

Route prediction for a person in water drifting in chosen basins using graph theory

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Abstract

In this paper, the route prediction for a person in water was performed on the basis of a developed graph algorithm. This person drifted in water under the influence of surface currents and wind. The total drift route for the person in water was established as the route in a weighted directed graph. Vertices of this graph correspond to given points within a given basin. Additionally, the graph's edges show possible directions of the overall human drift. The weight of the given edge describes the difference between the gradient of the edge and the total drift direction calculated on the basis of surface current field data and wind field data. An application has been created on the basis of a given algorithm which might be used to support the search for survivors in coastal areas (e.g. port basins, basins adjacent to the port, bays and sea areas) for which hydrodynamic models reliably reflect local phenomena.

Introduction

Search area prediction models for different objects in ocean waters are based on the International Maritime Organization (IMO) regulations which are presented in the International Aeronautical and Marine Search and Rescue Manual (IAMSAR) (ICAO & IMO, 2013). However, the methods presented in this manual may indicate an incorrect or too large search area in coastal waters. This is due to the fact that the methods of finding the datum position in these areas takes sea currents into account, that is, the main, large-scale flow of ocean waters caused by, among other things, large-scale winds; therefore, the methods presented in this manual are based on the natural phenomena occurring in large water reservoirs with characteristics of ocean basins. Sea currents less than 25 nautical miles (Nm) distance from the shore and less than 300 feet (100 m) water depth, and wind currents less than 20 Nm distance from the shore with water depth less than 30 m, are not taken into consideration. IAMSAR

recommends using data from short-term, reliable weather forecasts in coastal areas. These forecasts can be generated by hydrodynamic numerical models with high resolution.

Solving the problem of determining different objects' search areas requires considering, among other things, the following aspects: determining an accident area or an area where a drifting object has been observed and predicting an area where an object will drift to after a certain time period. The issue of determining an accident area or an area where a drifting object has been observed was solved by Pырchla (2008). This issue was solved on the basis of fuzzy set theory. An accident area was established on the basis of a visual observation stream. This area was divided into subareas with a membership function. This function describes the extent (between 0 and 1) to which the observer is convinced that the object belongs to a chosen subarea. The subareas were obtained by discretization of an accident area. As a result, a square grid was created. In each such subarea, one can assign a total current vector, which

affects an object located in this area, e.g. by using hydrodynamic models. Moreover, in each such sub-area we might define certain parameters of wind, which affect the object located in this area by using meteorological data or data generated by weather forecasting numerical models. In turn, for each sub-area, a center can be established. It is assumed that the subarea will move in the same manner as its center; therefore, this subarea may be identified by its center. An object's total drift route needs to be established from the points which describe the routes of the subareas' centers for an accident area or an area where a drifting object has been observed.

In this paper, a person in water route prediction algorithm is introduced. The person in water (PIW) moves under the influence of surface currents and wind in chosen basins. Furthermore, the performance of this algorithm is analyzed. The following basins are considered: port basins, basins adjacent to the port, bays, restricted areas and sea areas, where numerical models reliably reflect local phenomena. Possible PIW movement routes are modeled as the weighted directed graph routes. The subareas' centers, among which a PIW may move, are identified by graph vertices. The line segments joining the subareas' centers, that are routes where a PIW may move, are defined by the graph edges. Weights are assigned to the edges of the graph. The edge weight describes the difference between the gradient of this edge and the direction of the PIW total drift, associated with the outgoing vertex of the edge. A PIW will move from one vertex to another vertex of the graph along the minimum-weight edges. The algorithm presented in this paper may be implemented and used to locate survivors when planning search and rescue operations within the chosen basins.

Input data characteristics for an object's total drift route prediction model

Location and characteristics of the study area

The Gulf of Gdańsk was chosen as the study area. It is located in the southeastern part of the Baltic Sea, between Poland and Russia. The Gulf of Gdańsk, which has a semicircular shape, sinks into the southern Baltic shore, connecting the Taran Cape (54°58' N 19°59' E) and Rozewie Cape (54°50' N 18°20' E). The entry width is 58 Nm, and the entry depth in land is 36 Nm. The Vistula Lagoon connects directly with the waters of the bay by the Pilava Strait in the southeastern part of the bay, behind the Vistula Spit. The northwestern part of the Gulf of Gdańsk,

bordered by the Hel Spit from the northeastern side, is called the Bay of Puck (BHMW/HOPN, 2009).

Polish Marine Waters are characterized by, among others, a large variability in surface current directions (Pyrchla, 2008). Results from previous research indicate that the southern Baltic Sea region sea currents have different characteristics than those in large ocean basins (Pyrchla, 2008). A current's direction and speed are determined mainly by wind direction and speed, and in the Vistula River Mouth regions they also depend on the currents in its arms (BHMW/HOPN, 2009). Wind distribution depends mainly on the atmospheric circulation. In the coastal area, the local conditions have an impact on wind direction and speed (BHMW/HOPN, 2009).

Surface currents as input data for a PIW route prediction algorithm

The directions and speeds of surface currents, achieved at the chosen points of the basin at given time points, are input data for the designed PIW route prediction application. The points of the basin create a regular grid. Hydrodynamic models generate these data. In Polish Marine Waters, two operational systems are used: HIROMB (Funquist & Kleine, 2007) and M3D (Kowalewski, 1997). These models have the same reliability (Pyrchla & Kowalewski, 2009). Data used in this research was generated by the M3D model due to its higher resolution.

The operational hydrodynamic M3D model, created by the University of Gdańsk (UG) Oceanographic Institute, is characterized by high spatial resolution. In the special version of the M3D model – for the western part of the Gulf of Gdańsk – the spatial resolution of the discretization grid equals 0.1 Nm (185 m). In turn, the operational hydrodynamic HIROMB model, created by The Swedish Meteorological and Hydrological Institute (SMHI), is characterized by a spatial resolution of 1 Nm (1852 m).

The surface currents field forecast, presented in Figure 1, is used as input data for a graphical model. This forecast was generated by the M3D model for July 2nd 2012 at 2000UTC. The PIW drift route prediction starting points are indicated by the blue dots. The average surface current vector direction is south with an average speed of approximately 3.6 cm/s.

The data on surface currents fields as the input data for the graphical model will be updated. Data on surface currents fields at 2100UTC, 2200UTC were also generated by the M3D model. It turns out that over time the average surface current vectors'

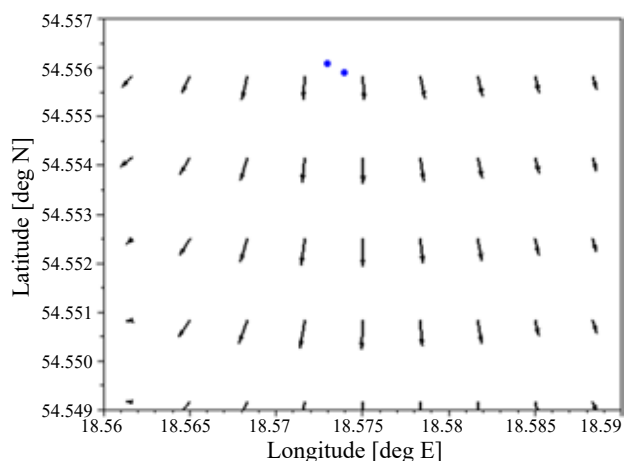


Figure 1. Sample forecast of the surface currents field (July 2nd 2012, 2000UTC)

direction change, becoming SSW and SW respectively. The average surface current speeds also increased: in the area around the blue dots presented in Figure 1, the forecasted average surface current speed was equal to approximately 9.7 cm/s at 2100UTC, and approximately 10 cm/s at 2200UTC.

Wind characteristics received from IMGW weather stations

Data on wind directions and speeds are also input data for the created PIW route prediction application. These data were received for the Institute of Meteorology and Water Management (IMGW) meteo stations. The following meteo stations were taken into consideration: Gdynia, Gdańsk – Northern Port and Hel. In the Gdynia meteo station, measurements are collected in six-hour time intervals. The wind direction is expressed as one of the 16 compass points. For July 2nd 2012 at 1800UTC, the following average wind parameters were achieved: NNE direction, 3 m/s speed. For the Gdańsk – Northern Port and Hel stations, measurements were collected in one-hour time intervals. For July 2nd 2012 at 2000UTC, 2100UTC, 2200UTC the average wind directions and average speeds are given in Table 1.

To establish the average wind direction and speed for July 2nd 2012 at 2000UTC, 2100UTC, 2200UTC for the western part of the Gulf of Gdańsk, the achieved measurements for the Gdańsk – Northern Port and Hel meteo stations were taken into consideration. Further, the calculated average wind parameters were compared to the Gdynia meteo station measurement at 1800UTC. The average wind directions and speeds are given in Table 2.

The established average wind directions and speeds correspond to the wind measurements for the

Table 1. Average wind directions and speeds for July 2nd 2012 for the chosen meteo stations

Meteo station	Hour [UTC]	Average wind direction [°]	Average wind speed [m/s]
Gdańsk – Northern Port	2000	53	4
	2100	13	3
	2200	50	4
Hel	2000	53	2
	2100	41	2
	2200	71	2

Table 2. Average wind directions and speeds for July 2nd 2012 for the western part of the Gulf of Gdańsk

Hour [UTC]	Average wind direction [°]	Average wind speed [m/s]
2000	53	3
2100	27	2.5
2200	60.5	5

Gdynia meteo station at 1800UTC: 3 m/s in the NNE direction. The averages presented in Table 2 were input to the application.

PIW leeway characteristics for the western part of the Gulf of Gdańsk

Wind affects the part of the PIW that is immersed causing leeway of the PIW. The leeway depends on the PIW's position in the water: Sitting PIW, Horizontal PIW or Vertical PIW. For the Gulf of Gdańsk area, which is characterized by low wind speeds, according to Allen and Plourde (Allen & Plourde, 1999) a PIW's leeway direction is the same as the wind direction; therefore, its speed may be established as follows:

Table 3. Leeway directions and speeds for July 2nd 2012 for the western part of the Gulf of Gdańsk

PIW Position	Hour [UTC]	Leeway direction [°]	Leeway speed [m/s]
Vertical PIW	2000	-127	0.2351
Vertical PIW	2100	-153	0.22925
Vertical PIW	2200	-119.5	0.2351
Sitting PIW	2000	-127	3.815
Sitting PIW	2100	-153	3.8125
Sitting PIW	2200	-119.5	3.815
Horizontal PIW – Survival Suit	2000	-127	5.2932
Horizontal PIW – Survival Suit	2100	-153	5.286
Horizontal PIW – Survival Suit	2200	-119.5	5.2932

$$\text{Vertical PIW} = 1.17\% \cdot W_{10m} + 0.2 \text{ [cm/s]} \quad (1)$$

$$\text{Sitting PIW} = 0.5\% \cdot W_{10m} + 3.8 \text{ [cm/s]} \quad (2)$$

$$\begin{aligned} \text{Horizontal PIW – Survival Suit} = \\ = 1.44\% \cdot W_{10m} + 5.25 \text{ [cm/s]} \end{aligned} \quad (3)$$

where W_{10m} is the 10-meter wind speed (m/s).

The leeway vector forecast has been established based on the data in Table 2. The leeway vector parameters are presented in Table 3.

PIW route prediction algorithm description based on a graphical model

A PIW's total drift route is presented as a route on a weighted directed graph. The PIW will drift along a route which is a sequence of edges. Moreover, this route is achieved by minimizing the difference between the PIW's total drift direction derived from the graphical model, and its total drift direction derived from the data generated by hydrodynamic models and the measured data provided by the IMGW, over certain time intervals.

The ordered triple (V, E, f) , where $V \neq \emptyset$, $E \subseteq V^2$ and $f: E \rightarrow R$, is called the *weighted directed graph* G . The set V is the *vertex set* of the graph G . The elements of the set V are the *vertices* of the graph G . The set E is the *edge set* of the graph G . The elements of the set E are the *edges* of the graph G . Let ij be an edge of the graph G . ij is called the *outgoing* edge of the vertex i and the *incoming* edge of the vertex j . The function f is the weight function of the graph G . The real number $w = f(ij)$ for $ij \in E$ is the *weight* of the edge ij .

In work by Kijewska (Kijewska, 2016), the concept of the weighted directed graph definition is presented. This graph describes the surface currents' interaction on the object immersed in water so that the part extending above the water is not larger than the human head. The considered basin is discretized. As a result of the discretization, a regular grid of nodes is achieved. These nodes are the points numbered consecutively from 1 to i in this basin. The location data are associated with the considered grid nodes by using geographical coordinates. In addition, surface currents' directions and speeds, generated by a hydrodynamic model, are also associated with those nodes. The vertex set V of the graph G is defined as the set

$$V = \{1, 2, 3, \dots, i\} \quad (4)$$

where the vertex i corresponds to the i -th node of the discretization grid. Moreover, the data assigned to the grid nodes may be associated with the vertices of

the graph. The ordered pair of the vertices i, j is the edge ij in the graph. This edge exists in the graph G , if the distance between the nodes i and j of the grid is not greater than some fixed number $r > 0$. Selecting the number r is described by Kijewska (Kijewska, 2016). The edges of the graph are routes, along which the PIW may move under the influence of surface currents affecting it. A weight is associated with each edge of the graph. This weight describes the difference between the gradient of this edge and the direction of the surface current assigned to the vertex, from which this edge extends.

It is worth noting that the wind affects the part of the PIW immersed under water. The strength of this effect depends on the PIW's position in the water – sitting, horizontal or vertical. The wind causes a leeway of the PIW. The PIW's total drift is computed by adding the surface current and the leeway.

Let the weighted directed graph $G = (V, E, f)$ be determined as in Kijewska (Kijewska, 2016), but the weight function $f: E \rightarrow R$ be determined as follows:

$$f(ij) = \begin{cases} b, & b \leq 180 \\ 360 - b, & b > 180 \end{cases} \quad (5)$$

where: $b = |\alpha - \beta_i|$, α – the gradient of the edge ij of the graph G , β_i – the direction of the PIW's total drift established at the vertex i . Therefore, the edge weight of the graph G may be described as the difference between the gradient of this edge and the direction of the total drift associated with the vertex, from which this edge extends.

Recalling that the centers of all the subareas within an accident area or an area where the PIW has been observed will be moved. Next, a node of the discretization grid located closest to the place where the PIW is should be identified. If the distance between this node and the PIW's position is too great, then the bilinear or nearest neighbor interpolation of the grid should be used. The node, located closest to the place where the PIW is, corresponds to a certain vertex of the graph G . The PIW will move from this vertex along the outgoing edge with the minimum-weight. The sequence of edges, where the PIW will move, creates its drift route.

The PIW drift prediction algorithm has been written in SCILAB and consists of the following steps:

1. the discretization of the considered basin; in addition, for each node of the discretization grid, information about its longitude and latitude is included;
2. loading the data (surface currents' directions and speeds and wind directions and speeds for the chosen basin over a fixed time point);

3. establishing surface currents' directions and speeds and wind directions and speeds at all of the nodes of the grid (e.g. by their bilinear or nearest neighbor interpolation);
4. establishing the geographical coordinates $(\varphi_p; \lambda_p)$ for the starting point p of the prediction (the starting point p is the grid point);
5. entering the time t_a for updating surface currents and wind data (this value may be established by the application based on the information about time intervals downloaded with new data);
6. entering the prediction time t_{pr} ;
7. determining the vertex set V of the graph G (recall that the vertex i of the graph G corresponds to the i -th node of the grid);
8. calculating the leeway direction and speed at node p of the grid;
9. calculating the PIW's total drift vector direction and speed at node p of the grid;
10. calculating the radius r of the circle encompassing the vertices of the graph G being the neighbors of the vertex p ;
11. defining the edge set E of the graph G ;
12. calculating the edge weights of the graph G ;
13. selecting the minimum-weight extending from vertex p ;
14. examining whether this weight is not greater than the allowed PIW route prediction error for one step. If this weight is greater than this error, then one should use bilinear or the nearest neighbor interpolation of the discretization grid and the data associated with it (such interpolation allows for the consideration of more PIW movement directions from a given vertex of the graph and decreases movement time between vertices of the graph) and return back to step 7;
15. moving the PIW along the minimum-weight edge to the new vertex j of the graph G ;
16. calculating the required time t of the PIW movement along this edge by the formula $t = s/V$, where s – the PIW route, V – the total drift speed associated with the vertex p ; in addition, the times required to move along the chosen edges of the graph are summed;
17. examining whether the time simulation t_{pr} is achieved or the vertex, where the PIW is located, is situated on land; if at least one of these conditions is satisfied, then the model terminates and the results are displayed on the screen (the predicted PIW drift route) and these route parameters should be saved in the file;
18. examining whether the data updating time t_a is achieved. If this condition is satisfied, then the

data on the surface currents and wind are updated, the edge weights of the graph are re-calculated. Next, the algorithm performs steps 7 and 8, but the vertex j (see step 15) is used in place of the vertex p when step 13 is performed.

Experimental verification of the graphical model algorithm

To examine the PIW's total drift route prediction accuracy based on the described graphical model, data from two real experiments are used. One of them was based on throwing a buoy into the water and tracking its total drift route by GPS. The buoy was constructed in such a way that it imitated a Vertical PIW. A second experiment was based on throwing a PIW clad in a survival suit (PIW/SS) into the water and tracking its total drift route. The PIW/SS floated in a horizontal position on the water's surface. These experiments were carried out on July 2nd 2012 at 2008UTC. The buoy was thrown into the Gulf of Gdańsk waters at longitude 18.573969° E and latitude 54.555896° N. In turn, the PIW/SS was thrown in at longitude 18.572973° E and latitude 54.556061° N.

Furthermore, computer simulations were carried out. From these simulations, the forecasted total drift routes of both the buoy and PIW/SS were calculated. These routes were computed on the basis of the presented graphical model.

Real and simulated routes of the PIW clad in a survival-suit

In Figure 2, the following routes are presented: the real total drift route of the PIW/SS measured by GPS (black color) and the simulated route based on the graphical model (blue color). Moreover, for

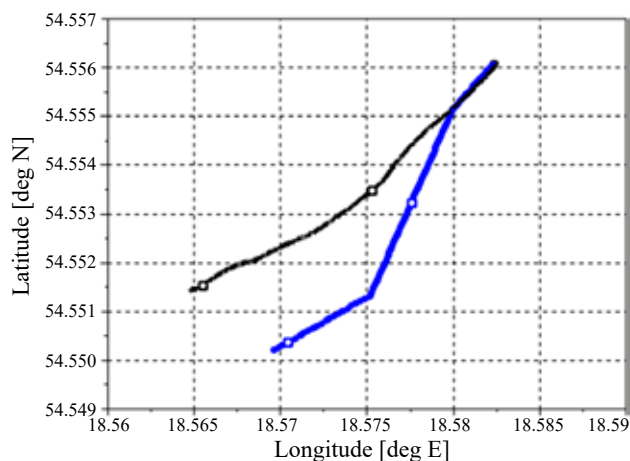


Figure 2. Route prediction of the PIW/SS (black – route of the real-life PIW/SS, blue – simulated route of the PIW/SS)

each of the routes, two points have been indicated. For each of the routes, the first point indicates the location where the PIW/SS was at 2100UTC. The second one is the point, where the PIW/SS was at 2200UTC. Each of these points has been marked as a white point on the routes. During the real experiment, it was measured by GPS that at 2100UTC the PIW/SS was located at longitude 18.570126° E, latitude 54.553486° N and at 2200UTC at longitude 18.566206° E, latitude 54.551537° N. When the simulated experiment was carried out on the basis of the devised graphical model, the PIW/SS was located at longitude 18.571032° E, latitude 54.553215° N at 2100UTC and at longitude 18.568175° E, latitude 54.550358° N at 2200UTC. The distance between the real location of the PIW/SS and the forecasted location equaled approximately 70 m at 2100UTC and approximately 185 m at 2200UTC.

Real and simulated routes of the buoy

In Figure 3, the following routes are presented: the real total drift route of the buoy measured by GPS (black color) and the simulated route based on the graphical model (blue color). Moreover, for each of the routes, two points have been indicated. For each of the routes, the first point indicates the location where the buoy was at 2100UTC and the second one is the point where the buoy was at 2200UTC. Each of these points has been marked in white on the plotted routes. During the real experiment, it was measured by GPS that at 2100UTC the buoy was located at longitude 18.572227° E, latitude 54.553867° N and at 2200UTC at longitude 18.569405° E, latitude 54.551866° N. When the simulated experiment was carried out on the basis of the devised graphical model the buoy was located

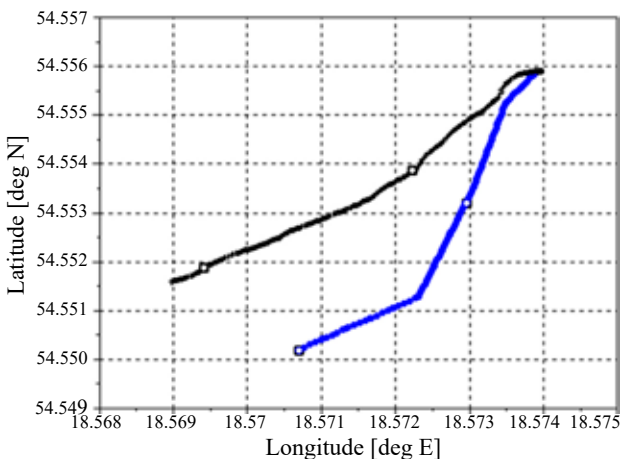


Figure 3. Route prediction of the buoy (black – route of the real-life buoy, blue – simulated route of the buoy)

at longitude 18.572957° E, latitude 54.5532° N at 2100UTC and at longitude 18.570699° E, latitude 54.550189° N at 2200UTC. The distance between the real location of the buoy and the forecasted location equaled approximately 90 m at 2100UTC and approximately 205 m at 2200UTC.

Conclusions

In this paper, a total drift route prediction algorithm for a person in water has been presented. This algorithm allows the prediction of the drift route in coastal basins. Furthermore, an experimental verification of the simulated person in water drift routes was carried out. It was observed that the person in water's real and simulated drift routes achieved a good agreement (the direction of the forecasted person in water drift route is generally in accordance with the observed direction). One may then conclude that the devised application based on the graphical model is able to reliably determine the person in water's total drift route. This has the effect of narrowing down the search area and decreasing the search time. It is also worth observing that the presented model takes into consideration data on surface current fields, wind fields and leeway fields. Furthermore, those data are updated during the simulation. This approach is dedicated to applying a greater use of data from hydrodynamic models and weather forecasting models during SAR operations. Currently, these models are being dynamically developed. The simulated results may be improved if the data on spatially-varying wind fields are entered from a reliable weather forecast model.

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