ESIA Italy
Annex 10 Sediment Dispersion
TAP (Trans Adriatic Pipeline): sediment dispersion study at the Italian landfall site
This project was prepared under the DHI Business Management System audited by DNV to be in compliance with ISO 9001: Quality Management System and with certification in progress.

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TAP (Trans Adriatic Pipeline): sediment dispersion study at the Italian landfall site

Prepared for ERM Italia S.p.A.
Represented by Simone Poli

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<th>Paola Letizia</th>
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APPENDIX E
Description of MIKE 3 MT FM model
1 Introduction

The scope of the work is to study, by means of numerical modelling, the sediment release and dispersion during the construction phase of the Trans Adriatic Pipeline (TAP). The present study is part of the Environmental and Social Impact Assessment (ESIA) for the offshore part of the Italian landfall of the TAP.

The pipeline is planned to go from Albania to Italy, covering a distance of more than 100 km. Figure 1-1 illustrates the pipeline route.

![Figure 1-1 Illustration of the pipeline route. Source: Google Earth](image)

In Chapter 2 the analysis of the offshore meteoric data is illustrated. In particular, the available data of wind, waves, tide, currents from the general circulation of the Adriatic Sea (the so called “baroclinic currents”), temperature and salinity are described. The analysis and processing of these raw data have led to the identification of representative meteoric conditions for the Italian landfall site.

Based on these analyses, two representative scenarios have been selected (Chapter 3). The assumptions and the results of the hydrodynamic and sediment dispersion models are illustrated in Chapters 4 and 5.
2 Offshore meteomarine conditions

The scope of this chapter is to provide a description of the available data of the meteomarine conditions offshore the Italian landfall site of the TAP. In particular, the following chapters describe the wind and wave conditions, both yearly and seasonal, tidal variations and the circulation in the southern Adriatic Sea (baroclinic currents).

2.1 Wind climate offshore the Italian Coast

The database used to analyse the wind climate conditions offshore the Italian coast comes from the Italian National Tide Gauge Network (RMN – Rete Mareografica Nazionale [1]). This Network provides measurements in terms of water level time series and wind time series, too (speed and direction). In particular the reference station used in the present study is located at Otranto, 20 Km South of the focused area, as shown in Figure 2-1.

Wind data for the specified station are available for the time interval 01/01/2009 - 10/11/2011. The available wind data are illustrated in a scatter table of wind speed vs. wind direction (Table 2-1) and in a yearly wind rose (Figure 2-2). The data are also represented also in seasonal wind roses (Figure 2-3).

The analysis of the wind data, as wind speed and directions, clearly shows that the most frequent winds come from north-west while the strongest winds (maximum wind speed higher than 15 m/s) come from the sector around north (320°N to 60°N).
Table 2-1  Yearly wind climate – scatter table of wind speed vs. wind direction. Source: wind data come from the Italian National Tide Gauge Network (RMN – Rete Mareografica Nazionale (www.mareografico.it) station: Otranto, period: 01/01/2009-10/11/2011 [1]

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Figure 2-2  Yearly wind rose. Source: the rose is processed by DHI on the basis of wind data coming from the Italian National Tide Gauge Network (RMN – Rete Mareografica Nazionale, www.mareografico.it [1]), station: Otranto, period: 01/01/2009-10/11/2011 [1]
The seasonal wind roses confirm for spring and summer the same behavior obtained from the yearly analysis. During winter, it can be noted a higher frequency of the winds coming from Quarter II and Quarter III, especially from the direction west – south west and south east. In autumn, winds from south east become prevalent, even if the strongest winds again come from directions around north.

Figure 2-3  Seasonal wind roses. Source: the roses are processed by DHI on the basis of wind data coming from the Italian National Tide Gauge Network (RMN – Rete Mareografica Nazionale, www.mareografico.it [1]), station: Otranto, period: 01/01/2009-10/11/2011 [1]

For the numerical modelling of representative meteomarine conditions (Chapter 4), the wind data are therefore taken from another database. In particular, the wind model realised by DHI for the Integrated Project Water and Global Change (WATCH, 2007-2011 [2]) has been used. This project, funded under the EU FP6, brings together the hydrological, water resources and climate communities, to analyse, quantify and predict the components of the current and future global water cycles and related water resources states, evaluates their uncertainties and clarifies the overall vulnerability of global water resources related to the main societal and economic sectors.

Within the framework of the Integrated Project Water and Global Change (WATCH, 2007-2011 [2]), also the setup of a global wind model was previewed; in particular for this model the simulation was executed with the newest version of the HIRHAM regional climate model using the ERA Interim as driving field covering the period from January 2000 to July 2009. This simulation was also executed in a restart every day mode in order to stay very close to the driving field.

The domain has an extension of 302 x 202 grid cells and covers the whole Europe (Figure 2-4). The velocity components U and V are computed in the HIRHAM model according to the grid
projection. An additional post processing was done on the wind vectors to fit them to the meridional (V component) and zonal (U component) coordinate system of the Earth. Wind speed is referred to a quote of 10 m and represents a mean value over an hour.

![Image of wind model](Image)

Figure 2-4 Image of one time step of the wind model. Source: Integrated Project Water and Global Change (WATCH, 2007-2011 [2])

### 2.2 Wave climate offshore the Italian landfall site

The database used to analyze the wave climate conditions at the Italian landfall site is the Italian National Wave Metric Network (RON – Rete Ondametrica Nazionale) [1]. This database provides, for a number of wave buoys, wave parameters in terms of wave heights, periods and directions. In particular, the reference buoy in the present study is located 7 Km offshore of Monopoli, approximately 115 Km north-west of the focused area as shown in Figure 2-5. Wave data are available for the time interval 01/07/1989 – 05/04/2008.

Wave data have been transferred to a “virtual buoy” nearby the focused area, according to the “fetches transposition method” (De Girolamo, Contini 1998). Due to the local orientation of the coastline, which shelters a number of wave directions, the wave transposition has been carried out only for waves coming from north-west to south-east, for the sector 140°N-320°N.
The transposed wave data are illustrated as wave rose (Figure 2-6) and as scatter table of wave height vs. wave direction (Table 2-1). The analysis of the wave data, in terms of significant wave height and wave directions, shows that the highest waves come from north–north east (maximum wave heights ranging from 5.0 and 5.5m). The overall frequency of waves coming from the first Quarter (directions from 0°N to 90°N) is similar to the overall frequency of waves coming from the fourth Quarter (directions from 270°N to 360°N) and slightly higher than the overall frequency of waves coming from the second Quarter (directions from 90°N to 180°N).
Table 2-2  Yearly wave climate – scatter table in terms of wave height vs. wave. Source: wave data come from the Italian National Wavemeter Network (RON – Rete Ondametrica Nazionale [1], www.mareografico.it), station: Monopoli, period: 01/06/1989-05/04/2008. The original data from the buoy have been processed by DHI according to the “fetches transposition method” (De Girolamo, Contini, 1998)

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Figure 2-6  Yearly wave rose. Source: the rose is processed by DHI on the basis of wave data coming from the Italian National Wavemeter Network (RON – Rete Ondametrica Nazionale [1], www.mareografico.it), station: Monopoli, period: 01/06/1989-05/04/2008. The original data from the buoy have been processed by DHI according to the “fetches transposition method” (De Girolamo, Contini, 1998)
In order to define the statistical correlation between significant wave heights \( (H_s) \) and peak wave periods \( (T_p) \), the following relationship (Mathiesen et al., 1994) suggested in the Italian Wave Atlas\(^1\) has been used:

\[
T_p = a (H_s)^b
\]

where the \( a \) and \( b \) parameters have been obtained by the statistical correlation of buoy data.

The data used in this analysis and the relationship obtained are illustrated in Figure 2-7.

2.3 Tidal conditions

Tide analysis has been carried out by means of the tool MIKE CMAP, developed by DHI [5]. This tool provides, together with nautical charts data, water level time series (astronomical tide variations) for a huge number of tidal stations worldwide. Both information are based on Admiralty Charts and Admiralty Tide Tables.

The tidal station used as reference for the present study is Otranto, 20 Km south of the Italian landfall site.

Figure 2-8 illustrates the astronomical tide cycle, in relation to a period which can be considered representative of the local average tidal conditions. As shown in the figure, the tide is semi-diurnal (two highs and two lows each day). During Spring Tide conditions the tide amplitude is in

the order of 0.25 m, while during Neap Tide conditions the tide amplitude does not exceed 0.10 m.

Figure 2-8  Astronomical tide cycle for the Otranto CMAP station. Source: The time series is extracted from the database available in the tool MIKE C-MAP, part of DHI software package [5], station: Otranto, period: 01/12/2010-31/12/2010

2.4  Currents from the general circulation of the Adriatic Sea, temperature and salinity

The analysis of currents from the general circulation of the Adriatic Sea (baroclinic currents), together with the analysis of temperature and salinity, has been carried out by processing data coming from the Mediterranean Forecasting System (MFS) database which is available within the framework of MyOcean EU Project [3].

MFS is a 3D global circulation model that provides daily analyses and 10-day forecasts of currents, temperature and salinity fields for the entire Mediterranean Sea at approximately 6.5 km resolution. MFS model is widely considered the state of the art of the models aiming at simulating the Mediterranean circulation.

Figure 2-9 illustrates the domain of the MFS Mediterranean circulation model through an example of surface temperature distribution over the whole basin, while Figure 2-10 shows an example of the current fields in the Adriatic Sea.
Figure 2-9  MFS Mediterranean model domain and example of temperature distribution in the whole basin. Source: the image is extracted from the GNOO (Gruppo Nazionale di Oceanografia Operativa) website, http://gnoo.bo.ingv.it/mfs/web_ita/contents.htm [3]

Figure 2-10  Example of MFS current fields for the Adriatic Sea. Source: the image is extracted from the GNOO (Gruppo Nazionale di Oceanografia Operativa) website, http://gnoo.bo.ingv.it/mfs/web_ita/contents.htm [3]
MFS data are available under MyOcean project [3] since 01/01/2006 (to date) and have been extracted for the model point of coordinates LON 18.500°, LAT 40.375°, located about 10 km offshore the Italian landfall site.

The localization of the MSF point is illustrated in Figure 2-11.

The sea temperature and salinity data, at surface, 10 m, 20 m and 30 m depth, have been processed and illustrated as yearly time series, for every year from 2006 to 2011, in Appendix A for temperature and Appendix B for salinity.

The current fields (as current speed and current mean direction), at surface, 10 m, 20 m and 30 m depth, have been processed and illustrated as monthly time series, for every year from 2006 to 2011, in Appendix C.

![Figure 2-11 Location of the Italian MFS point. Source: Google Earth](#)

**2.4.1 Currents, temperature and salinity offshore the Italian landfall site**

In the below plots the current fields, at surface, 10 m, 20 m and 30 m depth, as yearly current rose (from Figure 2-12 to Figure 2-15) and seasonal current roses (Figure 2-16 to Figure 2-19) are illustrated.

From the analysis of the surface current rose, it clearly appears that the strongest and most frequent currents come from north-west (maximum current speed around 0.5 m/s) flowing approximately along the Puglia coast.

The analysis of the current rose at 10 m depth shows that the strongest and most frequent currents come from north-west, similarly to what happens at surface, but there is a higher frequency of currents coming from south-east. In general, the currents at 10 m depth are weaker than at surface.

The yearly current rose at 20 m depth shows a trend which is very similar to the one obtained at 10 m depth, while at 30m it can be noticed a significant increase in the occurrence of southeasterly currents, which become prevalent if compared to the currents coming from north-west. From the analysis of these roses, it can be concluded that a significant stratification of currents is not clearly visible along the upper part of the water column at the Italian landfall site.
Figure 2-12  Surface yearly current rose generated using MyOcean Products [3]. Source: the rose is processed by DHI on the basis of the oceanographic data downloaded from MyOcean website (http://www.myocean.org/) for the point of coordinates LON 18.500°, LAT 40.375° for the period 01/01/2006-01/11/2011

Figure 2-13  10m depth current rose generated using MyOcean Products [3]. Source: the rose is processed by DHI on the basis of the oceanographic data downloaded from MyOcean website (http://www.myocean.org/) for the point of coordinates LON 18.500°, LAT 40.375° for the period 01/01/2006-01/11/2011
Figure 2-14  20m depth current rose generated using MyOcean Products [3]. Source: the rose is processed by DHI on the basis of the oceanographic data downloaded from MyOcean website (http://www.myocean.org/) for the point of coordinates LON 18.500°, LAT 40.375° for the period 01/01/2006-01/11/2011

Figure 2-15  30m depth current rose generated using MyOcean Products. Source: the rose is processed by DHI on the basis of the oceanographic data downloaded from MyOcean website (http://www.myocean.org/) for the point of coordinates LON 18.500°, LAT 40.375° for the period 01/01/2006-01/11/2011
The seasonal analysis (at surface, 10 m, 20 m and 30 m depth) confirms the yearly trend, that means that the prevalent sector is for north-west directions, except for deeper water (30 m) where a significant increase in the occurrence of southeasterly currents, which become prevalent, can be observed.

Figure 2-16  Surface seasonal current roses generated using MyOcean Products [3]. Source: the roses are processed by DHI on the basis of the oceanographic data downloaded from MyOcean website (http://www.myocean.org/) for the point of coordinates LON 18.500°, LAT 40.375° for the period 01/01/2006-01/11/2011
Figure 2-17  10 m depth seasonal current roses generated using MyOcean Products [3]. Source: the roses are processed by DHI on the basis of the oceanographic data downloaded from MyOcean website (http://www.myocean.org/) for the point of coordinates LON 18.500°, LAT 40.375° for the period 01/01/2006-01/11/2011

Figure 2-18  20 m depth seasonal current roses generated using MyOcean Products [3]. Source: the roses are processed by DHI on the basis of the oceanographic data downloaded from MyOcean website (http://www.myocean.org/) for the point of coordinates LON 18.500°, LAT 40.375° for the period 01/01/2006-01/11/2011
Figure 2-19  30 m depth seasonal current roses generated using MyOcean Products [3]. Source: the roses are processed by DHI on the basis of the oceanographic data downloaded from MyOcean website (http://www.myocean.org/) for the point of coordinates LON 18.500°, LAT 40.375° for the period 01/01/2006-01/11/2011.

Together with the currents, also temperature and salinity data coming from the MyOcean database [3] have been extracted and processed.

The analysis of yearly temperature and salinity trends, at surface, 10 m, 20 m and 30 m depths is illustrated in Appendix A and B, respectively.

The minimum temperature during the year is around 13.0°C and it is usually reached in February, while the maximum temperature is around 27.5°C (at surface) and it is usually reached in July. As an example, the 2010 temperature time series are illustrated in Figure 2-20.

Differences in temperature up to 6° between surface and 30 m depth can be found during summer (when the stratification is higher). During winter and autumn months, the stratification is negligible.

At the Italian landfall site, the stratification of the water column in terms of salinity is very weak (as an example, the 2010 salinity time series is illustrated in Figure 2-21): the maximum difference between surface and 30m depth is less than 0.5 PSU. There is no clear evidence of seasonal trends in the time series of salinity.
Figure 2-20 Example of yearly sea temperature at four different depths (0 m, -10 m, -20 m, -30 m) offshore the Italian coast. Source: the trends are processed by DHI on the basis of the oceanographic data downloaded from MyOcean website [3] (http://www.myocean.org/) for the point of coordinates LON 18.500°, LAT 40.375° for the period 01/01/2010-31/12/2010.

Figure 2-21 Example of yearly sea salinity at four different depths (0 m, -10 m, -20 m, -30 m) offshore the Italian coast. Source: the trends are processed by DHI on the basis of the oceanographic data downloaded from MyOcean website [3] (http://www.myocean.org/) for the point of coordinates LON 18.500°, LAT 40.375° for the period 01/01/2010-31/12/2010.
3  Representative meteomarine scenarios

In order to model the representative hydrodynamic conditions characterising the area around the pipeline route at the Italian landfall site, the following two different scenarios have been selected.

The meteomarine forcing which has been considered refers to wind, tide, currents from the general circulation of the Adriatic Sea (baroclinic currents), temperature and salinity, as illustrated in the previous chapters. Since the analysis of offshore data (Chapter 2) pointed out the presence of a seasonal trend, two representative scenarios for two different seasonal representative behaviours have been selected.

In order to model the hydrodynamic field due to typical conditions during the autumn/winter months (scenario 1) and the spring/summer months (scenario 2), for both scenarios a real period of 15 days has been considered, so that a complete tidal cycle is included in the simulation.

Scenario 1: Representative meteomarine conditions during autumn/winter season.

In order to select a reliable and representative scenario, for this autumn/winter scenario, with reference to the analysis of offshore data illustrated in Chapter 2, a time window during which currents come from north-north-west and are characterized by speed values with high frequency of occurrence has been selected. The vertical stratification of salinity and temperature is not relevant in these months. The selected time window is the period between 29/12/2007 and 12/01/2008.

In Table 3-1 the daily averaged values of velocity components, temperature and salinity at 18 reference depths for the 15-day period are illustrated (source: MyOcean database [3]).

In addition to temperature, salinity and currents from the general circulation of the Adriatic Sea (baroclinic currents), also wind conditions for the selected time window have been extracted. As illustrated in Chapter 2, the WATCH model database has been used [2]. In particular, the hourly values of wind velocity components U and V, together with the hourly atmospheric pressure for the period 29/12/2007 – 12/01/2008, have been extracted from the closest location (the closest cells) to the Italian landfall site.

Finally, the astronomical tide conditions at the site during the period 29/12/2007 – 12/01/2008 have been extracted from C-MAP database (Chapter 2); the time series for the 15 days is illustrated in Figure 3-1: an entire tidal cycle is represented.
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Table 3-1 Temperature (T), salinity (S), horizontal (U) and vertical (V) current velocity components at 18 different reference depths during the 15 days of the autumn/winter scenario. Source: oceanographic data downloaded from MyOcean website [3] (http://www.myocean.org/) for the point of coordinates LON 18.500°, LAT 40.375° for the period 29/12/2007 – 12/01/2008.
Scenario 2: Representative meteoromarine conditions during spring/summer season.

In order to select a reliable and representative scenario, for this spring/summer scenario, with reference to the analysis of offshore data illustrated in Chapter 2, a time window during which currents come generally from north–north-west (as well as for scenario 1) and are characterized by speed values with high frequency of occurrence has been selected. The vertical stratification of salinity and temperature is significant in these months. Important variability in temperature has been found between surface and 60 m depth, with differences of around 13°C, while the vertical salinity stratification is limited: the difference between surface and 60 m depth is of around 0.4 PSU. The selected time window is the period between 01/08/2008 and 15/08/2008.

In Table 3-2 the daily averaged values of velocity components, temperature and salinity at 18 reference depths for the 15-day period are illustrated (source: MyOcean database [3]).

Figure 3-1  Astronomical tide during the period 29/12/2007 – 12/01/2008 for the Otranto CMAP station. Source: The time series is extracted from the database available in the tool MIKE C-MAP, part of DHI software package [5], station: Otranto, period: 29/12/2007 – 12/01/2008.
**Table 3-2 Temperature (T), salinity (S), horizontal (U) and vertical (V) current velocity at 18 different reference depths during the 15 days analyzed. Source: oceanographic data downloaded from MyOcean website [3] (http://www.myocean.org) for the point of coordinates LON 18.500°, LAT 40.375° for the period 01/08/2008 – 15/08/2008.**

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<th>S [PSU]</th>
<th>U [m/s]</th>
<th>V [m/s]</th>
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</table>

*Note: Data from MyOcean website [3] for the point of coordinates LON 18.500°, LAT 40.375° for the period 01/08/2008 – 15/08/2008.*
As illustrated for scenario 1, in addition to temperature, salinity and currents from the general circulation of the Adriatic Sea (baroclinic currents), also wind conditions for the selected time window have been extracted. As illustrated in Chapter 2, the WATCH model database has been used [2]. In particular, the hourly values of wind velocity components U and V, together with the hourly atmospheric pressure for the period 01/08/2008 – 15/08/2008, have been extracted from the closest location (the closest cells) to the Italian landfall site.

Finally, the astronomical tide conditions at the Italian landfall site during the period 01/08/2008 – 15/08/2008 have been extracted from C-MAP database (Chapter 2) [5]; the time series for 15 days is illustrated in Figure 3-2: an entire tidal cycle is represented.

![Figure 3-2](image-url)
4 3D Hydrodynamic model

The numerical modelling study has been performed using the MIKEbyDHI package, developed by DHI. In particular, the 3D model MIKE 3 HD FM has been used for the simulation of hydrodynamic fields in the Italian landfall site.

The MIKE 3 primitive equation model is based on a flexible mesh approach and it has been developed for applications within oceanographic, coastal and estuarine environments. The spatial discretization of the equations is performed using a cell centered finite volume method.

The horizontal discretization can combine triangles and quadrilateral elements, while the vertical is based on a sigma or combined sigma-zed discretization. Together with the inclusion of the Flather boundary conditions, the model is ideal for down scaling the regional scale oceanographic models to high resolution coastal application. The regional scale resolution and bathymetry can be very well approximated at the boundaries, then gradually imposing the higher resolution through the flexible mesh approach.

A detailed description of MIKE 3 HD FM model is included in Appendix D.

In Section 4.1, a detailed description of the bathymetric data used in the model, together with a description of the model domain and the adopted horizontal and vertical resolution are illustrated. In Section 4.2 the results of the hydrodynamic model for the two scenarios are illustrated, while some considerations on tidal currents and wave generated currents can be found respectively in Section 4.3 and 4.4.

It has to be noticed that the model is not calibrated against measurements, due to unavailability of registered data.

4.1 Bathymetric data, model domain and resolution

For the bathymetric characterization of the area, a set of different bathymetric surveys at different resolution and scale has been used.

1. Puglia Region has developed a data portal to make available data to support the activities of development and planning. So, for a large scale bathymetric characterization of the area, this database of Puglia Region has been used [13] (Figure 4-1).

The bathymetry data included in the portal contains isolines every 5 m, from a depth of 5 m to a depth of 100 m. Isolines cover the whole area of interest (Figure 4-2).

2. ERM provided a more detailed survey covering the area of interest for the dredging and backfilling operations. This survey is available onshore, from a depth of 5 m to a depth of 65 m, in the zone around the area where the microtunnel will be realized and the pipeline will be laid. Isolines cover a length of about 2 km along the coast and they are represented every 5 m depth. Figure 4-4 illustrates the extension of the detailed bathymetric survey available.

3. A detailed bathymetric survey, provided by ERM, covering the pipeline track, from the exit of microtunnel (depth of about 20 m) to a depth of about 635 m, has been used (Figure 4-5).

The whole available data, handled within the DHI MIKE Zero platform, are represented in Figure 4-6, while the final result of this processing is illustrated in Figure 4-7.
Figure 4-1 Puglia Region data portal (www.sit.puglia.it [13])

Figure 4-2 Bathymetry data in the site of interest. Source: Puglia Region data portal (www.sit.puglia.it [13])
Figure 4-3  Bathymetry data from Puglia Region portal for the site of interest imported in MIKE Zero

Figure 4-4  Bathymetric data provided by ERM for the area of interest
Figure 4-5  Bathymetric data provided by ERM along the pipeline track

Figure 4-6  Bathymetric data used in the present study
The extension of the model domain is approximately equal to 31,000 m along the coast and to 14,000 m in the direction perpendicular to the coast. The maximum depth which can be found in the model domain is approximately equal to 105 m.

The model bathymetry has been constructed using the flexible mesh approach: the offshore spatial resolution (average length of triangles sides) is around 1,000 m; gradually, while approaching the coast and the pipeline route corridor, the resolution is finer, up to around 50 m. Along the pipeline route corridor, in the zone where the dredging operations will take place, a resolution of around 30 m has been selected; in this corridor a quadrangular mesh, instead of triangular, is used (Figure 4-8 and Figure 4-9). The quadrangular mesh is more suitable when simulating local sources of sediment, like in this case.

The vertical discretization is made of 8 sigma-layers combined with one zed-layer. The water depth between surface and -48 m is discretized through 8 sigma-layers, each one characterized by a variable thickness depending on the local water depth (i.e. when the water depth is 16 m, the thickness of each sigma-layer is 2 m), while the deeper part of the water column is discretized through a unique zed-layer.
Figure 4-8  Mesh used in the numerical model to study the Italian landfall site

Figure 4-9  Detail of the quadrangular mesh, where dredging and backfilling operations will take place
4.2 Results

In general, results show that the currents are stronger offshore than near shore. In fact the circulation is dominated by currents from the general circulation of the Adriatic Sea (baroclinic currents), which are stronger at higher depths, because of the lower interaction with the sea bed that causes energy dissipation and a reduction in the current speed.

Another important forcing that plays a significant role in the generation of the current field is the wind, the influence of which is very important at surface.

The following figures illustrate an example of the hydrodynamic fields at three different depths (surface, intermediate depth and sea bed depth).

The plots corresponding to “surface” and “intermediate depth” are referred to the upper and intermediate sigma-layer of the model, respectively. This means that the plots are not representative of the same depth everywhere: where the water depth is 48 m or higher, the intermediate depth is 24 m, where the water depth is shallower than 48 m, the intermediate depth is half of the local water depth. The plots corresponding to “sea bed depth” are referred to the deeper sigma-layer. This means that the plot is representative of what happens at the sea bed where the water depth is equal or shallower than 48 m (which is the limit of the sigma-layer – zed-layer interface). Where the water depth is deeper, the plot is representative of the behavior of the currents at the interface depth (48 m).

4.2.1 Scenario 1

Scenario 1 is representative of typical autumn/winter conditions. In these months the currents from the general circulation of the Adriatic Sea (baroclinic currents) are frequently directed from north-west to south-east and this direction can be found almost constant both along the 15 days simulated and along the water column, due to the reduced stratification.

The plots refer to two time steps: one is representative of an average condition of current speed and direction (08/01/2008), and the other representative of a condition characterized by higher current speed (05/01/2008).

In general, at surface the average current speed is around 0.10 ± 0.20 m/s (Figure 4-10) and doesn’t change significantly along the water column (Figure 4-11 and Figure 4-12).

The maximum current speed reached during the 15 days of simulation is approximately equal to 0.35 ± 0.45 m/s at surface (Figure 4-13. At the same time step, the maximum current speed at the sea bed depth is around 0.20 ± 0.25 m/s (Figure 4-15). During the day characterized by the highest values of current speed, the current flows in opposite direction (south east to north west) than the most frequent situation (north west to south east).

If we focus on the area where dredging and backfilling operations will take place, at surface the average current speed is around 0.10 m/s, and this speed is quite similar at the sea bed depth. In this zone the highest current speed reached during the 15 days of simulation is approximately equal to 0.35 m/s at surface and 0.20 m/s at the sea bed depth.
Figure 4-10  Hydrodynamic field at surface for the Italian landfall site during autumn/winter representative conditions (08/01/2008)
Figure 4-11 Hydrodynamic field at intermediate depth for the Italian landfall site during autumn/winter representative conditions (08/01/2008)
Figure 4-12  Hydrodynamic field at sea bed depth for the Italian landfall site during autumn/winter representative conditions (08/01/2008)
Figure 4-13  Hydrodynamic field at surface for the Italian landfall site during autumn/winter representative conditions (05/01/2008)
Figure 4-14  Hydrodynamic field at intermediate depth for the Italian landfall site during autumn/winter representative conditions (05/01/2008)
4.2.2 Scenario 2

Scenario 2 is representative of typical spring/summer conditions. Also in these months the currents from the general circulation of the Adriatic Sea (baroclinic currents) are frequently directed from north-west to south-east and this direction can be found almost constant along the 15 days of simulation but, due to the significant stratification of the water column, some differences in the hydrodynamic field can be noticed along the water column. In particular, the current tends to change its direction at a depth of about 40 m; it is important to underline that the water depth in the dredging zone is around 30 m, so the dredging and backfilling area is not influenced by this change of the current direction. In addition, the current speed significantly decreases along the water column: the reduction ratio between surface and sea bed depth current speed (up to -30 m) is around 60%.

The plots refer to two time steps: one is representative of an average condition of current speed and direction (08/08/2008), and the other is representative of a condition characterized by higher current speed (11/08/2008).

In general, at surface the average current speed is around 0.25 m/s (Figure 4-16) and decreases gradually in deeper water, up to an average speed of around 0.05 m/s or less at the sea bed depth (Figure 4-18). As already illustrated, in deeper water there is an inversion of the current direction.
The highest current speed reached during the 15 days of simulation is in the order of $0.45 \div 0.55$ m/s at surface (Figure 4-19). At the same time step, the highest current speed at the sea bed depth is around $0.10 \div 0.20$ m/s in most of the model domain (Figure 4-21).

If we focus on the area where dredging and backfilling operations will take place, the average current speed is around 0.15 m/s at surface, and around 0.05 m/s at the sea bed depth. In this zone the highest current speed reached during the 15 days of simulation is approximately equal to 0.30 m/s at surface and 0.20 m/s at the sea bed depth.

![Figure 4-16 Hydrodynamic field at surface for the Italian landfall site during spring/summer representative conditions (08/08/2008)](image)
Figure 4-17  Hydrodynamic field at intermediate depth for the Italian landfall site during spring/summer representative conditions (08/08/2008)
Figure 4-18  Hydrodynamic field at sea bed depth for the Italian landfall site during spring/summer representative conditions (08/08/2008)
Figure 4-19  Hydrodynamic field at surface for the Italian landfall site during spring/summer representative conditions (11/08/2008)
Figure 4-20  Hydrodynamic field at intermediate depth for the Italian landfall site during spring/summer representative conditions (11/08/2008)
Considerations on tidal currents

It is important to notice that the contribution of tidal currents in the representative current conditions at the Italian landfall site can be considered as negligible: specific simulations considering only tidal forcing have been performed and the conclusion is that the current speed induced by tidal variation is at least one order of magnitude lower than currents from the general circulation of the Adriatic Sea (baroclinic currents) and/or wind currents at surface (example in Figure 4-22, where the current field during a condition of spring tide is illustrated). This figure shows a maximum current speed of about 0.020 m/s and an average speed of about 0.004 m/s offshore and 0.014 m/s near shore along the coastline in shallower water.

Although it is negligible, the tidal current contribution is included as a separate forcing in both scenario 1 and scenario 2.
4.4 Considerations on wave generated currents

In general, during wave propagation from offshore to near shore, when approaching the so called surf zone, if the mean wave direction is not perpendicular to the isolines, a gradient in radiation stress fields at the sea bed generates longshore currents, which are characterized by higher speed in case of large waves and very oblique wave attack.

In general, longshore currents are not strong enough to lift the sediment from the seabed and disperse it in the water column: the main responsible for this is the mechanical action of wave breaking, while longshore currents are responsible for the horizontal movement of the suspended sediments once they have already been put in suspension.

In this case, the area where dredging and backfilling operations will take place is in relatively deep water (around 20-30 m): at these depths the interaction between the incident wave and the sea bed is not relevant, therefore very weak gradients of radiation stresses are generated. It is therefore reasonable to assume that the area of interest is out of the surf zone and therefore not affected by wave generated currents.
5 3D sediment dispersion model

The numerical modelling study of the sediment dispersion during dredging operations has been performed using the MIKE by DHI package, developed by DHI. In particular, the 3D model MIKE 3 MT FM has been used for the simulation of sediment dispersion in the area.

MT is a specific module developed to simulate the suspension and sedimentation of cohesive and mixed sediments under hydrodynamic forcing and external actions.

The mud transport model includes the following physical phenomena:

- flocculation due to concentration;
- flocculation due to salinity;
- density effects at high concentrations;
- hindered settling;
- consolidation;
- morphological bed changes.

A detailed description of MIKE 3 MT FM model [7] is included in Appendix E.

The sediment dispersion model is fully integrated with the hydrodynamic model MIKE 3 HD FM [6] (Chapter 4). During the MIKE 3 MT simulations the plume of suspended sediment released during dredging and backfilling operations changes in extension, shape and concentration according to hydrodynamics (advection) and dispersion conditions.

In Section 5.1 the methodological approach is illustrated, including the estimation of the dredging, release rates and settling velocity.

In Sections 5.2 and 5.2.2 the results of the sediment dispersion model as Suspended Sediment Concentrations (SSC) at different depths for the 2 representative scenarios are illustrated.

5.1 Methodological approach

5.1.1 Methodology of dredging operations

The pipeline landfall will be constructed using microtunnelling technology to minimize interferences with the coastline. Microtunneling is a process that uses a remotely controlled Micro Tunnel Boring Machine (MTBM) combined with the pipe jacking technique to directly install concrete jacking pipes.

At the end of the microtunnel, approximately at a water depth of 20 m at a distance from the coastline of around 860 m, a trench will be dredged, in which the pipeline will be laid.

Work on the pre-dredged trench shall be carried out by a backhoe dredger (Figure 5-1), in order to prepare the laying of the pipeline, and to recover the MTBM, in the proximity of the tunnel exit, seawards.

The length of the trench will be approximately 110 m. The dredged volume will be approximately equal to 15,500 m$^3$; it will be placed at the side of the trench and it will be reused to backfill the trench afterwards, once the pipeline will be in place.
According to ERM’s indications, the total duration of the dredging operations has been estimated equal to 60 days, while the duration of the backfilling operation has been estimated equal to 30 days.

Due to the above information, considering the dredged volume and the total duration of the operations, the expected dredging rate is around 10.76 m$^3$/hour, while the backfilling rate is around 21.53 m$^3$/hour.

**Figure 5-1  Typical Backhoe Dredger**

As mentioned in Chapter 3, in order to model the hydrodynamic field due to typical conditions during the autumn/winter and spring/summer months, a real period of 15 days has been considered. To study the transport of suspended sediments during the dredging and the backfilling operations, this time window is too short. Since the hydrodynamic scenarios aim at representing typical conditions, the results obtained in the 15-day hydrodynamic simulations have been replicated to cover the whole duration of the dredging and backfilling operations.

In particular, two different simulations have been performed, one to study the dispersion of suspended sediments during dredging operations and one during backfilling operations. In fact, since from information provided by ERM, the time that will pass between the two phases will not be shorter than 20-30 days, it is reasonable to assume that the suspended sediment released during dredging operations will be completely settled when the backfilling will start.

The hydrodynamic results have been therefore concatenated to obtain the whole duration necessary to run the MIKE 3 MT model; in particular 5 hydrodynamic simulations have been concatenated to study the sediment dispersion during the dredging operations and 3 for the backfilling operations. This means that the sediment dispersion has been studied not only during the activities, but also after some days, to study the fate of the plume also when the release of sediment will stop.

**5.1.2 Dredging rate, release rate, settling velocity**

During dredging and backfilling operations, both sand fraction and fine fraction are released in the water column. The sand fraction is assumed to settle nearby the release point and therefore its environmental impact is generally negligible. Following the above assumption, the numerical model only aims at simulating the dispersion and fate of the fine fraction of the sediment, which
can have a significant environmental impact since it can remain in suspension for a long time and migrate to sensitive areas.

Under the above assumption, the calculation of the sediment volume that will be modelled only refers to the fine fraction of the material. In order to quantify this fraction, the grain curves provided by ERM referring to the collected samples by FUGRO OCEANSISMICA S.p.A. have been used. In particular, the particle size analysis of the sample which is located closer to the dredging area has been considered (Figure 5-2). Referring to the “Trans Adriatic Pipeline – Environmental Report – Results Italian Landfall” provided by ERM, for the dredging zone the sample illustrated in Table 5-1 has been considered. Figure 5-3 illustrates the grain curve associated to the above sediment sample.

**Table 5-1 Sample used for the sediment dispersion study**

<table>
<thead>
<tr>
<th>Sample station</th>
<th>Sample coordinates [°]</th>
<th>Percentage of fine sediment [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAP_ENV_B4</td>
<td>LON 18.4003; LAT 40.3157</td>
<td>1.84</td>
</tr>
</tbody>
</table>

Figure 5-2 Location of the sample TAP_ENV_B4. Source: Google Earth
The grain diameter threshold between sand fraction and fine fraction has been assumed equal to 63 μm, accordingly to the Wentworth scale, a standard classification for clastic sediment and rock (Figure 5-4). The threshold is the limit between very fine sand and coarse silt.

<table>
<thead>
<tr>
<th>Millimeters (mm)</th>
<th>Micrometers (μm)</th>
<th>Phi (φ)</th>
<th>Wentworth size class</th>
<th>Rock type</th>
</tr>
</thead>
<tbody>
<tr>
<td>4096</td>
<td>400</td>
<td>-12.0</td>
<td>Boulder</td>
<td>Conglomerate/Brèccia</td>
</tr>
<tr>
<td>256</td>
<td>250</td>
<td>-8.0</td>
<td>Cobble</td>
<td></td>
</tr>
<tr>
<td>64</td>
<td>60</td>
<td>-6.0</td>
<td>Pebble</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>40</td>
<td>-2.0</td>
<td>Granule</td>
<td></td>
</tr>
<tr>
<td>2.00</td>
<td>200</td>
<td>-1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.00</td>
<td>100</td>
<td>0.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/2</td>
<td>0.50</td>
<td>1.0</td>
<td>Very coarse sand</td>
<td>Sand</td>
</tr>
<tr>
<td>1/4</td>
<td>0.25</td>
<td>2.0</td>
<td>Coarse sand</td>
<td></td>
</tr>
<tr>
<td>1/8</td>
<td>0.125</td>
<td>3.0</td>
<td>Medium sand</td>
<td></td>
</tr>
<tr>
<td>1/16</td>
<td>0.0625</td>
<td>4.0</td>
<td>Fine sand</td>
<td></td>
</tr>
<tr>
<td>1/32</td>
<td>0.031</td>
<td>5.0</td>
<td>Very fine sand</td>
<td></td>
</tr>
<tr>
<td>1/64</td>
<td>0.0156</td>
<td>6.0</td>
<td></td>
<td>Silt</td>
</tr>
<tr>
<td>1/128</td>
<td>0.0078</td>
<td>7.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/256</td>
<td>0.0039</td>
<td>8.0</td>
<td></td>
<td>Very fine silt</td>
</tr>
<tr>
<td></td>
<td>0.0006</td>
<td>14.0</td>
<td></td>
<td>Clay</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Mud</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Claystone</td>
</tr>
</tbody>
</table>

Figure 5-4  Wentworth scale for clastic sediment and rock standard classification.

On the basis of the expected dredging and backfilling rate (10.76 m³/hour and 21.53 m³/hour, respectively) and the ratio between fine fraction and sand fraction, it has been possible to quantify the dredging and backfilling rate of the fine part of the sediment. Based on the large
DHI experience within dredging studies, a **density of 1,900 Kg/m^3** is assumed to be reasonable for the fine fraction of sediments. Table 5-2 illustrates the dredging rates.

Table 5-2  Dredging and backfilling rates.

<table>
<thead>
<tr>
<th></th>
<th>rate [m^3/h]</th>
<th>rate fine fraction [m^3/h]</th>
<th>rate fine fraction [kg/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dredging</strong></td>
<td>10.76</td>
<td>0.20</td>
<td>0.1045</td>
</tr>
<tr>
<td><strong>Backfilling</strong></td>
<td>21.53</td>
<td>0.40</td>
<td>0.2090</td>
</tr>
</tbody>
</table>

The location of the release of sediment is not fixed in the model: through the use of the specific “dredging module” it has been possible to specify the location of the release point (i.e. the dredger location) at different time step of the simulation. During the 60 days of dredging activities, the release of sediment in the model therefore slowly moves along the trench route, while during the 30 days of backfilling operations the release of sediment describes the same route.

The amount of sediment actually released in the water column during dredging and backfilling operations is only a fraction of the dredged / backfilled sediment: the rate of release per unit of dredged / backfilled material is an "average" loss quantity that can take into account differences between dredging / backfilling methods and enables comparison between methods of total mass lost into the surrounding water. Blokland (1988) describes a systematic method for determining the quantity of sediment released into the immediate vicinity of the dredger, in kg/m^3 dredged. This is the so called "S-factor". It is based on in situ measurements of suspended sediment concentrations, rather than measured release rates from the dredger and so takes into account any dynamic plume effects. In this case the S-factor has been useful to estimate the magnitude of sediment losses because of the lack of site-specific information of the rate of release per unit of dredged material.

Kirby and Land (1991) made further use of the S-factor, and provided indications on losses of fine sediment that result from the different types of dredging operation in muddy sediment.

On the basis of the above references and on large DHI experience within dredging studies, a **release rate of 3%** of the dredging and backfilling rate is assumed to be associated to the Backhoe Dredger. The sediment is assumed to be released in the bottom layer.

Another important assumption when modelling sediment dispersion is the estimation of **settling velocity**. In this case, independently on the grain diameter variations from point to point, a settling velocity of 0.05 cm/s has been considered. This estimation is based both on DHI experience and on many references\(^2\) [8 ÷ 12] regarding the definition of settling velocity, which has been estimated to lie between 0.023 and 0.054 cm/s for suspended material characterized by diameters smaller than 50 μm.

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\(^2\) Måling af insitu faldhastigheder af klappet havnesediment i Grådyb. GRAS A/S July 2004


Edelvang, K Tial variation in the settling diameters of suspended matter on a tidal mud flat. Helgoländer meeresuntersuchungen 51: 269-279, 1997

Edelvang, K Austen, I The temporal variation of flocs and fecal pellets in a tidal channel. Estuarine, Coastal and shelf science 44: 361-367, 1997
5.2 Results

The dispersion and fate of the suspended sediment plume depend essentially on the hydrodynamic conditions, once fixed the release location and the release rate.

The following plots of results do not refer to the whole model domain, but only to a zone around the area of operations, in order to have a clearer comprehension of the results.

In particular, the following figures represent the maps of maximum Suspended Sediment Concentration (SSC) over the whole period of the two simulations (one for dredging operations and one for backfilling operations) at two different depths: in the sea bed layer and in the layer immediately above.

The illustration of the results has been done only for these two bottom layers because the suspended sediment remains confined in the deeper layers. No relevant SSC can be found in the upper layers.

It is important to put in evidence that, based on the DHI experience with measurements of suspended sediment concentration, the threshold value below which the measured concentration cannot be considered reliable is equal to 0.002 kg/m$^3$.

5.2.1 Scenario 1

During the dredging operations, in the autumn/winter months, at the sea bed (Figure 5-5), the plume (i.e. where the SSC is higher than the 0.002 kg/m$^3$) has an extension of around 210 m along the pipeline track, and 130 m perpendicularly to it. The extension of the plume is approximately centred on the dredged area.

In this scenario the maximum SSC can be found along the dredging stretch, with values that locally exceed 0.008 kg/m$^3$.

![Figure 5-5: Maximum Suspended Sediment Concentration in the sea bed layer during dredging operations in autumn/winter months](image)
During the dredging operations in the autumn/winter months, in the layer immediately above the seabed layer (Figure 5-6), the suspended sediment concentration is not relevant.

![Figure 5-6](image)

Figure 5-6  Maximum Suspended Sediment Concentration in the layer immediately above the seabed layer during dredging operations in autumn/winter months

During the backfilling operations, in the autumn/winter months, at the sea bed (Figure 5-7), the plume (i.e. where the SSC is higher than the 0.002 kg/m$^3$) has an extension of around 150 m along the pipeline track, and 240 m perpendicularly to it. The extension of the plume is approximately centred on the backfilled area.

In this scenario the maximum SSC can be found along the backfilling stretch, with values that locally exceed 0.015 kg/m$^3$. 
During the backfilling operations, in the autumn/winter months, at the layer immediately above the seabed layer (Figure 5-8), the suspended sediment concentration is not relevant.

Figure 5-7  Maximum Suspended Sediment Concentration in the sea bed layer during backfilling operations in autumn/winter months

Figure 5-8  Maximum Suspended Sediment Concentration in the layer immediately above the seabed layer during backfilling operations in autumn/winter months
5.2.2 Scenario 2

During the dredging operations, in the spring/summer months, at the sea bed (Figure 5-9), the plume (i.e. where the SSC is higher than the 0.002 kg/m³) has an extension of around 120 m along the pipeline track, and 180 m perpendicularly to it. The extension of the plume is approximately centred on the dredged area.

In this scenario the maximum SSC can be found along the dredging stretch, with values up to 0.010 kg/m³.

Figure 5-9 Maximum Suspended Sediment Concentration in the sea bed layer during dredging operations in spring/summer months
During the dredging operations, in the spring/summer months, at the layer immediately above the seabed layer (Figure 5-10), the suspended sediment concentration is again not relevant.

![Maximum Suspended Sediment Concentration in the layer immediately above the seabed layer during dredging operations in spring/summer months](image)

During the backfilling operations, in the spring/summer months, at the sea bed layer (Figure 5-11), the plume (i.e. where the SSC is higher than the 0.002 kg/m³) has an extension of around 150 m along the pipeline track, and 210 m perpendicularly to it. The extension of the plume is approximately centred on the dredged area.

In this scenario the maximum SSC can be found along the dredging stretch, with values that locally exceed 0.015 kg/m³.
During the backfilling operations, in the spring/summer months, at the layer immediately above the seabed layer (Figure 5-12), the suspended sediment concentration is again not relevant.
5.3 Settling of fine sediment in the model domain

The settling of fine sediment in the model domain, with particular focus on the area where the dredging and backfilling operations will take place, has been investigated.

The results of the 3D simulations have been post processed and maps illustrating the spatial distribution of the thickness of the settled sediment after dredging and backfilling operations has been delivered. In particular the results have been extracted after 67-days simulation, regarding the dredging operations, and after 37-days simulation, regarding the backfilling operations. This means that the results refer to the bed thickness change 1 week after the end of the dredging and the backfilling operations, whose total durations have been assumed respectively equal to 60 and 30 days.

The maximum value of total bed thickness change estimated is about 3 mm, that corresponds to a total net deposition accumulated of about 580 g/m². The maximum settling is reached along the pipeline track, in the middle of the dredging area.

A bed thickness change greater than 0.2 mm can be found over a distance of 180 m along the pipeline track, and 350 m perpendicularly to it. The extension of this area spreads clearly towards south-east (mean direction of the main current).

On the whole, the total bed thickness change obtained by modelling application during dredging operations and the one obtained during backfilling operations, both in autumn/winter scenario and spring/summer scenario, are very similar.

Locally, the total bed thickness change reached during the backfilling operation are slightly bigger than the one obtained at the end of the dredging operations because of the higher spill rate considered (see Table 5-2).

In addition, the extension and the shape of the area interested by the settling of fine sediments are slightly different at the end of the two meteomarine scenarios because of the different hydrodynamic conditions that transport and maintain in suspension the sediments.
Figure 5-13  Spatial distribution of the thickness of the settled sediment after dredging operations during autumn/winter months

Figure 5-14  Detail of the map illustrating the spatial distribution of the thickness of the settled sediment after dredging operations during autumn/winter months
Figure 5-15  Spatial distribution of the thickness of the settled sediment after backfilling operations during autumn/winter months

Figure 5-16  Detail of the map illustrating the spatial distribution of the thickness of the settled sediment after backfilling operations during autumn/winter months
Figure 5-17  Spatial distribution of the thickness of the settled sediment after dredging operations during spring/summer months

Figure 5-18  Detail of the map illustrating the spatial distribution of the thickness of the settled sediment after dredging operations during spring/summer months
Figure 5-19  Spatial distribution of the thickness of the settled sediment after backfilling operations during spring/summer months

Figure 5-20  Detail of the map illustrating the spatial distribution of the thickness of the settled sediment after backfilling operations during spring/summer months
5.4 Settling of sand in the model domain

As illustrated in Chapter 5.1, the numerical modelling of the sediment dispersion only refers to the fine fraction of the material.

This choice derives from the assumption that the sand fraction will settle nearby the release points, therefore being not relevant from an environmental impact perspective.

Following, a rough estimation of the amount of sand fraction which will settle around the release point has been investigated.

The amount of dredged material in terms of sand fraction is calculated as the difference of the already used dredging rates (total and fine fraction) illustrated in Table 5-2. Through simple desktop calculations involving settling velocity and current velocity, most of the released material (sand fraction) will settle in the first 50 m from the release zone.

A rough estimation for the dredged area brings approximately 50,200 g/m² of settled sand within the 50 m radius area, during the dredging operations, and the same amount during the backfilling operations.

6 Conclusions

This numerical modelling study aims at supporting the Environmental and Social Impact Assessment (ESIA) for the offshore part of the Italian landfall of the TAP. The pipeline is planned to go from Albania to Italy, covering a distance of more than 100 km.

In particular, the modeling study is focused on simulating the dispersion and fate of suspended sediment occurring during dredging and backfilling operations. During these activities, both sand fraction and fine fraction are released in the water column. The sand fraction is assumed to settle nearby the release point and therefore its environmental impact is generally negligible. Following the above assumption, the numerical model only aimed at simulating the dispersion and fate of the fine fraction of the sediment, which can have a significant environmental impact since it can remain in suspension for a long time and migrate to sensitive areas.

The meteomarine conditions which have been assumed as representative of typical conditions at the Italian landfall of the TAP derive from an accurate processing of collected data of winds, waves, both yearly and seasonal, tidal variations and circulation in the southern Adriatic Sea; two meteomarine scenarios have been finally selected as representative of typical conditions at the Italian landfall of the TAP:

- scenario 1: representative meteomarine conditions during autumn/winter season as wind, tide, currents from the general circulation of the Adriatic Sea, temperature and salinity profile;
- scenario 2: representative meteomarine conditions during spring/summer season as wind, tide, currents from the general circulation of the Adriatic Sea, temperature and salinity profile.

The simulations of hydrodynamic fields and sediment dispersion pattern confirmed that the dispersion and fate of the suspended sediment plume depends essentially on the hydrodynamic conditions, once fixed the release location and the release rate.

The highest concentration of suspended sediment can be found in the sea bed layer, along the dredged trench, and can reach values of about 0.010 kg/m³ during dredging operations and of about 0.015 kg/m³ during backfilling operations.

The sediment plume never reaches the surface, but remains confined in the deeper water. Already in the layer immediately above the sea bed layer, the suspended sediment
concentration becomes not relevant, the maximum value of suspended sediment concentration being everywhere lower than the minimum concentration that can be measured by instruments, for both representative scenarios.

Regarding the settling of fine sediment, the maximum value of total bed thickness change estimated is about 3 mm, reached along the pipeline track, in the middle of the dredging area. A bed thickness change greater than 0.2 mm can be found over a distance of 180 m along the pipeline track, and 350 m perpendicularly to it. The extension of this area spreads clearly towards south-east (mean direction of the main current).

7 References

[1] www.mareografico.it
RMN–Rete Mareografica Nazionale (Italian National Tide Gauge Network)
RON–Rete Ondametrica Nazionale (Italian National Wave Metric Network)


APPENDIX A

Yearly sea temperature
Figure 1  Sea temperature during 2006 at four different depths (0, -10, -20, -30m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) – MyOcean data.

Figure 2  Sea temperature during 2007 at four different depths (0, -10, -20, -30m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) – MyOcean data.
Figure 3  Sea temperature during 2008 at four different depths (0, -10, -20, -30 m a.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) – MyOcean data.

Figure 4  Sea temperature during 2009 at four different depths (0, -10, -20, -30 m a.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) – MyOcean data.
Figure 5  Sea temperature during 2010 at four different depths (0, -10, -20, -30m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) – MyOcean data.

Figure 6  Sea temperature during 2011 at four different depths (0, -10, -20, -30m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) – MyOcean data.
APPENDIX B

Yearly sea salinity
Figure 1  Sea salinity during 2006 at four different depths (0, -10, -20, -30 m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) – MyOcean data.

Figure 2  Sea salinity during 2007 at four different depths (0, -10, -20, -30 m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) – MyOcean data.
Figure 3  Sea salinity during 2008 at four different depths (0, -10, -20, -30m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) – MyOcean data.

Figure 4  Sea salinity during 2009 at four different depths (0, -10, -20, -30m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) – MyOcean data.
Figure 5  Sea salinity during 2010 at four different depths (0, -10, -20, -30m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) – MyOcean data.

Figure 6  Sea salinity during 2011 at four different depths (0, -10, -20, -30m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) – MyOcean data.
APPENDIX C

Offshore currents speed and direction
Figure 1  Current speed and direction during January 2006 at four different depths (0, -10, -20, -30 m a.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.

Figure 2  Current speed and direction during January 2007 at four different depths (0, -10, -20, -30 m a.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.
Figure 3  Current speed and direction during January 2008 at four different depths (0, -10, -20, -30 m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.

Figure 4  Current speed and direction during January 2009 at four different depths (0, -10, -20, -30 m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.
Figure 5  Current speed and direction during January 2010 at four different depths (0, -10, -20, -30 m. s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.

Figure 6  Current speed and direction during January 2011 at four different depths (0, -10, -20, -30 m. s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.
Figure 7  Current speed and direction during February 2006 at four different depths (0, -10, -20, -30 m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.

Figure 8  Current speed and direction during February 2007 at four different depths (0, -10, -20, -30 m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.
Figure 9  Current speed and direction during February 2008 at four different depths (0, -10, -20, -30 m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.

Figure 10  Current speed and direction during February 2009 at four different depths (0, -10, -20, -30 m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.
Figure 11  Current speed and direction during February 2010 at four different depths (0, -10, -20, -30 m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.

Figure 12  Current speed and direction during February 2011 at four different depths (0, -10, -20, -30 m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.
Figure 13  Current speed and direction during March 2006 at four different depths (0, -10, -20, -30 m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.

Figure 14  Current speed and direction during March 2007 at four different depths (0, -10, -20, -30 m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.
Figure 15  Current speed and direction during March 2008 at four different depths (0, -10, -20, -30m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.

Figure 16  Current speed and direction during March 2009 at four different depths (0, -10, -20, -30m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.
Figure 17  Current speed and direction during March 2010 at four different depths (0, -10, -20, -30m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.

Figure 18  Current speed and direction during March 2011 at four different depths (0, -10, -20, -30m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.
Figure 19  Current speed and direction during April 2006 at four different depths (0, -10, -20, -30 m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.

Figure 20  Current speed and direction during April 2007 at four different depths (0, -10, -20, -30 m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.
Figure 21  Current speed and direction during April 2008 at four different depths (0, -10, -20, -30m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.

Figure 22  Current speed and direction during April 2009 at four different depths (0, -10, -20, -30m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.
Figure 23 Current speed and direction during April 2010 at four different depths (0, -10, -20, -30m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.

Figure 24 Current speed and direction during April 2011 at four different depths (0, -10, -20, -30m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.
Figure 25  Current speed and direction during May 2006 at four different depths (0, -10, -20, -30m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.

Figure 26  Current speed and direction during May 2007 at four different depths (0, -10, -20, -30m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.
Figure 27  Current speed and direction during May 2008 at four different depths (0, -10, -20, -30m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.

Figure 28  Current speed and direction during May 2009 at four different depths (0, -10, -20, -30m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.
Figure 29  Current speed and direction during May 2010 at four different depths (0, -10, -20, -30m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.

Figure 30  Current speed and direction during May 2011 at four different depths (0, -10, -20, -30m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.
Figure 31  Current speed and direction during June 2006 at four different depths (0, -10, -20, -30m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.

Figure 32  Current speed and direction during June 2007 at four different depths (0, -10, -20, -30m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.
Figure 33  Current speed and direction during June 2008 at four different depths (0, -10, -20, -30m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.

Figure 34  Current speed and direction during June 2009 at four different depths (0, -10, -20, -30m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.
Figure 35  Current speed and direction during June 2010 at four different depths (0, -10, -20, -30m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.

Figure 36  Current speed and direction during June 2011 at four different depths (0, -10, -20, -30m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.
Figure 37  Current speed and direction during July 2006 at four different depths (0, -10, -20, -30m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.

Figure 38  Current speed and direction during July 2007 at four different depths (0, -10, -20, -30m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.
Figure 39  Current speed and direction during July 2008 at four different depths (0, -10, -20, -30m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.

Figure 40  Current speed and direction during July 2009 at four different depths (0, -10, -20, -30m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.
Figure 41  Current speed and direction during July 2010 at four different depths (0, -10, -20, -30 m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.

Figure 42  Current speed and direction during July 2011 at four different depths (0, -10, -20, -30 m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.
Figure 43  Current speed and direction during August 2006 at four different depths (0, -10, -20, -30 m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.

Figure 44  Current speed and direction during August 2007 at four different depths (0, -10, -20, -30 m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.
Figure 45  
Current speed and direction during August 2008 at four different depths (0, -10, -20, -30 m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.

Figure 46  
Current speed and direction during August 2009 at four different depths (0, -10, -20, -30 m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.
Figure 47  Current speed and direction during August 2010 at four different depths (0, -10, -20, -30 m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.

Figure 48  Current speed and direction during August 2011 at four different depths (0, -10, -20, -30 m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.
Figure 49  Current speed and direction during September 2006 at four different depths (0, -10, -20, -30 m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.

Figure 50  Current speed and direction during September 2007 at four different depths (0, -10, -20, -30 m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.
Figure 51  Current speed and direction during September 2008 at four different depths (0, -10, -20, -30 m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.

Figure 52  Current speed and direction during September 2009 at four different depths (0, -10, -20, -30 m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.
Figure 53  Current speed and direction during September 2010 at four different depths (0, -10, -20, -30m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.

Figure 54  Current speed and direction during September 2011 at four different depths (0, -10, -20, -30m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.
Figure 55  Current speed and direction during October 2006 at four different depths (0, -10, -20, -30 m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.

Figure 56  Current speed and direction during October 2007 at four different depths (0, -10, -20, -30 m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.
Figure 57  Current speed and direction during October 2008 at four different depths (0, -10, -20, -30m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.

Figure 58  Current speed and direction during October 2009 at four different depths (0, -10, -20, -30m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.
Figure 59  Current speed and direction during October 2010 at four different depths (0, -10, -20, -30 m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.

Figure 60  Current speed and direction during October 2011 at four different depths (0, -10, -20, -30 m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.
Figure 61  Current speed and direction during November 2006 at four different depths (0, -10, -20, -30m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.

Figure 62  Current speed and direction during November 2007 at four different depths (0, -10, -20, -30m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.
Figure 63  Current speed and direction during November 2008 at four different depths (0, -10, -20, -30 m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.

Figure 64  Current speed and direction during November 2009 at four different depths (0, -10, -20, -30 m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.
Figure 65 Current speed and direction during November 2010 at four different depths (0, -10, -20, -30 m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.

Figure 66 Current speed and direction during December 2006 at four different depths (0, -10, -20, -30 m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.
Figure 67  Current speed and direction during December 2007 at four different depths (0, -10, -20, -30 m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.

Figure 68  Current speed and direction during December 2008 at four different depths (0, -10, -20, -30 m m.s.l.) offshore the Italian landfall site (point 40.375°N 18.5°E) - MyOcean data.
Figure 69  
Current speed and direction during December 2009 at four different depths (0, -10, -20, -30 m a.s.l.) offshore the Italian landfall site (40.375°N 18.5°E) - MyOcean data.

Figure 70  
Current speed and direction during December 2010 at four different depths (0, -10, -20, -30 m a.s.l.) offshore the Italian landfall site (40.375°N 18.5°E) - MyOcean data.
APPENDIX D

Description of MIKE 3 HD FM model
MIKE 21 & MIKE 3 FLOW MODEL FM
Hydrodynamic Module
Short Description
**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.

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

**Flow Model FM modules**
- Hydrodynamic Module, HD
- Transport Module, TR
- Ecology Module, ECO Lab
- Oil Spill Module, ELOS
- Sand Transport Module, ST
- Mud Transport Module, MT
- Particle Tracking Module, PT

**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.
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, FL, simulated by MIKE 21 Flow Model FM

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 ECO Lab

Study of thermal recirculation
The Hydrodynamic Module can be coupled to the Ecological Module (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.

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

Model bathymetry of Taravao Bay, Tahiti

Example 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
- Wave radiation stresses
- Sources and sinks

**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

\[
\frac{1}{\rho_0} \frac{\partial p}{\partial x} - \frac{g}{\rho_0} \int_0^z \frac{\partial \rho}{\partial x} \, dz + F_x + \frac{\partial}{\partial z} \left( \frac{\partial u}{\partial z} \right) + u_S S
\]

\[
\frac{1}{\rho_0} \frac{\partial p}{\partial y} - \frac{g}{\rho_0} \int_0^z \frac{\partial \rho}{\partial y} \, dz + F_y + \frac{\partial}{\partial z} \left( \frac{\partial v}{\partial z} \right) + v_S S
\]

**Temperature and salinity**

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

\[
\frac{\partial T}{\partial t} + \frac{\partial uT}{\partial x} + \frac{\partial vT}{\partial y} + \frac{\partial wT}{\partial z} = F_T + \frac{\partial}{\partial z} \left( \frac{D_T}{\partial z} \right) + H + T_S S
\]

\[
\frac{\partial s}{\partial t} + \frac{\partial uS}{\partial x} + \frac{\partial vS}{\partial y} + \frac{\partial wS}{\partial z} = F_s + \frac{\partial}{\partial z} \left( \frac{D_s}{\partial z} \right) + s_S S
\]

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
- **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.

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.

**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
- **Initial conditions**
  - water surface level
  - velocity components
- **Boundary conditions**
  - closed
  - water level
  - discharge
- **Other driving forces**
  - wind speed and direction
  - tide
  - source/sink discharge
  - wave radiation stresses

View button on all the GUIs in MIKE 21 & MIKE 3 FM HD for graphical view of input and output files.
The Mesh Generator is an efficient MIKE Zero tool for the generation and handling of unstructured meshes, including the definition and editing of boundaries.

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 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 Jeppesen Norway.

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: www.mikebydhi.com/Download/DocumentsAndTools/Tools/AvailableData.aspx
**Model Output**

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

- **Basic variables**
  - water depth and surface elevation
  - flux densities in main directions
  - velocities in main directions
  - densities, temperatures and salinities

- **Additional variables**
  - Current speed and direction
  - Wind velocities
  - Air pressure
  - Drag coefficient
  - 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.

**Validation**

Prior to the first release of MIKE 21 & MIKE 3 Flow Model FM the model has successfully been applied to a number of rather basic idealized situations for which the results can be compared with analytical solutions or information from the literature.
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 (black) fine mesh and (red) measurements

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

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.
The MIKE 21 & MIKE 3 Flow Model FM are 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.

Graphical User Interface
The MIKE 21 & MIKE 3 Flow Model FM are 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.
**Parallelisation**
The computational engines of the MIKE 21/3 FM series are available in versions that have been parallelised using both shared memory (OpenMP) as well as distributed memory architecture (MPI). The result is much faster simulations on systems with many cores.

![MIKE 21/3 FM speed-up using multicore PCs for Release 2011 with distributed memory architecture (blue) and shared memory architecture that was part of Release 2009 (green)](image)

**Hardware and Operating System Requirements**
The MIKE 21 and MIKE 3 Flow Model FM Hydrodynamic Module supports Microsoft Windows XP Professional Edition (32 and 64 bit), Microsoft Windows Vista Business (32 and 64 bit) and Microsoft Windows 7 Enterprise (32 and 64 bit). Microsoft Internet Explorer 6.0 (or higher) is required for network license management as well as for accessing the Online Help.

The recommended minimum hardware requirements for executing MIKE 21 & MIKE 3 Flow Model FM are listed below:

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Requirement Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processor</td>
<td>3 GHz PC (or higher)</td>
</tr>
<tr>
<td>Memory (RAM)</td>
<td>4 GB (or higher)</td>
</tr>
<tr>
<td>Hard disk</td>
<td>160 GB (or higher)</td>
</tr>
<tr>
<td>Monitor</td>
<td>SVGA, resolution 1024x768</td>
</tr>
<tr>
<td>Graphic card</td>
<td>32 MB RAM (or higher), 32 bit true colour</td>
</tr>
<tr>
<td>Media</td>
<td>CD-ROM/DVD drive, 20 x speed (or higher)</td>
</tr>
</tbody>
</table>

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


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

MIKE by DHI
DHI
Agern Allé 5
DK-2970 Hørsholm
Denmark
Tel: +45 4516 9333
Fax: +45 4516 9292
www.mikebydhi.com
mikebydhi@dhigroup.com

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

![Modelling the world with flexible meshes](image)


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

APPENDIX E

Description of MIKE 3 MT FM model
MIKE 21 & MIKE 3 FLOW MODEL FM
Mud Transport Module
Short Description
**MIKE 21 & MIKE 3 Flow Model FM – Mud Transport Module**

This document describes the Mud Transport Module (MT) under the comprehensive modelling system for two- and three-dimensional flows, the Flexible Mesh series, developed by DHI.

The MT module includes a state-of-the-art mud transport model that simulates the erosion, transport, settling and deposition of cohesive sediment in marine, brackish and freshwater areas. The module also takes into account fine-grained non-cohesive material.

With the FM series it is possible to combine and run the modules dynamically. If the morphological changes within the area of interest are within the same order of magnitude as the variation in the water depth, then it is possible to take the morphological impact on the hydrodynamics into consideration. This option for dynamic feedback between update of seabed and flow may be relevant to apply in shallow areas, for example, where long term effects are being considered. Furthermore it may be relevant in shallow areas where capital or considerable maintenance dredging is planned and similarly at sites where disposal of the dredged material takes place.

Example of spreading of dredged material in Øresund, Denmark

The MT module is an add-on module to MIKE 21 & MIKE 3 Flow Model FM. It requires a coupling to the hydrodynamic solver and to the transport solver for passive components (Advection Dispersion module). The hydrodynamic basis is obtained with the MIKE 21 or MIKE 3 FM HD module. The influence of waves on the erosion/deposition patterns can be included by applying the Spectral Wave module, MIKE 21 FM SW.

Example of sediment plume from a river near Malmö, Sweden
**Application Areas**

The MT module is used in a variety of cases where the erosion, dispersion, and deposition of cohesive sediments are of interest. Fine-grained sediment may cause impacts in different ways. In suspension, the fines may shadow areas over a time span, which can be critical for the survival of light-depending benthic fauna and flora. The fine-grained sediment may deposit in areas where deposition is unwanted, for instance in harbour inlets. Furthermore, pollutants such as heavy metals and TBT are prone to adhere to the cohesive sediment. If polluted sediment is deposited in ecologically sensitive areas it may heavily affect local flora and fauna and water quality in general.

**Example of resuspension in the nearshore zone. Caravelas, Brazil.**

The MT module has many application areas and some of the most frequently used are listed below:

- Dispersion of dredged material
- Optimisation of dredging operations
- Siltation of harbours
- Siltation in access channels
- Cohesive sediment dynamics and morphology
- Dispersion of river plumes
- Erosion of fine-grained material under combined waves and currents
- Studies of dynamics of contaminated sediments

**Computational Features**

The main features of the MIKE 21 & MIKE 3 Flow Model FM Mud Transport module are:

- Multiple sediment fractions
- Multiple bed layers
- Flocculation
- Hindered settling
- Inclusion of non-cohesive sediments
- Bed shear stress from combined currents and waves
- Waves included as wave database or 2D time series
- Consolidation
- Morphological update of bed
- Tracking of sediment spills

**Example of modelled physical processes**
**Model Equations**

The governing equations behind the MT module are essentially based on Mehta et al. (1989). The impact of waves is introduced through the bed shear stress.

The cohesive sediment transport module or mud transport (MT) module deals with the movement of mud in a fluid and the interaction between the mud and the bed.

The transport of the mud is generally described by the following equation (e.g. Teisson, 1991):

\[
\frac{\partial c^i}{\partial t} + \frac{\partial uc^i}{\partial x} + \frac{\partial wc^i}{\partial y} + \frac{\partial wc^i}{\partial z} = \frac{\partial}{\partial x} \left( \frac{\nu_T x}{\sigma_T x} \frac{\partial c^i}{\partial x} \right) + \frac{\partial}{\partial y} \left( \frac{\nu_T y}{\sigma_T y} \frac{\partial c^i}{\partial y} \right) + \frac{\partial}{\partial z} \left( \frac{\nu_T z}{\sigma_T z} \frac{\partial c^i}{\partial z} \right) + S^i
\]

The transport of the cohesive sediment is handled by a transport solver for passive components (AD-module). The settling velocity \(w_s\) is a sedimentological process and as such it is described separately with the extra term \(\frac{\partial c^i w_s}{\partial z}\) using an operator splitting technique.

**Symbol list**

- \(t\): time
- \(x, y, z\): Cartesian co-ordinates
- \(u, v, w\): flow velocity components
- \(D_v\): vertical turbulent (eddy) diffusion coefficient
- \(\partial^i\): the \(i\)'th scalar component (defined as the mass concentration)
- \(w_s\): fall velocity
- \(\sigma_{Tx}\): turbulent Schmidt number
- \(\nu_T x\): anisotropic eddy viscosity
- \(S\): source term

The bed interaction/update and the settling velocity terms are handled in the MT module.

The sedimentological effects on the fluid density and viscosity (concentrated near-bed suspensions) are not considered as part of the mud process module. Instead they are provided as separate sub-modules as they are only relevant for higher suspended sediment concentrations (SSC).

**Settling velocity**

The settling velocity of the suspended sediment may be specified as a constant value. Flocculation is described as a relationship with the suspended sediment concentration as given in Burt (1986). Hindered settling can be applied if the suspended sediment concentration exceeds a certain level. To distinguish between three different settling regimes, two boundaries are defined, \(c_{floc}\) and \(c_{hindered}\), being the concentrations where flocculation and hindered settling begins, respectively.

**Constant settling velocity**

Below a certain suspended sediment concentration the flocculation may be negligible and a constant settling velocity can be applied:

\[w_s = k \quad c < c_{floc}\]

where \(w_s\) is the settling velocity and \(k\) is the constant.

**Flocculation**

After reaching \(c_{floc}\), the sediment will begin to flocculate. Burt (1986) found the following relationship:

\[w_s = k \left( \frac{c}{\rho_{sediment}} \right)^\gamma \quad \text{where} \quad c_{floc} > c > c_{hindered}\]

In which \(k\) is a constant, \(\rho_{sediment}\) is the sediment density, and \(\gamma\) is a coefficient termed settling index.

**Hindered settling**

After a relatively high sediment concentration \((c_{hindered})\) is reached, the settling columns of flocs begin to interfere and hereby reducing the settling velocity. Formulations given by Richardson and
Zaki (1954) and Winterwerp (1999) are implemented.

**Deposition**
The deposition is described as (Krone, 1962):

\[ D_D = w_s c_b p_D \]

where \( w_s \) is the settling velocity of the suspended sediment (m s\(^{-1}\)), \( c_b \) is the suspended sediment concentration near the bed, and \( p_D \) is an expression of the probability of deposition:

\[ p_D = 1 - \frac{\tau_b}{\tau_{cd}} \]

In the three-dimensional model, \( c_b \) is simply equal to the sediment concentration in the water cell just above the sediment bed.

In the two-dimensional model, two different approaches are available for computing \( c_b \). If the Rouse profile is applied, the near bed sediment concentration is related to the depth averaged sediment concentration by multiplying with a constant centroid height:

\[ c_b = \bar{c} \times \text{(centroid height)} \]

Teeter (1986) related the near bed concentrations to the Peclet number (\( P_e \)), the bed fluxes, and the depth averaged suspended sediment concentrations. In this case, the near bed sediment concentration is described as:

\[ c_b = \bar{c} \times \left(1 + \left(\frac{P_e}{1.25 + 4.75 \left( \frac{p_d}{2.5} \right)^{2.7}}\right)\right) \]

where \( P_e \) is the Peclet number:

\[ P_e = \frac{w_s h}{D_z} \]

where \( h \) is the water depth, \( D_z \) is the eddy diffusivity, both computed by the hydrodynamic model.

**Erosion**
Erosion features the following two modes.

**Hard bed**
For a consolidated bed the erosion rate can be written as (Partheniades, 1965):

\[ S_E = E \left( \frac{\tau_b}{\tau_{ce}} - 1 \right)^n \quad \tau_b > \tau_{ce} \]

Where \( E \) is the erodibility (kg m\(^{-2}\) s\(^{-1}\)), \( n \) is the power of erosion, \( \tau_b \) is the bed shear stress (N m\(^{-2}\)) and \( \tau_{ce} \) is the critical shear stress for erosion (N m\(^{-2}\)). \( S_E \) is the erosion rate (kg m\(^{-2}\) s\(^{-1}\)).

**Soft bed**
For a soft, partly consolidated bed the erosion rate can be written as (Parchure and Mehta, 1985):

\[ S_E = E \left( e^{\alpha \sqrt{\frac{\tau_b - \tau_{ce}}{\tau_{ce}}} - 1} \right) \quad \tau_b > \tau_{ce} \]

**Consolidation**
When long term simulations are performed consolidation of deposited sediment may be an important process. If several bed layers are used a transition rate (\( T_i \)) can be applied. This will cause sediment from the top layers to be transferred to the subsequently lower layers.

**Solution Technique**
The solution of the transport equations is closely linked to the solution of the hydrodynamic conditions.

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. In the horizontal plane an unstructured grid is used while in the vertical domain in the 3D model a structured mesh is used. 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 time integration is performed using an explicit scheme.
The MT module is a tool for estuarine sediment management in complex estuaries like San Francisco Bay, California, USA.

**Model Input**
The generic nature of cohesive sediment dynamics reveals a numerical model that will always call for tremendous field work or calibration due to measurements performed. The following input parameters have to be given:

- Settling velocity
- Critical shear stress for erosion
- Critical shear stress for deposition
- Erosion coefficients
- Power of erosion
- Suspended sediment
- Concentration at open boundaries
- Dispersion coefficients
- Thickness of bed layers or estimate of total amount of active sediment in the system
- Transition coefficients between bed layers
- Dry density of bed layers

**Model Output**
The main output possibilities are listed below:

- Suspended sediment concentrations in space and time
- Sediment in bed layers given as masses or heights
- Net sedimentation rates
- Computed bed shear stress
- Computed settling velocities
- Updated bathymetry

**Validation**
The model engine is well proven in numerous studies throughout the world:

**The Rio Grande estuary, Brazil**
In 2001, the model was applied for a 3D study in the Rio Grande estuary (Brazil). The study focused on a number of hydrodynamic issues related to changing the Rio Grande Port layout. In addition the possible changes in sedimentation patterns and dredging requirements were investigated.

**SSC in surface layer (kg/m$^3$), Rio Grande, Brazil**

Principle of 3D mesh
The figure below shows the most common calibration parameter, which is the suspended sediment concentration (SSC). The results are reasonable given the large uncertainties connected with mud transport modelling.

A comparison between measured and simulated SSC time series is shown below. The overall comparison is excellent.
The graphical user interface of the MIKE 21 & MIKE 3 Flow Model FM MT module including an example of the Online Help System

**Graphical User Interface**

The MIKE 21 & MIKE 3 Flow Model FM, Mud 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 utilities such as the Mesh Generator, the Data Viewer and the Data Manager.
**Parallelisation**

The computational engines of the MIKE 21/3 FM series are available in versions that have been parallelised using both shared memory (OpenMP) as well as distributed memory architecture (MPI). The result is much faster simulations on systems with many cores.

**Hardware and Operating System Requirements**

The MIKE 21 and MIKE 3 Flow Model FM Mud Transport Module supports Microsoft Windows XP Professional Edition (32 and 64 bit), Microsoft Windows Vista Business (32 and 64 bit) and Microsoft Windows 7 Enterprise (32 and 64 bit). Microsoft Internet Explorer 6.0 (or higher) is required for network license management as well as for accessing the Online Help.

The recommended minimum hardware requirements for executing MIKE 21 & MIKE 3 Flow Model FM Mud Transport Module are:

| Processor: | 3 GHz PC (or higher) |
| Memory (RAM): | 4 GB (or higher) |
| Hard disk: | 160 GB (or higher) |
| Monitor: | SVGA, resolution 1024x768 |
| Graphic card: | 32 MB RAM (or higher), 32 bit true colour |
| Media: | CD-ROM/DVD drive, 20 x speed (or higher) |

**Support**

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


For further information on MIKE 21 & MIKE 3 Flow Model FM software, please contact your local DHI office or the Software Support Centre:

MIKE by DHI  
DHI  
Agerne Allé 5  
DK-2970 Hørsholm  
Denmark  
Tel: +45 4516 9333  
Fax: +45 4516 9292  
www.mikebydhi.com  
mikebydhi@dhigroup.com

**References**


References on applications


