Scientific Journals
of the Maritime University of Szczecin

Zeszyty Naukowe
Akademii Morskiej w Szczecinie

2016, 46 (118), 189–196
ISSN 1733-8670 (Printed)
ISSN 2392-0378 (Online)
DOI: 10.17402/136

Received: 31.08.2015
Accepted: 08.03.2016
Published: 27.06.2016

Modeling the impact of surface currents in a harbor using graph theory

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Key words: hydrodynamic models, graph theory, Geographic Information System (GIS), Electronic Navigational Chart (ENC), accident

Abstract

Ensuring security in a harbor requires research into its infrastructure using spatial environmental data. This paper presents a methodology that defines the design of a graph for modeling the interactions between surface currents and moving objects. Combining this graph with port charts that integrate electronic navigation charts with coastal orthophotographs allows us to perform a multidimensional analysis. In addition, the complete information about navigation and harbor infrastructure allows us to predict the effects of currents on objects that are moving in the dock. The capabilities of this application were tested in the Gdynia harbor and the defined graph is based on sea currents generated by the numerical hydrodynamic model M3D.

Introduction

In the harbor area, accidents can occur both on the land and in the water. The crews of ships in port must therefore show vigilance and analyze all of the available information about the environment for the purpose of mooring or leaving port. Threats exist even when the ship is in a harbor. For example, one harbor accident happened on 17.05.2012 (at approximately 9 am) when the ferry Stena Spirit in the port of Gdynia hooked onto the arm of one of the cranes and the broken steel arm fell onto the containers stored on the wharf. This accident injured three people. In Polish ports, an average of three maritime accidents occurs every year (Yearbook, 2012). Accidents also take place in other European harbors, but the port administration is trying to mandate preventive actions to eliminate their occurrence (Port Information Guide, 2013). The solution presented in this paper can be used for this purpose.

In harbor docks there are many restrictions due to the local hydrometeorological conditions (e.g. water currents, strong winds or rain). In addition, the security in these areas depends on the intensity and diversity of the local economic activities and the protection of nature. The large number of transported objects, such as cargo-handling equipment, and the high traffic volume cause a significant increase in the amount of information required to ensure security; however, traditional nautical charts are insufficient due to the scant information contained in them (Pyrchla & Przyborski, 2003). Indeed, the provision of complete information is far beyond traditional marine cartography. A comprehensive analysis of a region allows the identification of the type of information mostly needed in a given area. This information must include the following:

- environmental information, including geographical and hydrodynamic data;

- characteristics of the activity carried out in the area (e.g. transportation, communication, and underwater works);
- characteristics of the marine and terrestrial infrastructure (e.g. navigation elements and port facilities), with the critical infrastructure necessary for a harbor to function (e.g. its basin and terminals);
- foreseeable scenarios of disruptions to the functioning of the structures or economic activity, as a result of the risks in the studied area and the probability of their occurrence.

The development of new technology and security measures is designed to reduce the risks from an expanding list of threats. Hybrid harbor maps represent a largely underused technology, which could provide useful information. The main repository for these maps is created in a network-centric geodatabase in the ArcGIS environment. To recognize the complete current situation, the entities that obtain, manage and use information should be linked with each other (preferably in real time) in order to be able to exchange information. Indeed, the main purpose of creating hybrid harbor maps is achieving information supremacy, thus increasing operation efficiency.

The structure of the upgraded geodatabase is adjusted to maintain a dialogue between the different sources of stored data, describing the atmosphere and hydrosphere (or combination of these data with other types of data). This database's structure also allows the use of a map as a base pattern to decide on the necessary actions. The proposed solution of a network-centric map is extremely useful for risk management issues in port areas (Gauss, Rötting & Kersandt, 2012). Information about the direction and speed of the currents in the basins is very important from a safety standpoint. The directions of these currents are linear, and no mesoscale eddies have been observed. The currents' parameters (i.e., their speed and direction) are determined by factors other than measurements in open water (Reissmann et al., 2009). The steps of the computational grid have to be much smaller than in the case of constricted bodies of waters, such as bays (Elken, 2011). Additionally, cross-sections for viewing the currents at different depths have to be taken at smaller intervals: approximately every 2 m. It is extremely important to depict the current situation in the region; this requirement ensures that the system in use has the necessary components, which are the following:

- a Geographical Information System (GIS);
- data from an Electric Navigational Chart;
- data from atmospheric and hydrodynamic models and from other applications;
- terrestrial data (e.g. orthophotographs and topographic maps).

The platform that integrates all of the data recorded in different standards and cartographic projections is GIS. For hydrographic vector data, the International Hydrographic Organization (IHO) S-57 Transfer Standard for Digital Hydrographic Data is used. Visualization is managed on the GIS system (ArcGIS), integrated with the S-57 Viewer. This unit provides the marine chart and utilizes symbols for the navigational marks in accordance with the S-52 norm S-52. To record an additional information layer, general results from international standards for hydrographic spatial data are used. Data from the numerical meteorological and hydrological forecasts are recorded in the form of numeric grid data. In the AML (Additional Military Layer) conception, we used two forms to exchange gridded data: GRIB (the Grid and Binary) and NetCDF (the Network Common Data Form). To create hydrometeorological data layers for the harbor area, we used the NetCDF form because it can be applied to the GIS system (ArcGIS 10). To ensure broad compatibility, we decided to use the NetCDF files' recommendation, which is included in the attribute convention made by the Unidata–Attribute Convention for Dataset Discovery (ACDD) as well as in the Climate and Forecast Metadata Convention (CF). These standards allow the use of multiple applications for the visualization and analysis of spatial data.

In this paper, we will discuss issues associated with the use of graph theory to model the infiltration of environmental data. The modeling of transit routes in conditions in which space is limited, such as docks, taking into account the environmental conditions, can be done in many ways (Thakur, Svec & Gupta, 2012). The solution proposed in this paper uses graph theory, which seems to be more suited to the actual conditions. This methodology can also be used to model the transport of sediments. The determination of the most common direction of currents can predict the sediment buildup inside the basins, which is a widely reported phenomenon in (Winterwerp, 2006) and the literature cited in their work. We will also describe the characteristics of spatial data derived from numerical hydrodynamics and meteorological forecasts by compiling additional layers of harbor maps.

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Marine hybrid maps of harbor areas

To prepare a map of Gdynia harbor as a platform for integrating all of the digital geospatial data from different sources, we used a Geographic Information System. This system allows a variety of thematic layers to be imposed on a common map: land coastal areas (e.g. topographic information and orthophotographs), marine electronic navigational charts (bathymetry and navigation symbols) and environmental data (from hydrodynamic and numerical weather models). GIS allows us to connect digital data stored in different standards and projections (Figure 1).

Orthophotographs for Gdynia harbor were recorded in graphical format, which allows additional geo-referenced information (GeoTIFF), and in the Polish National Geodetic Coordinate System 2000 (PUWG 2000); the latter format is recommended in Poland for large-scale maps. Electronic data for maritime navigational charts are presented in the IHO S-57 format. An addition to standard ArcGIS, Viewer S-57 allows the visualization of S-57 data in compliance with S-52 standards for chart content and display aspects. ArcGIS 10.0 also allows cells from an electronic navigational chart (ENC) that follows the S-57 standards, to be imported into a geodatabase. Therefore, it is possible to conduct geospatial analyses with S-57 data and ENCs.

Multi-dimensional spatial data were successfully processed and visualized in the NetCDF form's standard development by the Unidata Program Center in the University Corporation for Atmospheric Research (UCAR). NetCDF is a combination of data format, interfaces and software libraries that support the creation, access and sharing of files, where these files have multidimensional data organized in tables. This solution allows us to consider the treatment time as an additional dimension. We can choose, for example, a field with information about the currents at the appropriate hour and create animation in real time using the Time Slider tool in the ArcGIS program.

NetCDF files are self-describing, i.e., they have information (metadata) about the data contained in them. The recorded data can therefore be interpreted without any additional information. Metadata contain information about the recorded parameters (e.g. the units, the correct range of the data, and the lack of data encoding) the data's source and their geospatial properties (such as the dimensions of arrays, resolution, and projections). The NetCDF standard

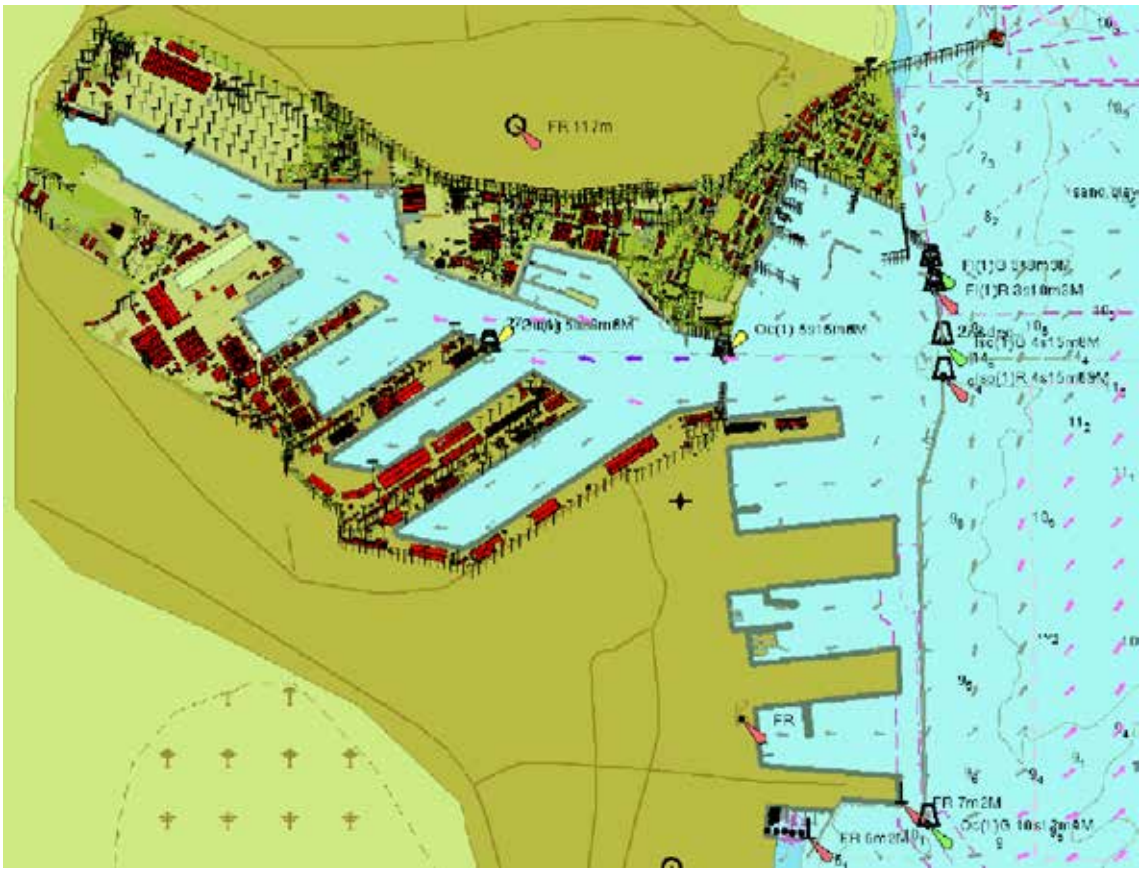

Figure 1. Maps of the Gdynia harbor reservoir with a thematic layer showing – currents from the numeric hydrodynamic model

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is independent of the computer architecture, and furthermore, it is in a machine-independent format of floating-point numbers. This format allows immediate access to the data, which means that any part of a dataset can be read effectively without reading the previous data. Moreover, the user can add data to an existing file without changing its structure (but only in one dimension). In addition, there are ways to change the file structure as well as parallel input-output operations. Since NetCDF is an open format, the user can record data in many ways. This flexibility is the reason that standardization is needed in the way in which data is described and introducing conventions for metadata is vital.

Information about the dataset's dimensions, attributes, and variables should be saved in Unidata's convention, namely ACDD, which provides the capability of reading files through the many applications that have been designed for the visualization and processing of geospatial information. The convention specifies the axis definition (by indicating names, directions, etc.). The attributes of the metadata usually contain a series of important information about the data's origin, projection, and source as well as their status or authors. Furthermore, these data allow binding of geographical data and display maps for different applications, e.g. in the GIS system. The standard names and units of the parameters should be given in accordance with the Climate and Forecast Metadata Convention (CF) Standard. Moreover, the attributes allow the definition of the ranges and special values of the areas that lack sufficient data.

Hydrodynamic models provide information about the dynamics of marine areas, such as currents and waves, and hydrological parameters, such as water temperature, salinity, and sea level. Currently, for the Gulf of Gdansk, data are available from the WAM wave model (Paplińska, 1999), which has been working in the ICM since 2002, with a spatial resolution of approximately 16.7 km. In the Institute of Oceanography at the University of Gdansk (IO UG), project PROZA (http://proza.ocean.univ.gda.pl) is underway, and it uses the WAM model with resolutions of five or two nautical miles; however, this work still adopts a nested waving WAM model on a regional scale (the Baltic Sea and the south Baltic) and on SWAN on a local scale (the Gulf of Gdansk and its North Port neighbor).

In the case of hydrodynamic models, there are two operating systems: HIROMB (Funquist, 2001) and M3D (Kowalewski, 1997; Kowalewski & Kowalewska-Kalkowska, 2011). These models have similar reliability (Pyrchla & Kowalewski, 2009). For our hybrid harbor map, the modeled data were downloaded from the M3D model because of the possibility of obtaining results at much higher resolutions. For the experiments presented in this paper, we launched a special version of the M3D model with a resolution of 0.1 nautical miles (approximately 185 m). The model uses so-called σ-coordinates from 18 layers of unequal thickness in the vertical direction. Moreover, this model uses data from the numerical weather forecast model derived from the UM model running in the ICM and allows for 60-hour forecasts of currents, sea level, temperature and salinity. In the calculation, we take into account the climatic effects of river runoff and the exchange of water in the North Sea through its open boundary.

A graph as a model of the interactions of surface currents in a harbor's waters

This paper presents a methodology for defining a graph that will model the interactions of the surface currents in a harbor's waters. As an example of a harbor reservoir, we used a map of Gdynia harbor. Data for the construction of this model were derived from the hydrodynamic numeric M3D model, which generates specific grid nodes based on the direction and speed of the surface current.

Using these data as a starting point, we developed the concept of building a directed graph with weights (i.e. a network). The vertices of our graph correspond to nodes of discretization in the harbor grid. For each vertex of the graph there are at most eight outgoing and eight incoming. For each on one of these edges a value of the weight function has been assigned. The basis for determining this weight function is the direction of the surface current in the nodes of the discretization grid, determined by the hydrodynamic model.

Graph theory is a branch of discrete mathematics widely used in many scientific disciplines, such as geodesy. In previous works (e.g. Kozioł, 2002; Clementini & Billen, 2006; Cruz Guzman, Lewandowicz & Oziewicz, 2006; Egenhofer, 2010; Packa & Lewandowicz, 2010), graph models were used to describe geographic data of regions, micro-regions, parcels, roads, and bike trails. These graphs describe the spatial relationships between different geographic objects. It is worth noting that these objects are on the ground, and furthermore, the examined relationships do not change in the course of the analysis.

The aim of this study is to develop a new graph model for a completely different type of spatial data.

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These data pertain to the interactions of surface currents that occur in a selected basin and derive from numerical hydrodynamic models that generate information regarding the currents with a time step that represents an additional hurdle.

A hydrodynamic model determines the directions and speeds of surface currents in the discretization grid nodes. In the following pages, indicates the number of discretization grid nodes, each one described in terms of latitude and longitude. We use this notation:

- (x_i, y_i), where i is the node of the discretization grid ($i = 1,2,...,n$);
- x_i – the longitude of i-th node;
- y_i – the latitude of i-th node;
- α_i – the direction of the surface current at i-th node;
- v_i – the speed of the surface current at i-th node.

Based on data from the hydrodynamic model, we built a directed graph with weights (a network). This graph is a model of a surface's current interactions, which occur in the waters of Gdynia harbor and affect the objects in the water.

A directed graph (which will from here on be referred to simply as *a graph*) is an ordered pair of two sets (V, E), where $V \neq 0$ and $E \subseteq V^2$; this graph is denoted by $G = (V, E)$. The elements of V are the vertices of the graph G, and the elements of E are its edges. A graph with weights is a network where each edge has been assigned a number, called the edge weight.

In a graph $G = (V, E)$, which is a model of the interactions of the surface currents in Gdynia harbor's waters, the set of vertices is defined as follows:

$$V = \{1,2,...,n\} \tag{1}$$

where the vertex i corresponds to a node (x_i, y_i) of the discretization grid. Thus, vertex 1 corresponds to the node (x_1, y_1), vertex 2 corresponds to the node (x_2, y_2), etc.

In the graph $G = (V, E)$, the set of edges is of the form:

$$\begin{aligned} E &= \left\{(i,j) \in V^2 : \left|(x_i, y_i)(x_j, y_j)\right| \le \sqrt{d_1^2 + d_2^2}\right\} = \\ &= \left\{(i,j) \in V^2 : \sqrt{(x_j - x_i)^2 + (y_j - y_i)^2} \le \sqrt{d_1^2 + d_2^2}\right\} = \\ &= \left\{(i,j) \in V^2 : (x_j - x_i)^2 + (y_j - y_i)^2 \le d_1^2 + d_2^2\right\} \end{aligned} \tag{2}$$

where d_1 is the discretization step of the longitude and d_2 is the discretization step of the latitude (Figures 2 and 3).

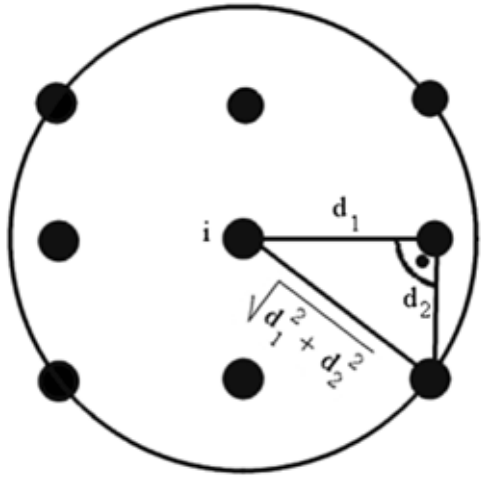

Figure 2. Vertex *i* and its neighbors

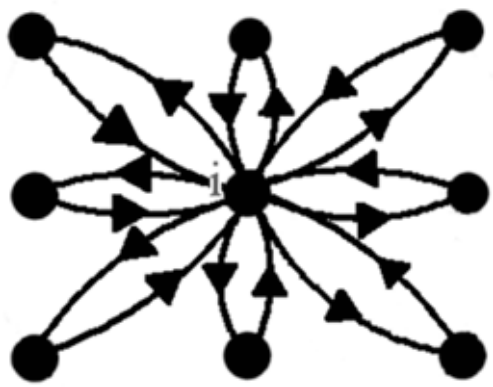

Figure 3. Vertex *i* and incident outgoing and incoming edges

In our case, $d_1 = d_2$.

The definition of the edge set E implies that an edge $(i, j) \in E$ if and only if the edge $(j, i) \in E$. Thus, each vertex of the graph G has the same number of outgoing and incoming edges. In addition, each vertex of the graph G is incident with at most eight incoming edges and at most eight outgoing edges.

Let $f : E \to R_+ \cup \{0\}$ be a map, which will be called a weight function because exactly one non-negative real number will be associated to each edge of the graph G. This number will be called the weight of the edge.

Recall that α_i indicates the direction of the corresponding current, which was designated by the hydrodynamic model in the node (x_i, y_i). The direction of current α_i is specified in degrees ($-180° < \alpha_i \le 180°$) (Figure 4).

A vertex i of graph G corresponds to node (x_i, y_i) of the discretization grid. Recall that each vertex of the graph G is incident with at most eight outgoing edges (Figure 5).

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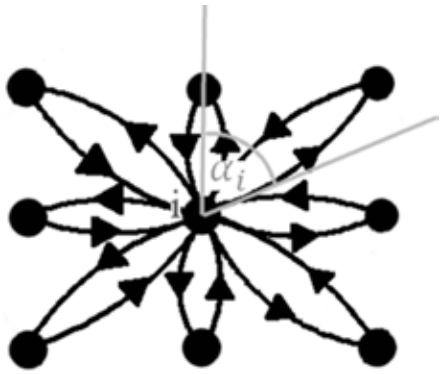

Figure 4. Direction of current α_i at the vertex i

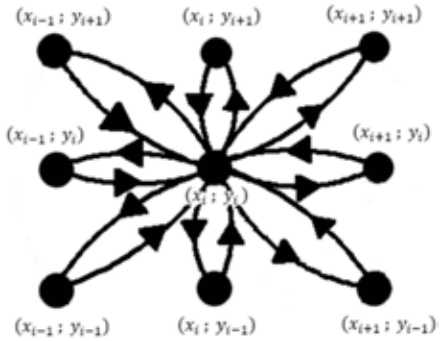

Figure 5. Vertex i with node (x_i, y_i) and its neighbors, with their corresponding nodes, in the discretization grid

Consider all of the outgoing edges $(i, k) \in E$ with the vertex i, where k is the ending vertex of the edge (i, k).

If the vertex k corresponds to the node (x_i, y_{i+1}), then the edge (i, k) is associated with the angle $\beta = 0°$.

If the vertex k corresponds to the node (x_{i+1}, y_{i+1}), then the edge (i, k) is associated with the angle $\beta = 45°$.

If the vertex corresponds to the node (x_{i+1}, y_i), then the edge (i, k) is associated with the angle $\beta = 90°$.

If the vertex corresponds to the node (x_{i+1}, y_{i-1}), then the edge (i, k) is associated with the angle $\beta = 135°$.

If the vertex corresponds to the node (x_i, y_{i-1}), then the edge (i, k) is associated with the angle $\beta = 180°$.

If the vertex corresponds to the node (x_{i-1}, y_{i+1}), then the edge (i, k) is associated with the angle $\beta = -45°$.

If the vertex corresponds to the node (x_{i-1}, y_i), then the edge (i, k) is associated with the angle $\beta = -90°$.

If the vertex corresponds to the node (x_{i-1}, y_{i-1}), then the edge (i, k) is associated with the angle $\beta = -135°$ (Figure 6).

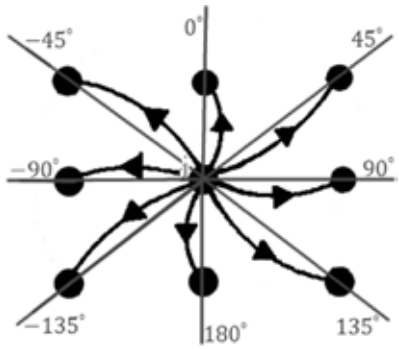

Figure 6. The angles $\beta \in B$ were assigned to the outgoing edges of the vertex i

Let $B = \{-135°, -90°, -45°, 0°, 45°, 90°, 135°, 180°\}$.

Assume that the edge (i, k) is associated with an angle $\beta \in B$. Let $a = |\beta - \alpha_i|$, where α_i is the direction of the surface current at the node (x_i, y_i), which corresponds to the vertex i in the graph G. We define the weight function $f: E \to R_+ \cup \{0\}$ as follows:

$$f(e) = \begin{cases} a, & \text{if } a \le 180 \\ 360 - a, & \text{if } a > 180 \end{cases} \tag{3}$$

The quantity $w = f(e)$ is the weight of the edge $e \in E$. In this way, we obtain a fully defined graph $G = (V, E)$, which is a model of the interaction between surface currents in the waters of the Gdynia harbor. Thus, the prepared model can be used to predict the effects of a current's influence on the ships in the harbor area. The analysis of data allows the determination of the influence of the water on different parts of a ship, or on other objects present in the water. The graph model can also be used to predict the propagation of debris in the dock. In addition, the location in which pollution starts can be indicated.

Practical formulation of a graph for Gdynia harbor

Data from hydrodynamic models are multi-faceted (Breivik & Allen, 2008) and their usefulness depends, to a large extent, on the tools that we use to analyze them. An example of using the results of a hydrodynamic model to plot the location of a maritime accident was given in (Pyrchla, 2008). In the second reference, fuzzy set theory is used as a tool to analyze data from the hydrodynamic M3D model. Another example of using of data from hydrodynamic models for operational planning in the coastal zone was shown in (Pyrchla & Przyborski, 2011). Next, a tool for aiding navigation using graph theory is presented in this paper.

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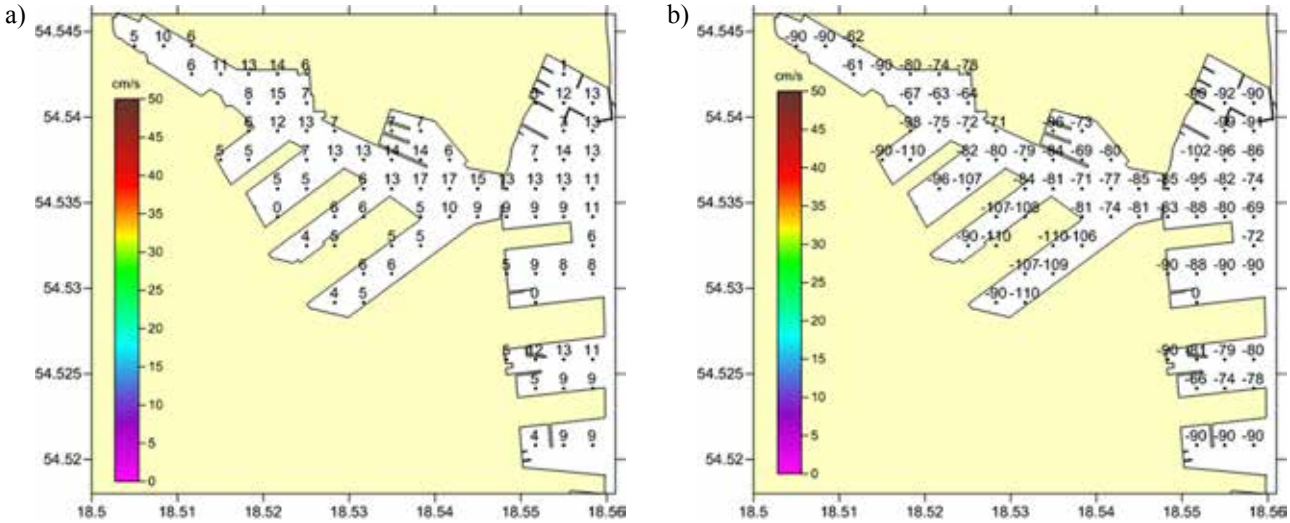

Figure 7. Data on the surface currents in the waters of Gdynia harbor as designated in the hydrodynamic M3D model: a) current speeds, b) current directions

To examine the usefulness of data from numeric weather and hydrodynamic models, we conducted simulation experiments, designating routes of a drifting object in Gdynia harbor. The experiment was based on data from the hydrodynamic M3D model. The values of the currents' speeds on a surface are shown in Figure 7.

The methodology of the graph model that we defined above was used to analyze the interactions of surface currents on a drifting object in the harbor under study. It is assumed that the object is immersed in water and does not extend above the surface. In addition, it only moves under the influence of surface currents. The route of the object's movement, which is determined by graphs based on the maps of the currents, is shown in Figure 8. Information about the weights of the edges was calculated from the currents, as described previously. Blue lines indicate the route followed by an object drifting from point A to point B.

Experience with hydrodynamic models shows that they can be very effective in the search for objects at sea. Indeed, these models have particular importance in coastal zones where the dynamics of the sea are very complicated. The conducted experiments have highlighted the need for wider studies on the use of hydrodynamic models and the inclusion of wind directions and wave phenomena from the corresponding numerical models.

Conclusions

Harbor waters are areas where the directions and speeds of currents can be analyzed with the same approach adopted in coastal basins. Indispensable help in this case is provided by data from numerical

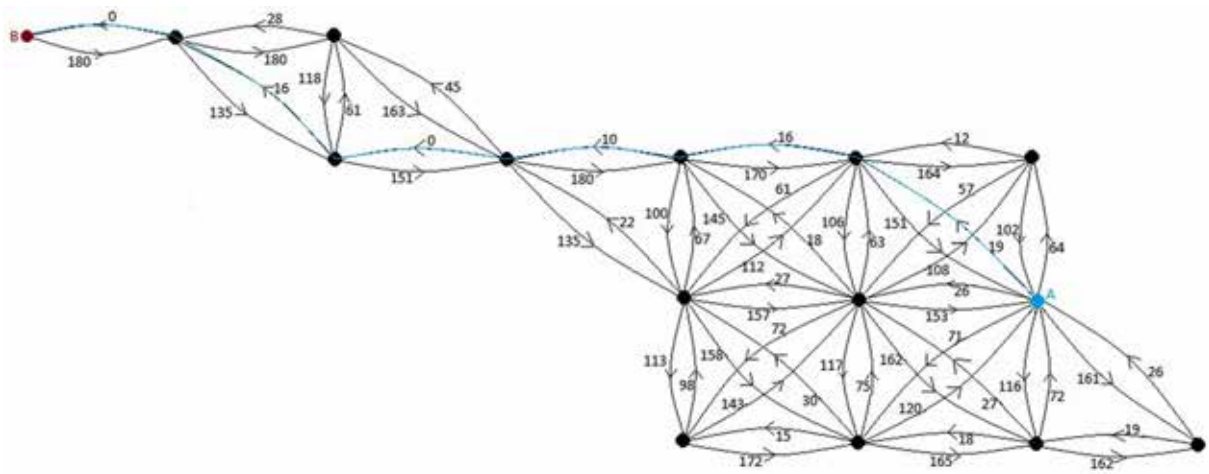

Figure 8. The route of an object's movement as it drifts in the waters of Gdynia harbor. This figure was created in accordance with the methodology presented in this paper

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hydrodynamic models. To use these data, the resolution cannot be larger than 0.1 nautical miles (approximately 185 meters).

In this paper, we argued that using the right tools to analyze the impact of the currents makes it possible to predict the movements of drifting objects in the harbor area. The combination of these tools and hybrid maps of the harbor allows the prediction of how strongly the currents will affect moving ships, and consequently, the harbor infrastructure. The NetCDF format allows geospatial information derived from numerical hydrodynamic models to be easily entered into electronic navigational charts. Furthermore, graph theory allows a prediction on the impact of this information. Using GIS to integrate all the data and tools guarantees an easy visualization.

In this paper, we presented ways of visualizing essential environmental data. The current short-term forecasts from hydrodynamic models (of the water temperature, salinity, sea level, ocean currents, and state undulations) form a basis for generating additional layers of electronic charts. In the example of Gdynia harbor, we showed that data from a numerical hydrodynamic model are necessary when we want to predict phenomena such as the propagation of pollutants and identification of polluters. The information obtained in the present paper complements the information provided by standard electronic navigational charts (ENCs). The concept of a graph as a model of the interactions of currents in water is the first attempt to use graph theory to model the infiltration of environmental data into restricted areas.

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