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# Analysis of Wind and Drifter Movement Parameters in Terms of Navigation Safety: The Example of Szczecin Lagoon

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***Abstract:***

***Purpose:*** *The article presents a comparative analysis of the drift movement in the water area of Szczecin Lagoon (southern Baltic, Poland) and wind parameters in the examined region for the dry summer season.*

***Design/Methodology/Approach:*** *Experimental tests were conducted to determine the relationship between the drifter movement parameters and wind parameters in Szczecin Lagoon area. A set of surface drifters was designed for the experimental study at the Maritime University of Szczecin. Drifters were custom-made to track surface currents. In situ experiments were performed from the end of June till mid-October 2018. Statistical analysis of directional and linear data allowed to link the directions and speeds of moving drifters with wind parameters recorded in two places, Świnoujscie and Trzebież.*

***Findings:*** *As a result of the conducted research, it was ascertained that the direction and speed of air masses flow are parameters that strongly affect the movement of surface waters of Szczecin Lagoon. A significant correlation was found between the wind direction and the drift direction. The coefficient of surface drift was also specified to determine the relationship between drift speed and wind speed.*

***Originality/value:*** *The presented research is a complete novelty in the area of the Szczecin Lagoon. The results obtained in the study may be beneficial for the maritime administration, which is responsible for the safety of navigation in the studied water area. The analysis can be used for projecting the track of pollutants in water.*

***Keywords:*** *Safety, surface flow, wind, surface drifter, Szczecin Lagoon.*

***JEL classification:*** *C69.*

***Paper Type:*** *Research study.*

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## 1. Introduction

One of the aspects of safety management in an area such as Szczecin Lagoon, is managing a rescue operation to search for survivors or to neutralize pollution. In both cases, the direction in which the survivor or contaminants travel is extremely important. Understanding the flow of surface waters of Szczecin Lagoon may give an insight into the movement patterns of objects in water, such as lost property, pollutants (oil spills) or drifting micro-organisms. Szczecin Lagoon is a small and shallow reservoir with limited and slow water exchange (55 days; Schiewer, 2008). Its waters mostly remain not stratified. Only some central regions show temporary vertical displacements. According to the Institute of Meteorology and Water Management (pol. - Instytut Meteorologii i Gospodarki Wodnej - IMGW, 1980), due to small depth, Szczecin Lagoon waters mix in the bottom zone, affected by wind waves. Therefore, these waters of Szczecin Lagoon can be considered homogeneous, except those areas in direct vicinity of the straits linking it with the Baltic Sea and the River Odra.

Szczecin Lagoon is typical brackish intermediate reservoir fed with fresh water from the Odra and periodical ingress of sea water of 6 PSU (Practical Salinity Unit) through the Świna Strait from the Baltic Sea (Bangel *et al.*, 2004). The salinity of Szczecin Lagoon in various periods ranges from 0.3 to 4 PSU and averages 1.4 PSU. Salinity in the central part varies from 0.5 to 2 PSU. (Radziejewska and Schernewski, 2008; Schiewer, 2008). In the summer season the lagoon has low level of salinity, uniform practically all across its depth to the bottom.

Szczecin Lagoon is considered a small and relatively safe body of water for sailing and motor boat sports. However, squalls occurring in the area are strong and unexpected in terms of wind direction and force. It should be noted that this study does not cover surface flows during storms (such research is not planned in the future, either). The tests were conducted in low and moderate wind conditions. There is no Stokes drift in Szczecin Lagoon because all waves disappear when the wind, the factor generating waves, disappears. Besides, the depth of the lagoon is very small and when the wind stops blowing, friction forces suppress the currents. The seisha phenomenon was not taken into account simply because the phenomenon in the examined area does not occur.

The analysis can be used for projecting the track of pollutants in water (oil spills from ships, other chemicals brought in by the river Odra floating on the surface of the lagoon) (Przywarty *et al.*, 2018). The Odra river can transport pollutants from its upstream sections, adjacent cities and towns or from the fields. Szczecin Lagoon links the ports of Szczecin and Świnoujscie, which in total handled 29 million tons of cargo and 81.451 TEU containers in 2018. The cargo to Szczecin was transported by ships of a maximum length 215 m and draft 9.15 m. Additionally, Szczecin Lagoon is home to several smaller commercial ports, such as Nowe Warpno, Police, Przytór, Trzebież, Stepnica and other. Therefore, the research may bring direct benefits to the natural environment.

The experiment and analysis results may be useful in surface current validation (at a depth 0 m) for Szczecin Lagoon using the PM3D model (three-dimensional hydrodynamic model of Baltic Sea developed at the Institute of Oceanography, University of Gdańsk) for online display in the SatBałtyk system (www.satbaltyk.pl). The knowledge of these currents may be used in search and rescue operations. Besides, the research results may be useful for the improvement of hydrometeorological forecasts.

Despite many factors, such as wind force, differences in water level between the Pomorska Bay (the Baltic) and Szczecin Lagoon, inflow of fresh water from the Odra, surges of sea water from the Baltic, all of which may theoretically affect the water circulation in Szczecin Lagoon, short-time variation in surface flows is primarily related to wind force in the area. The impact of wind on surface waters is particularly noticeable in small bodies of water (Vandenbulcke *et al.*, 2009), such as Szczecin Lagoon. Therefore, other factors that may affect surface water circulation were not taken into account in the study.

Many studies of similar nature have been described in available publications. The analysis of drifter movement depending on wind parameters was conducted in the area of the Gulf of Finland in 2011 and 2013 (Delpeche-Ellmann *et al.*, 2016). The publication (Chang *et al.*, 2012) analyses relationships between the observed surface current vectors and strong wind vector (20-50 m/s) for the northwest parts of the Pacific Ocean. Studies of hydrodynamic models of surface waters are conducted in a number of research centres. Findings on the distribution of surface drifters in the Baltic Sea in 2010 and 2011 were described in (Kjellsson and Döös, 2012). The authors compare drifter trajectories with those generated by a numerical model using parameters of strong gusty winds from the regional ocean model. In the (Vandenbulcke *et al.*, 2009) surface drift of two buoys was tracked, launched in the Adriatic Sea during sea tests DART06 and in the Ligurian Sea during the experiment MREA07. The researchers used hyper-ensemble techniques, i.e. combining various models to obtain the best possible forecast of their trajectories. The model of surface drift of drifters was also used, based on wind models.

In Maio *et al.* (2016) the most likely area of search was estimated by statistical and deterministic models of drift. The main objective of that article was to develop a new approach to the determination of drift based on a 'person overboard' event that took place in the Tyrrhenian Sea in July 2013. In Cho *et al.* (2014), an operational system of modelling search and rescue operations was developed for the purpose of predicting tracks of casualties or material traces of accidents in coastal seas in the north-western region of the Pacific. The system used a stochastic model for the estimation of the trajectories of drifting objects. The study of drifting debris of sea accidents MH370 consisted in numerical modelling using the forward particle tracking technique (Nesterov, 2018). Four models were considered with respect to the leeway factors and drift angles, including a proposed model of random distribution of the leeway factors of particles. In Abascal *et al.* (2012), the technology of ocean observation by high frequency radar (HF) was used. This technology is not available for Szczecin Lagoon due to its small size and depth. This study aims at statistical analysis of the compatibility between the parameters of surface drifters' movement in Szczecin Lagoon and the parameters of winds prevailing in the area.

The research problem is to determine the extent to which wind force is responsible for surface drift. In the future, the authors plan to examine other factors that may affect surface drift on Szczecin Lagoon. Section 2 presents the research area, research methods and tools, i.e., drifters. Section 3 includes comparative analysis of surface drifter movement and wind parameters in Szczecin Lagoon and conclusions.

## 2. Research Area

Szczecin Lagoon is a body of water extending from the mouth of Poland's second longest river - Odra. The area of Szczecin Lagoon is bound by these coordinates: 53º42'N - 53º52'N, 013º53'E - 014º36'E. In the north, the lagoon is separated from the Baltic Sea by two islands: Wolin and Uznam (Usedom). It is divided into Great Lagoon (Polish: Wielki Zalew), 409.7 km² in area, within the territory of Poland, and Small Lagoon (German: Kleinest Haff), 277.2 km² (The Institute of Meteorology and Water Management, 1980), almost entirely German territory. The southern boundary of Great Lagoon is defined by the line joining Jasienica channel (western shore of the lagoon) and the mouth of the Krępa River (eastern shore). In this study, in situ experiments were carried out in the area of Great Lagoon, further called Szczecin Lagoon.

The Świna is responsible for 60% of water exchange between Szczecin Lagoon and Pomorska Bay. The other two straits are very shallow and their share is 20% each. The inflow of salt water from the Baltic Sea through long and narrow water straits depends on wind direction and force, atmospheric pressure, sea state and water level in the lagoon. The inflow is stronger in autumn and winter. However, the impact of the Baltic Sea waters is small due to the size of the straits cross-sections, topography of the coast of Pomorska Bay and the breakwater profile at the lagoon boundary. The latter is to ensure safe navigation and maintain the required depth of the Świnoujście-Szczecin fairway.

The main source feeding Szczecin Lagoon is the Odra estuary - 91.5% (The Institute of Meteorology and Water Management, 1980). The average flow showed significant fluctuations in particular years and was also dependent on the season of the year. The average flow in the lower section of the river was 565 $m^3$/s (PWN encyclopaedia, 2019). The lowest rate of water flow into Szczecin Lagoon occurs in summer months (e.g. in 1970: June 700 $m^3$/s, July 450 $m^3$/s, August 470 $m^3$/s, September 438 $m^3/s$; (The Institute of Meteorology and Water Management, 1980). This study was conducted in summer.

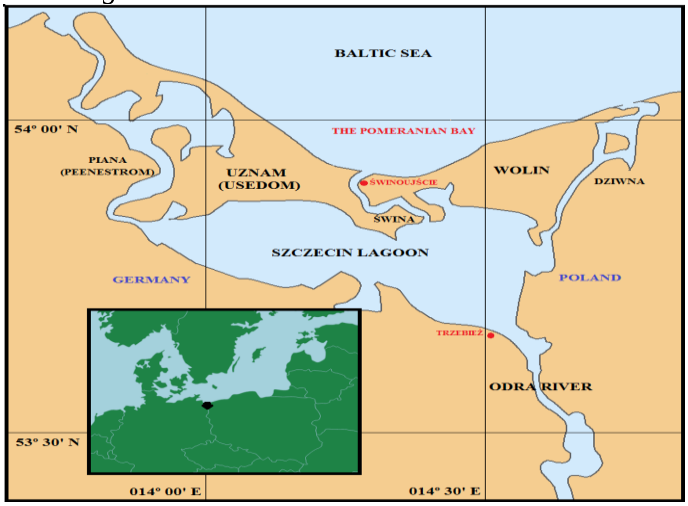
Szczecin Lagoon lies in a region typical of sea climate of medium latitudes, with relatively small temperature fluctuations, many cloudy days, high air humidity, and prevailing winds from the west. Air circulation is mostly affected by lows from Iceland (mainly in winter) and highs from the Azores (mainly in summer). Most air masses move from the west. Fronts associated with low pressure systems cause frequent and dynamic weather changes. At the time of the experiment, i.e. late spring and early summer, low pressure areas, although numerous, are less intensive, but featuring strong squalls and storms. In spring, easterly and north-easterly winds prevail, while in summer south-westerly and north-westerly winds are more frequent. Only occasionally winds from south-east and south are experienced in that period. Calm days are rare, making up 2% – 7% of the year (Baltic Pilot, 2018).

In situ experiments using a surface drifter were performed from the end of June till mid-October 2018. The summer conditions turned out to be different than usual. It was a very hot summer (50 years data - 1966 to 2015). The average temperature in the growing period (April to September) measured in all synoptic stations was from 2.5° C to 2.6° C above the mean standard (Szczecin, Łódź) (The Institute of Meteorology and Water Management, 2019). Masses of hot air flew in from various directions: Scandinavia pushed by northerly winds, from Western Europe, from the Mediterranean Sea pushed by southern wind and by north-westerly wind thanks to the high pressure system, created between lows from Scandinavia/Russia and British Islands/North Sea.

However, the wind prevailing during in-situ experiments blew from the NW-N-NE sector. Precipitation was lower or significantly lower than the ten-year average. Drought struck western Poland in particular (precipitation in Szczecin in the growing season 2018 was below 200 mm (The Institute of Meteorology and Water Management, 2019)). During the drought period the inflow of water to Szczecin Lagoon severely dropped. The publication (The Institute of Meteorology and Water Management, 1980) state that the change in water level in Szczecin Lagoon, related to the atmospheric pressure gradient was only by a few centimetres due to the size of its area. According to the SatBałtyk system forecasts for Szczecin Lagoon concerning the days of the in situ experiment, the change of water level oscillated between 32 and 64 cm, with the mean difference of 45 cm. However, for short periods of time, such as those of single experiments, differences amounted to a few centimetres.

The lagoon is approximately 28 km long and over 52 km wide (Baltic Pilot, 2018). The shape of the shore and the bottom create hazards, as these combined with dynamically changing hydrometeorological conditions, have led to many tragedies. The bottom in the central part of Szczecin Lagoon is covered by mud which lies at a depth 4.5 – 5.5 m. Muddy parts of the lagoon are surrounded by a belt of sandy shoals 1 - 1.5 m deep, sloping sharply towards the muddy bottom (Wolnomiejski and Witek, 2013). The average depth of Szczecin Lagoon is 3.8 m. The largest natural depth of Szczecin Lagoon is 8.5 m, situated in the narrower section between the Great and Small Lagoons.

***Figure 1.*** *Szczecin Lagoon*




***Source:*** *Own study, based on NAVI-SAILOR 3000 ECDIS-i and www.online/seterra.com.pl.*

Nearly 25% of the surface area has a depth 0 – 2 m, while approximately 96% has a depth less than 6 m. The largest depth, 10.5 m is the effect of dredging of the fairway linking Szczecin and Świnoujście on the Baltic Sea. The Świnoujście-Szczecin fairway and Kanał Piastowski runs along the natural connection between Szczecin Lagoon and Pomeranian Bay, along the Świna strait. This link plays an important role in the exchange of water between Szczecin Lagoon and the Baltic Sea. The ports in Szczecin and Świnoujście make up one of the largest port complexes in the Baltic Sea region. Besides, Kanal Piastowski also brings about the formation of unique hydro chemical conditions on Szczecin Lagoon (Majewski, 1958; 1964; 1972; Maliński, 1968; Mierzyński, 1964; Robakiewicz, 1993).

## 3. Data

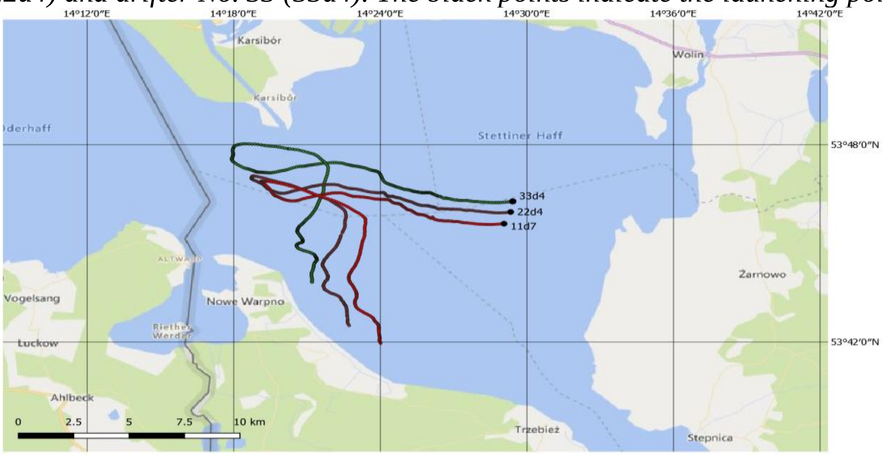
Experimental tests were conducted to determine the relationship between the drifter movement parameters and wind parameters in Szczecin Lagoon area. A set of surface drifters was designed for the experimental study (Figure 2) at the Maritime University of Szczecin. Because the research focused on surface currents, the drifter has a balanced displacement, so that it does not stand out of the water and is not exposed to wind impact. Only a very small part of it is prominent, allowing the transmission of radio signal. Due to the low centre of gravity, drifter motions are limited. The drifter is placed in a closed, semi-transparent, polypropylene housing of approx. one litter volume. The total mass of the drifter is approximately 800 g. The lower inside part contains a 5-volt battery, with a mass of 500 g. Right under the cover is a SPOT Trace® tracker. Google MapsTM supports in approximately real time the display of GPS coordinates of the tracker. The remaining volume of the drifter inside is filled with foam that immobilizes the battery and tracker and ensures buoyancy. The drifter's position is recorded at 10 minutes intervals.

***Figure 2.*** *Surface drifter*

***Source:*** *Own study.*

The initial locations for each launching were determined individually, depending on wind parameters and to maximize the experiment duration (considering the costs of launching and recovery). The drifters were floating through Szczecin Lagoon until they got stuck in the reeds or the batteries went flat and needed recharging (after about two weeks). In most cases (over 90%) drifters made it to the reeds in the shore zone of Szczecin Lagoon. In the remaining cases drifters most likely had collisions with water craft and were destroyed. The drifters were released one by one, at a few minutes' intervals, from the same position or within a radius of 40 - 50 meters. An example one day drift is shown in Figure 3.

***Figure 3.*** *Trajectories of three drifters (30 July): drifter No. 11 (11d7), drifter No. 22 (22d4) and drifter No. 33 (33d4). The black points indicate the launching points*




***Source:*** *Own study, the base map obtained from bing maps comes from the SatBałtyk system: www.satbaltyk.pl.*

As the trajectories were almost identical, the analysis was limited to drifter 11 (further referred to as the drifter). For comparative analysis, wind direction and speed were measured at the measuring points of the Institute of Meteorology and Water Management in Trzebież (53º 39'N, 014º 31'E) and Świnoujście (53º 55'N, 014º 15'E) (Figure 1). The wind parameters were measured at a height of 10 m. At present, Trzebież and Świnoujście are two locations closest to Szczecin Lagoon, where the Institute of Meteorology and Water Management makes wind measurements and offers access to the data. The measurements directly in Szczecin Lagoon area are not performed by the Institute of Meteorology and Water Management.

## 4. Research Methods

In this work the authors try to verify the impact of wind on the movements of the designed surface drifter by comparing the relevant parameters (direction and speed) and the resultant direction distributions for drift and wind. The direction data were used for calculations of mean drift directions and the concentration coefficients of drift directions relative to mean drift directions.

The average speed and standard deviation of the surface drifter were also established. Besides, the average direction and speed of air masses were calculated. The term air masses movement direction is understood as the direction, from which wind is blowing, increased by 180 degrees (to compare the directions of the drifter movements' trajectories with air mass direction).

The average drift direction and average direction of air masses flow were calculated as proposed by (Mardia and Jupp, 2000). The mean direction was calculated by the following formula:

$$\bar{\varphi} = \operatorname{arctg} \frac{\sum_{i=1}^{n} \sin \varphi_i}{\sum_{i=1}^{n} \cos \varphi_i} \tag{1}$$

where $\varphi_i$ is a series of directions calculated from readouts of the drifter position (geographical coordinates) or series of air masses directions, $n$ is the number of measurements recorded during one release.

To define the dispersion of calculated directions of drift and air mass flows around the calculated mean directions, the concentration coefficient was calculated by the following formula:

$$L = \sqrt{\left(\sum_{i=1}^{n} \sin \varphi_i\right)^2 + \left(\sum_{i=1}^{n} \cos \varphi_i\right)^2} \cdot 100\% \tag{2}$$

This measure can be interpreted as a percentage of data accumulated around the average direction. A measure of the correlation between two circular variables was estimated by coefficient presented by Jammalamadaka and SenGupta (2001). The circular correlation coefficient was calculated as:

$$r = \frac{\sum_{i=1}^{n} \sin\left(\varphi_i - \overline{\varphi}\right) \cdot \sin\left(\gamma_i - \overline{\gamma}\right)}{\sqrt{\sum_{i=1}^{n} \sin^2\left(\varphi_i - \overline{\varphi}\right) \cdot \sum_{i=1}^{n} \sin^2\left(\gamma_i - \overline{\gamma}\right)}} \tag{3}$$

The significance of this coefficient was tested using the statistic $z_r$:

$$z_r = r\sqrt{\frac{n\lambda_{20}\lambda_{02}}{\lambda_{22}}} \tag{4}$$

where

$$\lambda_{ij} = \frac{1}{n}\sum_{k=1}^{n} \sin^i\left(\varphi_k - \overline{\varphi}\right)\sin^j\left(\gamma_k - \overline{\gamma}\right) \tag{5}$$

The statistic $z_r$ is approximately distributed as a standard normal.

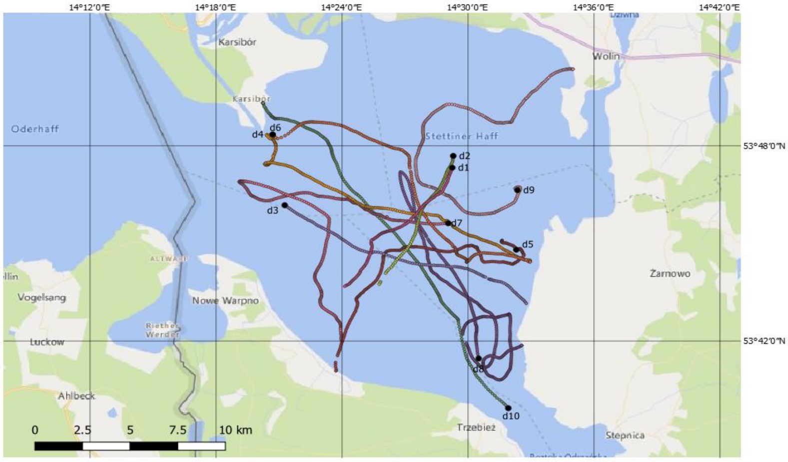
To achieve a better visual presentation related to the drift parameters, graphically selected direction distributions are graphically depicted as a rose diagram: rose of drift directions and air mass movement parameters measured at the meteorological stations in Trzebież and Świnoujście. These distributions are presented as directions in which the wind is blowing (turned by 180 degrees compared to conventional wind roses). Drift direction distributions are based on calculations using two subsequent positions recorded at approximately 10 minute intervals. These distributions show certain conformity with the directions considered herein.

To determine the relationship between drift speed and wind speed, the coefficient of relationship between them was also specified. This coefficient describes drift speed as a percentage of wind speed.

## 5. Results

The drifter trajectories were varied (Figure 4). Sometimes the drifter was moving in a straight line, sometimes its direction changed rapidly. The comparison of the trajectory in the same area of the lagoon shows that their direction to a large extent depended on factors other than the drifter location. In some areas of the lagoon indicated in Figure 4 the drifter moved in various directions and at various speeds. The trajectories d7 and d8 change abruptly by approximately 180°, caused by relatively strong wind direction change and sudden reduction of speed (nearly to 0 m/s). Significant changes in the drift trajectory may be related to small wind speeds, which resulted in significant changes in wind direction (see: d5, d7, d8, d9). Permanent wind gave a constant trajectory of the drifter (see the trajectories: d1, d2, d3, d4, d10).

***Figure 4.*** *Ten trajectories of the drifter*




***Source:*** *Own study.*

The basic data of the drifter launches are presented in Table 1.

***Table 1.*** *General data for launching the drifter. The launch number (1-10), date of launching (day, month in 2018), drift duration (in hours), launch start and end positions are given in geographic coordinates (in degrees) and distance travelled*

| Launch number | Date of launching | Duration (*h*) | Start positions | | End positions | | Distance travelled (*m*) |
|---|---|---|---|---|---|---|---|
| | | | $\varphi$ (*deg.N*) | $\lambda$ (*deg.E*) | $\varphi$ (*deg.N*) | $\lambda$ (*deg.E*) | |
| 1 | 29.06 | 24 | 53.78855 | 14.48773 | 53.72776 | 14.40228 | 9330 |
| 2 | 30.06 | 20 | 53.79413 | 14.48841 | 53.72882 | 14.42964 | 8436 |
| 3 | 06.07 | 24 | 53.76892 | 14.35553 | 53.71898 | 14.54646 | 14244 |
| 4 | 07.07 | 39 | 53.80555 | 14.34501 | 53.74031 | 14.54955 | 18671 |
| 5 | 10.07 | 47 | 53.75138 | 14.52734 | 53.68436 | 14.39524 | 17467 |
| 6 | 13.07 | 43 | 53.80556 | 14.34505 | 53.74090 | 14.54948 | 28042 |
| 7 | 30.07 | 65 | 53.76001 | 14.48275 | 53.69945 | 14.40024 | 35861 |
| 8 | 16.08 | 88 | 53.69074 | 14.50869 | 53.69743 | 14.54279 | 45460 |
| 9 | 06.09 | 27 | 53.77719 | 14.53882 | 53.83897 | 14.58360 | 28685 |
| 10 | 13.10 | 41 | 53.66608 | 14.53098 | 53.82165 | 14.33727 | 28625 |

***Source:*** *Own study.*

Tables 2 and 3 present basic statistics of drifter trajectories. Table 2 shows mean directions (from equation (1) and coefficient of concentration (from equation (2) for trajectories of drifters and air masses. Table 3 presents an average speed (from equation (3)) for drift and wind, as well as standard deviations of these parameters. Besides, the coefficients of surface drift were obtained, i.e. percentage ratio of drift speed to wind speed. The measurement data of air mass movement parameters were collected at the meteorological stations in Trzebież and Świnoujście.

***Table 2.*** *Parameters describing the direction of drifter movement for 10 launches in summer 2018. Directions of air masses movement are determined for Trzebież and Swinoujście (L - launch number, AD - mean drift direction; CD - coefficient of concentration of drift direction; AT - mean direction of air masses movement in Trzebież; coefficient of concentration of air masses direction in Trzebież; AS - mean direction of air masses movement in Świnoujście; CS- coefficient of concentration of air masses movement direction in Świnoujście; DT- difference between mean direction of drift and mean direction of air masses in Trzebież; DS– difference between average direction of drift and average direction of air masses movement in Świnoujście)*

| L | AD (*deg.*) | CD (%) | AT (*deg.*) | CT (%) | AS (*deg.*) | CS (%) | DT (*deg.*) | DS (*deg.*) |
|---|---|---|---|---|---|---|---|---|
| 1 | 221 | 93.4 | 207 | 96.6 | 239 | 64.2 | 14 | -18 |
| 2 | 207 | 98.0 | 209 | 98.4 | 226 | 98.9 | -2 | -19 |
| 3 | 114 | 96.7 | 99 | 95.8 | 107 | 88.8 | 15 | 7 |
| 4 | 119 | 79.2 | 106 | 76.1 | 125 | 64.0 | 13 | -6 |
| 5 | 229 | 58.8 | 217* | 57.0* | 231 | 76.4 | 12* | -2 |
| 6 | 121 | 75.7 | 106 | 83.9 | 119 | 85.3 | 15 | 2 |
| 7 | 239 | 36.6 | 244 | 28.6 | 218 | 32.9 | -5 | -5 |
| 8 | 90 | 10.3 | 49 | 14.5 | 17** | 47.9** | 41 | 73** |
| 9 | 16 | 36.2 | 19 | 57.0 | 16 | 64.6 | -3 | 0 |
| 10 | 322 | 93.1 | 334 | 99.3 | 348 | 99.6 | -12 | -26 |

***Note:*** ** Data only for the first 18 hours of testing; **No data from 12.00 to 24.00/16.08.18*
***Source:*** *Own study.*

***Table 3.*** *Parameters describing the speed of drifter movement for 10 launches in summer 2018. The air masses speeds are calculated for Trzebież and Świnoujście (L - launch number; ASD - mean speed of drift; SSD - standard deviation of drift speed; AST - mean wind speed in Trzebież; SST standard deviation of wind speed in Trzebież; ASS – average wind speed in Świnoujście; SSS- standard deviation of wind speed in Świnoujście; SRT- coefficient of surface drift for Trzebież; SRS- coefficient of surface drift for Świnoujście).*

| L | ASD (*m/s*) | SSD (*m/s*) | AST (*m/s*) | SST (*m/s*) | ASS (*m/s*) | SSS (*m/s*) | SRT (%) | SRS (%) |
|---|---|---|---|---|---|---|---|---|
| 1 | 0.108 | 0.0296 | 5.53 | 1.63 | 5.70 | 2.80 | 2 | 1.9 |
| 2 | 0.122 | 0.0412 | 6.16 | 1.81 | 6.55 | 1.49 | 2 | 1.9 |
| 3 | 0.164 | 0.0389 | 4.12 | 1.05 | 4.18 | 1.68 | 4 | 3.9 |
| 4 | 0.138 | 0.0580 | 3.28 | 1.96 | 2.93 | 1.41 | 4.2 | 4.7 |
| 5 | 0.104 | 0.0418 | 2.45* | 1.46* | 5.71 | 2.70 | - | 1.8 |
| 6 | 0.117 | 0.0390 | 2.59 | 1.20 | 3.93 | 1.87 | 4.5 | 3 |
| 7 | 0.106 | 0.0467 | 2.16 | 1.45 | 3.34 | 1.69 | 4.9 | 3.2 |
| 8 | 0.121 | 0.0430 | 2.37 | 1.56 | 2.57** | 0.88** | 5.1 | - |
| 9 | 0.111 | 0.0320 | 2.14 | 1.37 | 3.02 | 1.85 | 5.2 | 3.7 |
| 10 | 0.154 | 0.0661 | 3.51 | 0.88 | 3.55 | 0.61 | 4.4 | 4.3 |

***Source:*** *Own study.*

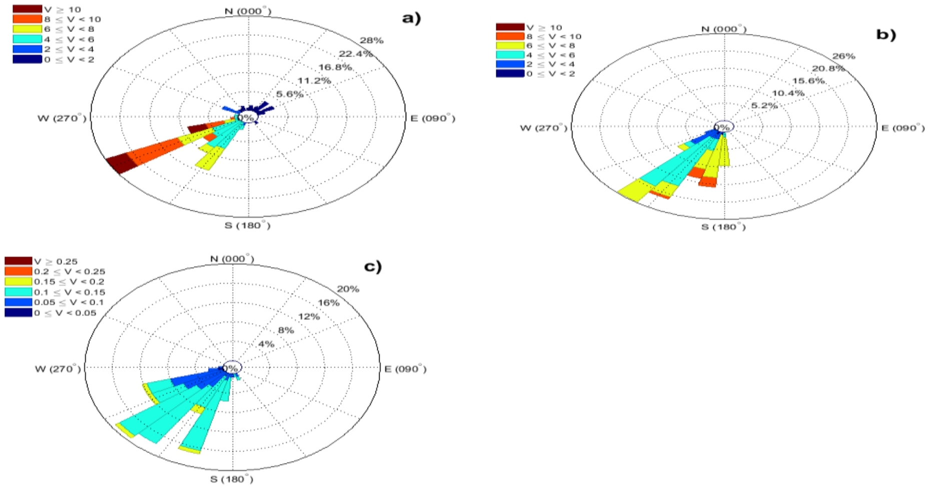
For better visualization of the relationship between drifter track parameters in experiments conducted in Szczecin Lagoon area and the parameters of air masses measured in the towns of Trzebież and Świnoujście, direction distributions are presented graphically, referred to as roses of the winds and drifts, separately for individual drift launches. The drifter trajectories after launch No 1 is shown in Figure 5. The black spot marks the starting point of the experiment.

***Figure 5.*** *Trajectory No. 1 (d1) of the drifter*


***Source:*** *Own study.*

Figure 6 presents the following direction distributions for drifter No 1: a) wind rose for Świnoujście, b) wind rose for Trzebież and c) rose diagram for directions of the drifter No 1. One should note that the directions indicated in three rose diagrams are similar. Besides, greater similarity is observed for Trzebież than for Świnoujście.

***Figure 6.*** *Directional distributions of the wind conditions and drift parameters (units - [m/s]), for the launch No.1*




***Source:*** *Own study.*

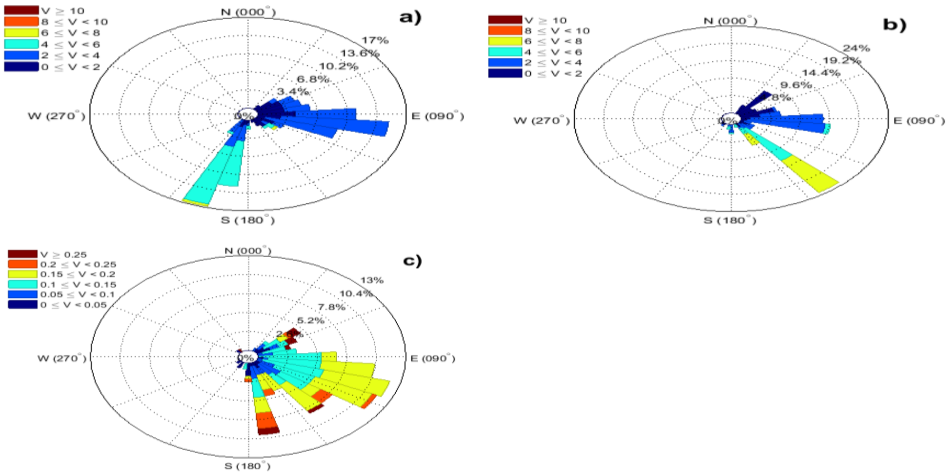
The circular correlation coefficient *r* between wind direction and drift direction is equal to 0.584 for Trzebież and 0.552 for Świnoujście. Both are statistically significant. Trajectory after launch 4 is shown in Figure 7. The black point marks the start of the experiment.

***Figure 7.*** *Trajectory No. 4 (d4) of the drifter*


***Source:*** *Own study.*

Figure 8 presents the following direction distributions for drifter No 4: a) wind rose for Świnoujście, b) wind rose for Trzebież, c) rose diagram for the drifter.

***Figure 8.*** *Directional distributions of the wind conditions and drift parameters (units - [m/s]) for the launch No.4*




***Source:*** *Own study.*

The circular correlation coefficient *r* between wind direction and drift direction for the launch No.4 is equal to 0.814 for Trzebież and 0.785 for Świnoujście. Both are statistically significant.

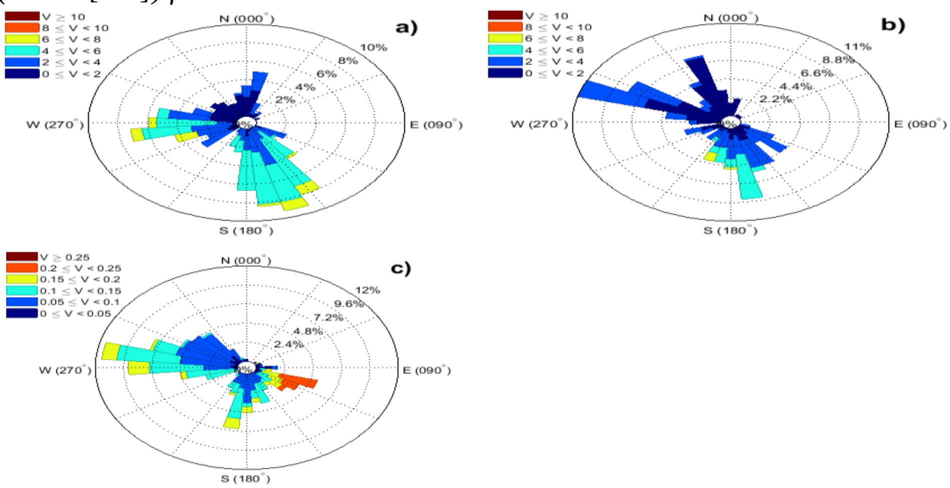
The trajectories No 1 and No. 4 did not significantly change direction. The trajectory No. 1 was generally moving in the south-west direction, and drift speed was fluctuating, but it did not exceed 0.16 m/s. Trajectory No. 4 had more varied direction, but the drifter was mainly moving southeast. The drifter speed was less varied than for trajectory No. 1, but it did not exceed 0.26 m/s.

***Figure 9.*** *Trajectory No. 7 (d7) of the drifter*


***Source:*** *Own study.*

The trajectories No. 7 and No. 9 were characterised by variable direction and speed. The drift speed for experiment No 7 varied between 0.003 m/s and 0.240 m/s, while for experiment No. 9 - from 0.016 to 0.270 m/s. The trajectory No 7 is shown in Figure 9, and trajectory No. 9 – in Figure 11. Figure 10 presents the following direction distributions for trajectory No. 7: a) wind rose for Świnoujście, b) wind rose for Trzebież and c) rose diagram for the drifter.

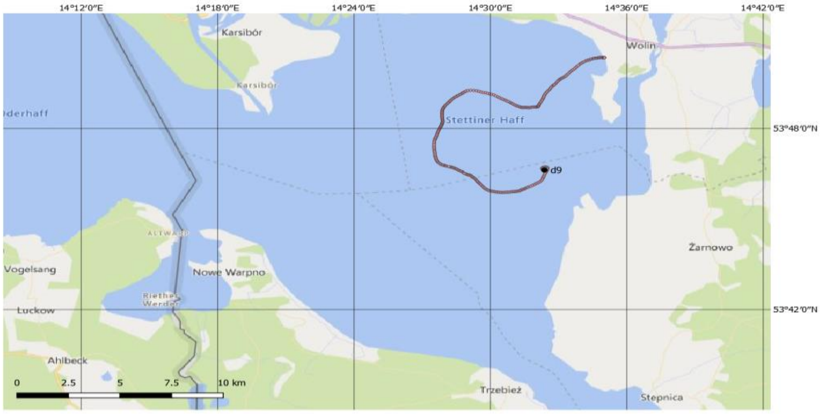
***Figure 10.*** *Directional distributions of the wind conditions and drift parameters (units - [m/s]) for the launch No. 7*




***Source:*** *Own study.*

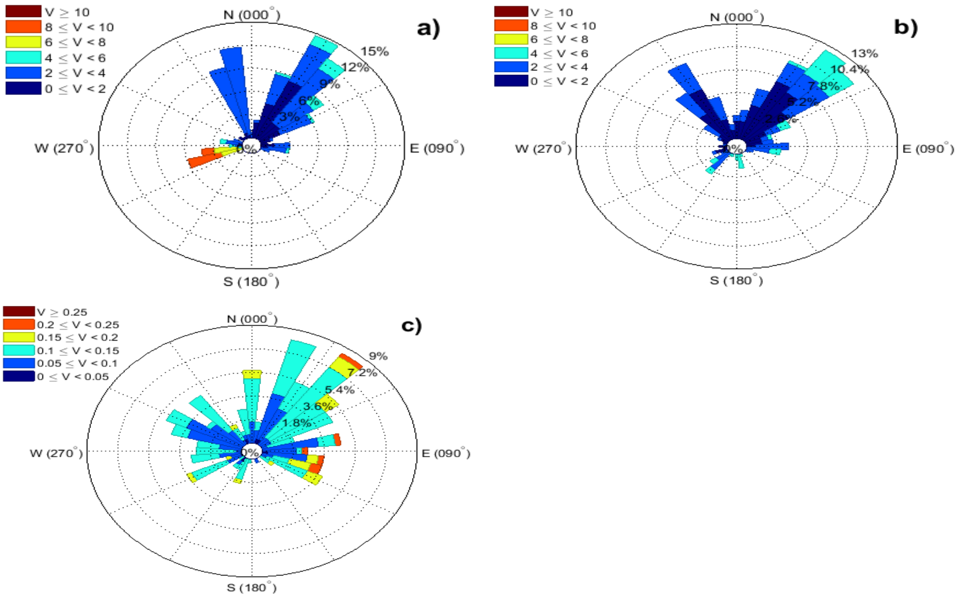
The circular correlation coefficient r between wind direction and drift direction for the launch No. 7 is equal to 0.882 for Trzebież and 0.910 for Świnoujście. Both are statistically significant. The same data, following the same principles, are presented for trajectory No. 9 in Figure 12. The circular correlation coefficient r between wind direction and drift direction for the launch No. 9 is equal to 0.904 for Trzebież and 0.854 for Świnoujście. Both are statistically significant.

***Figure 11.*** *Trajectory No. 9 (d9) of the drifter*




***Source:*** *Own study.*

***Figure 12.*** *Directional distributions of the wind conditions and drift parameters (units - [m/s]) for the launch No. 9*




***Source:*** *Own study.*

## 6. Discussion and Concluding Remarks

Ten drifter trajectories display a large variety. There are two types of drifter trajectories: when drift direction is similar to the straight line (Nos 1, 2, 3, 4, 4, 6, 10), and where the direction varies (Nos 5, 7, 8, 9). Comparing the direction distributions of drift with direction distributions of air masses, we can observe that their directions are largely consistent, and that the direction of surface water layer movement is generally the result of wind impact. This is confirmed by the determined circular correlation coefficients.

Taking into account the surface drift coefficient (Table 3, column 8 and 9), we can distinguish two types of drift: drift with a low coefficient - approximately 2% (trajectories 1, 2, 5) and with high coefficient (trajectories 3, 4, 6, 7, 8, 9 and 10). The low drift coefficient was obtained at wind speeds, measured at Trzebież and Świnoujście, reaching at least 0.6 m/s. The wind speed less than 1 m/s was recorded only in isolated cases (for trajectories 1, 2, and 5, in eight measurements). In the case of trajectories 1, 2 and 5 the first quartile of wind speed changed from 3.9 m/s to 5.3 m/s.

Besides, in 75% of the measurements, wind speed had a value of at least 3.9-5.3 m/s. The trajectories Nos 1, 2 and 5 have several common characteristics. One of them is the prevailing direction of air masses flow, i.e. NNE and NE. Another feature is the high coefficient of concentration around the mean direction of drift and of air masses movement: over 90% for trajectory 1, over 98% for trajectory 2 and more than 76% for trajectory 5 (lower value is the result of changing directions). The third common feature is the mean drift speed, from 0.10 m/s to 0.12 m/s, reflecting stable, nearly rectilinear drifter movement when winds were blowing from NNE and NE.

High coefficients of surface drift (4-5%) were obtained for the trajectories: 3, 4, 6, 7, 8, 9 and 10. During those launches, sectors NW, N, W and SE of wind direction prevailed. The mean wind speed for trajectories 3, 4, 6, 7, 9, 10 was lower than in the case of trajectories 1, 2 and 5 and varied from 2.14 to 4.18 m/s, compared to the mean drift speed, which was higher than for trajectories 1, 2, and 5 and was 0.106 – 0.164 m/s. Besides, the mean wind speed for trajectory 3 was approximately 4.2 m/s, while the mean drift speed for trajectory 3 was the highest: 0.164 m/s. Such a high mean drift speed can be attributed to the existence of a deep water fairway Świnoujście-Szczecin and movement of the drifter across the central, deepest part of Szczecin Lagoon. A similar drifter behaviour was observed for trajectory No 10, where it drifted on the Świnoujście-Szczecin fairway, mainly through the central part of Szczecin Lagoon. Standard deviations of drift for trajectories 3 and 10 were high (Table 3, column 3), due to the change of local conditions, when the drifter was moving in the area of Roztoka Odrzańska, where the River Świna joins the lagoon or in shallow waters.

In the case of launches 4, 6, 7, 8 and 9, in main sections of drifter trajectories, wind was weak or very weak, and its mean speed did not exceed 3.28 m/s. Detailed data analysis (i.e. module of differences between subsequent directions) demonstrated a large conformity between the movement direction change and wind direction change resulting from significant decrease of wind speed. After wind speed increases, the direction of air masses movement got stable, so did the drift direction. The drift speed was usually higher in the central part of Szczecin Lagoon, approximately 0.150 – 0.250 m/s. The lowest mean wind speed of approximately 2.14 – 3.34 m/s was obtained for trajectories 7, 8 and 9, while standard deviations of wind speed compared to mean wind speed were high, 1.37 to 1.85 m/s. Besides, significant and multiple changes of drift direction are observed. The calculated concentration coefficients (Table 2, columns: 3, 5, 7) describe relatively low concentration of drift or wind directions around their mean directions.

It should be borne in mind that the in-situ experiments were conducted at various wind directions and speeds. The drifter trajectories were varied, too. Summarizing the test results we can state that wind impact on the behaviour of drifters was very strong. In many cases, the drifter movement direction was compatible with the direction of the wind. The direction and speed of air masses flow are parameters that strongly affect the movement of surface waters of Szczecin Lagoon. At wind speeds of at least 2-3 m/s the wind direction stabilizes, and so does drift direction. Moreover, drift trajectory usually conforms with wind direction. Changes of wind direction are more pronounced when wind force is low.

Alterations of drift direction are generally caused by wind direction changes. It has been found through the experiments that in some areas of Szczecin Lagoon - Roztoka Odrzańska or nearby breakwater at the Świna mouth, other factors affect movement parameters. In this case, inflow of water from the Odra and outflow to the Świna strait are important, but in a limited area. These waters of Szczecin Lagoon will be examined by the authors in the future. Surface water flow rates in Szczecin Lagoon are diversified; from 0 to 0.3 m/s. Highest speeds were recorded in the central part of the lagoon, in the fairway, close to the Świna mouth, and in the neighbourhood of Roztoka Odrzańska.

From the perspective of a search and rescue operation in Szczecin Lagoon, it should be noted that the drifter in most cases got stranded in the reeds near Warnołęka (south-west shore of the lagoon) or in vicinity of Czarnocin (eastern shore of the lagoon). Besides, the longest drifting times of trajectories Nos 7 and 8 may be due to a considerable change in wind direction (almost 180 degrees). For a period of time the drifter floated along the same track in the opposite direction. The drift duration oscillated around 33 hours before it stopped in the reeds or shallow water. That was an average time of a single experiment.

The article provides theoretical framework for the insight into the dynamics of water movements in Szczecin Lagoon. The test results can be utilized for modelling movements of survivors, enhancing the effectiveness of search and rescue operation, search for lost property, polluted water or microorganisms. Besides, the study delivered data for the determination of relations between the surface water mass flows in Szczecin Lagoon and air masses movements in the region. Such data have not been available so far. To date, unfortunately, taking account of drift parameters, the surface of Szczecin Lagoon has not been sufficiently included in any of the existing hydrodynamic models. This makes further research even more challenging.

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