METHODOLOGICAL TOOL
Usefulness of numerical modelling to assess new offshore disposal sites

"Application of ecosystem principles for the location and management of offshore dumping sites in SE Baltic Region (ECODUMP)"

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PART 1

Preliminary assumptions to modelling of spreading fine fractions of sediments during their deposition on the dumping sites
1. Introduction

One of the tasks of the ECODUMP project (Application of ecosystem principles for the location and management of offshore dumping sites in SE Baltic region) was to evaluate the usefulness of numerical modeling to study the characteristics of dumping sites in different operational phases and under various environmental forcings.

The objective of this study was to present the methodology which was applied to build the numerical model used in the analysis of hydrodynamic processes during deposition of dredged material on offshore dumping sites. The model was constructed with the use of the licensed, Danish software package MIKE 21 Coupled Model FM. Both Russian and Polish groups decided to build their models, within the ECODUMP project, on the basis of the above mentioned software. This software package has been developed for years in the Danish Hydraulic Institute (DHI) and it is used for calculations of flows, waves and sediment transport, both in the coastal zone and in the open sea. Obviously, this is not the only way to model the impact of offshore dumping sites. For example, the Lithuanian group has chosen the SHYFEM software as a tool to build numerical models within the ECODUMP project. That software is not the subject of this study and it has been described in Lithuanian reports.

The authors of this study would like to present a method for the construction of the model, as well as for the collection of source data to be used in the model, verification of the sources and collection of data for model calibration. In addition, they propose types of data which would contribute to the reliability of the model, e.g. parameters of bottom sediments in the area of a dumping site. The aim of this work is to use the existing software efficiently. Readers who are deeply interested in the MIKE software, i.e. equations, numerical methods, software limitations and future innovations, should look for detailed, specific information concerning MIKE software package and get interested in excellent courses and consultations conducted by DHI investigators.

This study has been divided into two parts. The first part is focused on the construction of the model. In this part, the following issues have been discussed: initial assumptions regarding the operating range of the model, numerical mesh generation, definition of initial and boundary conditions, characteristics of dredged material and bottom sediments, and technology of works. Moreover, several analyses used for model calibration and verification have been presented in this part.

In the second part, the results obtained from the simulation performed using numerical models have been discussed. Different graphic forms which can be used to assess the adverse impact of dredged material disposal operations on the surrounding marine environment have been proposed. The measures of the impact are: suspended sediment concentration, extent of the plume impact, time of occurrence of elevated concentrations in the water column (resulting from the discharge of dredged material on the selected dumping site), as well as potential for the movement of deposited material as a consequence of strong currents.

The work is aimed at showing the practical benefits of numerical modeling.
2. Data required for model setup

2.1 Model layout

The construction of each numerical model is related to the adoption of certain assumptions and making some selections that should lead to the creation of the most effective tool. The first step includes the selection of the calculation area. In the initial phase, the area that is directly investigated is known, e.g. in the current task – the area of the dumping site which is clearly geographically defined. However, determination of the area that may be affected by operations associated with dredged material deposition is much more difficult. The extent of the impact can vary greatly depending on the environmental forcing factors, which include sea currents, waves, wind, tides, etc.

When building numerical models, it is advised to introduce the minimum number of open boundaries, for which it is necessary to define boundary conditions. Boundary conditions at the borders of the model are crucial to the results of the calculations. In case of any uncertainties regarding description of the boundaries of the model, it is recommended to increase the distance of the boundaries from the main analyzed area. To some extent, such approach can minimize the influence of an uncertain condition on the whole calculation.

The best results are obtained in the local model (spatially limited) when it is possible to generate all the necessary boundary conditions from the model which operates at a much lower resolution on a regional scale. A hypothetical example of such approach would be to generate boundary conditions for a local model (e.g. Gulf of Riga, Gulf of Gdańsk) from a regional model of the Baltic Sea. In practice, boundary conditions are often adopted for extended boundaries, based on: locally conducted measurements, other models operating on a regional scale or hypothetical assumptions.

In the construction of a model, natural contours of the shoreline or characteristic elements of bottom topography are often taken into account.

Time scales of the modeled issues were different for each of the partners of the project. The time horizon of long-term modeling is usually one year or several years, while in the short-term modeling it relates to weeks or months. For a long-term scale, the modeling was focused on the search for the answers to the questions: How can the material deposited on the dumping site be transported in the process of resuspension? Is any negative impact possible (e.g. sedimentation on the existing waterways, impact on sensitive areas)? While for a short-term scale, the goal of the modeling was to determine the adverse environmental impact of dredged material deposition.

2.1.1 Design of the model area with definition of its boundaries

In the preparatory phase, several options of computational areas for the analysis of dumping sites selected by each of the ECODUMP project partners were tested. These tests covered both existing dumping sites and hypothetical areas for future dumping sites. Schematically, sample computational areas have been presented in Fig. 1.

Model I was used for the analyzed dumping sites located within Lithuanian waters. In this area there are two open boundaries. The distance of the western boundary of the model from the land, near Klaipeda, is approx. 35 km, and the distance from the offshore boundaries of the dumping site
exceeds 20 km. Hence, the influence of the boundary condition on the analyzed areas is important. Moreover, the area of Model I is subject to alongshore currents, so the condition adopted at the northern boundary is of crucial importance for the whole current field inside the model area. For such edges of the model, boundary conditions have to be specified precisely. Errors at the boundaries would significantly affect the results of numerical simulations. On the other hand, for such area, it is acceptable to adopt forcing condition (wind parameters) which is constant in space and varying in time.

The distance of boundaries from the analyzed dumping site in Model II is considerable and exceeds 200 km and 120 km, respectively, in relation to the western and northern boundary. With such large distances, boundary conditions will have less direct impact on the local area of the examined dumping site. However, imposition of the forcing condition becomes more complicated, since the assumption of its constancy in space may be questionable for such a large area.

In Model III, the natural shape of the shoreline was used to build the model in the gulf area. Similarly as in the case of Model I, high accuracy in the adoption of boundary conditions is required. It is worth noting that in the model with more complex shoreline, the importance of wind forcing in relation to the effect of boundary conditions may vary, depending on the direction of main forces. The impact of the peninsula and shallow areas can also play an important role.

For example, to build the model for Gdynia dumping site, the numerical mesh was generated only for the western part of the Gulf of Gdańsk. However, numerical simulations, particularly those related to hydrodynamic conditions, showed an increased sensitivity of the results of numerical calculations to close proximity of the dumping site (area marked with red lines in Fig. 2 and the adopted marine boundary of the model. As a consequence, an adjustment was made, involving the extension of the model so that the marine boundary was on the outline of the gulf.

Fig. 1. Examples of model area selection
For the studies of local issues, it is recommended to build local models which sometimes require verification, possible corrections and paying particular attention to the definition of boundary conditions.

![Fig. 2. A) Preliminary selected model area for the analysis of Gdynia dumping site, B) Model area after correction](image)

### 2.1.2 Rules for numerical mesh generation

Each computational area must be divided into elements. In the case of numerical mesh generation of Flexible MESH type, it is possible to use rectangular and triangular elements. For the areas which are geometrically simpler but important for the calculations, such as channels or special-purpose regions, rectangular elements, which are more efficient because of lower CPU usage in computers, can be used. On the other hand, the advantage of using triangular elements is that the outline of the designated computation area is definitely better, especially when the shoreline is highly developed. In any case, more accurate projection is connected with longer calculation time.

In the initial phase, the numerical mesh is generated automatically, with limited involvement (including assumptions on the size of individual elements) of the supervisor. The example of the initial numerical mesh for Gdynia dumping site, with limitation of the element surface area maximally to 0.75 km², has been shown in Fig. 3. After analyzing lots of calculation results and applying recommendations of software developers, it becomes clear that mesh refinement in the areas where water depths decrease is an approach that provides tangible benefits. The mesh shown in the previous figure will be changed into the version shown in Fig. 4, after application of the above mentioned operation.

Next steps related to the modification of the computational mesh are directly connected with the purpose of the model. For example, in the present task concerning the analysis of the processes occurring during deposition of dredged material on offshore dumping sites, sudden modifications in the size of mesh elements should be avoided, as this may lead to a false image of changes in concentrations of suspended sediments. When the sediment plume crosses the border between relatively small and significantly bigger elements, it becomes diluted only numerically and it is not a physical process. On the other hand, at the site of disposal operations, it is advisable to generate elements with the smallest surface area. Hence, it is necessary to gradually move from a region with the smallest elements to the region with considerably larger elements. Of course, in theory, the best solution would be to apply the maximum fine mesh over the entire modeled area but, unfortunately,
it would extend greatly the time of all the calculations and, consequently, prevent their rational performance. Fig. 5 shows the modification of the mesh within the dumping site and the adjacent area. For example, in the prepared model, the numerical mesh was gradually refined (surface area of the smallest elements of the mesh did not exceed 2500 m²) within Gdynia dumping site and the adjacent area in order to obtain the most accurate simulation results.

It is advised to modify numerical mesh in order to create effective models. The effectiveness should be understood, on the one hand, as the increase in details within the sites which are subject to the analysis and, on the other hand, as the ability to perform calculations faster (coarse structured mesh) in the areas of lower priority.

Fig. 3. Initial discretization of numerical mesh

Fig. 4. Effect of numerical mesh refinement in the areas of shallow depths
2.1.3 Bathymetric data

A definite depth is assigned to each element of the mesh. Proper projection of bottom topography is one of the most important structural elements of the model. In practice, it often happens that the analyzed area is subject to additional high-resolution bathymetric measurements. Very often there are no such data for the adjacent waters. It is advised to use all the bathymetric data during the construction of the numerical model. When data of better quality (higher resolution) are available, even for fragmented areas within the adopted model area, they should be used.

For example, the process of using the variety of bathymetric data to build the model of Gdynia dumping site has been presented below. During the construction of the Gulf of Gdańsk model, bathymetric data of different resolutions for different areas were available, as shown in Fig. 6. Within the ECODUMP project, special high-resolution measurements were conducted for the area of Gdynia dumping site and data of 5x5 m grid were used in the construction of the numerical model. Archival bathymetric data for Puck Bay and inner part of the Gulf of Gdańsk, owned by the Maritime Institute in Gdańsk, enabled to supplement the numerical model with data of 25x25 m resolution. In the areas with the greatest depths, in outer part of the Gulf of Gdańsk, less accurate data were used. Adoption of all the available data resulted in the following bathymetric map (Fig. 7).
2.1.4 Selection of calculation modules

MIKE 21 Coupled model FM package allows to combine different calculation modules and enables the interaction of results obtained in calculations. In the construction of models related to offshore dumping sites and dredged material deposition, users can choose out of the following modules:

- Hydrodynamic,
- Sand Transport,
- Mud Transport,
- Spectral Wave.
Previously mentioned interactions can be explained as follows: sea currents defined in the *Hydrodynamic module* generate changes in the sea bottom (e.g. *Sand Transport module*) which, in turn, cause changes in the characteristics of flows. We can find many such interactions. Combining too many calculation modules can potentially lead to more errors and can significantly extend the time of calculations. Therefore, it is advisable to build the model using an optimum selection of modules for a specific physical issue.

In the case of analyzing spreading of suspended sediments during deposition of dredged material, the proposed model should consist of the *Hydrodynamic module* and the *Mud Transport module*. It results from the fact that disposal operations can be carried out only under certain wind and wave conditions (calm or moderate), and thus the effect of waves can be omitted. In addition, sand and coarse fractions, which settle on the bottom relatively fast, would not be transported in the suspended form.

In the analysis of the potential movement of sediments deposited on a dumping site, the modules should be selected in a different way. Resuspension of sediments is caused by higher flow velocities at the bottom. Currents which are able to move sediments, in non-tidal seas, are generated by winds, waves, densities differences or sea level gradients. In order to build the model to study transport of sandy sediments, the following modules should be used: *Hydrodynamic, Sand Transport and Spectral Wave*. In the similar task, however, aimed at the analysis of suspended solids generated by resuspension, also three modules should be taken into account and instead of the *Sand Transport module*, the one which deals with mud should be used.

In the selection of calculation modules to build a model, it is essential to take into account the physical phenomena related to the analyzed issues and not to forget about the efficiency of the entire model.

### 2.2 Boundary and initial conditions

Knowledge of environmental conditions in the area of water body and inside this water body is necessary for the construction of a numerical model to simulate hydrodynamic processes taking place during deposition of dredged material on a dumping site and to analyze the fate of deposited sediments influenced by environmental forcings. The process reflected by numerical simulations is the result of conditions imposed by the user at the edges of the model, state of the environment at the starting time (defined by initial conditions) and all the interactions with the environment (environmental forcings) occurring during the simulation.

It is required to determine conditions at the edges of the model for each of the modules separately. In the case of the *Hydrodynamic module*, it is possible to impose boundary conditions in one of the following ways:

- determination of flow velocity components and their variability,
- adoption of flux components with changes in time and space,
- definition of water level fluctuations,
- characterization of the discharge at the boundary,
- determination of the combined condition (velocity components, variability of the water level and, if possible, also definition of the discharge)
• adoption of the boundary as land boundary (closed)

For the Spectral Wave module, it is possible to select one of the following types of boundary conditions:

• wave conditions defined by wave spectral parameters, by wave energy spectrum or by spectral moments (see MIKE Spectral Waves Manual),
• superposition of the energy spectra determined from wave parameters for wind-sea and swell,
• lateral boundary,
• reflective boundary,
• closed boundary.

In the transport modules (Sand Transport Module, Mud Transport Module), boundary conditions can be of Dirichlet type (determination of concentration levels at open boundaries) or Neumann type (defined as zero gradient). In addition, the condition describing land boundary can be imposed.

To achieve the highest accuracy of numerical calculations, it is necessary to choose boundary conditions which are as close as possible to real conditions. For their determination, as previously mentioned, it is required to analyze measurement data in detail or use data from regional numerical models. In the absence of actual measurement data, which is common situation for marine areas, in engineering practice, the results of operational numerical models are used. The best approximation is to apply in the local model the results obtained from the similar operational model of a regional scale by using a nested technique.

In the absence of a model from the same group/class of models, operating on a regional scale, in practice, boundary conditions are often adopted for longer boundaries from locally conducted measurements or the results are taken from other regional operational models. Another common technique is to generate hypothetical boundary conditions. This technique is frequently used to study extreme events.

When building a model, it may happen that the initial condition inside the computing area is unknown. As an example of such situation in the task analyzed in the present study, the concentration level of suspended sediments has been chosen. It is expected that the results of calculations would show the impact of the analyzed action (disposal of dredged material) on the environment. Therefore, it is acceptable to adopt the initial value as zero and to analyze the increase in concentration of suspended sediments caused by simulated operations. Such model is referred to as the excess model.

In case of adoption of the results from other operational models, it is recommended to verify data taken to create boundary conditions, initial conditions or environmental forcings by comparison with the measured values.

2.2.1 Sources of data

In the case of the Baltic Sea, data which can be used in a local model can come from regional models, such as: UMPL, HIRLAM, COAMPS (pressure, wind parameters), HIROMB (variability of water levels, sea currents), WAM (wave parameters). Measurement data used to verify the model can be derived from specific points, for example, from mareographic stations or from the equipment installed at
sea, such as: acoustic profilers of AWAC type, buoys and measuring buoys equipped with various sensors.

Sources which can be used for the construction of boundary conditions, initial conditions and environmental forcings in the southern Baltic region have been presented below.

**Meteorological conditions** – the main forcing factor, largely responsible for the generation of sea currents, wind waves and having great influence on the variability in water levels and wind conditions. For large areas where wind parameters (i.e. direction and speed) cannot be unified, spatial characteristics of winds described by components such as wind speed and pressure varying in time, should be used. In the case of limited areas, it is allowed to use the simplifying assumption that wind is uniform in space and variable in time. For the issues in which the role of wind is not important, this forcing factor can be neglected. In the case of applying actual wind forcings in a numerical model, the results of one of the regional-scale atmospheric models, such as: COAMPS, UMPL or HIRLAM can be used. It should be noted that data used to verify wind parameters are taken from measurements carried out at coastal stations, and the roughness of surface causes that the speeds over water bodies are greater than over the land.

**Hydrological conditions** – for the Baltic Sea, parameters such as variability in the water level and current field are calculated in the regional HIROMB model, which grid resolution is now 1 nautical mile. Variability in the water level is the basic boundary condition, however, for more spatially limited local models, it is advisable to combine this condition with spatio-temporal characteristics of flows at marine edges of the model, by defining components of the velocity. Reduction of the model area causes that the accuracy of the adopted hydrodynamic boundary condition increases. For boundaries where significant differences, especially those concerning flows, are observed, it is advised to examine the extent of the variation in the regional HIROMB model and use the appropriate number of points for the construction of the boundary condition in the local model. In the areas with diverse shoreline, it is recommended, if possible, to verify model results by in-situ measurements. Variability in water levels, introduced as the boundary condition, should be verified by measurements carried out at adjacent coastal stations.

**Wave conditions** – there are several models operating on a regional scale which are used to forecast wave conditions for the Baltic Sea. One of such models is the spectral WAM model (Günter, 2002), which describes surface waves in a satisfactory way. For the construction of local models, even the Danish Hydraulic Institute uses the operational model based on MIKE system. The WAM model, which operationally works at the Maritime Institute in Gdańsk, was repeatedly verified, showing its practical usefulness (Cieślikiewicz and Swerpel, 2005 Paplińska, 1999). According to the remarks in section 2.1.4, in using the **Spectral Wave module** at open boundaries, it is most common to apply parametric description of the wave spectrum characterized by the following parameters: significant wave height $H_w$, wave peak period $T_p$, wave direction $\theta$ and spreading factor $n$. In water bodies where swells play an important role, it is recommended to include this type of waves in the spectrum. Boundaries which are perpendicular to isobaths, connected to the shoreline and shorter than the appropriate offshore boundary, are advised to be defined as lateral. Based on analyses performed in the ECODUMP project, where model wave parameters were compared with measured parameters, the hypothesis of high compliance of the definite elements should be considered correct. A slight
overestimation in the significant wave height $H_s$ was observed in the WAM model only in the case of extremely heavy storms.

### 2.2.2 Methods of verification

In the case of calculations concerning Gdynia dumping site, carried out in the ECODUMP project, in the absence of measurement data, an approach to use boundary and forcing conditions obtained from the regional-scale models (HIRLAM, HIROMB, WAM) in the local MIKE model was applied. When adopting such approach, it is always required to check the reliability of data both in terms of trends and moment values. In order to verify the adopted approach, the results taken from the models were compared with measurements obtained from hydrological coastal stations and from the measurement instrument installed in the area of model calculations. By using the results of measurements from coastal stations, we obtain values from long registration periods. On the other hand, in the results collected by special instruments installed for the purpose of the project or specific project task, data series are much shorter. Nevertheless, all the measurement data collected taking into account calibration procedures, have a great value and can be used to verify numerical models.

Verification is based on the study of correlation between sequences of results obtained from models and measurement series.

For example, in this study, there has been presented a method of verification for the variable describing fluctuations in the water level. Temporal variability of water levels [cm] was analyzed in the period from 2013.09.01 to 2013.10.31, at 5 coastal water gauge stations (Vistula River Mouth, Northern Port of Gdańsk, Gdynia, Puck, Hel). Results of observations from these stations showed that they were in good agreement with one another (Error! Reference source not found.8). It was reflected by high values of linear correlation coefficients ($r > 0.9$), which are the measure of linear statistical relationship between two processes. For example, for two extreme coastal stations: Hel and Vistula River Mouth, the linear correlation coefficient $r$ equaled 0.95. When analyzing the presented results of measurements quantitatively, it must be emphasized that Hel station represents the most open site of all the above stations, while Vistula River Mouth is the location where the local impact of the large river is the greatest. Thus, differences in the values for these two extreme stations should be the greatest.
Generally, it can be assumed that the variation in sea water levels within a relatively small area, i.e. Gulf of Gdańsk, is very similar at all the observation stations.

For further analysis, two stations located closest to the modeled area (Gdynia and Hel) were selected. The results of observations at these two stations, from a period of one month (2013.09.19 - 2013.10.19), were compared with the results obtained from the regional HIROMB model. In order to be able to compare the results, values of sea water level changes derived from the model (relative values) were converted to absolute values, in such a way that their compliance was related to average values from the examined period for the station.

The results of comparisons showed good agreement in both cases: Gdynia-HIROMB and Hel-HIROMB (Error! Reference source not found.9). Linear correlation coefficients are as follows:

\[ r_{\text{Gdynia-HIROMB}} = 0.96, \quad r_{\text{Hel-HIROMB}} = 0.95. \]
Fig. 10. Comparison of changes in sea water level [cm] at two water gauge stations: Gdynia (top) and Hel (bottom) with data obtained from the HIROMB model

The above analysis, which confirmed good agreement of the results of sea water level changes from the HIROMB model and the results from observations at coastal stations (Gdynia, Hel), justifies the adoption of data obtained from the regional HIROMB model for further numerical calculations in the MIKE model.

A wider range of analyses concerning the verification of data sources used to create boundary conditions and environmental forcings was presented in the report by Marcinkowski and Olszewski (2014).

2.3 Seabed characteristics

Determination of seabed parameters is crucial in modeling resuspension and transportation of sediments deposited on dumping sites, and less important in modeling the disposal of dredged material. Obtaining proper data for determination of seabed characteristics is quite expensive. Preliminary information on the geological structure may be collected from geophysical surveys. However, such data are not accurate and need to be supplemented with laboratory analyses of surface sediment samples and/or deeper samples taken from the cores. Parameters such as: grain-size distribution curve or percentage of fine fractions <0.063mm, determined in the laboratory, are the basis for the construction of actual computational models. In practice, characteristics of bottom sediments required for numerical modeling is often adopted based on data from geological atlases. However, in some situations such way of determination of seabed properties can lead to the
adoption of incorrect assumptions. It is important to determine geotechnical parameters, which describe the potential of sediments to be transported, for different types of sediments which constitute the adopted sediment layers. Parameters such as sediment thickness and characteristics of sediment evolution in time are equally important from the point of view of numerical modeling of the fate of dredged material deposited on the seabed.

In modeling, it is possible to adopt up to 12 layers of sediments which build the modeled seabed. From a practical point of view, however, it is advisable to limit their number to a minimum. Distribution of sediment layers should reflect diverse structure of the sea bottom in a sufficient way. In a short period of time, immediately after the disposal of dredged material, the top layer is prone to erosion. This layer has very small thickness and extremely unfavorable geotechnical parameters, it needs to be clearly defined in a model and described as at least two layers. Sediments have different density values, depending on their geological history, content of organic particles, sedimentation conditions etc. Parameters which characterize modeled sediment layers and their proneness to erosion have to be specified in the constructed numerical models. For sediments consisting of the finest fraction, the authors of the software recommend to use dry density values specified in Tab. 1., and critical shear stress values for sediments prone to resuspension, presented in Tab. 2.

Tab. 1 Typical bed densities (DHI, MIKE 21 FM, Manual)

<table>
<thead>
<tr>
<th>Sediment age</th>
<th>General description</th>
<th>Geological behaviour</th>
<th>Dry density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freshly deposited (1 day)</td>
<td>Fluffy</td>
<td>Mobile fluid mud</td>
<td>50-100</td>
</tr>
<tr>
<td>Weakly consolidated (1 week)</td>
<td>Mud</td>
<td>Fluid stationary mud</td>
<td>100-250</td>
</tr>
<tr>
<td>Medium consolidated (1 month)</td>
<td>Deforming cohesive bed</td>
<td></td>
<td>250-400</td>
</tr>
<tr>
<td>Highly consolidated (1 year)</td>
<td>Stationary cohesive bed</td>
<td></td>
<td>400-550</td>
</tr>
<tr>
<td>Stiff mud (10 years)</td>
<td>Stiff clay</td>
<td>Stationary cohesive bed</td>
<td>550-650</td>
</tr>
</tbody>
</table>

Tab. 2 Critical shear stresses – recommended values (DHI, MIKE 21 FM, Manual)

<table>
<thead>
<tr>
<th>MUD TYPE</th>
<th>DENSITY [kg/m³]</th>
<th>TYPICAL $\tau_{ce}$ [N/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mobile fluid mud</td>
<td>180</td>
<td>0.05 – 0.10</td>
</tr>
<tr>
<td>Partly consolidated mud</td>
<td>450</td>
<td>0.20 – 0.40</td>
</tr>
<tr>
<td>Hard mud</td>
<td>600+</td>
<td>0.60 – 2.00</td>
</tr>
</tbody>
</table>
Next parameter which characterizes sea bottom is its roughness. This value is expressed in meters and most often defined as sediment grain diameter multiplied by a factor of 2.5. In the case of very fine sediments, it is advisable to define the roughness as 0.001 m.

Macroscopic analysis of core samples collected within the ECODUMP project at the dumping site showed that the surface layer of sediments is constituted mainly by sandy and silty fractions: from fine-grained sands and silty sands to silts. The results of analyses confirmed the assumptions of the MIKE software developers that sediments deposited relatively recently can be characterized by significantly loose structure. Finer fractions observed in the sediments of the area adjacent to the dumping site give evidence that the sediments are dispersed during disposal of suspended dredged material.

2.4 Dredged material characteristics

Proper determination of the parameters of the material deposited on a dumping site is very important for the construction of the model to simulate deposition operations. Dredged material, obtained as a result of maintenance dredging operations in the waterways and harbor basins, rarely can be treated as homogeneous. Hence, it is necessary to define the material for the purpose of modeling as several fractions of sediments. Number of fractions in the model is limited to 8. However, it is recommended to set the minimum number which describes the dredged material in a satisfactory way. Description of each type of sediments forming the slurry requires the determination of:

- velocity and way of settling of sediment particles,
- sediment deposition criteria.

The free falling occurs when the number of particles is small. In this case, each particle falls in an independent way, without affecting the neighboring particles. Granular particles are most frequently subject to free falling. In case of higher particle concentration we can observe flocculation process and the velocity of falling increases. Further increase in the concentration of suspended sediments leads to the process of hindered settling. A more detailed description of the way of suspended sediment falling and sedimentation, depending on the level of its concentration, can be found in the literature (Van Leussen, 1988; MIKE21 FM Manual, 2014). Fall velocity of sediments can be determined in laboratory conditions. The dependence of this velocity and grain-size diameter has been presented in Tab. 3.

<table>
<thead>
<tr>
<th>SEDIMENT TYPE</th>
<th>GRAIN DIAMETER [mm]</th>
<th>AVERAGE DIAMETER [mm]</th>
<th>FALL VELOCITY [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>0.0020 – 0.0040</td>
<td>0.0030</td>
<td>0.00002</td>
</tr>
<tr>
<td>Very Fine Silt</td>
<td>0.0040 – 0.0080</td>
<td>0.0060</td>
<td>0.00006</td>
</tr>
<tr>
<td>Fine Silt</td>
<td>0.0080 – 0.0160</td>
<td>0.0120</td>
<td>0.00019</td>
</tr>
<tr>
<td>Medium Silt</td>
<td>0.0160 – 0.0320</td>
<td>0.0240</td>
<td>0.00050</td>
</tr>
<tr>
<td>Coarse Silt</td>
<td>0.0320 – 0.0625</td>
<td>0.0473</td>
<td>0.00150</td>
</tr>
<tr>
<td>Very Fine Sand</td>
<td>0.0625 – 0.1250</td>
<td>0.0938</td>
<td>0.00350</td>
</tr>
<tr>
<td>Fine Sand</td>
<td>0.1250 – 0.2500</td>
<td>0.1875</td>
<td>0.00700</td>
</tr>
<tr>
<td>Medium Sand</td>
<td>0.2500 – 0.5000</td>
<td>0.3750</td>
<td>0.01700</td>
</tr>
</tbody>
</table>
In order to define each type of sediments, for the purpose of the model, it is necessary to determine sediment deposition criteria. It can be achieved by indication of the threshold for shear stress, below which the process of sedimentation starts. These threshold values of the shear stress would always be lower than the adopted values of the critical shear stress, which characterize the same kind of sediments deposited on the bottom and above which their movement is initiated.

### 2.5 Technology of transport and unloading

Methods of transport and unloading of dredged material are selected according to its type. Dredged material can be transported to a dumping site by pipelines, in dredger hoppers or in dump scows.

In modeling, transport and unloading should be presented in the form which is as close to actual operations as possible. The routes of dump scows or dredgers should be carefully mapped in the model, taking into account their velocities during transport and unloading. In addition, it is necessary to specify the way of unloading, which is characterized by the intensity of discharge expressed in kg/s, duration of unloading of a large dump scow (dredger) and the entire sequence of disposal works. This type of works can last for a period of several weeks or even months.

It has been indicated in section 2.4 that dredged material may consist of several fractions, and each of them behaves differently in the water column. Sands and gravels almost immediately fall and stay at the bottom. Other situation occurs in the case of single fine-silt and clay particles of 0.063 – 0.002 mm and <0.002 mm in diameter, respectively. These fine particles remain long in the water column before they finally settle on the bottom.

Each of the fine fractions goes into the suspended state in a different extent, and it becomes one of the major problems when selecting parameters for numerical models. This is not always dependent on the diameter of the particles because, for example, the smallest fractions (clays), due to their large cohesion cannot be crushed easily and in the form of lumps fall to the bottom very quickly. The percentage of clay fractions, which become suspended in the water column, would be lower than silty fractions, which diameters are larger but cohesion is lower. The amount of dredged material which goes into the suspension depends not only on the type of sediments but also on all the technological operations. These operations include: way of dredging, transport and unloading of dredged material.

Most often, it is assumed that 3% of the total weight of fine-grained sand would become suspended. This information is widespread in the literature, however, there is no information on finer sediments. In case of significant mechanical dilution of silty fractions (e.g. caused by method of unloading or segregation during transport), it can be expected that up to 30% of the volume of such sediments may go into the state of suspension.

When carrying out bigger projects and in the construction of more accurate numerical models, it is advisable to conduct laboratory analyses concerning the characteristics of the deposited material.
Another parameter which describes unloading technology is the intensity of discharge. It depends on the load capacity of a transportation vessel and on the duration of discharge. These parameters are necessary to build the model and each time they have to be obtained from the company which performs dredging operations and from the investor who accepted the technology of discharge.

3. Summary

The objective of the study was to present the principles of building numerical models used to determine the fate of dredged material deposited on the seabed, at offshore dumping sites which are subject to the influence of different environmental forcings. In the ECODUMP project, open-source and licensed software programs have been used.

The process of task development has been divided into two parts. The first part is related to the construction of the model. In this part, the following issues are included: assumptions regarding the size of the area being under the influence of disposal operations, numerical mesh generation, initial and boundary conditions, required characteristics of dredged material and bottom sediments, and essential technological information on dredging/disposal works. Moreover, main data sources needed to build the model and methods for their verification have also been presented in the first part.

The developed algorithms allow to model the fate of deposited material both for a long-term (years) and short-term (weeks/months) scale. In terms of long-term predictions, calculations were focused on the answers to the questions: How can the material deposited on the dumping site be transported in the process of resuspension? What impact does it have on the environment? On the other hand, short-term calculations were aimed to identify the negative environmental impact of dredged material deposition.

In the phase of numerical model preparation, calculations for the several selected existing dumping sites and hypothetical areas for future dumping sites were carried out. The analyzed locations were selected by the partners of the ECODUMP project.

In the present study, the following issues have been discussed:

- appropriate selection of the numerical mesh, so as not to introduce numerical errors in the calculations and, simultaneously, create effective models,
- proper mapping of the sea bottom,
- proper selection of initial and boundary conditions, particularly in the absence of actual measurement data,
- verification of data sources for boundary conditions,
- determination of seabed parameters,
- characteristics of the deposited material,
- projection of the actual schedule and technology of dredged material deposition in calculations.
PART 2
Use of numerical modelling results
1. Introduction

The ECODUMP project (Application of ecosystem principles for the location and management of offshore dumping sites in SE Baltic region) was implemented in the years 2011 – 2014. The main partners of the project were: Coastal Research and Planning Institute (CORPI) in Klaipeda, Maritime Institute in Gdaňsk and the Atlantic Branch of P.P. Shirshov Institute of Oceanology of the Russian Academy of Sciences in Kaliningrad.

One of the ECODUMP project tasks was to evaluate the usefulness of numerical modeling to assess disposal sites exposed to environmental forcings in different phases of their development. This task was divided into two parts. The first part focused mainly on the phase of model construction and has been presented in the first part of the Report. In the present second part of the Report, both the results and the conclusions arising from the numerical simulations have been described.

As written in the Report I, the local model obtained in the study was built on the basis of the licensed Danish software MIKE 21 Coupled Model FM (2008). Boundary and initial conditions in this model were adopted from the so-called regional model which covered the entire Gulf of Gdaňsk. This regional model was, in turn, nested in the regional model of the Baltic Sea. As noted in the first part of the study, the results obtained from regional models were used for the construction of initial and boundary conditions.

Although the correctness of these results was partially verified based on the available measurements, the number of assumptions introduced during the construction of the model required from the user to check the correctness of the model each time using the experimental measurements. When analyzing complex processes, e.g. spread of the suspension under the influence of environmental forcings, it is recommended to divide the validation process into modules, i.e. separate analysis of hydrodynamic parameters, wave parameters or transport phenomena. Such methodology was used in the validation process of the constructed model. Specifically, it was related to the analysis of the compliance of its individual components (modules) with the values experimentally measured during the ECODUMP project.

In the following part of the study, the usefulness of the results of numerical simulations for the practical use in the assessment of the impact of dredged material on the environment has been analyzed. This analysis concerned both phases: disposal of dredged material at offshore dumping sites and behavior of the material under the influence of the marine environment.

The choice of location for dumping sites and disposal operations has to be taken in such a way as to take into account the impact on:

- biological environment,
- physico-chemical environment,
- protected areas and species,
- areas of human activity.

Currently, numerical modeling is a tool used more and more frequently in environmental studies. The popularity of modeling causes that it often becomes a replacement for experimental studies that
require more time and large financial resources for measurement equipment. However, it should be emphasized that in the phase of model validation, it is virtually impossible not to conduct actual physical measurements. It is important to know which instruments and measurement methods are used, be aware of their limitations and recognize errors in experimental results.

Comments on the results obtained from numerical simulations have also been included in the study. The authors have pointed out some ways of presenting the results and they have shown how to use them to assess the impact.

2. Numerical model validation

Each constructed numerical model should undergo the process of validation. The purpose of this process is to estimate errors resulting from the assumptions adopted in the model which is solved numerically. The validation allows to determine to what extent the model, developed using specific software, describes actual physical phenomena. In other words, the validation assesses the correctness of the model in the light of experimental studies. In the present task, empirical validation based on the comparison of simulation results with data obtained from experimental measurements was performed. Discrepancies between model results and actual measurements allow to better define the assumptions made for the purpose of dumped material simulation, to modify computational mesh discretization or to adjust boundary conditions. Validation process is carried out after the construction of a model and is based on the assessment of compliance between empirical measurement series and their calculated equivalents.

2.1 In-situ measurements

The research carried out in the marine environment, within the ECODUMP project, included: bathymetric surveys, grab sampling and core collection in the dumping site area, analysis of dumped sediments, as well as the measurements of variations in sea water level, wave parameters, distribution of sea currents in the vertical profile and point measurement of sea water turbidity. The aim of the first group of measurements and sample collection was to obtain information that could help to set up the model, especially in the field of characteristics of bottom sediments and dumped material. The parameters such as: consistency of dredged material, content of different size fractions and the amount of the material which would go into suspension during disposal operations, are crucial for the accuracy of the constructed model. The results from the first group of measurements were used to verify and modify the assumptions of the model.

The results of measurements from the second group were primarily used to empirically validate the model, but also they turned out to be useful to describe hydrodynamics of the basin where the research was conducted. It should be noted that experimental results do not need to be more accurate in terms of quantity than the results of numerical calculations. However, the experimental data reflect actual conditions in the most reliable way.

In the ECODUMP project, the measurements were conducted accurately and according to general recommendations. Due to limited reliability of a single measurement, the whole series of hydrodynamic measurements was planned. In addition, measurement instruments were changed between the measurement series. The operators complied with the measurement procedures of the Maritime Institute. As it was impossible to conduct simultaneous measurements in different
locations (equipment limitations), the results of measurements performed within another research task were partially used.

In the area of the investigated dumping site, an acoustic current profiler Nortek AWAC was installed at the bottom. Additionally, that measurement station was equipped with an optical backscatter sensor for measuring turbidity. The sensor, after the process of calibration, was able to provide information about the concentration of suspended particles by detecting near infrared (NIR) radiation scattered from suspended particles.

The results obtained from the current profiler concerned different types of hydrodynamic phenomena. Basic information provided by the measurements was the distribution of sea currents as a function of water depth in the area where AWAC was installed. Three components of the velocity vector were recorded, with the speed module and current direction being one of the most important.

For example, Fig. 2a shows the speed module (solid line) and current direction (points) recorded at a depth of 13.5 m. In addition, the variability of these parameters has been presented in a chosen period of six days. The frequency of measurements and the duration of a single sample are to be determined by a user who defines the research program. The distribution of current speed in the whole water column for a chosen moment in time has been presented in Fig. 2b. The speed of current, as a main factor forcing the movement of sediments, has been included in the validation.

![Figure 2a](image1.png)

**Fig. 2. Example of current speed recorded by AWAC: a) module and direction at a chosen water depth, b) speed distribution against depth in a chosen moment**

Validation of hydrodynamic modules in mathematical-numerical models, especially the comparative analysis of current fields, indicates that in the case of marine basins with diverse shoreline and bathymetry, it is not easy to obtain the desired compliance. As previously mentioned, the development has to cover not only numerical models but also, to the same extent, measurement techniques.
In spectral wave module, the comparative analysis is related to parameters that characterize waves. A comparison of wave heights (significant wave height $H_s$) obtained from numerical simulations and measurements is most often presented in the literature. However, the other wave parameters such as: wave period, direction and spreading factor, are not less important. For the measurements of wave height and period, the central beam of the measurement device, in particular its feature called Acoustic Surface Tracking, is used. Fig. 3 shows an example of wave parameters recorded in a period of two weeks at a point located on the dumping site. It is recommended to analyze all the wave parameters because, if they are included, the picture of waves in a basin is more accurate. This applies especially to the cases where the swell plays a significant role in wave motion. In addition, it is advisable to compare experimental results and those obtained from the numerical model (after statistical and spectral analyses). An example of the recorded measurement after spectral analysis has been presented in Fig. 4.

Another parameter taken into account in the validation process is the variability in sea water level. Fluctuations in the water level were recorded by a pressure sensor in the measurement device. Fig. 5 shows an example of a record for a 23-day measurement period. In the validation process, the correlation between the values obtained from measurements and the results of numerical simulations for the same period of time were studied. As previously mentioned, it is recommended to carry out several series of measurements and, if it is possible, conduct the measurements in different locations.
Fig. 5. Example record of a variability in sea water level

Also, other physical parameters measured in the marine environment can be used in the validation process. In the case of the model built based on SHYFEM software, partners from Lithuania used the results of sea water level, salinity and temperature measurements in the process of validation. Measurements of turbidity or suspended solids concentration are the other parameters used to validate and calibrate numerical models. It is advisable to use the results of turbidity measurements conducted during periods of intensive environmental forcing, in order to determine the concentration of suspended solids occurring naturally in the marine environment. In the works carried out in the framework of the ECODUMP project, an OBS type sensor was also used. Measurements conducted directly over the bottom surface, in calm conditions, indicated concentrations of up to 5 mg/l in the dumping site area. Unfortunately, measurement records from the storm period were not representative because of the sensor failure.

2.2 Numerical model results versus measurements

After performing numerical simulations, based on the local MIKE21 model (in which values obtained from regional models, including HIROMB and WAM, were imposed as boundary and forcing conditions), the results were compared with the real data obtained from measurements in the selected point within the dumping site.

The purpose of this comparison was to validate the numerical model and calibrate hydrodynamic and wave modules on the basis of the measurement data.

The comparison of numerical model results after the calibration and the values of sea level, significant wave height and water flow velocity, measured at the point where AWAC instrument was installed, have been shown in the following figures (Fig. 6, Fig. 7, Fig. 8).

A good agreement was observed between the results of water levels, wave heights and current speeds from measurements and those calculated from the model.

During calibration of the hydrodynamic model, it was necessary to introduce changes in the initially taken values of bottom roughness and in the characteristics of friction at the sea surface. After their introduction, the agreement between the measured current speeds and those calculated from the model was improved.
Fig. 6. Comparison of sea level changes in time (2014.02.10-2014.03.09) between the results from the MIKE model and data measured by AWAC in the chosen point within the dumping site

Fig. 7. Comparison of significant wave height changes in time (2013.11.16-2013.12.10) between the results from the MIKE model and data measured by AWAC in the chosen point within the dumping site

Fig. 8. Comparison of current speed changes in time (2013.11.16-2013.12.10) between the results from the MIKE model and data measured by AWAC in the chosen point within the dumping site

The most difficult challenges in the process of validation and calibration of the model are related to the transport modules. On the one hand, it is connected with expensive and difficult to carry out measurement session(s) and, on the other hand, with large amount of empirical parameters which occur in numerical models.

In the case of analyzing signals from instruments for measuring turbidity and concentration of suspended solids, it is recommended to collect, in at the time of measurements, water samples for control analyses. Indications of the instrument usually change with the concentration of suspended solids.
solids and they also depend on the type of suspended solids in the suspension. Measurements should be carried out under conditions when the concentration of the suspended solids is changing. Such situation occurs when environmental conditions change rapidly, or it can be caused by human activity (dredging, burying pipelines, disposal of dredged material etc.).

Configuration parameters used in the mud transport module are far less known and described in the literature, and the range of their use is very broad. The parameters defined in the model and used in the calibration of the model are: speed of free fall, boundary shear stress, percentage of a certain fraction which goes into suspension in the water column. The numerical model is sensitive to the above parameters.

3. Analysis of model results

The outcome of numerical simulations concerning the spread of suspension illustrates the whole process of sediment deposition occurring in the marine environment. During the simulation, extensive sets of results are created, including the consecutive time steps of the behavior of dumped material which is subject to the influence of various external factors, such as: wind, sea currents, waves, physical properties of water, turbulence, bottom topography and shoreline diversity. All these factors have an impact on the spread of suspension in the basin, and in each time step they modify its concentration, the extent of its impact and thickness of sediments that are created. The main difficulty in preparing final reports is related to the need of selection of representative data sets. It concerns both the presentation of selected time steps and the implementation of post processing of the results in order to obtain the best possible description of the modeled phenomenon.

3.1 Effects of coastline and bathymetry

In the case of disposal of sediments on the open-sea dumping sites, e.g. Łeba, Ustka, Darłowo, Kołobrzeg or Klaipeda, the impact of a quite uniform shoreline is secondary and, practically, it is not taken into account in the calculations. But when dumping sites are located in bays and lagoons with highly varied shoreline, its influence on the calculation results is clear.

A classic example of the impact of varied shoreline and bathymetry on the circulation of waves and currents can be found in the Bay of Puck together with part of the Gulf of Gdańsk. This area is surrounded by the Hel Peninsula on one side and, on the other side, by varied shoreline with sandspits, small bays, alluvial fans at river mouths, shoals, underwater sills and troughs, which all lead to specific water flows that are not a direct result of wind or wave impact. These modified currents are the major factor that determine the direction of sediment movement. An example modification of the current circulation in the above-mentioned region has been shown in Fig. 9.
Fig. 9. Current circulation calculated for a water body with varied shoreline and bathymetry
For water bodies with diverse shoreline and large local depth amplitudes, it is difficult to a priori predict the dominant direction of sediment transport based on known environmental forcing conditions. Therefore, when planning works associated with the disposal of dredged material, it is advisable to use the numerical modeling as an effective tool to describe real hydrodynamic conditions occurring in a water body.

3.2 Water flow direction
Regardless of the impact of varied shoreline and bathymetry on the directions of water flow in open waters and bays, presented in section 3.1, the situations when wind and wave directions are not consistent with current directions can also be observed. When sensitive areas such as fisheries, spawning grounds, aquacultures etc., are found to be influenced by a dumping site, under unfavorable current direction, the knowledge of the characteristics of the currents may allow to make proper decisions concerning the time of disposal and the amount of dredged material to be disposed. An example of the calculated directions of suspension spread which is variously directed with respect to the forcing condition, i.e. wind, has been presented in Fig. 10.
Fig. 10. Calculated directions of suspension spread with respect to wind direction:

a) consistent directions, b) deviated directions, c) opposite directions
In open areas, including the areas of bays where there are no disturbing factors, the direction of suspension spread almost coincides with the direction of wind. The case presented in Fig. 10a is related to the Gulf of Gdańsk area when the wind blows from the SE sector, while the situation shown in Fig. 10b is associated with winds of increasing speed from NE-E direction. The opposite directions of wind and suspension spread occur when the wind blows from the west, as shown in Fig. 10c. For the cases discussed above, the use of numerical modeling turns out to be a very useful tool when implemented before disposal operations. It potentially indicates the directions of suspension spread depending on forcing factors. In order to systematically increase the reliability of numerical modeling, the exchange of experience between the institutions responsible for the supervision of offshore dumping sites and people who construct and work with numerical models should be encouraged.

3.3 Suspended sediment concentration and the range of its impact

One of the basic criteria for assessing the impact of the works associated with dredged material disposal at offshore dumping sites on the environment is the estimation of the increase in concentrations of suspended solids above the environmental background level. The permissible concentrations can be specified in recommendations or standards, and can also result from ecological studies conducted for selected areas or for particular investment projects. It is recommended that the works related to the disposal of dredged material are carried out in such a way that the permissible concentrations for particular waters bodies are not exceeded. Most often it is controlled by the technology of unloading, specifically, the frequency of unloading, duration of unloading the dredgers or dump scows and spatial range at which the unloading is carried out. It should be noted, however, that the most important thing from the ecological point of view is that the disposal works and dredged material should have a very limited and controlled impact on neighboring areas. Hence, the use of numerical modeling in the analysis of the impact of works conducted on dumping sites should refer primarily to the estimation of the spreading of suspended solids and their concentrations, mainly outside the dumping sites. In contrast, local and short-term processes (e.g. unloading) are less important.

For the analysis of the impact range and the distribution of average concentrations of suspended solids, two-dimensional numerical models, where the outcome for concentrations is averaged over the entire water depth of the water body in a particular place, can be used. The calculations from the model allow to present the distribution of averaged concentrations of suspended solids at each time step. Usually, the most common is to show only the particular moments, e.g. largest linear range of the plume, maximum spatial impact of the suspension, extreme concentrations of the suspension, etc. For example, Fig. 11 shows the maximum spatial impact of the suspension for a selected simulation at Gdynia dumping site (dredged material transported by dump scows). This type of depiction, in accordance with the previous remark, involves a single time-step of numerical simulation (snapshot) and is very useful in the presentation of extreme situations.
Fig. 11. Momentary extreme concentration of suspended solids during the discharge of dredged material from dump scows in the area of the dumping site.

For a more comprehensive presentation of the results of numerical models, it is recommended to post-process the data. As a result of such operations, it is possible to create maps of maximum concentrations of the suspension at every point of the adopted calculation area or maps showing the areas where the threshold concentration for the suspension is exceeded. These maps do not represent a specific time-step but they have an envelope character of the concentration levels for the full duration of the simulation. Fig. 12 shows an example of the map of maximum concentrations of suspended solids, calculated for the area of the dumping site and for the adjacent area. The presented maximum levels of concentrations occurred in the study area during the disposal of 94,000 m³ of dredged material in the period of 1.5 month. Such maps are a useful tool for the assessment of environmental disturbances caused by disposal works carried out in the area of offshore dumping sites.
3.4 Exposure time of suspension

In studies on the environmental effects of dumping sites, two types of impacts are particularly important. The first one is related to the process of deposition in the selected area. Apart from contaminated sediments that are not the subject of this study, the behavior of the finest fractions is potentially considered as the most unfavorable. These fractions may remain suspended in the water column for a long time and be transported with water for considerable distances, far from the designated area of a dumping site. The second type of adverse impact can be due to a significant increase in forcing factors (sea currents, waves) that affect the previously deposited material. The so-called resuspension process, defined as a renewed suspension of precipitated particles, mainly involves the finest fractions. In both of the above mentioned impacts, the amount of the sediments that are transported is important – their concentration in the water column, and on the other hand, the residence time in the state of suspension. The longer the sediments remain in the water column, the greater the distance over which the suspension can be transported. Therefore, the residence time in the water column is an important factor taken into account in the analyzes. One of the possible ways of the graphic presentation of this phenomenon is to show the exceedance time of a certain threshold of suspended solids concentration at every point of the adopted area of calculation. This period of time can be expressed as a percentage of the total simulation time. This means that if the simulation time in the scenarios is for example 60 days, the percentage values presented in the map refer to this period. Therefore, for example, the area bounded by the isoline of 2% means a region in which the exceedance time of a concentration threshold lasts 28.8 hours. The adopted threshold concentration value presented in the maps refers to the permissible values or concentrations that are hazardous from the ecological point of view. An example of such...
interpretation has been presented in Fig. 13, for the calculations related to the Gdynia dumping site. The simulation shows a 1.5 month period of time and the adopted threshold concentration of the suspension is 30 mg/l.

![Diagram](image)

**Fig. 13.** Percentage of 30 mg/l threshold exceedance time for sediment concentration resulting from the discharge of dredged material from dump scows in the area of the dumping site.

Thanks to the use of numerical models, the duration of suspension impact can be estimated. The proposed way of presenting the results of calculations, similarly as in chapter 3.3, is global, describes the entire period of numerical simulation and requires the use of data post-processing with respect to the calculation results obtained from models.

### 3.5 Deposited sediment thickness

In order to present the results of computational simulation concerning the layer of sediments formed as a result of dredged material disposal in the area of a dumping site, several ways of the analysis can be proposed.

One of these is to show the state of the bottom at any time step of the simulation. It is a kind of image of the situation that existed temporarily and in the next time steps it could be fully or partially changed as a result of the hydrodynamic situation in the sea, or due to changes in the way of disposal or type of dredged material. Another way of presentation and analysis of the results is to show the state of the bottom after completion of a certain phase of operations – e.g. at the end of any sequence of dredged material disposal from a specified number of dump scows or after a certain period of disposal operations in a cycle: dredging – transport – disposal.

From the ecological point of view, the information on the maximum thicknesses of sediments in the whole analyzed area and during the entire simulation is very important. To obtain this result, it is necessary to apply one of the procedures (post-processing of the calculation results) which allows to select data which we are interested in.
Thicknes of the sediment layer in the area of the dumping site and its vicinity, after the computational simulation, has been presented in Fig. 14. The outcome of this simulation shows the layer of sediments formed by sedimentation of fine fractions after the disposal works (discharge from dump scows) had been finished. The additional time needed for the sedimentation of suspension on the area of calculation has been added. This example shows that the thickness of the sediment layer formed outside the dumping site is insignificant. Maps which are made in such a way are an important element supporting the assessment of changes in the environment caused by the disposal of dredged material.

![Fig. 14. Thickness of the sediment layer in the area of the dumping site and its vicinity after disposal works](image)

4. Summary

One of the tasks in the ECODUMP project was to investigate the usefulness of numerical modeling in the assessment of the locations proposed for offshore dumping sites. The numerical models were constructed based on the known and recognized software packages such as: MIKE 21 by the Danish Hydraulic Institute or SHYFEM by Oceanography, ISMAR-CNR, Venezia. The analysis of all steps of the construction of models for the assessment of the impact of offshore dumping sites in different phases of their development, revealed several important issues that should be taken into account during the verification and calibration of the model. These should include the following:

- verification of individual modules (hydrodynamic, spectral wave, transport) included in numerical models, using the results of available empirical measurements,
- study of the effects of complex configuration of shorelines and bathymetry on the hydrodynamics of the basin,
- implementation of the measurements of suspended sediment concentrations and the use of the results (including historical) of such measurements conducted during increased forcing conditions (wind, waves, currents) in the calibration of numerical models,
- determination of physical parameters of dredged material deposited on dumping sites and native sediments that are present in the area of dumping sites; the use of such parameters in the constructed model.

The conducted calculations showed the usefulness of numerical modeling in the analysis of phenomena related to the use of offshore dumping sites. The following phenomena are the most important.

- Spread of the sediments deposited at dumping sites during disposal operations. In the model this process is analyzed both in terms of distribution and variation in the concentration of suspension and in terms of spreading of the plume.
- Spread of the sediments deposited at dumping sites as a result of intensive environmental forcings, in the process of resuspension. It is taken into account in the model that the shear stress for sediments at the dumping site can be exceeded and they can be re-introduced in the state of suspension to the water column.
- Sedimentation of dredged material that is deposited at dumping sites. As a result of numerical simulation, the image of the thickness of new sediment layer at the analyzed area is obtained.
- Time of residence of the deposited material in the state of suspension.

Another important issue related to the use of modeling is the presentation of results. In the studies and reports, it is very common to use graphical way of presentation that illustrate extreme situations (maximum concentration, range, thickness, intensity of resuspension, etc.) related to a specific moment (snapshots) in the simulation, obtained directly from the implementation of a particular model. Equally important graphical way of presentation is to show the effects of the entire period of dredging/disposal operations. These types of maps are obtained from post-processing of the calculation results. In this study we have presented several examples of results presentation, however, other ways of presentation are also possible.

In conclusion, it should be emphasized that the range of data necessary to build numerical models is still assessed as insufficient. It is advisable to develop the exchange of information between stakeholders (management units, teams supervising the operations, contractors of dredging works, scientific groups responsible for modeling of the phenomena related to the use of dumping sites) involved in the management and use of offshore dumping sites.
References


