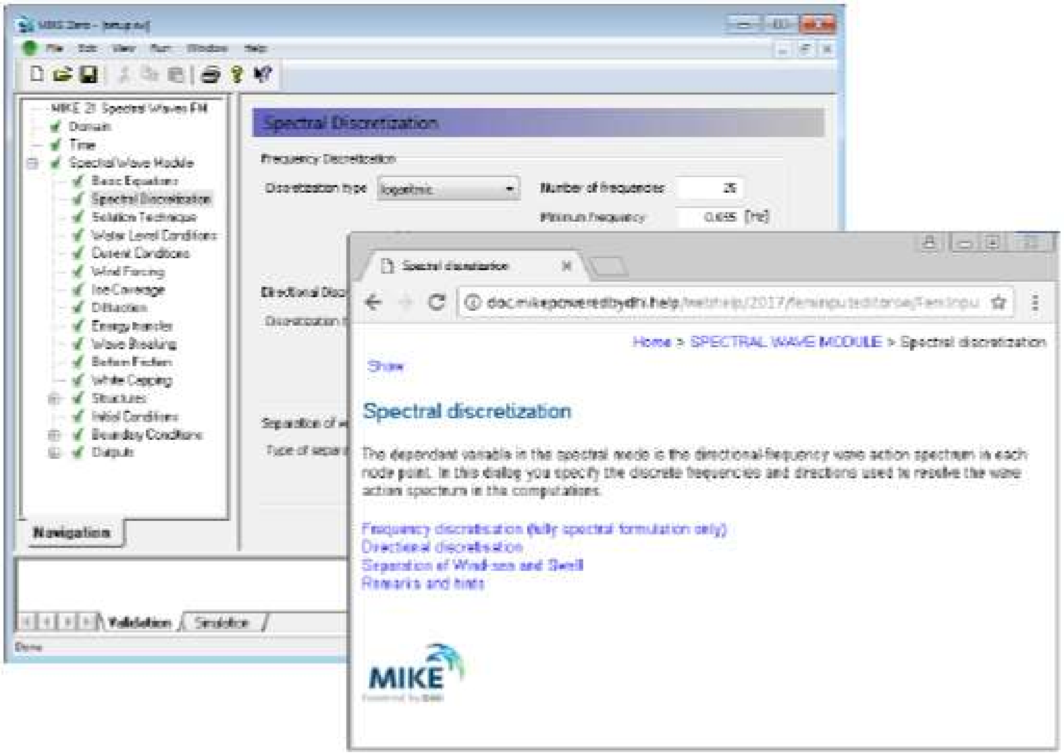
A MIKE 21 SW hindcast application in the Baltic Sea. The upper chart shows the bathymetry and the middle and lower charts show the computational mesh. The lower chart indicates the location of the measurement stations



Time series of significant wave height, H_{m0}, peak wave period, T_p, and mean wave direction, MWD, at Darss sill (Offshore, depth 20.5 m). (——) Calculation and (o) measurements. The RMS value on H_{m0} is approximately 0.2 m



Time series of significant wave height, H_{m0}, at Gellen (upper, depth 8.3m) and Bock (lower, depth 5.5 m). (——) Calculation and (o) measurements. The RMS value on H_{m0} is approximately 0.15 m



Discretization type: logarithmic

Number of frequencies: 25

Minimum frequency: 0.055 [Hz]

Spectral discretization

The dependent variable in the spectral mode is the directional-frequency wave action spectrum in each node point. In this dialog you specify the discrete frequencies and directions used to resolve the wave action spectrum in the computations.

Frequency discretization (fully spectral formulation only)
Directional discretization
Separation of Wind-sea and Swell
Remarks and hints

Graphical user interface of MIKE 21 SW, including an example of the Online Help System

Graphical User Interface

MIKE 21 SW is operated through a fully Windows integrated Graphical User Interface (GUI). Support is provided at each stage by an Online Help System.

The common MIKE Zero shell provides entries for common data file editors, plotting facilities and a toolbox for/utilities as the Mesh Generator and Data Viewer.

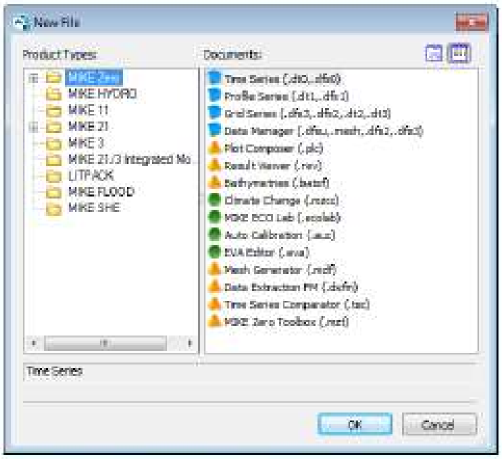
FEMA Approval of MIKE 21

The US Federal Emergency Management Agency (FEMA) has per May 2001 officially approved MIKE 21 for use in coastal Flood Insurance Studies.

The three modules, which are the hydro-dynamic module, near-shore spectral wind-wave module and offshore spectral wind-wave module, have been accepted for coastal storm surge, coastal wave heights, and coastal wave effect usage.

For more information please check www.fema.gov/fhm and www.dhisoftware.com

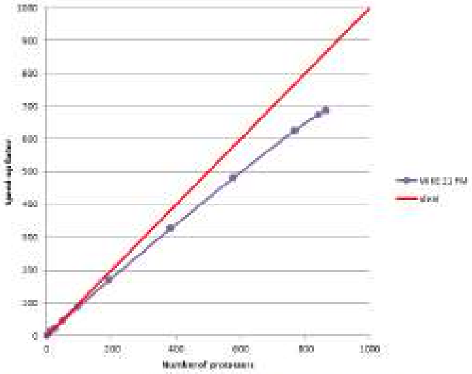
FEMA approval of the MIKE 21 package



Overview of the common MIKE Zero utilities

Parallelisation

The computational engines of the MIKE 21/3 FM series are available in versions that have been parallelised using both shared memory as well as distributed memory architecture. The latter approach allows for domain decomposition. The result is much faster simulations on systems with many cores.



Example of MIKE 21 HD FM speed-up using a HPC Cluster with distributed memory architecture (purple)

Hardware and Operating System Requirements

The MIKE Zero Modules support Microsoft Windows 7 Professional Service Pack 1 (64 bit), Windows 10 Pro (64 bit), Windows Server 2012 R2 Standard (64 bit) and Windows Server 2016 Standard (64 bit).

Microsoft Internet Explorer 9.0 (or higher) is required for network license management. An internet browser is also required for accessing the web-based documentation and online help.

The recommended minimum hardware requirements for executing the MIKE Zero modules are:

Processor:	3 GHz PC (or higher)
Memory (RAM):	2 GB (or higher)
Hard disk:	40 GB (or higher)
Monitor:	SVGA, resolution 1024x768
Graphics card: (GUI and visualisation)	64 MB RAM (256 MB RAM or higher is recommended)

Support

News about new features, applications, papers, updates, patches, etc. are available here:

www.mikepoweredbydhi.com/Download/DocumentsAndTools.aspx

For further information on MIKE 21 SW, please contact your local DHI office or the support centre:

MIKE Powered by DHI Client Care
Agern Allé 5
DK-2970 Hørsholm
Denmark

Tel: +45 4516 9333
Fax: +45 4516 9292

mike@dhigroup.com
www.mikepoweredbydhi.com

Documentation

The MIKE 21 & MIKE 3 FM models are provided with comprehensive user guides, online help, scientific documentation, application examples and step-by-step training examples.

References

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Young, I.R., (1999). Wind generated ocean waves, in Elsevier Ocean Engineering Book Series, Volume 2, Eds. R. Bhattacharyya and M.E. McCormick, Elsevier.

Komen, G.J., Cavaleri, L., Doneland, M., Hasselmann, K., Hasselmann S. and Janssen, P.A.E.M., (1994). Dynamics and modelling of ocean waves. Cambridge University Press, UK, 560 pp.

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

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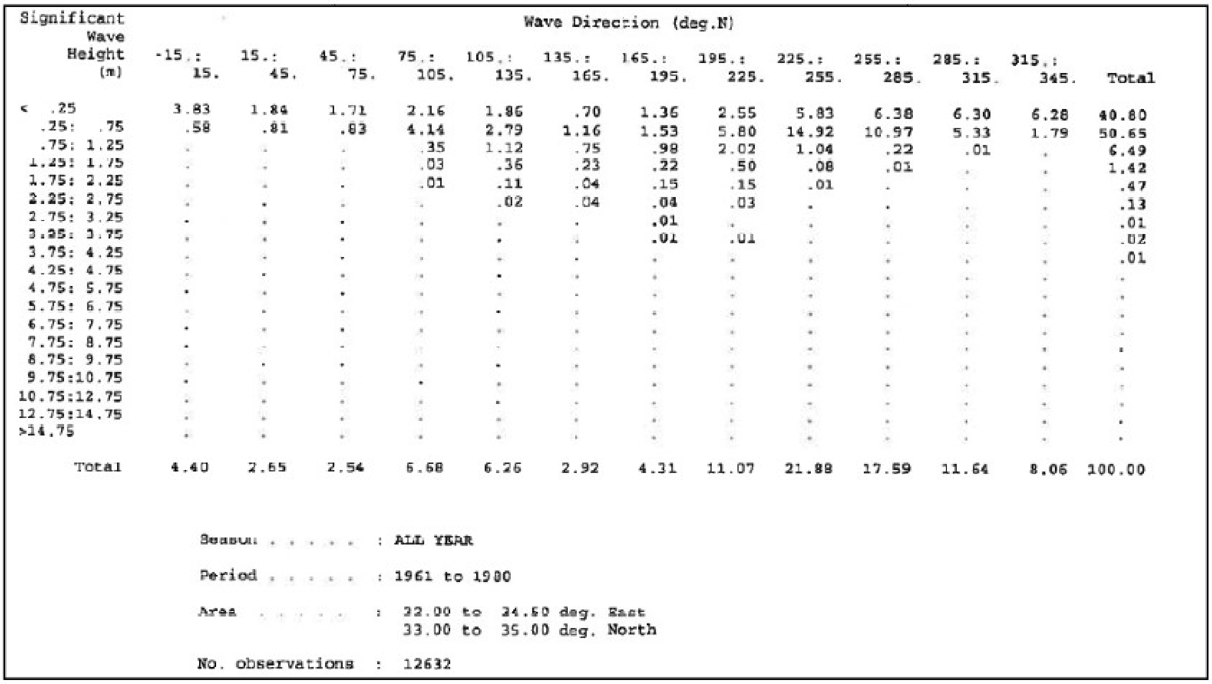
Kofoed-Hansen, H., Johnson, H.K., Højstrup, J. and Lange, B., (1998). Wind-wave modelling in waters with restricted fetches. In: Proc of 5th International Workshop on Wave Hindcasting and Forecasting, 27-30 January 1998, Melbourne, FL, USA, pp. 113-127.

Kofoed-Hansen, H, Johnson, H.K., Astrup, P. and Larsen, J., (2001). Prediction of waves and sea surface roughness in restricted coastal waters. In: Proc of 27th International Conference of Coastal Engineering, pp.1169-1182.

Al-Mashouk, M.A., Kerper, D.R. and Jacobsen, V., (1998). Red Sea Hindcast study: Development of a sea state design database for the Red Sea.. *J Saudi Aramco Technology*, **1**, 10 pp.

Rugbjerg, M., Nielsen, K., Christensen, J.H. and Jacobsen, V., (2001). Wave energy in the Danish part of the North Sea. In: Proc of 4th European Wave Energy Conference, 8 pp.

APPENDIX G WAVE AND WIND CONTIONS



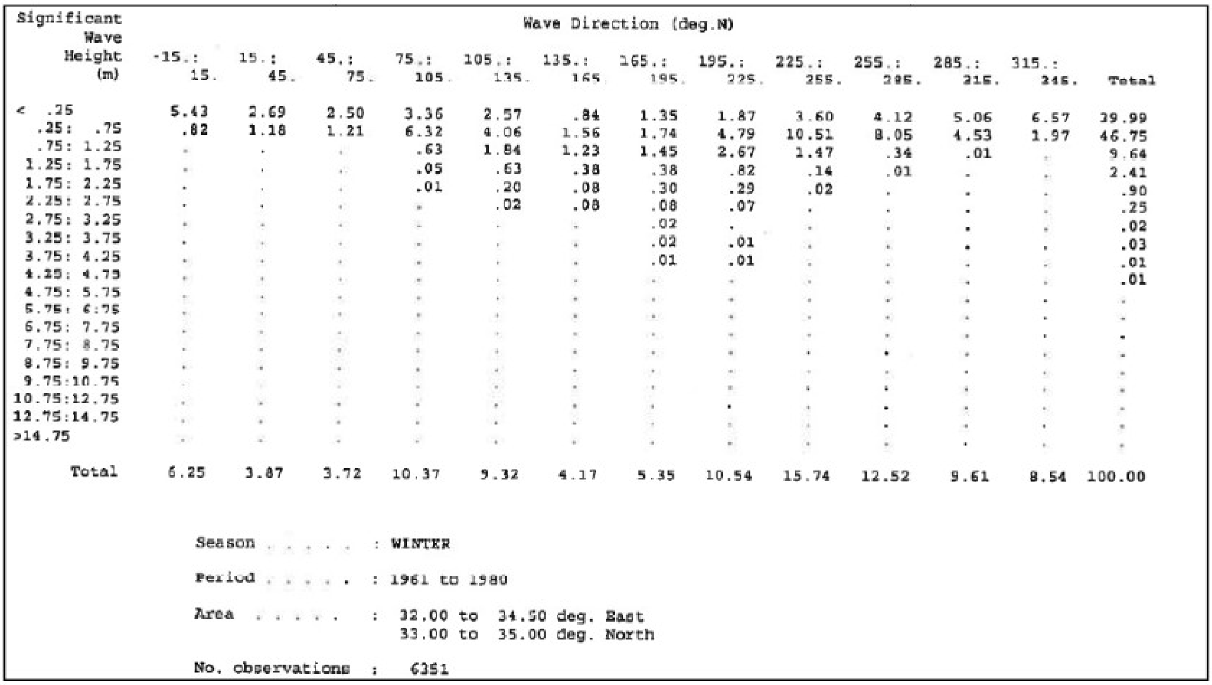
Significant Wave Height (m)	Wave Direction (deg.N) -15.: 15.	15.: 45.	45.: 75.	75.: 105.	105.: 135.	135.: 165.	165.: 195.	195.: 225.	225.: 255.	255.: 285.	285.: 315.	315.: 345.	Total
< .25	3.83	1.84	1.71	2.16	1.86	.70	1.36	2.55	5.83	6.38	6.30	6.28	40.80
.25: .75	.58	.81	.83	4.14	2.79	1.16	1.53	5.80	14.92	10.97	5.33	1.79	50.65
.75: 1.25	.	.	.	.35	1.12	.75	.98	2.02	1.04	.22	.01	.	6.49
1.25: 1.75	.	.	.	.03	.36	.23	.22	.50	.08	.01	.	.	1.42
1.75: 2.25	.	.	.	.01	.11	.04	.15	.15	.01	.	.	.	.47
2.25: 2.75	.	.	.	.	.02	.04	.04	.03	.	.	.	.	.13
2.75: 3.25	.	.	.	.	.	.	.01	.	.	.	.	.	.01
3.25: 3.75	.	.	.	.	.	.	.01	.01	.	.	.	.	.02
3.75: 4.25	.	.	.	.	.	.	.	.	.	.	.	.	.01
4.25: 4.75	.	.	.	.	.	.	.	.	.	.	.	.	.
4.75: 5.75	.	.	.	.	.	.	.	.	.	.	.	.	.
5.75: 6.75	.	.	.	.	.	.	.	.	.	.	.	.	.
6.75: 7.75	.	.	.	.	.	.	.	.	.	.	.	.	.
7.75: 8.75	.	.	.	.	.	.	.	.	.	.	.	.	.
8.75: 9.75	.	.	.	.	.	.	.	.	.	.	.	.	.
9.75:10.75	.	.	.	.	.	.	.	.	.	.	.	.	.
10.75:12.75	.	.	.	.	.	.	.	.	.	.	.	.	.
12.75:14.75	.	.	.	.	.	.	.	.	.	.	.	.	.
>14.75	.	.	.	.	.	.	.	.	.	.	.	.	.
Total	4.40	2.65	2.54	6.68	6.26	2.92	4.31	11.07	21.88	17.59	11.64	8.06	100.00

Season . . . . . . : ALL YEAR

Period . . . . . . : 1961 to 1980

Area . . . . . . : 32.00 to 34.50 deg. East
33.00 to 35.00 deg. North

No. observations : 12632



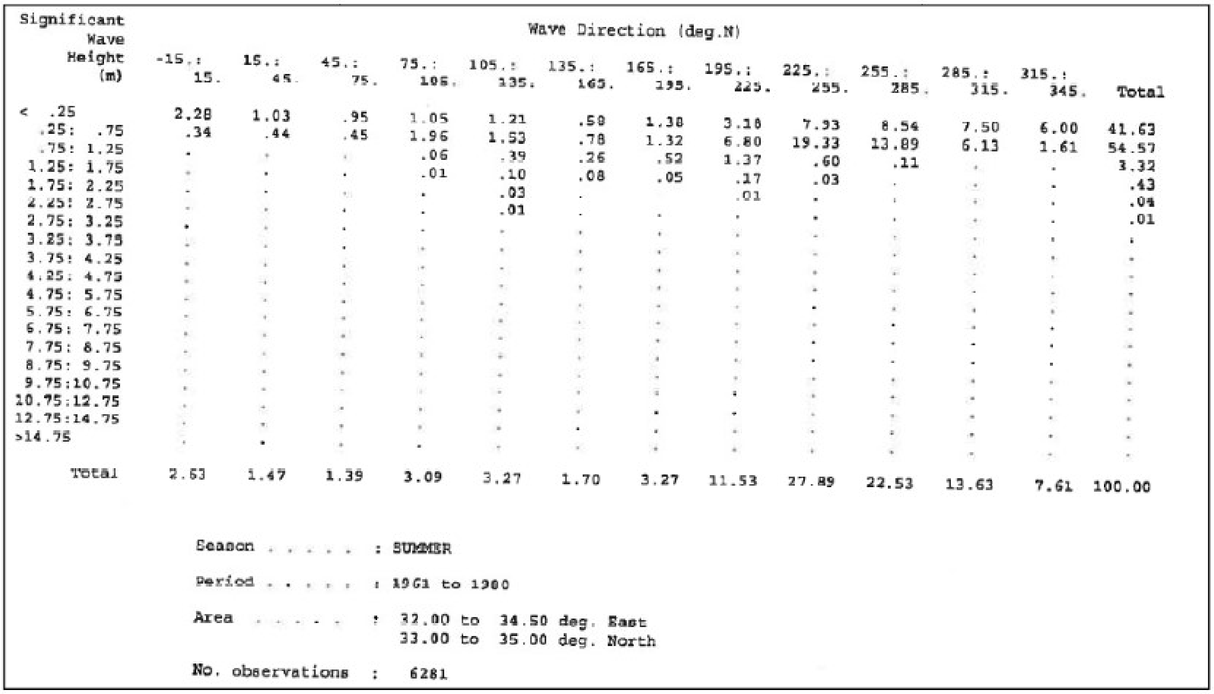
Significant Wave Height (m)	Wave Direction (deg.N) -15.: 15.	15.: 45.	45.: 75.	75.: 105.	105.: 135.	135.: 165.	165.: 195.	195.: 225.	225.: 255.	255.: 285.	285.: 315.	315.: 345.	Total
< .25	5.43	2.69	2.50	3.36	2.57	.84	1.35	1.87	3.60	4.12	5.06	6.57	39.99
.25: .75	.82	1.18	1.21	6.32	4.06	1.56	1.74	4.79	10.51	8.05	4.53	1.97	46.75
.75: 1.25	.	.	.	.63	1.84	1.23	1.45	2.67	1.47	.34	.01	.	9.64
1.25: 1.75	.	.	.	.05	.63	.38	.38	.82	.14	.01	.	.	2.41
1.75: 2.25	.	.	.	.01	.20	.08	.30	.29	.02	.	.	.	.90
2.25: 2.75	.	.	.	.	.02	.08	.08	.07	.	.	.	.	.25
2.75: 3.25	.	.	.	.	.	.	.02	.	.	.	.	.	.02
3.25: 3.75	.	.	.	.	.	.	.02	.01	.	.	.	.	.03
3.75: 4.25	.	.	.	.	.	.	.01	.01	.	.	.	.	.01
4.25: 4.75	.	.	.	.	.	.	.	.	.	.	.	.	.01
4.75: 5.75	.	.	.	.	.	.	.	.	.	.	.	.	.
5.75: 6.75	.	.	.	.	.	.	.	.	.	.	.	.	.
6.75: 7.75	.	.	.	.	.	.	.	.	.	.	.	.	.
7.75: 8.75	.	.	.	.	.	.	.	.	.	.	.	.	.
8.75: 9.75	.	.	.	.	.	.	.	.	.	.	.	.	.
9.75:10.75	.	.	.	.	.	.	.	.	.	.	.	.	.
10.75:12.75	.	.	.	.	.	.	.	.	.	.	.	.	.
12.75:14.75	.	.	.	.	.	.	.	.	.	.	.	.	.
>14.75	.	.	.	.	.	.	.	.	.	.	.	.	.
Total	6.25	3.87	3.72	10.37	9.32	4.17	5.35	10.54	15.74	12.52	9.61	8.54	100.00

Season . . . . . : WINTER

Period . . . . . : 1961 to 1980

Area . . . . . : 32.00 to 34.50 deg. East
33.00 to 35.00 deg. North

No. observations : 6351



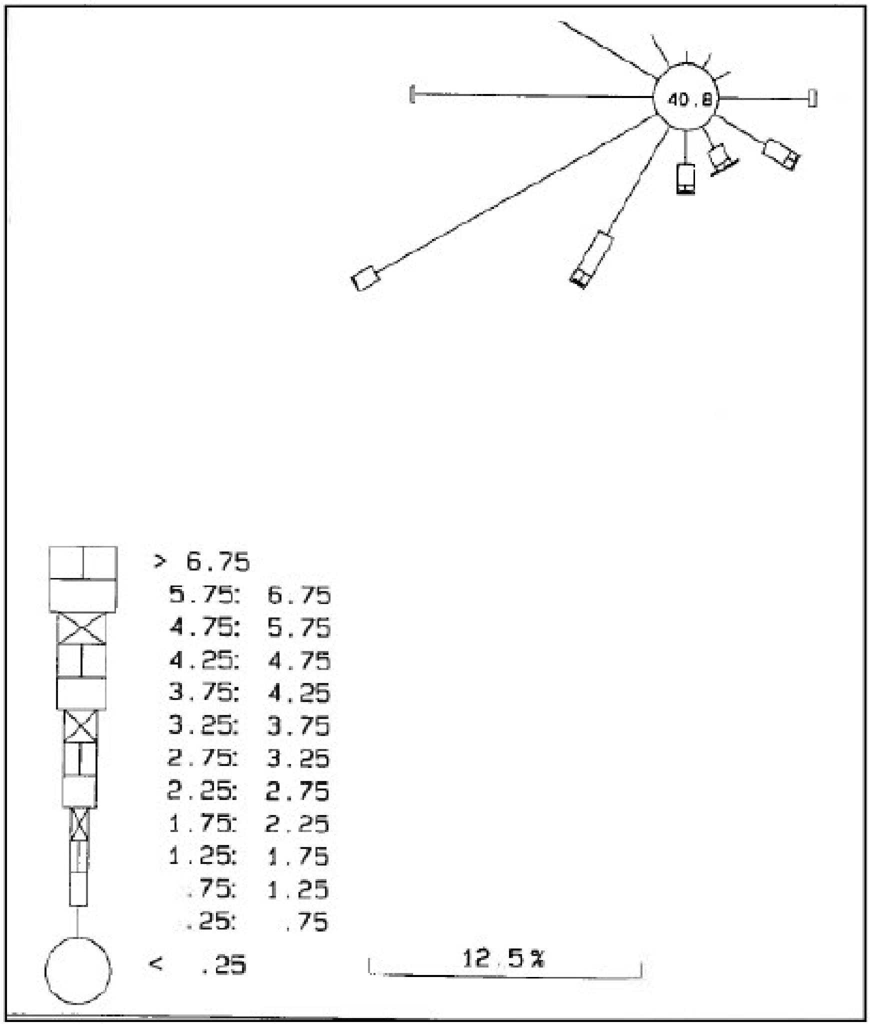
Significant Wave Height (m)	Wave Direction (deg.N)												
	-15.: 15.	15.: 45.	45.: 75.	75.: 105.	105.: 135.	135.: 165.	165.: 195.	195.: 225.	225.: 255.	255.: 285.	285.: 315.	315.: 345.	Total
< .25	2.28	1.03	.95	1.05	1.21	.58	1.38	3.18	7.33	8.54	7.50	6.00	41.63
.25: .75	.34	.44	.45	1.96	1.53	.78	1.32	6.80	19.33	13.89	6.13	1.61	54.57
.75: 1.25	.	.	.	.06	.39	.26	.52	1.37	.60	.11	.	.	3.32
1.25: 1.75	.	.	.	.01	.10	.08	.05	.17	.03	.	.	.	.43
1.75: 2.25	.	.	.	.	.03	.		.01	.	.	.	.	.04
2.25: 2.75	.	.	.	.	.01	.	.	.	.	.	.	.	.01
2.75: 3.25	.	.	.	.	.	.	.	.	.	.	.	.	.
3.25: 3.75	.	.	.	.	.	.	.	.	.	.	.	.	.
3.75: 4.25	.	.	.	.	.	.	.	.	.	.	.	.	.
4.25: 4.75	.	.	.	.	.	.	.	.	.	.	.	.	.
4.75: 5.75	.	.	.	.	.	.	.	.	.	.	.	.	.
5.75: 6.75	.	.	.	.	.	.	.	.	.	.	.	.	.
6.75: 7.75	.	.	.	.	.	.	.	.	.	.	.	.	.
7.75: 8.75	.	.	.	.	.	.	.	.	.	.	.	.	.
8.75: 9.75	.	.	.	.	.	.	.	.	.	.	.	.	.
9.75:10.75	.	.	.	.	.	.	.	.	.	.	.	.	.
10.75:12.75	.	.	.	.	.	.	.	.	.	.	.	.	.
12.75:14.75	.	.	.	.	.	.	.	.	.	.	.	.	.
>14.75	.	.	.	.	.	.	.	.	.	.	.	.	.
Total	2.63	1.47	1.39	3.09	3.27	1.70	3.27	11.53	27.89	22.53	13.63	7.61	100.00

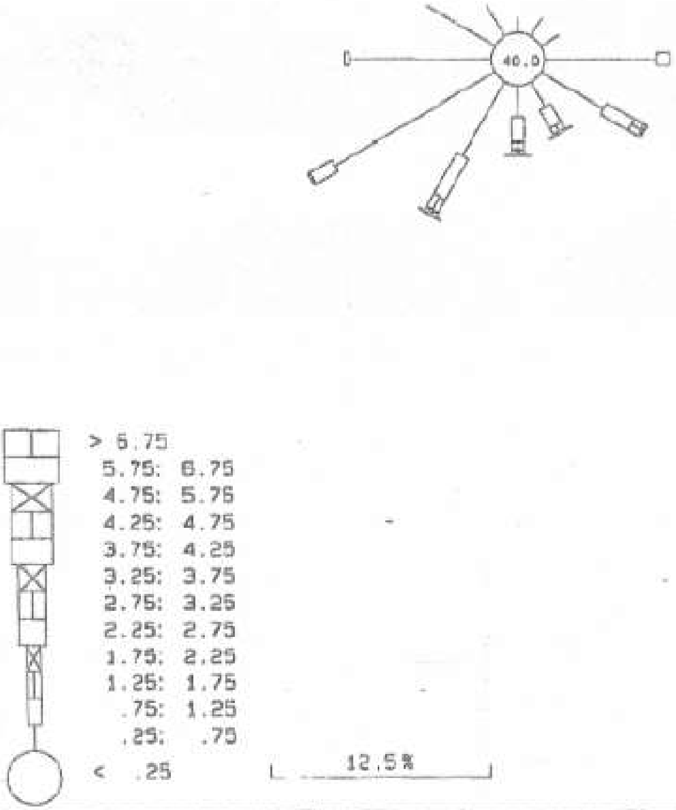
Season . . . . . . : SUMMER

Period . . . . . . : 1961 to 1980

Area . . . . . . : 32.00 to 34.50 deg. East
33.00 to 35.00 deg. North

No. observations : 6281


40.8
> 6.75
5.75: 6.75
4.75: 5.75
4.25: 4.75
3.75: 4.25
3.25: 3.75
2.75: 3.25
2.25: 2.75
1.75: 2.25
1.25: 1.75
.75: 1.25
.25: .75
< .25
12.5%



Wave height rose at the 20 m contour
near Moni Marina

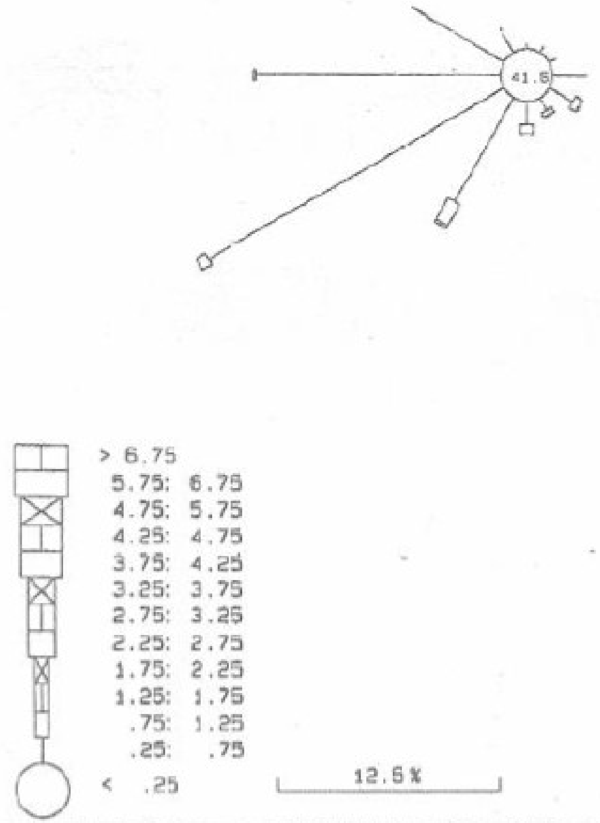
Sea + Swell

WINTER

DELFT HYDRAULICS

H1458

FIG.



Wave height rose at the 20 m contour
near Moni Marina

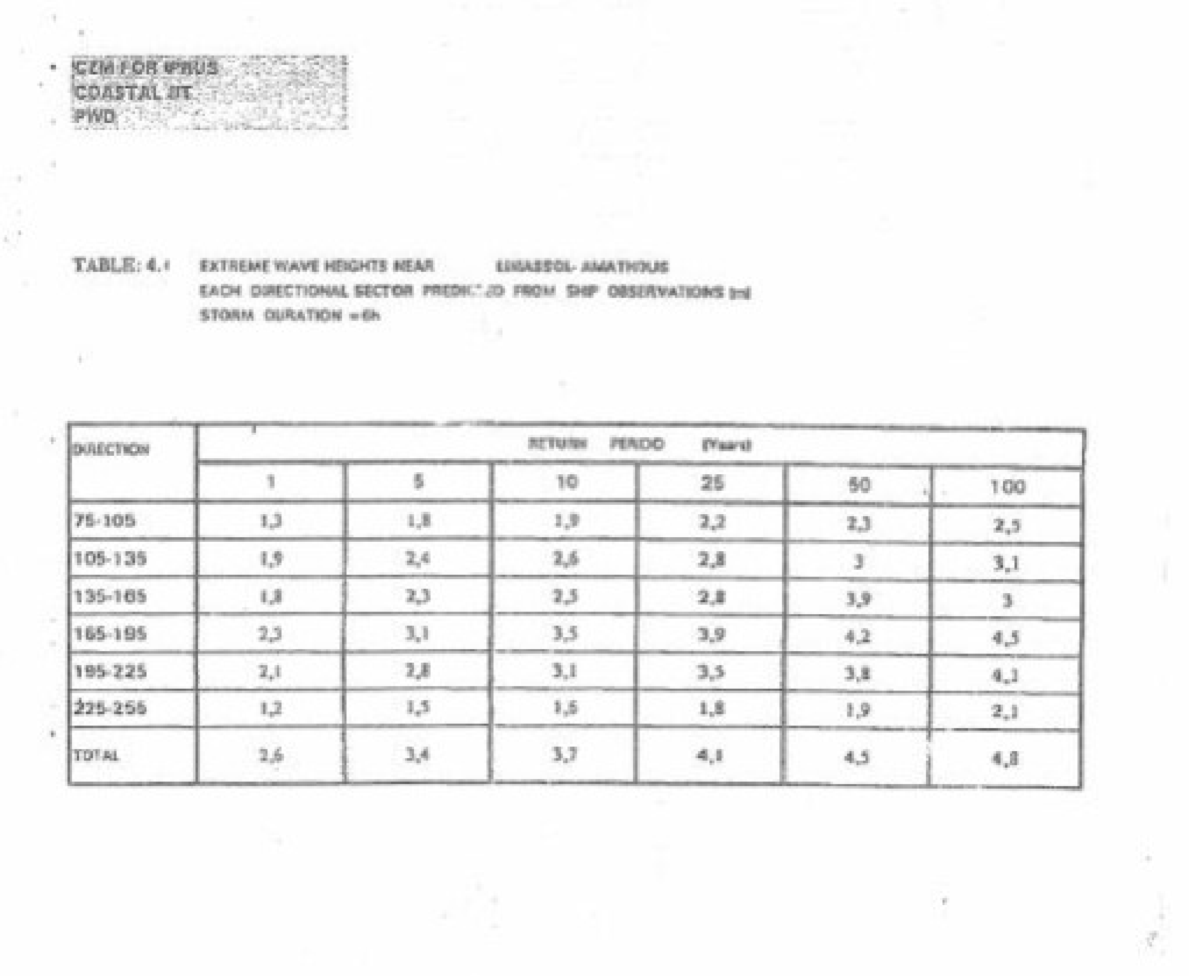
Sea + Swell

SUMMER

DELFT HYDRAULICS

H1456

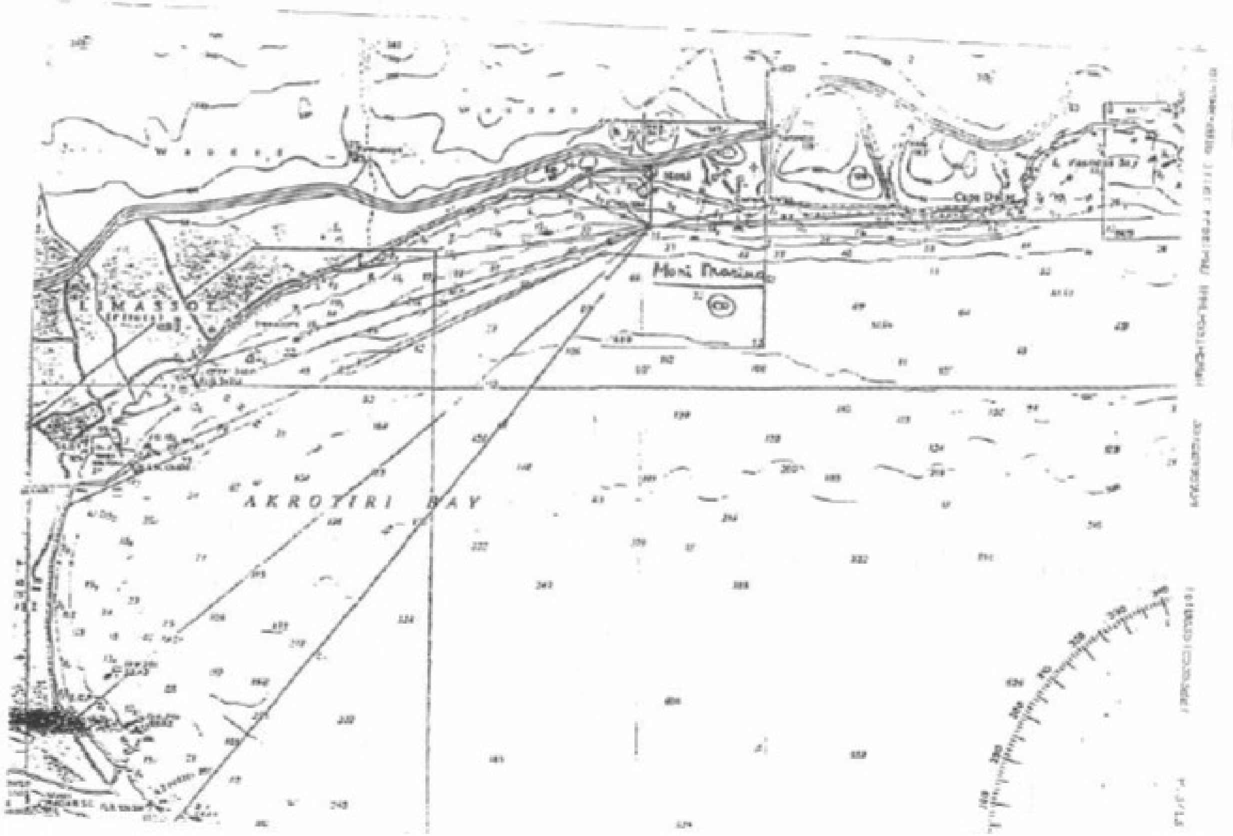
FIG.



CEM FOR CYPRUS
COASTAL UNIT
PWD

TABLE: 4.1 EXTREME WAVE HEIGHTS NEAR LIMASSOL- AMATHOUS
EACH DIRECTIONAL SECTOR PREDICTED FROM SHIP OBSERVATIONS [m]
STORM DURATION =6h

DIRECTION	RETURN PERIOD (Years)					
	1	5	10	25	50	100
75-105	1,3	1,8	1,9	2,2	2,3	2,5
105-135	1,9	2,4	2,6	2,8	3	3,1
135-165	1,8	2,3	2,5	2,8	3,9	3
165-195	2,3	3,1	3,5	3,9	4,2	4,5
195-225	2,1	2,8	3,1	3,5	3,8	4,1
225-255	1,2	1,5	1,6	1,8	1,9	2,1
TOTAL	2,6	3,4	3,7	4,1	4,5	4,8



LIMASSOL
AKROTIRI BAY

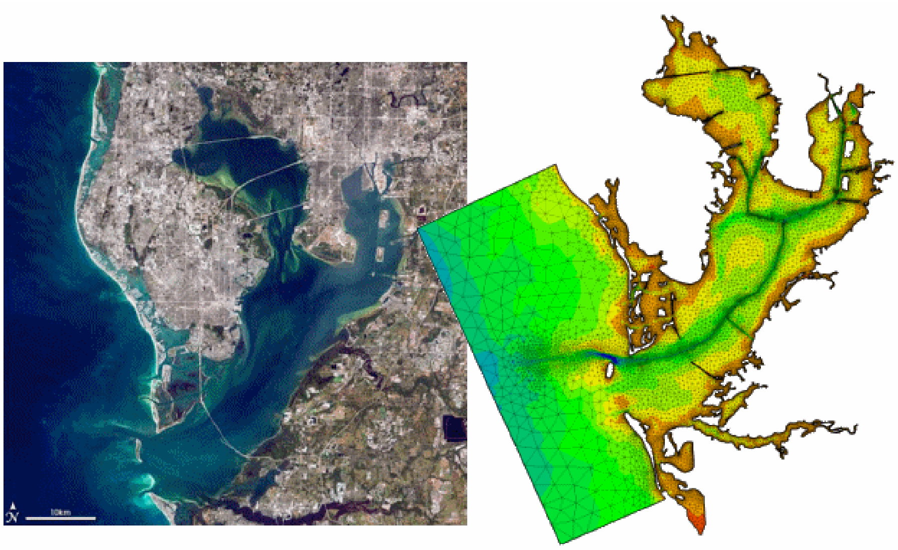
Observed Wave Height (m)	Wave Direction (deg.N)												
	-15.: 15.	15.: 45.	45.: 75.	75.: 105.	105.: 135.	135.: 165.	165.: 195.	195.: 225.	225.: 255.	255.: 285.	285.: 315.	315.: 345.	Total
< .25	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50
.25: .75	4.62	4.65	4.59	4.59	4.60	4.54	4.69	4.55	4.67	4.63	4.64	4.59	4.62
.75: 1.25	4.80	4.78	4.72	4.86	4.67	4.72	4.88	4.81	4.80	4.75	4.71	4.79	4.77
1.25: 1.75	5.68	5.20	5.52	5.38	5.36	5.45	4.90	5.36	5.32	5.19	5.48	5.65	5.35
1.75: 2.25	6.49	5.99	5.54	5.69	6.24	5.49	6.13	6.39	6.30	5.81	5.91	6.11	5.97
2.25: 2.75	5.83	5.83	5.36	6.50	5.83	8.96	5.83	6.36	6.66	6.88	6.44	6.50	6.56
2.75: 3.25	4.50	6.50	6.50	5.83	.	.	6.50	6.90	6.81	6.50	6.19	7.21	6.59
3.25: 3.75	.	5.83	.	.	.	.	8.50	.	8.50	7.79	7.52	4.50	7.51
3.75: 4.25	.	.	.	.	.	.	.	.	8.50	8.50	9.17	6.50	8.26
4.25: 4.75	.	.	.	.	.	.	.	10.50	6.50	8.50	.	.	8.50
4.75: 5.75	.	.	.	.	.	.	.	14.50	.	.	12.50	6.50	11.17
5.75: 6.75	.	.	.	.	.	.	.	.	.	.	.	.	.
6.75: 7.75	.	.	.	.	.	.	.	.	.	.	.	.	.
7.75: 8.75	.	.	.	.	.	.	.	.	.	.	.	.	.
8.75: 9.75	.	.	.	.	.	.	.	.	.	.	.	.	.
9.75:10.75	.	.	.	.	.	.	.	.	.	.	.	.	.
10.75:12.75	.	.	.	.	.	.	.	.	.	.	.	.	.
12 :14.75	.	.	.	.	.	.	.	.	.	.	.	.	.
>14.75	.	.	.	.	.	.	.	.	.	.	.	.	.
Total	4.74	4.72	4.75	4.76	4.73	4.73	4.75	4.84	4.89	4.83	4.81	4.76	4.80

Season . . . . . : ALL YEAR

Period . . . . . : 1961 to 1980

Area . . . . . : 32.00 to 34.50 deg. East
33.00 to 35.00 deg. North

No. observations : 12632



MIKE 21 & MIKE 3 Flow Model FM

Hydrodynamic Module

Short Description

MIKE213_HD_FM_Short_Description_.docx / AJS/EBR/NHP / 2017-10-02

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MIKE 21 & MIKE 3 Flow Model FM

The Flow Model FM is a comprehensive modelling system for two- and three-dimensional water modelling developed by DHI. The 2D and 3D models carry the same names as the classic DHI model versions MIKE 21 & MIKE 3 with an 'FM' added referring to the type of model grid - Flexible Mesh.

The modelling system has been developed for complex applications within oceanographic, coastal and estuarine environments. However, being a general modelling system for 2D and 3D free-surface flows it may also be applied for studies of inland surface waters, e.g. overland flooding and lakes or reservoirs.

MIKE 21 & MIKE 3 Flow Model FM is a general hydrodynamic flow modelling system based on a finite volume method on an unstructured mesh

The Modules of the Flexible Mesh Series

DHI's Flexible Mesh (FM) series includes the following modules:

Flow Model FM modules

- Hydrodynamic Module, HD
- Transport Module, TR
- Ecology Modules, MIKE ECO Lab/AMB Lab
- Oil Spill Module, OS
- Mud Transport Module, MT
- Particle Tracking Module, PT
- Sand Transport Module, ST
- Shoreline Morphology Module, SM

Wave module

- Spectral Wave Module, SW

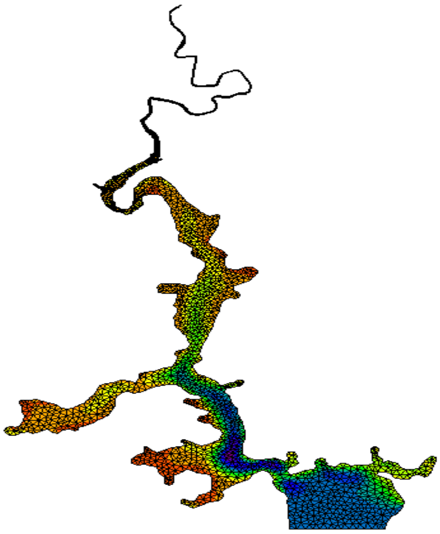
The FM Series meets the increasing demand for realistic representations of nature, both with regard to 'look alike' and to its capability to model coupled processes, e.g. coupling between currents, waves and sediments. Coupling of modules is managed in the Coupled Model FM.

All modules are supported by advanced user interfaces including efficient and sophisticated tools for mesh generation, data management, 2D/3D visualization, etc. In combination with comprehensive documentation and support, the FM series forms a unique professional software tool for consultancy services related to design, operation and maintenance tasks within the marine environment.

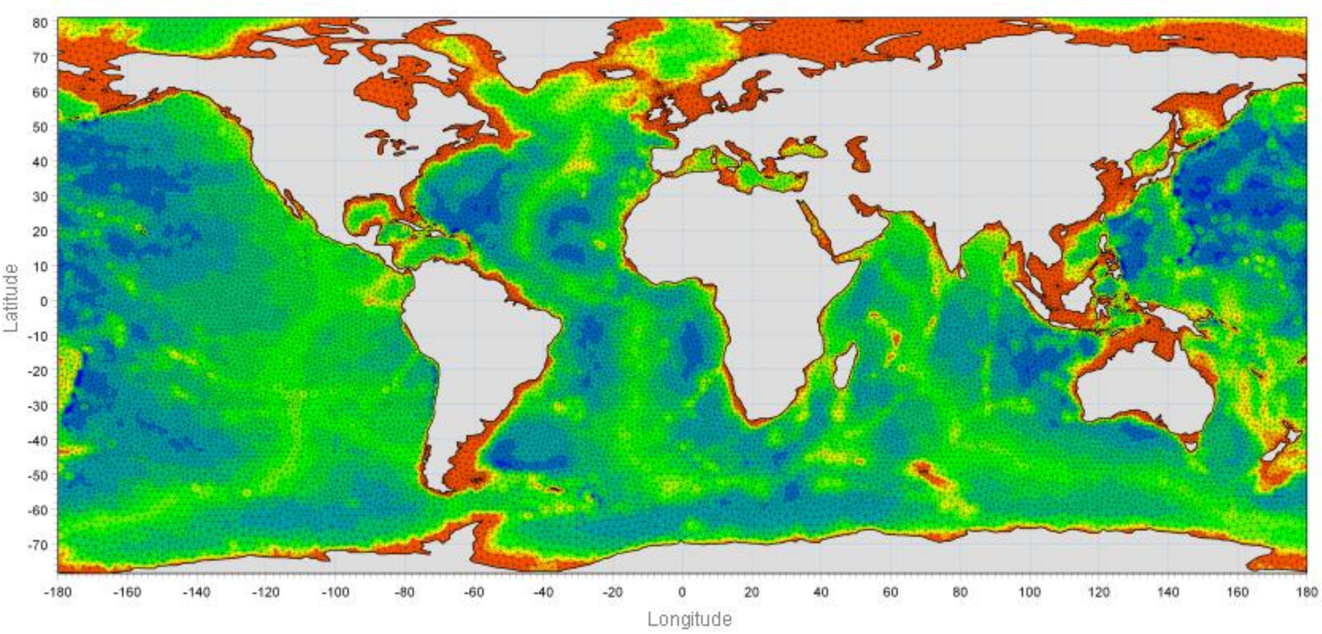
An unstructured grid provides an optimal degree of flexibility in the representation of complex geometries and enables smooth representations of boundaries. Small elements may be used in areas where more detail is desired, and larger elements used where less detail is needed, optimising information for a given amount of computational time.

The spatial discretisation of the governing equations is performed using a cell-centred finite volume method. In the horizontal plane, an unstructured grid is used while a structured mesh is used in the vertical domain (3D).

This document provides a short description of the Hydrodynamic Module included in MIKE 21 & MIKE 3 Flow Model FM.



Example of computational mesh for Tamar Estuary, UK



MIKE 21 & MIKE 3 FLOW MODEL FM supports both Cartesian and spherical coordinates. Spherical coordinates are usually applied for regional and global sea circulation applications. The chart shows the computational mesh and bathymetry for the planet Earth generated by the MIKE Zero Mesh Generator

MIKE 21 & MIKE 3 Flow Model FM - Hydrodynamic Module

The Hydrodynamic Module provides the basis for computations performed in many other modules, but can also be used alone. It simulates the water level variations and flows in response to a variety of forcing functions on flood plains, in lakes, estuaries and coastal areas.

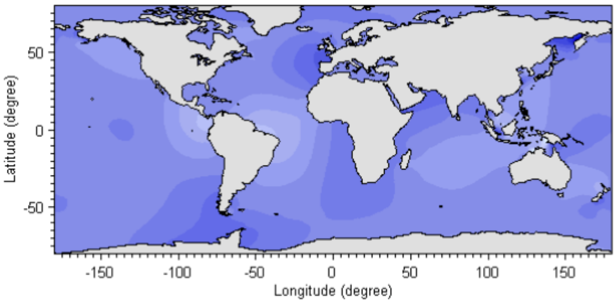
Application Areas

The Hydrodynamic Module included in MIKE 21 & MIKE 3 Flow Model FM simulates unsteady flow taking into account density variations, bathymetry and external forcings.

The choice between 2D and 3D model depends on a number of factors. For example, in shallow waters, wind and tidal current are often sufficient to keep the water column well-mixed, i.e. homogeneous in salinity and temperature. In such cases a 2D model can be used. In water bodies with stratification, either by density or by species (ecology), a 3D model should be used. This is also the case for enclosed or semi-enclosed waters where wind-driven circulation occurs.

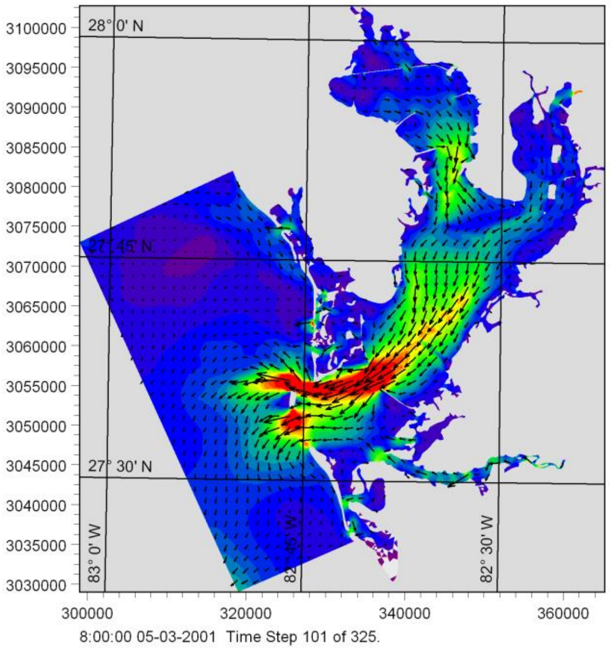
Typical application areas are

- Assessment of hydrographic conditions for design, construction and operation of structures and plants in stratified and non-stratified waters
- Environmental impact assessment studies
- Coastal and oceanographic circulation studies
- Optimization of port and coastal protection infrastructures
- Lake and reservoir hydrodynamics
- Cooling water, recirculation and desalination
- Coastal flooding and storm surge
- Inland flooding and overland flow modelling
- Forecast and warning systems

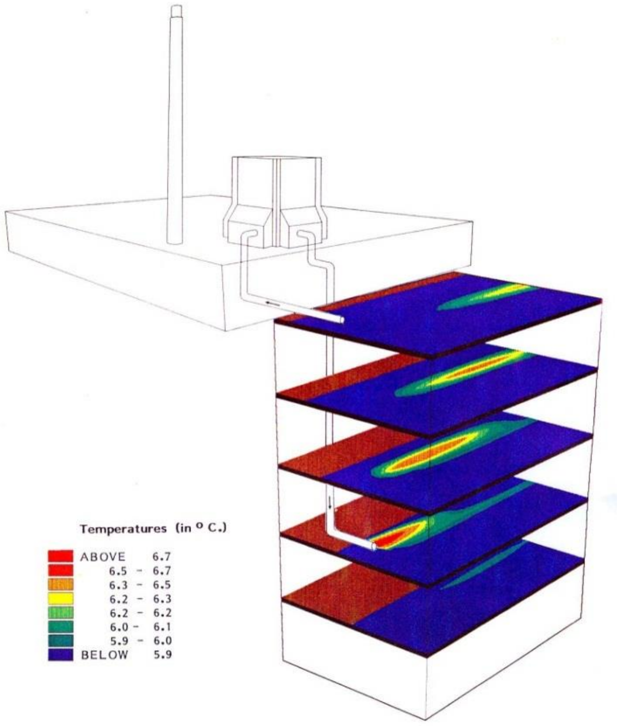


Example of a global tide application of MIKE 21 Flow Model FM. Results from such a model can be used as boundary conditions for regional scale forecast or hindcast models

The MIKE 21 & MIKE 3 Flow Model FM also support spherical coordinates, which makes both models particularly applicable for global and regional sea scale applications.



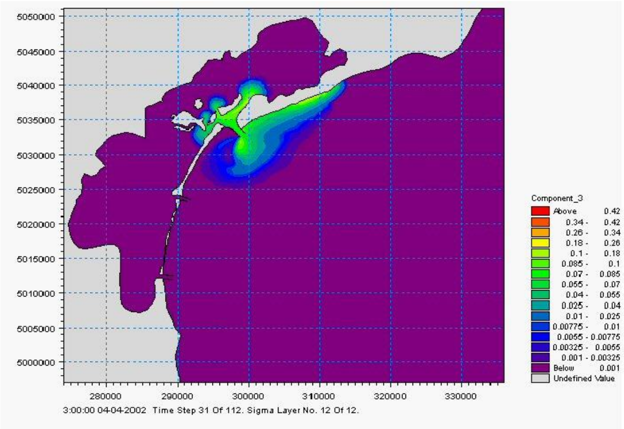
Example of a flow field in Tampa Bay, Florida, simulated by MIKE 21 Flow Model FM



Study of thermal plume dispersion

Typical applications with the MIKE 21 & MIKE 3 Flow Model FM include cooling water recirculation and ecological impact assessment (eutrophication)

The Hydrodynamic Module is together with the Transport Module (TR) used to simulate the spreading and fate of dissolved and suspended substances. This module combination is applied in tracer simulations, flushing and simple water quality studies.



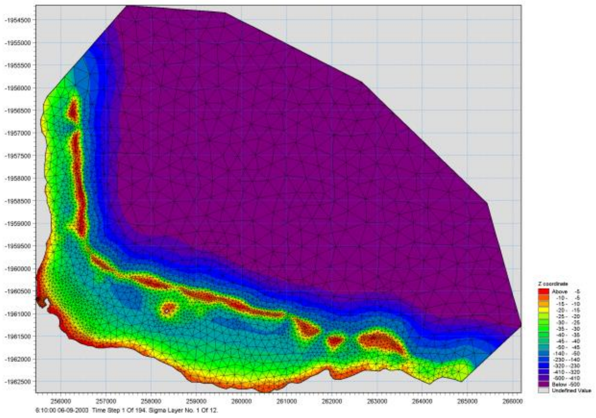
Tracer simulation of single component from outlet in the Adriatic, simulated by MIKE 21 Flow Model FM HD+TR

Prediction of ecosystem behaviour using the MIKE 21 & MIKE 3 Flow Model FM together with MIKE ECO Lab

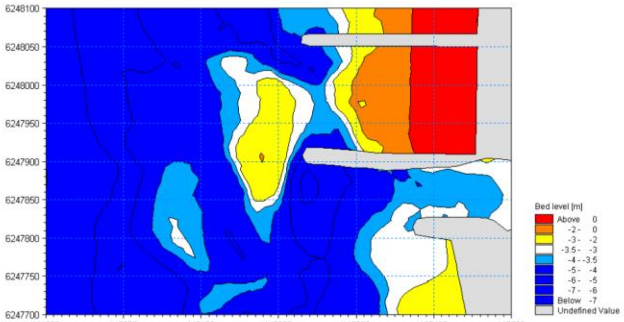
The Hydrodynamic Module can be coupled to the Ecological Module (MIKE ECO Lab) to form the basis for environmental water quality studies comprising multiple components.

Furthermore, the Hydrodynamic Module can be coupled to sediment models for the calculation of sediment transport. The Sand Transport Module and Mud Transport Module can be applied to simulate transport of non-cohesive and cohesive sediments, respectively.

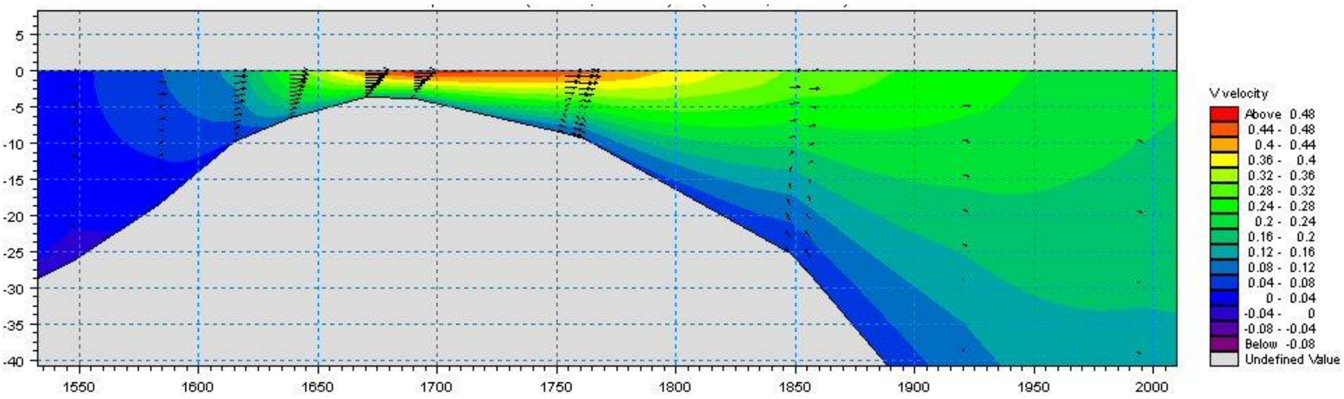
In the coastal zone the transport is mainly determined by wave conditions and associated wave-induced currents. The wave-induced currents are generated by the gradients in radiation stresses that occur in the surf zone. The Spectral Wave Module can be used to calculate the wave conditions and associated radiation stresses.



Model bathymetry of Taravao Bay, Tahiti



Coastal application (morphology) with coupled MIKE 21 HD, SW and ST, Torsminde harbour Denmark



Example of vertical profile of cross reef currents in Taravao Bay, Tahiti simulated with MIKE 3 Flow Model FM. The circulation and renewal of water inside the reef is dependent on the tides, the meteorological conditions and the cross reef currents, thus the circulation model includes the effects of wave induced cross reef currents

Computational Features

The main features and effects included in simulations with the MIKE 21 & MIKE 3 Flow Model FM – Hydrodynamic Module are the following:

- Flooding and drying
- Momentum dispersion
- Bottom shear stress
- Coriolis force
- Wind shear stress
- Barometric pressure gradients
- Ice coverage
- Tidal potential
- Precipitation/evaporation
- Infiltration
- Heat exchange with atmosphere
- Wave radiation stresses
- Sources and sinks, incl. jet
- Structures

Model Equations

The modelling system is based on the numerical solution of the two/three-dimensional incompressible Reynolds averaged Navier-Stokes equations subject to the assumptions of Boussinesq and of hydrostatic pressure. Thus, the model consists of continuity, momentum, temperature, salinity and density equations and it is closed by a turbulent closure scheme. The density does not depend on the pressure, but only on the temperature and the salinity.

For the 3D model, the free surface is taken into account using a sigma-coordinate transformation approach or using a combination of a sigma and z-level coordinate system.

Below the governing equations are presented using Cartesian coordinates.

The local continuity equation is written as

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=S$$

and the two horizontal momentum equations for the x- and y-component, respectively

$$\frac{\partial u}{\partial t}+\frac{\partial u^2}{\partial x}+\frac{\partial vu}{\partial y}+\frac{\partial wu}{\partial z}=fv-g\frac{\partial \eta}{\partial x}-\frac{1}{\rho_0}\frac{\partial p_a}{\partial x}-\frac{g}{\rho_0}\int_z^\eta \frac{\partial \rho}{\partial x}dz+F_u+\frac{\partial}{\partial z}\left(\nu_t\frac{\partial u}{\partial z}\right)+u_sS$$

$$\frac{\partial v}{\partial t}+\frac{\partial v^2}{\partial y}+\frac{\partial uv}{\partial x}+\frac{\partial wv}{\partial z}=-fu-g\frac{\partial \eta}{\partial y}-\frac{1}{\rho_0}\frac{\partial p_a}{\partial y}-\frac{g}{\rho_0}\int_z^\eta \frac{\partial \rho}{\partial y}dz+F_v+\frac{\partial}{\partial z}\left(\nu_t\frac{\partial v}{\partial z}\right)+v_sS$$

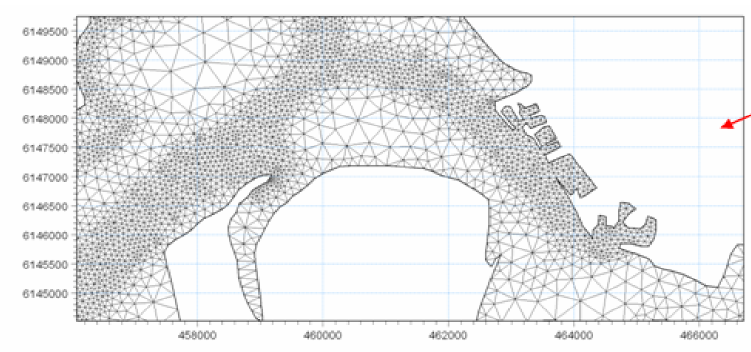
Temperature and salinity

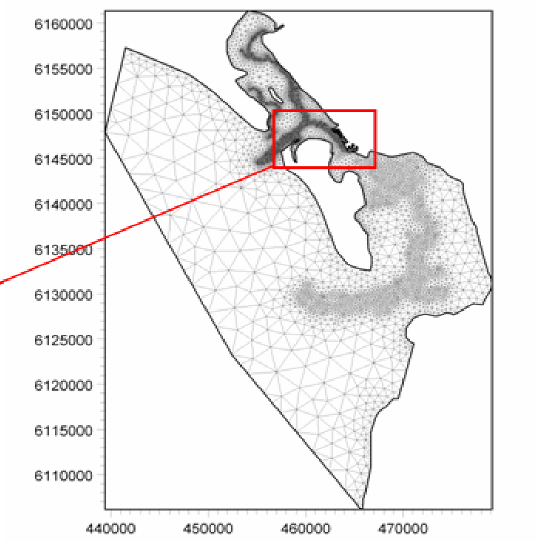
In the Hydrodynamic Module, calculations of the transports of temperature, *T*, and salinity, *s* follow the general transport-diffusion equations as

$$\frac{\partial T}{\partial t}+\frac{\partial uT}{\partial x}+\frac{\partial vT}{\partial y}+\frac{\partial wT}{\partial z}=F_T+\frac{\partial}{\partial z}\left(D_v\frac{\partial T}{\partial z}\right)+\hat{H}+T_sS$$

$$\frac{\partial s}{\partial t}+\frac{\partial us}{\partial x}+\frac{\partial vs}{\partial y}+\frac{\partial ws}{\partial z}=F_s+\frac{\partial}{\partial z}\left(D_v\frac{\partial s}{\partial z}\right)+s_sS$$

Unstructured mesh technique gives the maximum degree of flexibility, for example: 1) Control of node distribution allows for optimal usage of nodes 2) Adoption of mesh resolution to the relevant physical scales 3) Depth-adaptive and boundary-fitted mesh. Below is shown an example from Ho Bay, Denmark with the approach channel to the Port of Esbjerg





The horizontal diffusion terms are defined by

$$(F_T, F_s) = \left[\frac{\partial}{\partial x}\left(D_h \frac{\partial}{\partial x} \right) + \frac{\partial}{\partial y}\left(D_h \frac{\partial}{\partial y} \right) \right] (T, s)$$

The equations for two-dimensional flow are obtained by integration of the equations over depth.

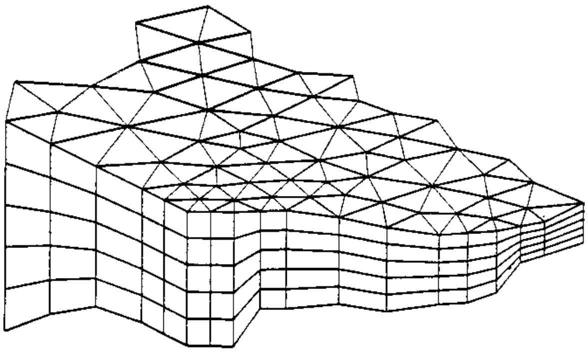
Heat exchange with the atmosphere is also included.

Symbol list

t	time
x, y, z	Cartesian coordinates
u, v, w	flow velocity components
T, s	temperature and salinity
D_v	vertical turbulent (eddy) diffusion coefficient
$\hat{H}$	source term due to heat exchange with atmosphere
S	magnitude of discharge due to point sources
T_s, s_s	temperature and salinity of source
F_T, F_s, F_c	horizontal diffusion terms
D_h	horizontal diffusion coefficient
h	depth

Solution Technique

The spatial discretisation of the primitive equations is performed using a cell-centred finite volume method. The spatial domain is discretised by subdivision of the continuum into non-overlapping elements/cells.



Principle of 3D mesh

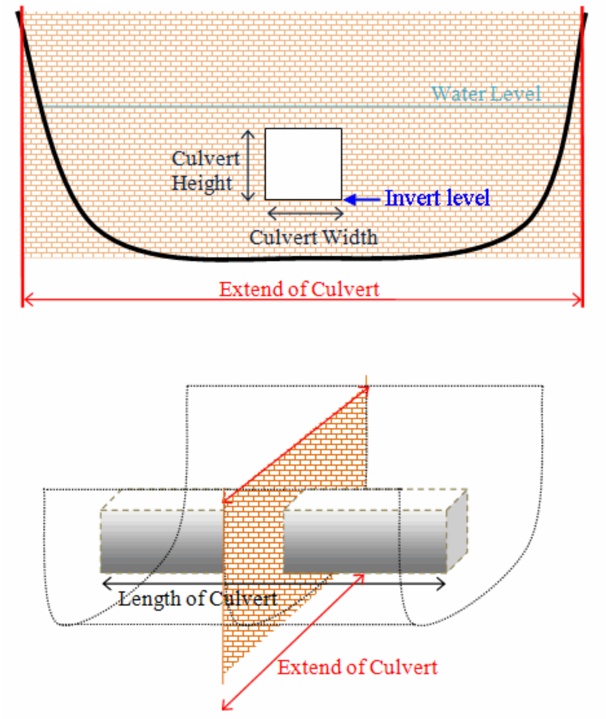
In the horizontal plane an unstructured mesh is used while a structured mesh is used in the vertical domain of the 3D model. In the 2D model the elements can be triangles or quadrilateral elements. In the 3D model the elements can be prisms or bricks whose horizontal faces are triangles and quadrilateral elements, respectively.

The effect of a number of structure types (weirs, culverts, dikes, gates, piers and turbines) with a horizontal dimension which usually cannot be resolved by the computational mesh is modelled by a subgrid technique.

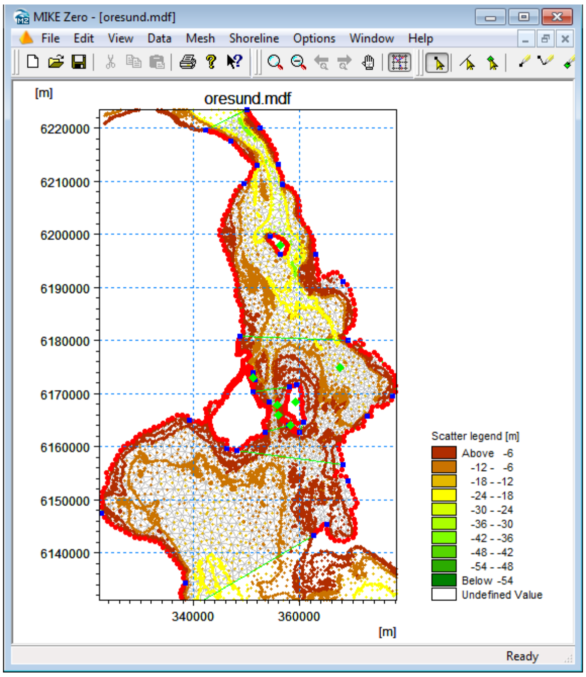
Model Input

Input data can be divided into the following groups:

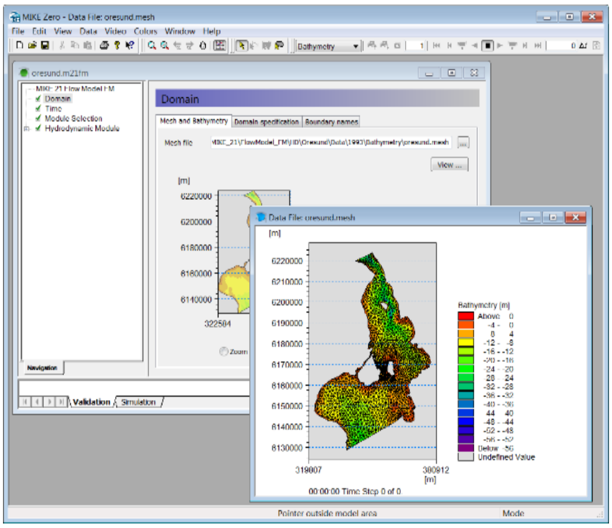
- Domain and time parameters:
  - computational mesh (the coordinate type is defined in the computational mesh file) and bathymetry
  - simulation length and overall time step
- Calibration factors
  - bed resistance
  - momentum dispersion coefficients
  - wind friction factors
  - heat exchange coefficients
- Initial conditions
  - water surface level
  - velocity components
  - temperature and salinity
- Boundary conditions
  - closed
  - water level
  - discharge
  - temperature and salinity
- Other driving forces
  - wind speed and direction
  - tide
  - source/sink discharge
  - wave radiation stresses
- Structures
  - Structure type
  - location
  - structure data



Setup definition of culvert structure



The Mesh Generator is an efficient MIKE Zero tool for the generation and handling of unstructured meshes, including the definition and editing of boundaries

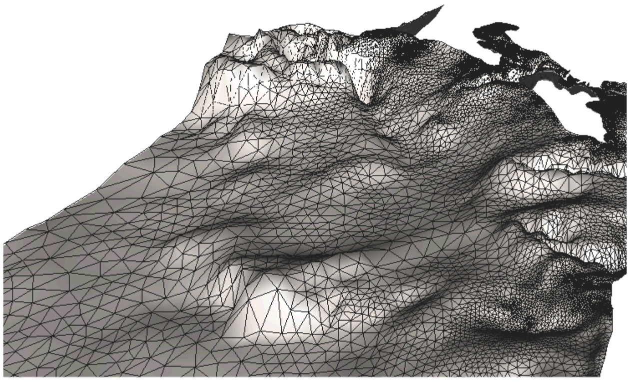


View button on all the GUIs in MIKE 21 & MIKE 3 FM HD for graphical view of input and output files

2D visualization of a computational mesh (Odense Estuary)

Providing MIKE 21 & MIKE 3 Flow Model FM with a suitable mesh is essential for obtaining reliable results from the models. Setting up the mesh includes the appropriate selection of the area to be modelled, adequate resolution of the bathymetry, flow, wind and wave fields under consideration and definition of codes for defining boundaries.

Bathymetric values for the mesh generation can e.g. be obtained from the MIKE Powered by DHI product MIKE C-Map. MIKE C-Map is an efficient tool for extracting depth data and predicted tidal elevation from the world-wide Electronic Chart Database CM-93 Edition 3.0 from C-MAP Norway.

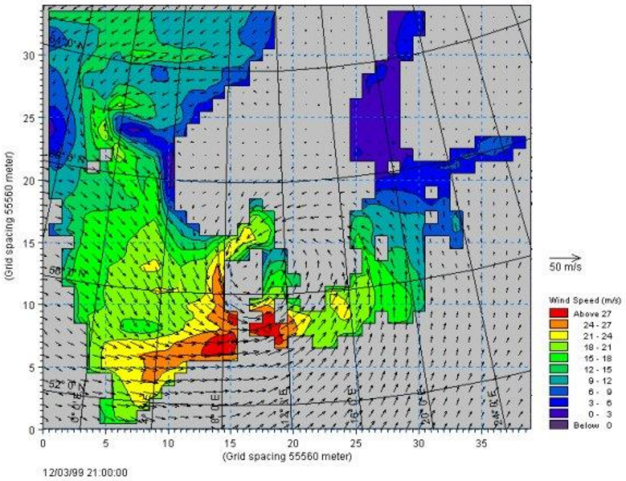


3D visualization of a computational mesh

If wind data is not available from an atmospheric meteorological model, the wind fields (e.g. cyclones) can be determined by using the wind-generating programs available in MIKE 21 Toolbox.

Global winds (pressure & wind data) can be downloaded for immediate use in your simulation. The sources of data are from GFS courtesy of NCEP, NOAA. By specifying the location, orientation and grid dimensions, the data is returned to you in the correct format as a spatial varying grid series or a time series. The link is:

http://www.waterforecast.com/hindcastdataproducts



The chart shows a hindcast wind field over the North Sea and Baltic Sea as wind speed and wind direction

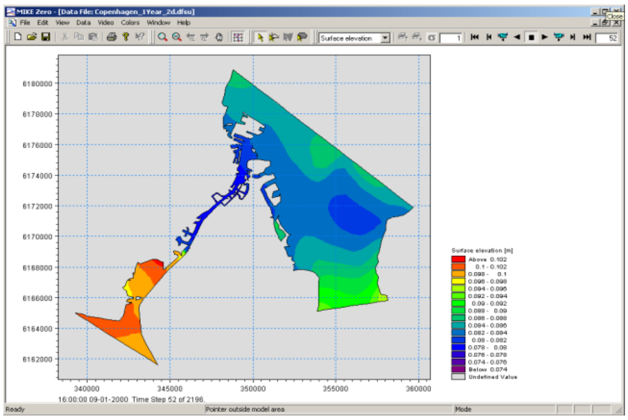
Model Output

Computed output results at each mesh element and for each time step consist of:

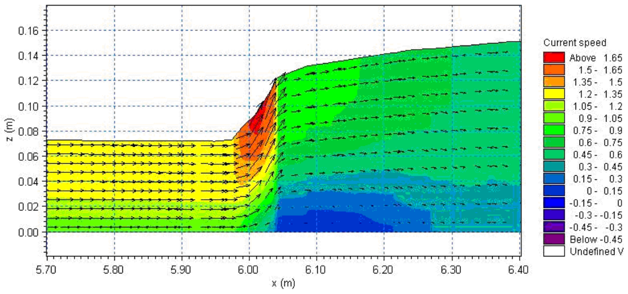
- Basic variables
  - water depths and surface elevations
  - flux densities in main directions
  - velocities in main directions
  - densities, temperatures and salinities
- Additional variables
  - Current speed and direction
  - Wind velocity
  - Air pressure
  - Drag coefficient
  - Precipitation/evaporation
  - Courant/CFL number
  - Eddy viscosity
  - Element area/volume

The output results can be saved in defined points, lines and areas. In the case of 3D calculations, the results are saved in a selection of layers.

Output from MIKE 21 & MIKE 3 Flow Model FM is typically post-processed using the Data Viewer available in the common MIKE Zero shell. The Data Viewer is a tool for analysis and visualization of unstructured data, e.g. to view meshes, spectra, bathymetries, results files of different format with graphical extraction of time series and line series from plan view and import of graphical overlays.



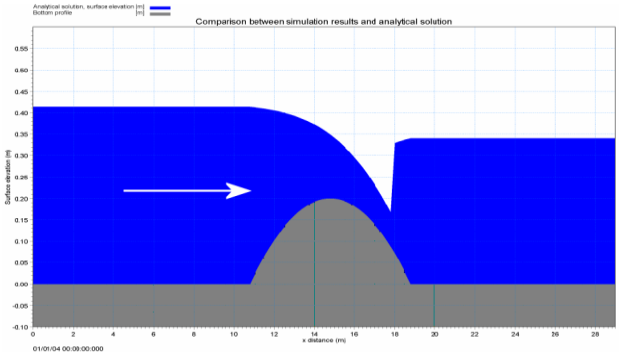
The Data Viewer in MIKE Zero – an efficient tool for analysis and visualization of unstructured data including processing of animations. Above screen dump shows surface elevations from a model setup covering Port of Copenhagen



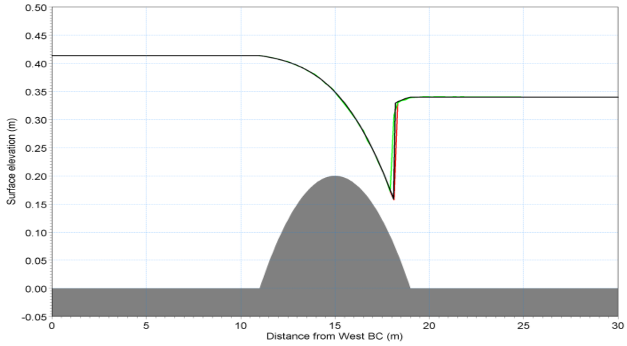
Vector and contour plot of current speed at a vertical profile defined along a line in Data Viewer in MIKE Zero

Validation

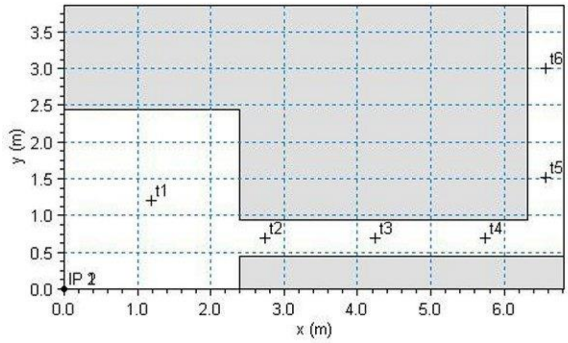
Prior to the first release of MIKE 21 & MIKE 3 Flow Model FM in year 19xx the model has successfully been applied to a number of basic idealized situations for which the results can be compared with analytical solutions or information from the literature.



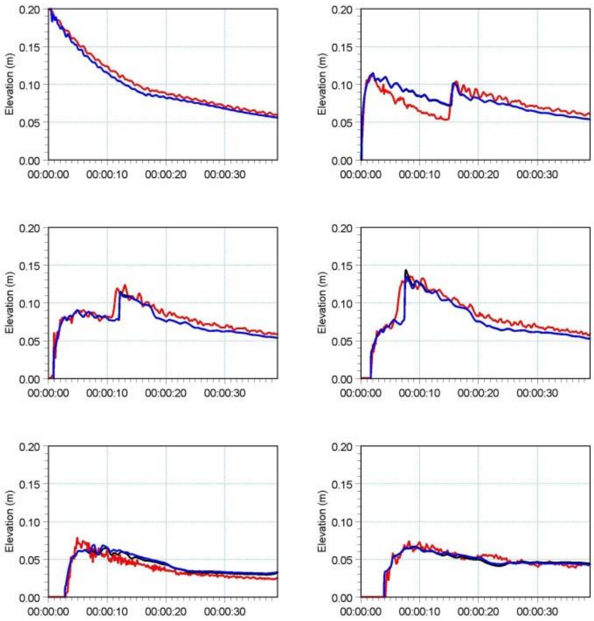
The domain is a channel with a parabola-shaped bump in the middle. The upstream (western) boundary is a constant flux and the downstream (eastern) boundary is a constant elevation. Below: the total depths for the stationary hydraulic jump at convergence. Red line: 2D setup, green line: 3D setup, black line: analytical solution



A dam-break flow in an L-shaped channel (a, b, c):

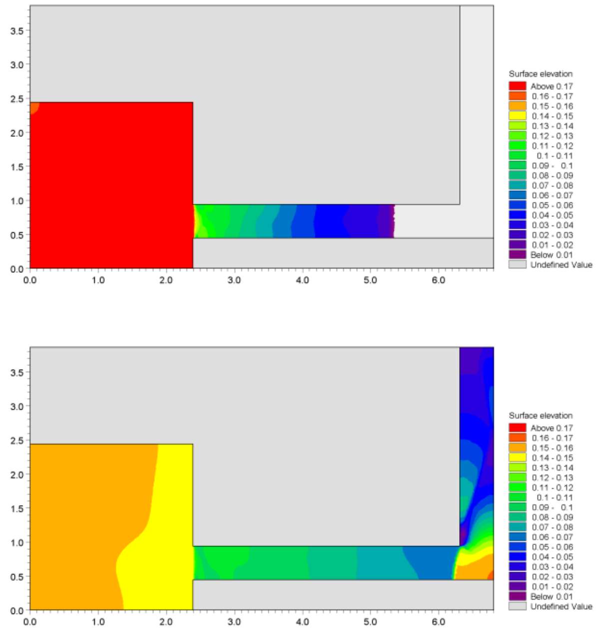


a) Outline of model setup showing the location of gauging points



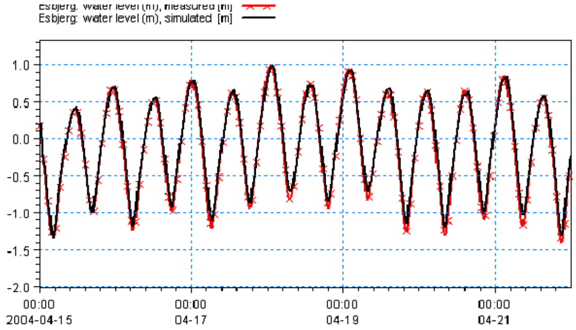
b) Comparison between simulated and measured water levels at the six gauge locations. (Blue) coarse mesh solution (black) fine mesh solution and (red) measurements

The model has also been applied and tested in numerous natural geophysical conditions; ocean scale, inner shelves, estuaries, lakes and overland, which are more realistic and complicated than academic and laboratory tests.

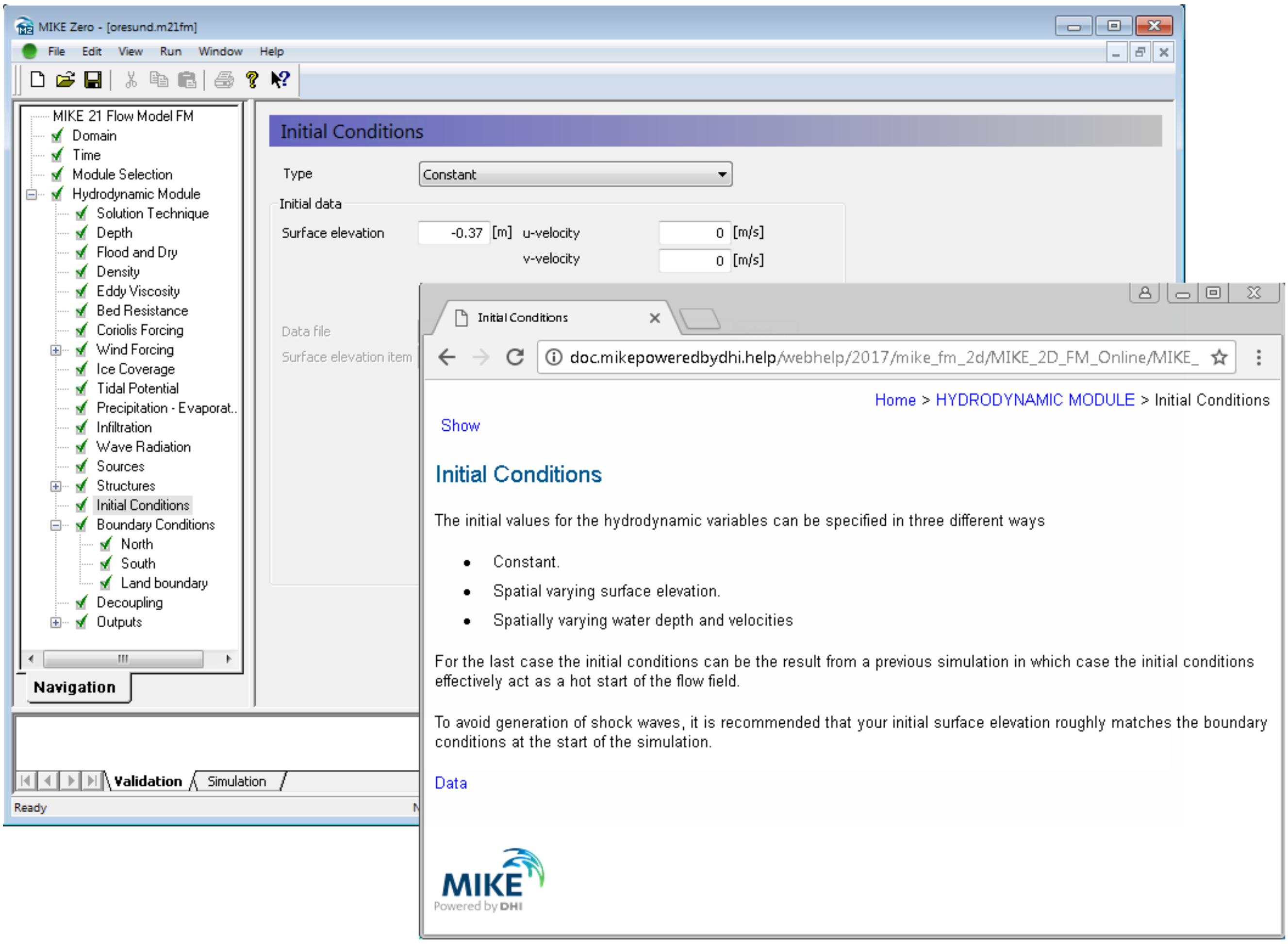


c) Contour plots of the surface elevation at T = 1.6 s (top) and T = 4.8 s (bottom)

Example from Ho Bay, a tidal estuary (barrier island coast) in South-West Denmark with access channel to the Port of Esbjerg.



Comparison between measured and simulated water levels



Initial Conditions

Type: Constant

Initial data

Surface elevation: -0.37 [m] u-velocity: 0 [m/s]

v-velocity: 0 [m/s]

Data file

Surface elevation item

Initial Conditions

The initial values for the hydrodynamic variables can be specified in three different ways

- Constant.
- Spatial varying surface elevation.
- Spatially varying water depth and velocities

For the last case the initial conditions can be the result from a previous simulation in which case the initial conditions effectively act as a hot start of the flow field.

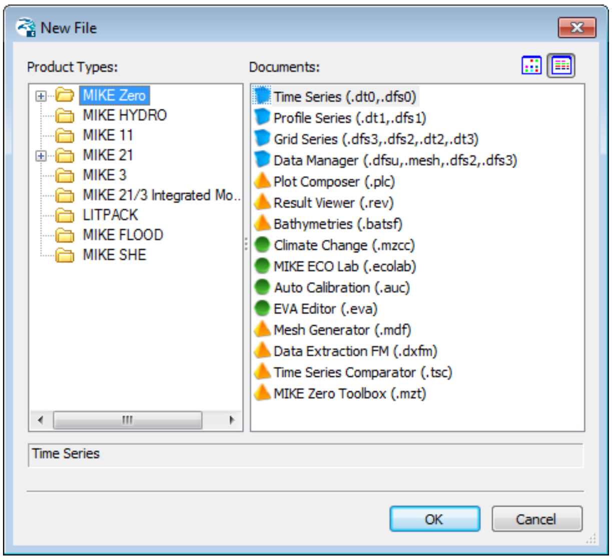
To avoid generation of shock waves, it is recommended that your initial surface elevation roughly matches the boundary conditions at the start of the simulation.

The user interface of the MIKE 21 and MIKE 3 Flow Model FM (Hydrodynamic Module), including an example of the extensive Online Help system

Graphical User Interface

The MIKE 21 & MIKE 3 Flow Model FM Hydrodynamic Module is operated through a fully Windows integrated graphical user interface (GUI). Support is provided at each stage by an Online Help system.

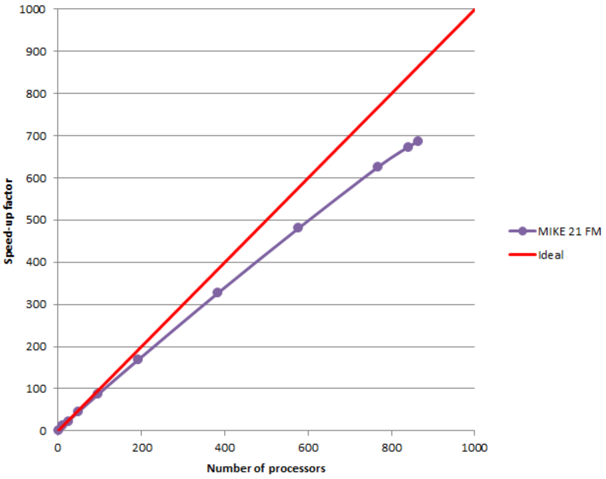
The common MIKE Zero shell provides entries for common data file editors, plotting facilities and utilities such as the Mesh Generator and Data Viewer.



Overview of the common MIKE Zero utilities

Parallelisation

The computational engines of the MIKE 21 & MIKE 3 FM series are available in versions that have been parallelised using both shared memory as well as distributed memory architecture. The latter approach allows for domain decomposition. The result is much faster simulations on systems with multiple cores. It is also possible to use a graphics card (GPU) to perform computational intensive hydrodynamic computations.



Example of MIKE 21 HD FM speed-up using a HPC Cluster with distributed memory architecture (purple)

Hardware and Operating System Requirements

The MIKE Zero Modules support Microsoft Windows 7 Professional Service Pack 1 (64 bit), Windows 10 Pro (64 bit), Windows Server 2012 R2 Standard (64 bit) and Windows Server 2016 Standard (64 bit).

Microsoft Internet Explorer 9.0 (or higher) is required for network license management. An internet browser is also required for accessing the web-based documentation and online help.

The recommended minimum hardware requirements for executing the MIKE Zero modules are:

Processor:	3 GHz PC (or higher)
Memory (RAM):	2 GB (or higher)
Hard disk:	40 GB (or higher)
Monitor:	SVGA, resolution 1024x768
Graphics card: (GUI and visualisation)	64 MB RAM (256 MB RAM or higher is recommended)
Graphics card: (for GPU computation)	1 GB RAM (or higher). requires a NVIDIA graphics card with compute capability 2.0 or higher

Support

News about new features, applications, papers, updates, patches, etc. are available here:

www.mikepoweredbydhi.com/Download/DocumentsAndTools.aspx

For further information on MIKE 21 and MIKE 3 Flow Model FM software, please contact your local DHI office or the support centre:

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Further Reading

Petersen, N.H., Rasch, P. “Modelling of the Asian Tsunami off the Coast of Northern Sumatra”, presented at the 3rd Asia-Pacific DHI Software Conference in Kuala Lumpur, Malaysia, 21-22 February, 2005

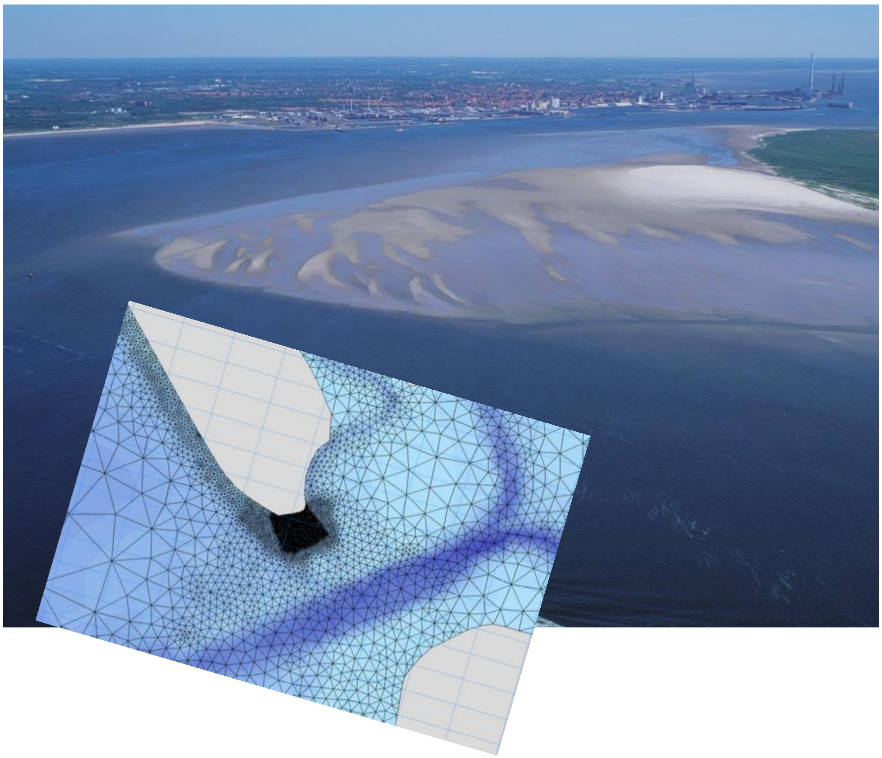
French, B. and Kerper, D. Salinity Control as a Mitigation Strategy for Habitat Improvement of Impacted Estuaries. 7th Annual EPA Wetlands Workshop, NJ, USA 2004.

DHI Note, “Flood Plain Modelling using unstructured Finite Volume Technique” January 2004 – download from

http://www.theacademybydhi.com/research-and-publications/scientific-publications

Documentation

The MIKE 21 & MIKE 3 Flow Model FM models are provided with comprehensive user guides, online help, scientific documentation, application examples and step-by-step training examples.



MIKE 21 & MIKE 3 Flow Model FM

Sand Transport Module

Short Description

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MIKE213_ST_FM_ShortDescription.docx / IAJS/SKR / 2017-10-03

MIKE 21 & MIKE 3 Flow Model FM – Sand Transport Module

This document describes the Sand Transport Module (ST) under the comprehensive modelling system for two-dimensional and three dimensional flows, the Flow Model FM, developed by DHI.

The MIKE 21 & MIKE 3 Flow Model FM, Sand Transport Module (ST) is the module for the calculation of sediment transport capacity and resulting bed level changes for non-cohesive sediment (sand) due to currents or combined waves-currents.

The ST Module calculates sand transport rates on a flexible mesh (unstructured grid) covering the area of interest on the basis of the hydrodynamic data obtained from a simulation with the Hydrodynamic Module (HD) and possibly wave data (provided by MIKE 21 SW) together with information about the characteristics of the bed material.

The MIKE 21 & MIKE 3 Flow Model FM, Sand Transport Module, is a numerical tool for the assessment of non-cohesive sand transport ratesand morphological evolution

The simulation is performed on the basis of the hydrodynamic conditions that correspond to a given bathymetry. It is possible to include feedback on the rates of bed level change to the bathymetry, such that a morphological evolution can be carried out.

To achieve a full morphological model in case of combined waves and currents, the wave and flow modules are applied in the coupled mode. This mode introduces full dynamic feedback of the bed level changes on the waves and flow calculations.

Application Areas

The Sand Transport Module can be applied to quantify sand transport capacity in all areas where waves and/or currents are causing non-cohesive sediment movements. The ST module can be used on all scales from regional areas (10 kilometres) to local areas around coastal structures, where resolutions down to metres are needed.

Tidal inlets represent a complex water area where the coastal sections are fully exposed to waves and where the conditions upstream of and in the inlet are dominated by pure currents and where helical motions can have a significant impact on the resulting transport pattern. The Sand Transport Module is developed to span the gap from the river to the coastal zone.

Example of application area: Tidal Inlet

The ST module covers accordingly many different application areas: The most typical ones are:

- Shoreline management
- Optimization of port layouts
- Shore protection works
- Stability of tidal inlets
- Sedimentation in dredged channels or port entrances
- Erosion over buried pipelines
- River morphology

For example, the morphological optimization of port layouts, taking into consideration sedimentation at port entrances, sand bypassing and downdrift impact; detailed coastal area investigation of the impact of shore protection structures on adjacent shoreline; sand loss from bays due to rip currents, etc.

Solution Methods

The MIKE 21 & MIKE 3 Flow Model FM, Sand Transport Module covers the range from pure currents to combined waves and currents including the effect of wave breaking.

The numerical implementation is different for the case of pure current and the combined wave-current case.

The sand transport calculations in a 3D model set-up are carried out using a mean horizontal velocity component. The sand transport calculations are thus not truly three-dimensional. However, the findings that a more detailed 3D hydrodynamic model can give of the hydrodynamic conditions near the bed are included either by the depth-integrated currents of the 3D flow field or by using the bottom stress value to calculate a corresponding mean horizontal velocity component.

Sand transport in combined waves and currents – the quasi-3D approach

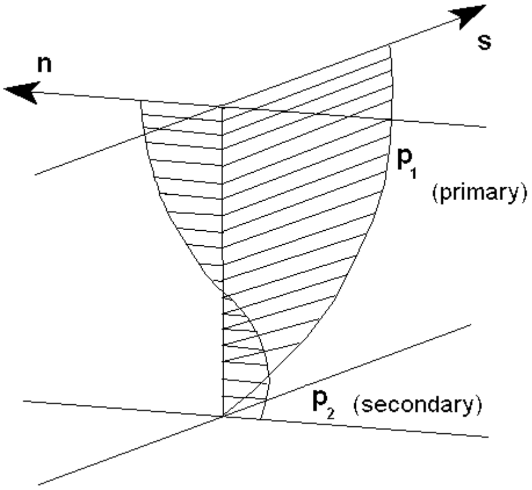
In case of combined waves and currents the sand transport rates are found by interpolation in a table created prior to the simulation. The generation of the transport rates in the table are based on the quasi-3D approach, where the local wave conditions, current profile and grain properties are considered. The effects of the following parameters on the local current profile and thereby on the sand transport can be included in the model:

1. the angle of propagation of waves relative to the flow direction
2. the loss of energy due to wave breaking
3. the gradation of the bed material
4. the formation of ripples on the sea bed
5. the slope of the sea bed
6. undertow
7. wave asymmetry
8. streaming

The inclusion of the effects of 4 – 9 is optional and offers flexibility for the user to design the most appropriate model set-up for the actual application.

The ‘quasi-3D’ refers to the details of the modelling approach: The vertical sediment diffusion equation is solved on an intrawave period grid to provide a detailed description of the non-cohesive sediment transport for breaking/non-breaking waves and current.

The input to the sand transport model is a mean horizontal velocity component, typically depth-integrated currents. However, as suspended sand transport takes place in the turbulent boundary layer, which is thin in case of waves and covers the whole depth in fully developed steady currents, a description of the vertical distribution of the flow is required. This is obtained by a local ‘point model’, which includes enough computational points over the water column to resolve the wave boundary layer and the distribution of suspended sediment. The secondary flow profile is also having a significant impact on the sand transport



Primary and secondary velocity profiles

The transport rates are then found by interpolation in the tables using the local depth, wave conditions, mean horizontal velocity component and properties of the bed material. The sand transport model is a ‘sub-grid model’, which resolves processes not captured by the hydrodynamic model(s).

Sand transport in pure currents

The sand transport description in pure currents is a state-of-the-art model capable of including lag-effects from the flow and the suspended load in the morphological development.

The lag-effects on the suspended load are determined from an advection-dispersion equation that includes effects from over-loading or under-loading of the concentration of the suspended sediment and the helical flow pattern. This approach is often referred to as a non-equilibrium sediment description, where erosion and deposition of the bed is controlled by under-loading and over-loading of the suspended sediment in the water column.

The inclusion of helical flow (in 2D) and the non-equilibrium sediment description is optional, i.e. the model can also be executed as a ‘point model’ where lag-effects are disregarded (equilibrium sediment description) or only used to adjust the direction of the bed load.

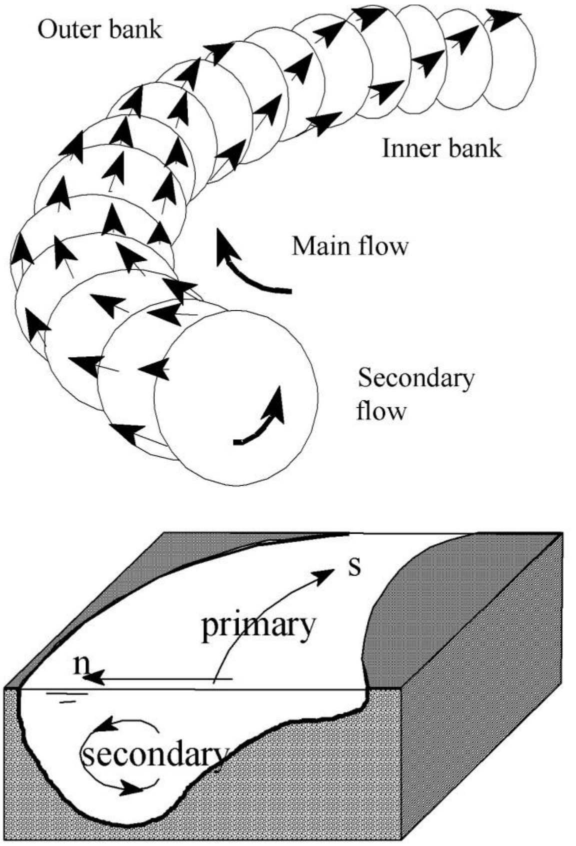


Illustration of helical flow

The bed load description includes gravitational effects forced from longitudinal and lateral bed slopes. Furthermore, it will adjust for the deviation of the bed shear stress from the mean flow, if helical flow is included in the model.

Four different sand transport formulas are available for determination of the equilibrium bed load capacity, while three formulas are available for the suspended load:

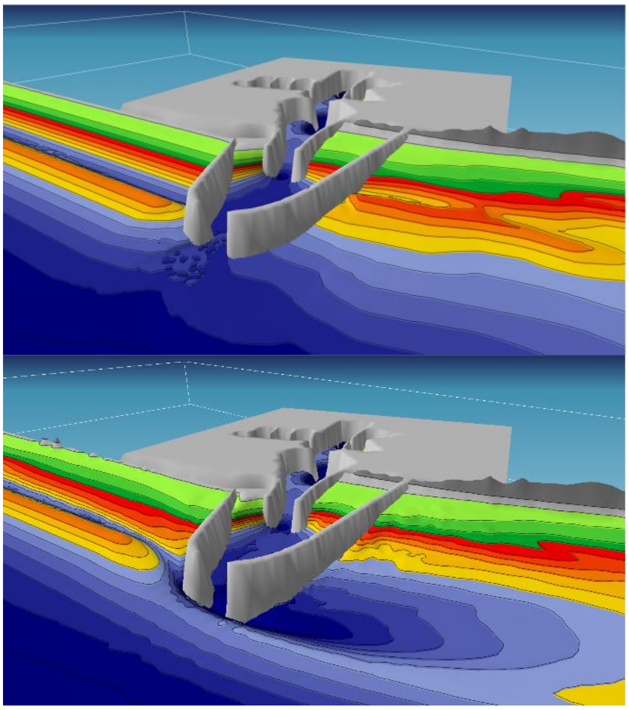
- the Engelund-Hansen total load transport theory
- the Engelund-Fredsøe total load (bed load plus suspended load) transport theory
- the Van Rijn total load (bed load plus suspended load) transport theory
- the Meyer-Peter and Müller bed load transport theory

The equilibrium sand transport capacities are calculated on the basis of local water depth, mean horizontal velocity component, Manning number/ Chezy number and properties of the bed material (median grain size and gradation), which may vary throughout the model area.

Morphology

Morphological evolution is imposed by increasing/decreasing the bed level of each mesh element in accordance with the sedimentation rate/ erosion rate. Changes to the bed affect directly the wave transformation and flow during model execution.

The morphological feedback to flow and waves introduces a completely new level of freedom in the model, which makes model setup and interpretation increasingly difficult but the added value of the results are highly valuable.



Example of morphological evolution (Grunnet et al., 2009) Bypass around Hvide Sande Port. Top: initial bathymetry. Bottom: Simulated bathymetry. Visualised in DHIs MIKE Animator Plus.

The morphological evolution can furthermore controlled by:

- Morphological speedup factor
- Bed porosity
- Sediment layer thickness

The morphological model is typically useful in areas where 2D morphological evolution is expected, e.g.:

- Response to greenfield port construction, and port expansion
- Bypass around detached breakwaters and groynes
- Shoreface nourishments
- Tidal estuaries and canals

Model Input Data

The necessary input data can be divided into the following groups:

- Domain
    - bathymetry data (incl. map projection)
    - simulation length
- Hydrodynamic data
    - water depth and flow fields (provided by the Flow Module)
- Wave data (if required)
    - wave height, period, direction (provided by the Spectral Wave Module or similar)
- Sediment properties
    - size and gradation of bed material
- Morphology parameters
    - update frequency
    - slope failure
    - sediment layer thickness

The main task in preparing the input data for the ST module is to generate a bathymetry and to assess the hydrodynamic and wave conditions.

In case of sand transport in combined wave and current a sand transport table, that contains a representative number of sand transport rates for interpolation during the simulation, is required as input. The sand transport tables can be generated using the MIKE 21 Toolbox program 'Generation of Q3D Sediment Tables'.

In case of wave influence, a DHI wave module (MIKE 21 PMS or MIKE 21 SW) can simulate the radiation stresses necessary for generating the wave-driven current.

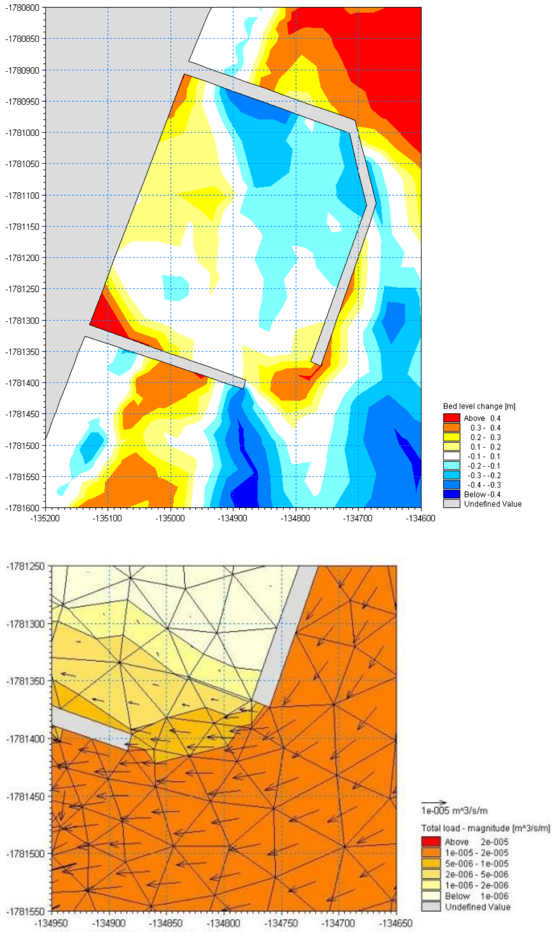
If the simulation is to be run in coupled mode, the MIKE 21 SW module is set up to generate the wave conditions by using the Coupled Model FM input editor.

Per default the hydrodynamic conditions are simulated together with the sand transport rates.

However, for the coupled model it is possible to run in de-coupled mode, providing the hydrodynamic conditions and wave conditions as external data files.

Model Output Data

Two types of output data can be obtained from the model; sediment transport rates and resulting morphological changes.



Simulated morphological change by a harbour and detail of sand transport rates at the harbour entrance

The format of the data may be as points, lines or areas and in any subset required. In the Outputs dialog, output variables are selected between lists of basic and additional output variables. The basic output variables are for example; SSC, bed load-, suspended load- and total load in x- and y-direction including rate of bed level change, bed level change and bed level. The additional output variables are for example transport variables given as magnitude and direction as well as accumulated values, including input hydrodynamic and wave variables.

Examples of Applications and Results

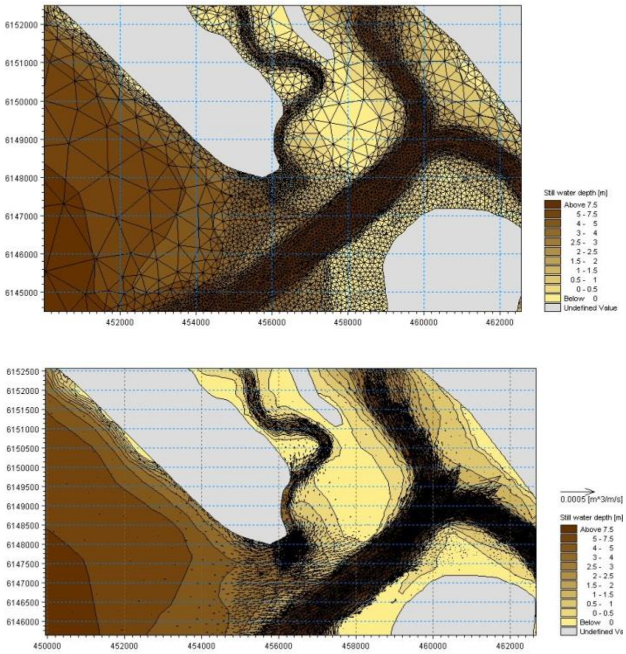
Location map for the examples: Grådyb and Torsminde

Grådyb

Grådyb is a tidal estuary facing the North Sea coast. A major port facility is located inside the estuary. An access channel with a depth of 12 m is maintained by dredging. About 1 million m^3 of sediment are dredged every year and bypassed to not destabilise the down drift coast.

Aerial view of Grådyb estuary. Copyright Port of Esbjerg

The following figures show a flexible grid bathymetry and a ‘snap shot’ of simulated sand transport in a subset of the model area.



Sub set of the flexible model grid and simulated sand transport

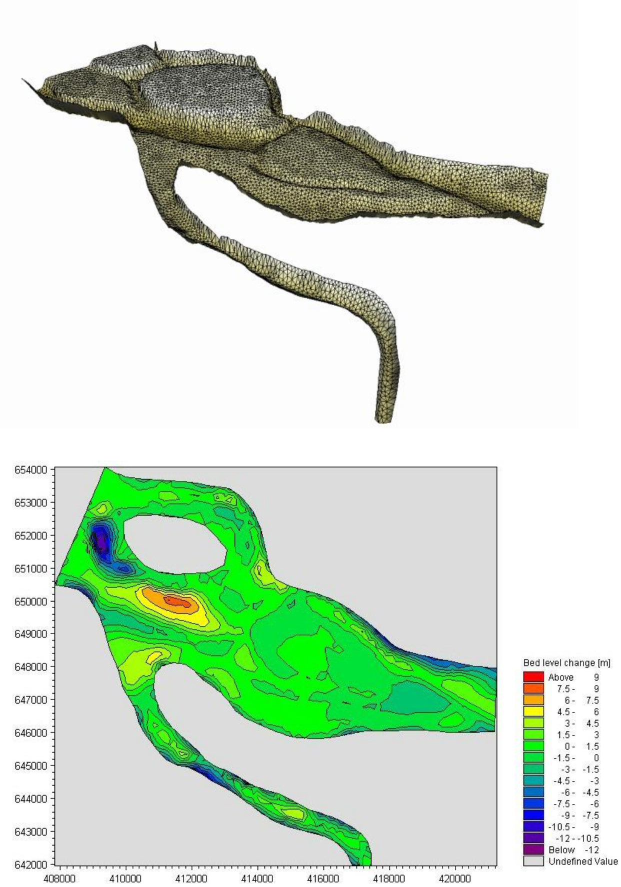
The plots illustrate the flexibility of the model set-up where the critical areas are covered with a very dense grid and the tidal flats are resolved by a somewhat coarser grid.

Gorai River

The Gorai River is a spill channel to the Ganges River. The morphological behaviour at the offtake is of great interest, because the Gorai River is an important source of fresh water supply in the region.

Aerial view of Gorai River

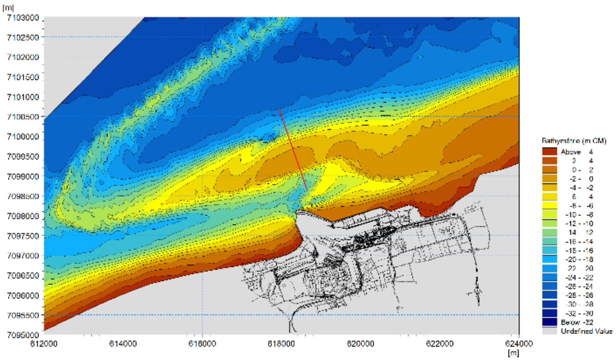
The non-equilibrium concept including helical flow was applied to estimate the morphological changes of the system after the time period of a monsoon.



Mesh bathymetry in 3D and Model predicted bed level changes induced by the passage of the 1999 monsoon

Calais harbour expansion

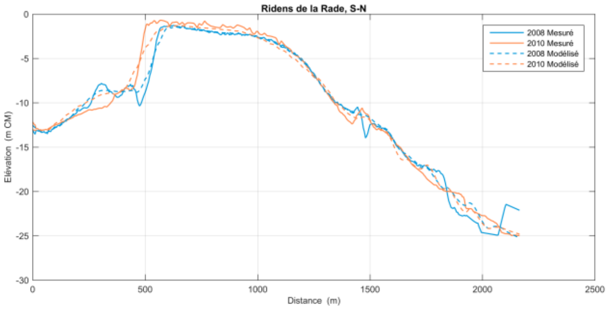
As part of a new major expansion of Calais harbour a model study of the development of the tidal banks in the vicinity of Calais harbour was undertaken in 2015-2017. The study involved calibration of the measured evolution of the tidal banks and a prediction of the bank evolution in response to the future expansion.



Model domain for the morphological model at Calais harbour. The red line indicates the position of a cross-section shown below.

The geographical location of Calais harbour makes the wave and current conditions particularly dynamic. The large tidal range (up to 7m) generates strong tidal currents and modulates the nearshore waves over a tidal cycle.

The morphological modelling covered 20 years of evolution. A model strategy, which included a morphological tide combined with a schematisation of sea-states, was required to complete the detailed 2D modelling within a reasonable period.



Calibration: Comparison of modelled and measured southward movement of the bank: Ridens de la Rade from 2008-2010.

The morphological model results aided in the understanding of the hydrodynamic conditions of the area, which were necessary for design of the new harbour breakwaters. Further, a study of the incremental construction of the breakwaters was done to analyse pre-dredging strategies and back-filling rates.

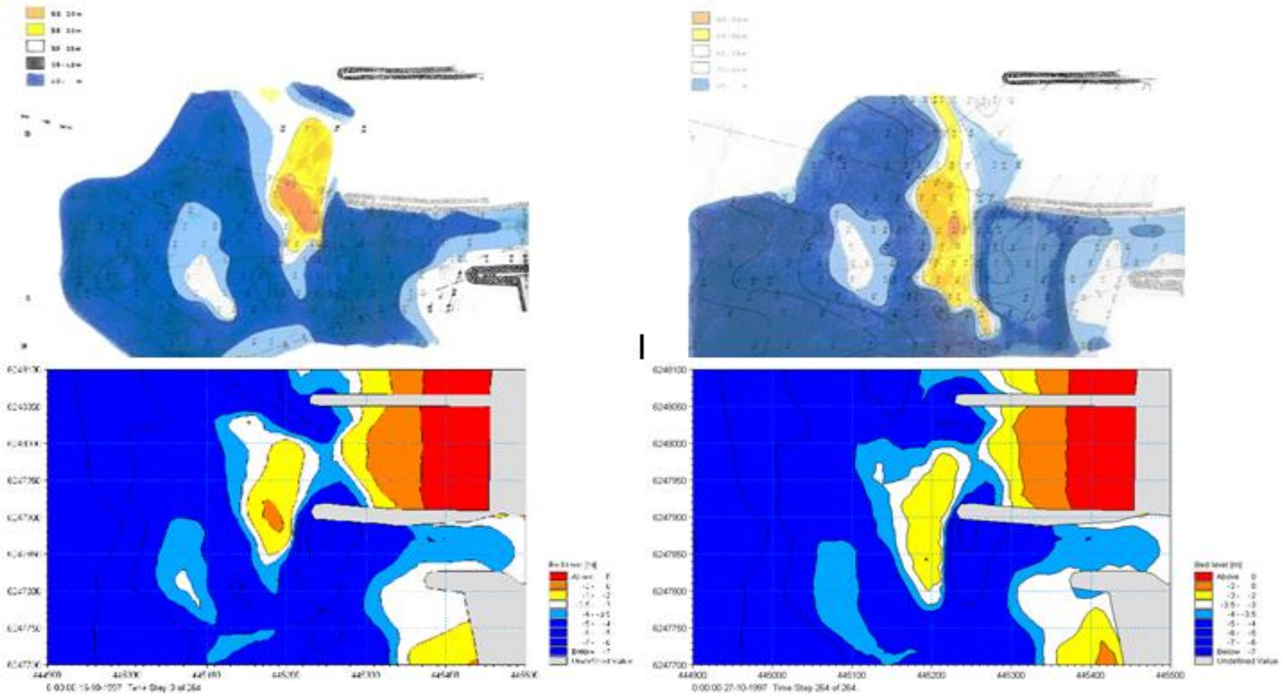
Torsminde Harbour

Torsminde fishery harbour is located at a tidal inlet on the west coast of Jutland, Denmark, on one of the narrow tidal barriers, which divide coastal lagoons from the sea. The port is located at the entrance to the coastal lagoon Nissum Fjord. Sluices regulate the water exchange between the lagoon and the sea. Torsminde harbour is located in the central part of a very exposed stretch, where the net littoral drift is southward with an order of magnitude of 0.4 million m^3/year, but where the gross transport is several times larger.

As a result, severe sedimentation and shoaling problems affected the harbour entrance and a need for alternative layout of the harbour made it necessary to make preliminary investigations of the sand transport pattern in the area.

Running the MIKE 21 Flow Model FM in coupled mode with the SW Module and ST module, the morphological changes during a specified period can be estimated.

The following figures show a comparison of the measured and simulated bathymetry in front of the harbour entrance, before and after a 10-day period in October 1997.

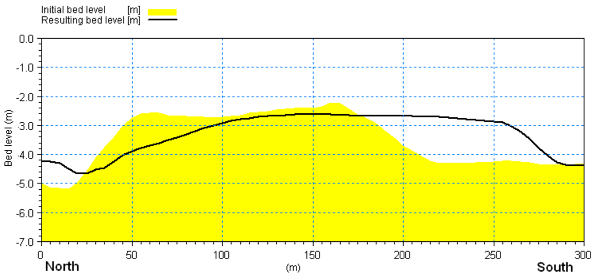


Comparison of measured and simulated bathymetries in front of the harbour entrance. Upper: measured. Lower: calculated. Left: before storm. Right: after storm

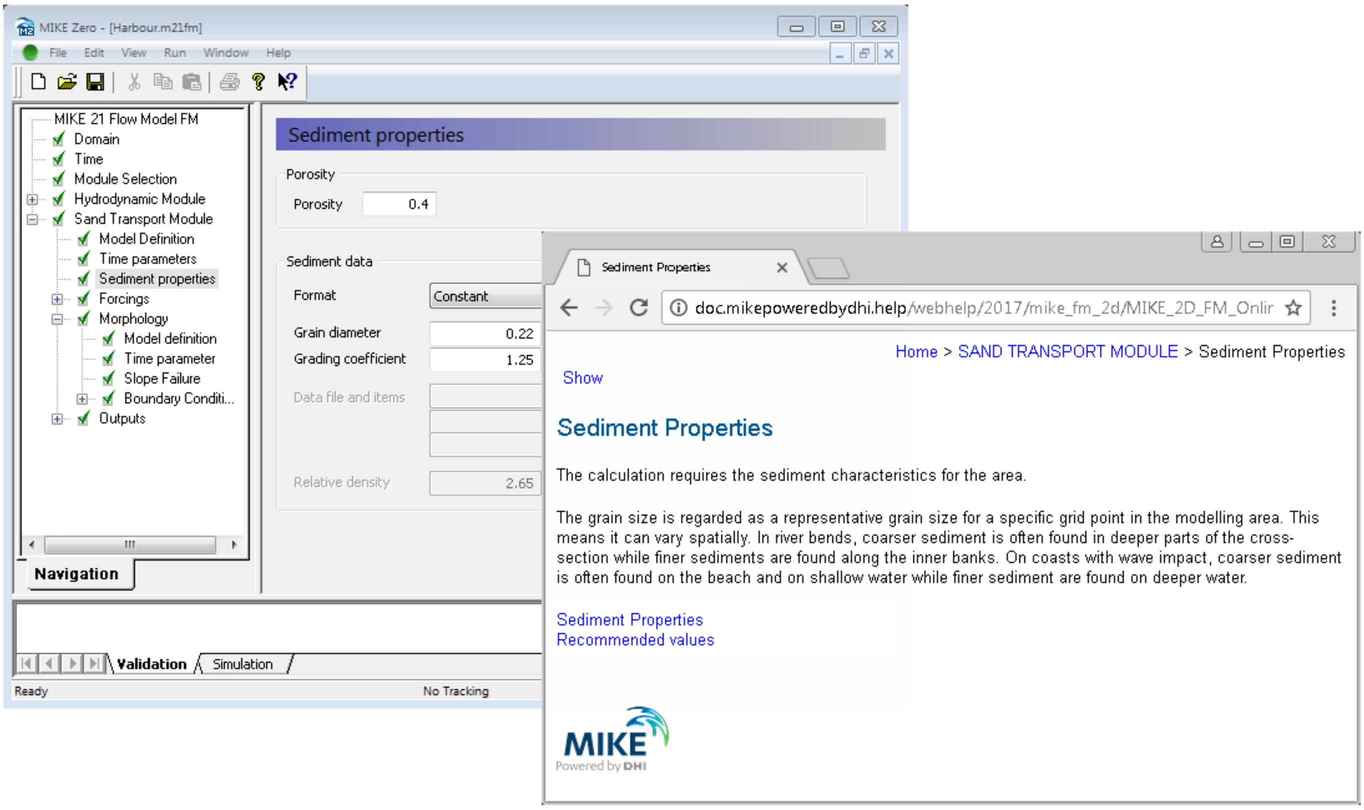
The pre-dominant wave direction during the simulation period was from the North-West. This caused the bar in front of the harbour entrance to migrate further south, thus blocking the harbour entrance.

To view the bar migration in detail the simulated bed levels are extracted along a north-south line extending from the northern jetty to past the harbour entrance.

The results are shown in the figure below.



Bed level across the harbour entrance: before and after simulation



Sediment properties

Porosity

Porosity 0.4

Sediment data

Format Constant

Grain diameter 0.22

Grading coefficient 1.25

Data file and items

Relative density 2.65

Sediment Properties

The calculation requires the sediment characteristics for the area.

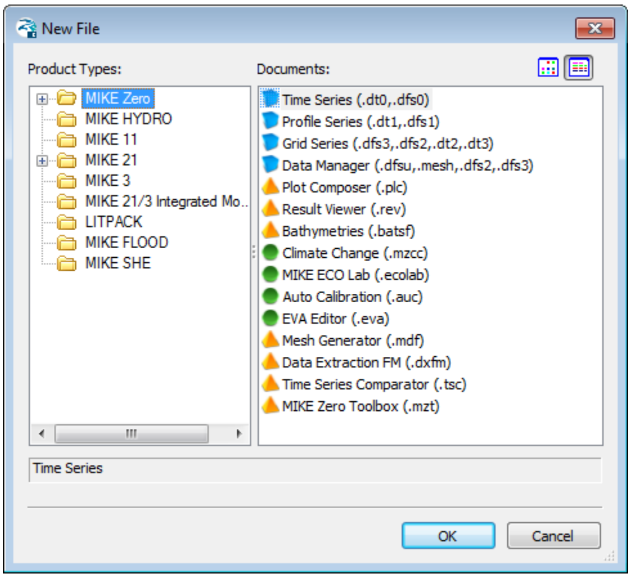
The grain size is regarded as a representative grain size for a specific grid point in the modelling area. This means it can vary spatially. In river bends, coarser sediment is often found in deeper parts of the cross-section while finer sediments are found along the inner banks. On coasts with wave impact, coarser sediment is often found on the beach and on shallow water while finer sediment are found on deeper water.

Graphical user interface of the MIKE 21 Flow Model FM, Sand Transport Module, including an example of the Online Help System

Graphical User Interface

The MIKE 21 & MIKE 3 Flow Model FM, Sand Transport Module is operated through a fully Windows integrated Graphical User Interface (GUI). Support is provided at each stage by an Online Help System.

The common MIKE Zero shell provides entries for common data file editors, plotting facilities and a toolbox for/utilities as the Mesh Generator and Data Viewer.



Overview of the common MIKE Zero utilities

Parallelisation

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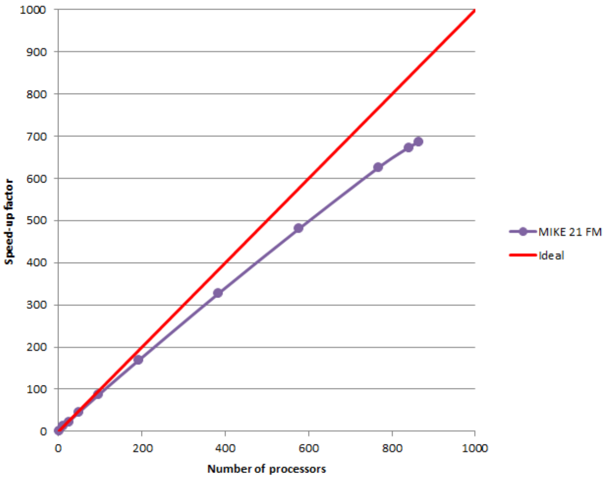

Example of MIKE 21 HD FM speed-up using a HPC Cluster with distributed memory architecture (purple)

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Graphics card: (GUI and visualisation)	64 MB RAM (256 MB RAM or higher is recommended)

Further reading

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Niemann et al. (2006): Morphological modelling of a Danish tidal inlet. Proceedings of ICCE 2006.

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