Scientific Journals
of the Maritime University of Szczecin

Zeszyty Naukowe
Akademii Morskiej w Szczecinie

2019, 59 (131), 62–71
ISSN 1733-8670 (Printed)
ISSN 2392-0378 (Online)
DOI: 10.17402/353

Received: *26.04.2019*
Accepted: *25.07.2019*
Published: *30.09.2019*

Research into leeways in the regions of the Świnoujście–Szczecin fairway on the Szczecin Lagoon

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Key words: leeway, wind, downwind, crosswind, in-situ experiments, surface drifters, fairway, Szczecin Lagoon

Abstract

The paper analyzes the influence of air mass movement on moving (the leeway) surface water in the Świnoujście–Szczecin fairway region on the Szczecin Lagoon. The Szczecin Lagoon includes waters of the Odra River estuary (Poland's second largest river) and the southern Baltic Sea. To calculate the leeway parameters, a relevant surface drifter was outlined and constructed. The data on the leeway of the drifter was obtained from *in-situ* experiments conducted on the Szczecin Lagoon in the summer of 2018. In turn, the air mass movement data was recorded at meteorological stations in Trzebież and Świnoujście. A statistical analysis of the leeway parameters of the drifter was also presented. Distributions of the leeway and wind speeds in the Świnoujście–Szczecin fairway regions were established. Moreover, linear regressions between the leeway and wind parameters were performed by decomposing the leeway into its downwind and crosswind components for each 10-minute sample. It is worth highlighting that relationships between these components of the leeway and wind parameters were studied for weak, medium, and stronger winds. This research may be useful for increasing navigation safety in the Świnoujście–Szczecin fairway regions on the Szczecin Lagoon.

Introduction

Inland shipping includes the carriage of cargo, as well as fishing, sailing, and tourist activities. All of these functions occur on the Szczecin Lagoon, since this reservoir contains both Polish marine waters and inland surface waters. Polish sea areas are divided into internal sea waters, territorial seas, and exclusive economic zones (Act, 1991). Poland contains internal sea waters and territorial seas, the former of which are composed of parts of the Gulf of Gdańsk and the Vistula Lagoon. Other internal Polish sea waters include a part of the Nowowarpieńskie Lake and a part of the Szczecin Lagoon, along with the Dziwna and Świna Straits and the Kamieński Lagoon, located east of the border between Poland and Germany, and the portion of the Odra River between the Szczecin Lagoon and Szczecin port. The boundaries between the inland surface waters, the internal sea waters, and the territorial sea waters in the Szczecin Lagoon region are the following (Regulation, 2018):

- on the Dąbie Lake – the perpendicular lines where the waters of the Babina Nurt (Polish: Nurt Babina) run to the Odra River and in the estuary of the Duńczyca River, and the Przesmyk Orli water race (Polish: ciek Przesmyk Orli) to the Mieleński Piercing (Polish: Przekop Mieleński);
- on the Iński Nurt canal – border points No. 660 and 472;
- on the Łarpia river – the perpendicular line to the axis of the riverbed 750 m from the estuary of the Odra River;
- on the Gunica river – the perpendicular line to the axis of the riverbed 1400 m higher than the Odra River estuary – the Roztoka Odrzańska.

Considering the components of the natural environment, Poland has good conditions for developing inland shipping, since large rivers and the channels between them create an extensive river system. Moreover, Polish rivers are covered with low amounts of ice during winter, and many towns are located on and near these rivers. On the other hand, the rivers with low water levels need to be dredged. The Szczecin and Świnoujście seaports are fundamentally important for inland shipping. The route between these ports passes through the Świnoujście-Szczecin fairway with a length of 67.7 km, which passes through the 20-km-long Szczecin Lagoon. It is used by seagoing ships and also by inland fleets (barges, cutters, passenger ships). Furthermore, the transshipment points of the Odra River estuary and the Szczecin Lagoon include:

- the river-sea port of the Chemical Factory "Police";
- small ports, harbors, and marines of the Szczecin Lagoon, including Stepnica, Trzebież, Nowe Warpno, Wolin, Zalesie, Lubin, and Wapnica;
- the cargo handling quay at the Ognica, used for the transshipment of agricultural products.

It is worth adding that the current inland waterways network is a proper connection of the Odra estuary with the European Union, in particular in Germany.

Hydrometeorological conditions are a major problem for the inland rolling stock on the Świnoujście-Szczecin fairway, and these conditions must be analyzed to ensure safe navigation. Despite many factors which may affect the Szczecin Lagoon waters, wind conditions are one of the most important, and the short-term variability of surface currents on this lagoon should be related to wind parameters. This property is particularly noticeable on small reservoirs, such as the Szczecin Lagoon (Vandenbulcke et al., 2009).

The aim of this paper is to analyze the leeway in the Świnoujście–Szczecin fairway regions on the Szczecin Lagoon. According to Allen and Plourde (Allen & Plourde, 1999), leeway is the movement of an object induced by wind (10 m reference height) and waves relative to the ambient current (between 0.3 and 1.0 m depth). In another work (Breivik & Allen, 2008), wave drift forces acting on small objects (< 30 m) can be omitted when the wave length is more than about six times the object's length. Thus, Allen and Plourde (Allen & Plourde, 1999) made the assumption that even for objects as large as a cargo container or small boat, leeway can be expressed in most sea states as a function of the wind only. Moreover, these authors maintain (Allen & Plourde, 1999) that the leeway of small drifting objects tends to increase linearly over typical wind speed periods.

Breivik et al. (Breivik et al., 2011) developed a method for conducting leeway field experiments to establish drift properties of small objects. Namely, linear relationships between the downwind and crosswind components of the leeway and wind were given. The experiments allowed for the determination of their coefficients. In turn, Brushett el al. (Brushett et al., 2014) obtained the downwind and crosswind leeway coefficients for three small crafts common to Pacific island communities. The leeway was studied at three localizations within the tropical North Pacific Ocean: approx. 15 km off the western coast of Chuuk Lagoon in the Federated States of Micronesia, approx. 20 km to the north of the Puluwat Atoll, and approx. 10 km to the west of Apra Harbor, Guam.

An analysis of drift as a function of wind parameters was also carried out for the Gulf of Finland in 2011 and 2013 (Delpeche-Ellmann, Torsvik & Soomere, 2016). The authors observed that in many cases, the drift was similar to the direction in which the wind was blowing. In turn, in (Vandenbulcke et al., 2009), surface drift of two buoys launched in the Adriatic Sea during the DART06 sea trials and in the Ligurian Sea during the MREA07 experiment, was predicted. In another paper (Brillinger and Stewart, 2010), tag currents were compared: the zonal and meridional currents with the geostrophic currents derived from the polar-orbiting satellites of the Argos Data Collection and Location Service system. The tag currents were received during the surface drifting movements of a small satellite-linked radio transmitter tag after it detached from a whale shark in the western Indian Ocean. It is worth highlighting that the authors concluded that the motions of the drifting tag were prevalently impacted by sea surface currents. To explain the selective onshore transport processes of meso- and microplastics drifting in coastal waters, the authors in (Isobe et al., 2014) combined the results of *in-situ* experiments with those of a numerical particle-tracking model. This research has exhibited the near-shore trapping of mesoplastics using the Stokes drift and terminal velocities dependent on particle sizes.

Certain statistics regarding 227 satellite-tracked drifters deployed in the Gulf of Maine from 1988 to 2007 was achieved by Manning et al. (Manning et al., 2009). A deceleration of surface flow was observed from eastern Maine (Cutler) toward Massachusetts

(Mass) Bay, as well as a flow acceleration on the east side of Cape Cool, and another deceleration near the Great South Channel. The mean residual velocities downstream of Cutler in the Eastern Maine Coastal Current were usually near 16 cm/s and quickly decreased to roughly 9 cm/s. In turn, the surface circulation patterns in the Mozambique Channel were explained using the trajectories of 82 satellite-tracked drifters from 2000–2010 and complementary satellite-derived altimetry. In turn, in (Olascoaga et al., 2013) the authors described that more than 300 satellite-tracked near-surface drifting buoys were deployed in the northeastern Gulf of Mexico. The authors observed that near-surface transport in the Gulf of Mexico was significantly influenced by mesoscale circulation. In turn, Kasyk et al. (Kasyk et al., 2016) and Pyrchla et al. (Pyrchla et al., 2017) proposed methods based on the graph theory and the M3D hydrodynamic model for predicting the movements of surface water masses in basins adjacent to the port. The findings of the numerical models were related to the measurements carried out using dedicated surface drifters during *in-situ* experiments. However, to obtain data on surface currents and wind to perform such numerical modelling, geographic information systems such as the Maritime Network-Centric Geographic Information System in the Gulf of Gdańsk (Pyrchla et al., 2016) have been employed.

In this paper, some statistical analysis of the parameters of the leeway and wind are presented. The authors establish certain linear relationships between the leeway and wind forces for regions of the Świnoujście–Szczecin fairway. The histograms of the leeway and wind speeds and the distributions fitted to them are presented for three groups of wind conditions: weak, medium, and stronger winds. This study is based the leeway data recorded during the *in-situ* experiments which were conducted in the summer (late June – mid-October) in 2018. In turn, the wind parameters were recorded by the Institute of Meteorology and Water Management (IMGW) at the Trzebież and Świnoujście meteorological stations.

Research area, data, and methods

The Szczecin Lagoon includes waters of the Odra River estuary (Poland’s second largest river) and the southern Baltic Sea. The area is bounded by the following positions: latitude ca. 53°42' N – 53°52' N, longitude ca. 013°53' E – 014°36' E. The Baltic Sea is connected to the Szczecin Lagoon via the Dziwna, Świna, and Piana straits. The Świna Strait is the most important to the Szczecin Lagoon hydrological system. The currents in these three straits are formed by the exchange of water between the Baltic Sea and the Szczecin Lagoon. The Szczecin Lagoon is about 28 km long and over 52 km wide (BHMW, 2009) with an average depth of 3.8 m and a largest natural depth of 8.5 m. The greatest depth of 10.5 m is the effect of the deepening of the busy Świnoujście–Szczecin fairway, which leads to the Szczecin Lagoon from Szczecin to the Baltic Sea. The Świnoujście–Szczecin fairway, together with the Piastowski Channel, play an important role in the exchange of waters between the Szczecin Lagoon and the Baltic Sea.

Experimental studies have been carried out to describe relationships between the leeway and the wind in regions of the Świnoujście–Szczecin fairway on the Szczecin Lagoon which can be navigated by merchant vessels, fishing vessels, and sailing ships passing through the Szczecin Lagoon. Moreover, regions approx. 3 km away from the Świnoujście–Szczecin fairway were investigated, which means that the diameter of the studied water area within the Świnoujście–Szczecin fairway was approx. 6 km. For this study, the geographical coordinates of the drifter position, launched eleven times on the Szczecin Lagoon, associated with the considered regions of the Świnoujście–Szczecin fairway, were selected.

To conduct *in-situ* experiments, an appropriate drifter was constructed which had a balanced buoyancy, so that it did not protrude from the water, and approx. 80% of its volume was under water. The drifter was equipped, with a SPOT Trace locator which determined the geographical position of the drifter with a GPS receiver and sent data in real time via a satellite network. Subsequent positions of the drifter were recorded at 10-minute intervals. The *in-situ* experiments on the Szczecin Lagoon waters were conducted in the summer of 2018 (late June – mid-October).

In turn, wind parameters (direction and speed) were measured at a height of 10 m in the technical basins of the Institute of Meteorology and Water Management (IMGW) at the meteorological stations at Trzebież (53°39' N, 014°31' E) and Świnoujście (53°55' N, 014°15' E). Currently, Trzebież and Świnoujście are the closest locations to the Szczecin Lagoon where IMGW performs measure wind parameters and make them available to users online. IMGW does not perform measurements in the area of the Szczecin Lagoon itself.

Allen (Allen, 2005) showed that the leeway could be decomposed into its downwind (DWL) and crosswind (CWL) components. Moreover, the study claimed that the downwind component of the leeway tended to follow a nearly linear relationship with the wind speed which allowed the crosswind component of the leeway to be analyzed with reference to the wind separately from its downwind component. Linear regressions between the wind speed and the downwind or crosswind leeway components can be found in (Allen, 2005). Due to the (small) size and the shape (symmetry) of the drifter, the authors in this paper consider the following linear equations:

$$L_d = a_d \cdot W_{10} + b_d + \varepsilon_d \qquad (1)$$
$$L_c = a_c \cdot W_{10} + b_c + \varepsilon_c$$

where:

L_d – downwind leeway speed (DWL) [cm/s],
L_c – crosswind leeway speed (CWL) [cm/s],
W_{10} – 10-m wind speed [m/s],
a_d – slope of DWL [%],
a_c – slope of CWL [%],
b_d – offset of DWL [cm/s],
b_c – offset of CWL [cm/s],
ε_d – error term of DWL [cm/s],
ε_c – error term of CWL [cm/s].

The parameters of the linear equations (1) were calculated as the least squares estimates. In addition, the authors assumed Gaussian errors about the linear regressions in equations (1). Namely, the error terms ε_d, ε_c (i.e. the standard errors $S_{L_dW_{10}}$, $S_{L_cW_{10}}$) are enough to calculate errors of the downwind and crosswind components of the leeway.

Furthermore, the authors have calculated certain basic statistical parameters of the leeway of the drifter and of the wind blowing during the *in-situ* experiments in the Świnoujście–Szczecin fairway regions. The histograms of the speeds of the leeway of the drifter, the leeway components, and the wind speeds are also presented. These parameters and histograms have been measured to facilitate understanding the distributions of the speeds of flows of the water and air masses in the studied water area and to identify how they vary.

Analysis of leeway in the Świnoujście–Szczecin fairway regions

At the beginning of the study, the directions and speeds of the leeway were calculated for the Świnoujście–Szczecin fairway regions using the measured geographical coordinates of the drifter positions. In turn, the histogram of these leeway speeds was created, which is shown along with the normal distribution fitted in Figure 1.

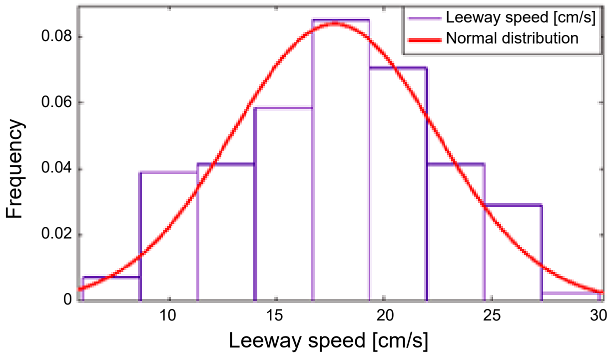

Figure 1. Histogram of the leeway speeds calculated for the regions of the Świnoujście-Szczecin fairway. The data was recorded during the *in-situ* experiments in the summer of 2018

Figure 1 shows that the most common leeway speeds in the Świnoujście–Szczecin fairway regions exceeded 15 cm/s, indicating that the leeway speeds of the studied waters were usually higher than other regions of the Szczecin Lagoon. The statistical parameters of the leeway speeds are presented in Table 1.

Table 1. Descriptive statistics of the leeway speeds distribution in the regions of the Świnoujście–Szczecin fairway

Parameters	Values
minimum [cm/s]	7.34
maximum [cm/s]	28.63
mean [cm/s]	17.70
median [cm/s]	17.64
first quartile [cm/s]	14.60
third quartile [cm/s]	21.03
5% of percentile [cm/s]	10.17
10% of percentile [cm/s]	11.02
90% of percentile [cm/s]	24.23
95% of percentile [cm/s]	25.64
percent of the leeway speeds above 20 cm/s [%]	32.90
percent of the leeway speeds below 10 cm/s [%]	4.50
standard deviation [cm/s]	4.80
kurtosis	–0.67
skewness	–0.03

In turn, the normal distribution of the leeway speeds in Figure 1 have a mean of 17.70 cm/s and a standard deviation 4.80 cm/s. Thus, the typical values of the leeway speed in the Świnoujście–Szczecin fairway regions range from 12.90 cm/s to 22.50 cm/s. The log of the likelihood ratio is equal to –458.004. In turn, the Pearson’s chi-square goodness-of-fit test provided the following values: chi-square statistic of 4.5839, degrees of freedom: 6, p-value: 0.5982. Then, the chi-square goodness-of-fit test did not require rejection of the null hypothesis at the 5% significance level which stated that the recorded leeway speeds came from a normally-distributed population with the parameters: $\mu = 17.70$ and $\sigma = 4.80$.

To compare the leeway and wind parameters, the wind speeds measured at the Trzebież and Świnoujście meteorological station were first analyzed. The histogram of the recorded wind speeds and the log-logistic distribution fitted to it are shown in Figure 2.

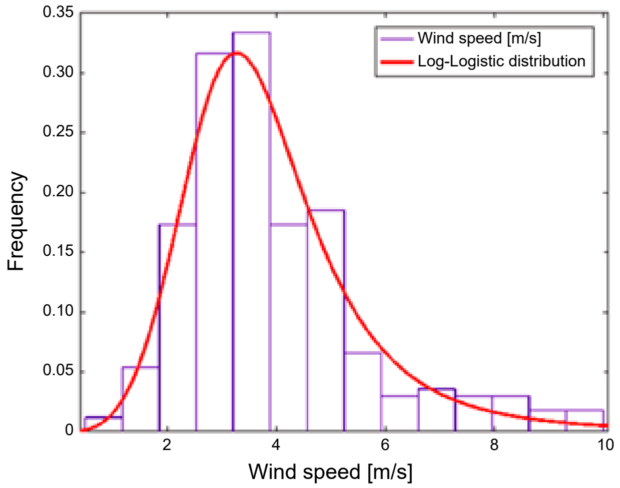

Figure 2. Histogram of the wind speeds recorded at the meteorological stations for the regions of the Świnoujście–Szczecin fairway. The data was recorded during *in-situ* experiments conducted during the summer of 2018

The mean value of the recorded wind speeds was 3.97 m/s, and the standard deviation was 1.85 m/s. As it can be seen in Figure 2, the typical wind speeds during the movement of the drifter in the Świnoujście–Szczecin fairway regions were between 2 m/s and 5 m/s. This means that the wind speeds were usually moderate. The minimum recorded wind speed was 0.60 m/s, and the maximum was 9.80 m/s. The first quartile of the wind speeds was 2.90 m/s, and the third quartile was 4.70 m/s. The parameters of the log-logistic distribution of the recorded wind speeds were the following: $\mu = 1.29$ and $\sigma = 0.22$. The log likelihood ratio was –449.516. In turn, the chi-square goodness-of-fit test provided the following values: chi-square of 7.0448, degrees of freedom: 6, p-value: 0.3167. Then, the chi-square goodness-of-fit test did not require rejection of the null hypothesis at the 5% significance level which stated that the recorded wind speeds come from a population with a log-logistic distribution with the parameters $\mu = 1.29$ and $\sigma = 0.22$.

No relationship was observed between the recorded for the overall set of wind and leeway speeds, but certain relationships were established for some wind speed intervals. For this purpose, the recorded wind speeds were separated into three groups: one from 0 m/s to 3.3 m/s (low wind speeds), another from 3.3 m/s to 5.5 m/s (medium wind speeds), and the third group from 5.5 m/s to 9.8 m/s (higher wind speeds). For certain groups, relationships between the wind speeds and the leeway components were sought separately. To establish such relationships, for each 10-min step of the measurement of the geographical position of the drifter transmitted by the GPS system, the radial coordinates of the leeway were calculated. They were then used to compute the downwind and crosswind components of the leeway. To set relationships between the wind and the leeway, Figure 3 was created.

By analyzing the data and graphs in Figure 3, it can observed that the downwind components of the leeway are very similar to the leeway speeds, and the differences between them are usually equal to hundredths or decimals. This means that the leeway directions are maintained in a high compliance with the direction of the air masses motions, In turn, the values of the crosswind components of the leeway (Figure 3) indicate that the drifter more often diverged to the left than to the right from the wind directions. However, the crosswind components of the leeway are usually very small (approx. 10 cm/s).

In the first three graphs in Figure 3, the wind speeds from 0 m/s to 3.3 m/s (the low wind speeds) were studied. No relationship was observed between these wind speeds and the leeway speeds or the leeway downwind and crosswind components. As Figure 3 shows, at low wind speeds, the leeway speeds are very different and factors other than wind speed significantly affect the leeway speed of the drifter.

For wind speeds from 3.3 m/s to 5.5 m/s (medium wind speeds), certain linear relationships were observed between the wind speeds and the downwind and crosswind components of the leeway in Figure 3. Namely, the speeds of the leeway and its components usually increased with the wind speeds.

Figure 4 shows the linear relation between the medium wind speeds and the downwind components of the leeway. This relationship is as follows:

$$L_d = 3.9710\% \cdot W_{10} + 0.9007 \text{ [cm/s]} \tag{2}$$

where W_{10} is the wind speed in m/s.

Thus, the slope of DWL is equal to $a_d \pm \sigma(a_d) = 3.9710 \pm 1.1570$ [%], and the offset of DWL is – $b_d \pm \sigma(b_d) = 0.9007 \pm 4.8235$ [cm/s]. This means

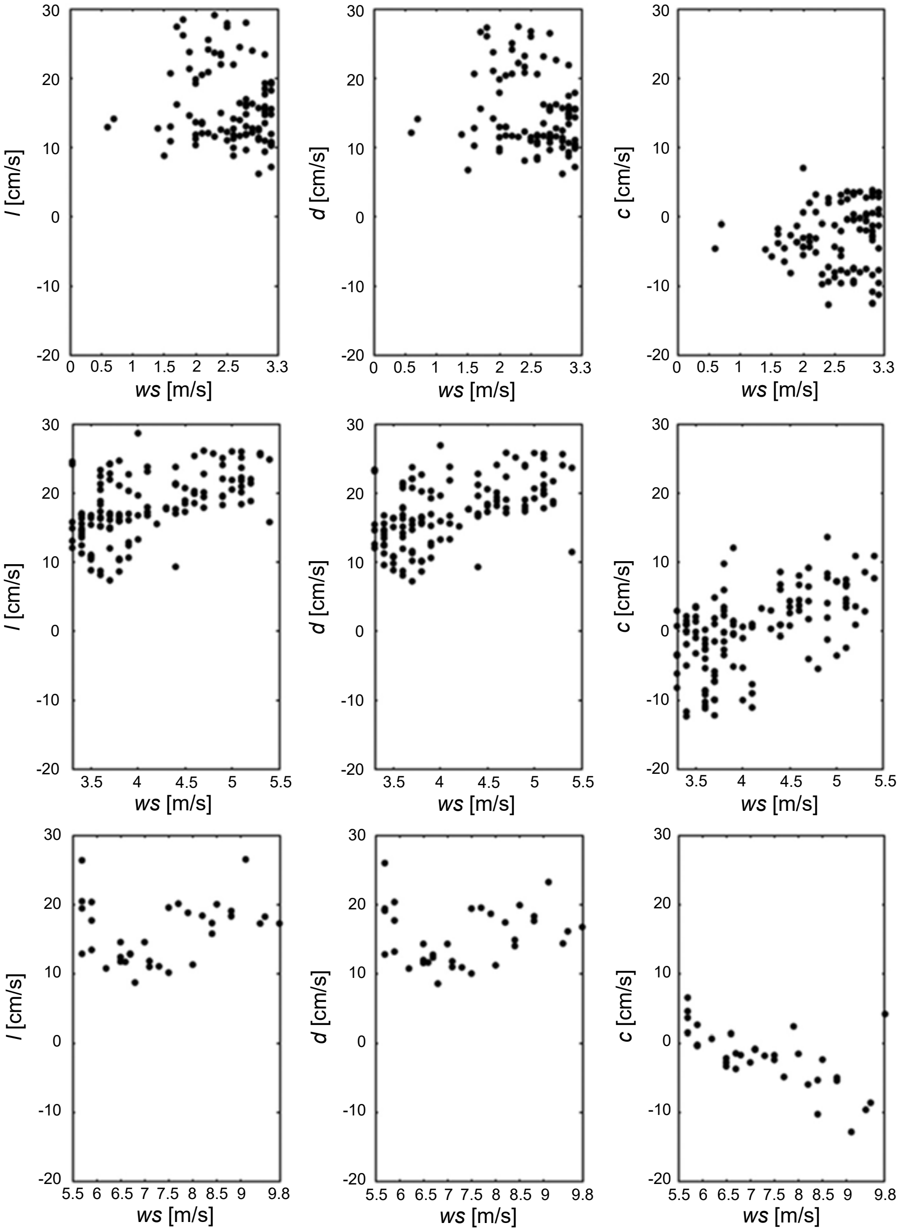

Figure 3. Wind speed (*ws* in [m/s]) versus the leeway speed (*l* in [cm/s]), the downwind component of the leeway (*d* in [cm/s]), or the crosswind component of the leeway (*c* in [cm/s]). The wind speeds were separated into three groups: from 0 m/s to 3.3 m/s (*N* = 93), from 3.3 m/s to 5.5 m/s (*N* = 120,) and from 5.5 m/s to 9.8 m/s (*N* = 34)

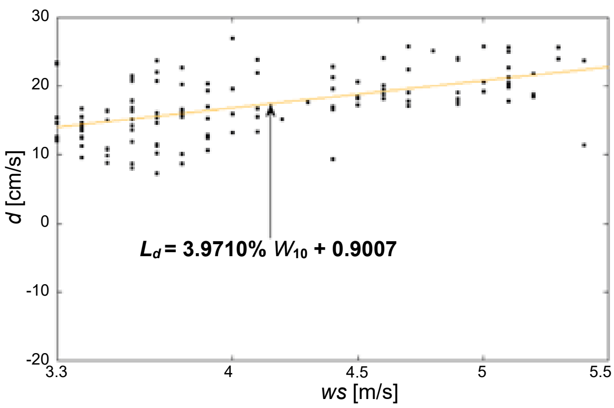

Figure 4. Wind speed (*ws* in [m/s]) from 3.3 to 5.5 versus the downwind component (*d* in [cm/s]) of the leeway and the linear relationship between them

that in this case, the downwind component of the leeway was approx. 3.9710% of the wind speed in m/s, which is an increase of 0.9007. The norm of residuals was 43.2090 cm/s, and the sum of squares due to error (summed square of residuals) SSE was 1867 cm/s. The error term (the standard error $S_{L_d W_{10}}$) ε_d was 3.9500 [cm/s], R^2 was 0.2812, the adjusted R^2 was 0.2751, and the root mean squared error (RMSE) was 3.978.

It can be observed from the graph of the relation between the wind speed from 3.3 m/s to 5.5 m/s and the crosswind component in Figure 3 that for wind speeds close to 3.3 m/s (slightly higher), the drifter usually diverged to left. In turn, for wind speeds close to 5.5 m/s (slightly less), the same drifter usually diverged to right. Moreover, the crosswind components of the leeway were usually small.

Figure 5 shows a relationship between the medium wind speeds and the crosswind components of the leeway. This linear relationship is as follows:

$$L_c = 5.2050\% \cdot W_{10} - 21.2100 \text{ [cm/s]} \qquad (3)$$

where W_{10} is the wind speed in m/s.

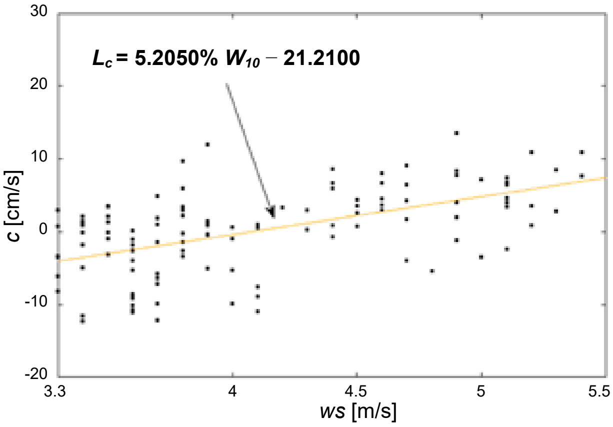

Figure 5. Wind speed (*ws* in [m/s]) from 3.3 to 5.5 versus the crosswind component (*c* in [cm/s]) of the leeway and the linear relationship between them

Thus, the slope of CWL was $a_c \pm \sigma(a_c) = 5.2050 \pm 1.4145$ [%] and the offset of CWL was – $b_c \pm \sigma(b_c) = -21.2100 \pm 5.8950$ [cm/s]. The norm of residuals was 52.8050 cm/s, and the sum of squares due to error (SSE) was 2788 [cm/s]. The error term (the standard error $S_{L_cW_{10}}$) ε_c was 4.8200 [cm/s], R^2 was 0.3104, the adjusted R^2 was 0.3045, and the RMSE was 4.861.

In turn, for wind speeds from 5.5 m/s to 9.8 m/s (stronger wind speeds), certain linear relationships between the wind speeds and the leeway components were also established. In Figure 3, the downwind components of the leeway increased along with the wind speeds from 5.5 m/s to 9.8 m/s. Meanwhile, the crosswind components of the leeway decreased when the wind speeds increased. Moreover, the crosswind components of the leeway usually slightly diverged to the left of the wind direction.

In turn, Figure 6 shows the linear relationship between the stronger wind speeds and the downwind components of the leeway. This relationship is as follows:

$$L_d = 4.2600\% \cdot W_{10} - 12.2100 \text{ [cm/s]} \qquad (4)$$

where W_{10} is the wind speed in m/s.

Thus, the slope of DWL was $a_d \pm \sigma(a_d) = 4.2600 \pm 1.1934$ [%] and the offset of DWL was – $b_d \pm \sigma(b_d) = 12.2100 \pm 8.8615$ [cm/s]. The norm of residuals was equal to 23.4060 cm/s and the sum of squares due to error (SSE) was 547.8 [cm/s]. In turn, the error term (the standard error $S_{L_dW_{10}}$) ε_d was 4.0100 [cm/s], R^2 was 0.01622, the adjusted R^2 was –0.01452, and the RMSE was 4.138.

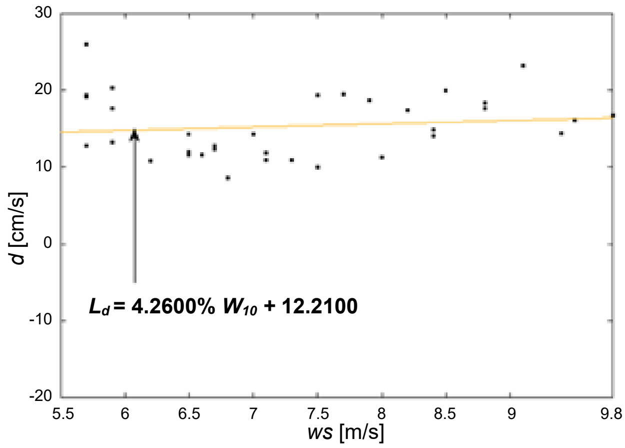

Figure 6. Wind speed (*ws* in [m/s]) from 5.5 to 9.8 versus the downwind component (*d* in [cm/s]) of the leeway and the linear relationship between them

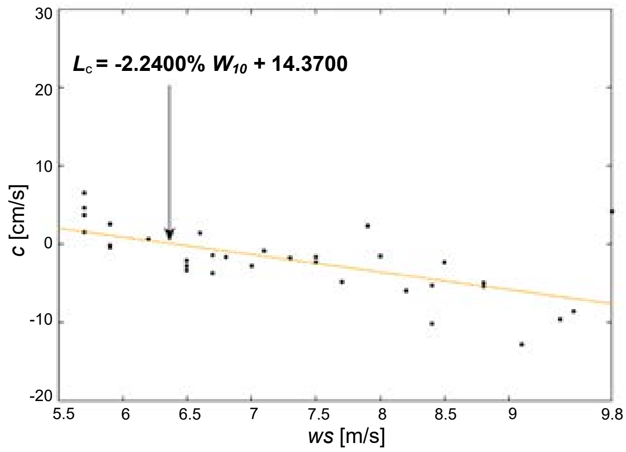

Figure 7. Wind speed (*ws* in [m/s]) from 5.5 to 9.8 versus the crosswind component (*c* in [cm/s]) of the leeway and the linear relationship between them

Figure 7 shows the relationship between the stronger wind speeds and the crosswind components of the leeway. The following linear relationship was established:

$$L_c = -2.2400\% \cdot W_{10} + 14.3700 \text{ [cm/s]} \qquad (5)$$

where W_{10} is the wind speed in m/s.

Thus, the slope of CWL was equal to $a_c \pm \sigma(a_c) = -2.2400 \pm 0.9655$ [%] and the offset of CWL was – $b_c \pm \sigma(b_c) = 14.3700 \pm 7.1680$ [cm/s]. The norm of residuals was equal to 18.9330 [cm/s] and the SSE was 358.4 cm/s. The error term (the standard error $S_{L_c W_{10}}$) ε_c was 3.2500 [cm/s], R^2 was 0.411, the adjusted R^2 was 0.3926, and the RMSE was 3.347.

The causes of errors in the obtained linear regressions may have been influenced by the different wind and leeway measurement locations (drifter motion measurements were conducted in the water, wind measurements were performed on the land near the Szczecin Lagoon coast), errors of wind and leeway measuring devices, waves in the Lagoon waters, water motion caused by nearby passing vessels, drifter motions caused by direct wind action (20% of the drifter was over the water surface), signal transmission errors via GPS, a variation in the depth of the Lagoon, the assumption on the linear shape of the regression function, and a detailed analysis of outliers and their possible filtering out. The variance of errors in models (2) and (3) (at the medium wind power between 3.3 m/s and 5.5 m/s) was greater than in models (4) and (5) (at the stronger wind power between 5.5 m/s and 9.8 m/s). The wind power during this study was not significantly differentiated (from 0.6 m/s to 9.8 m/s), and the regression models were established only for wind speeds from 3.3 m/s to 9.8 m/s.

Histograms of the leeway components are presented in Figures 8–11. In Figure 8, the histogram of all downwind components of the leeway is presented and a lognormal distribution is fitted to them. This lognormal distribution has a mean of logarithmic value of 2.73 cm/s which have a standard deviation of 0.32 cm/s. The log likelihood ratio was –744.758. The chi-square goodness-of-fit test provided the following values: chi-square statistic of 11.5506, 7 degrees of freedom, and a p-value of 0.1163. Then the chi-square goodness-of-fit test did not require rejection of the null hypothesis at the 5% significance level which stated that the recorded wind speeds come from a population with a lognormal distribution in which $\mu = 2.73$ and $\sigma = 0.32$.

When considering a maximum wind speed of 3.3 cm/s, the histogram of the downwind components of the leeway is obtained (Figure 9). The normal distribution has a mean of 16.84 cm/s and a standard deviation of 4.61 cm/s. The log likelihood ratio was –453.421. In turn, the chi-square goodness-of-fit test provided a chi-square value of 5.6993, 7 degrees of freedom, and a p-value of 0.5753. Then, the chi-square goodness-of-fit test did not require rejection of the null hypothesis at the 5% significance level which stated that the downwind components of the leeway at wind speeds from 3.3 m/s come from a population with a normal distribution in which $\mu = 16.84$ and $\sigma = 4.61$.

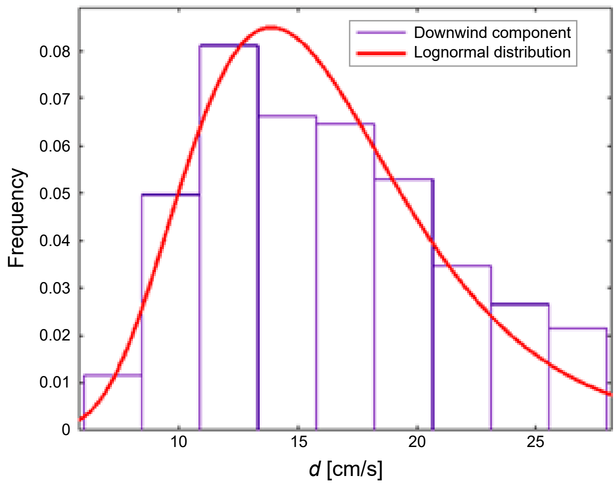

Figure 8. Histogram of all downwind components of the leeway fitted with a lognormal distribution

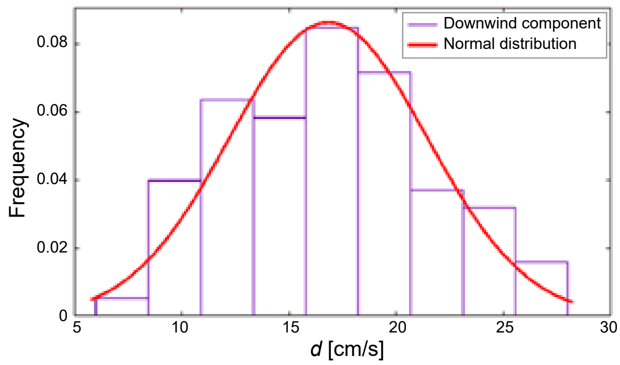

Figure 9. Histogram of the downwind components of the leeway for wind speeds from 3.3 m/s fitted to a normal distribution

The histogram of all crosswind components of the leeway is presented in Figure 10 and is fitted with a normal distribution with a mean of –1.26 cm/s and a standard deviation of 5.39 cm/s. The log likelihood ratio equals –766.15. The chi-square goodness-of-fit test provided the following values: a chi-square statistic of 9.1153, 6 degrees of freedom, and a p-value of 0.1672. Then, the chi-square goodness-of-fit test did not require rejection of the null hypothesis at the 5% significance level which stated that the crosswind components of the leeway at wind speeds from 3.3 m/s come from a population with a normal distribution in which $\mu = -0.26$ and $\sigma = 5.39$.

When wind speeds from 3.3 m/s are considered, the histogram of the crosswind components of the leeway is obtained and presented in Figure 11. The normal distribution had a mean of –0.26 cm/s and a standard deviation of 5.59 cm/s. The log likelihood ratio was –483.177. The chi-square goodness-of-fit test provided the following values: a chi-square of 6.8611, 6 degrees of freedom, and a p-value of 0.3339. Then the chi-square goodness-of-fit test did

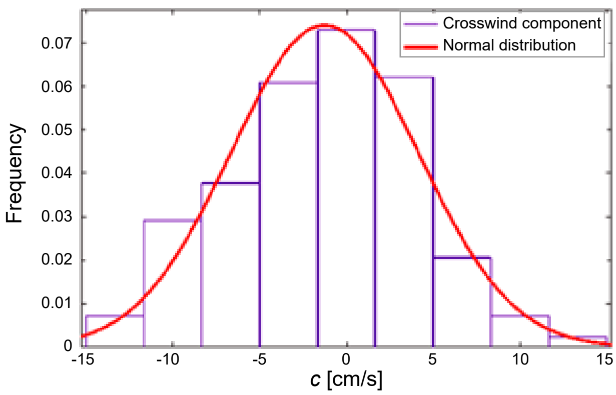

Figure 10. Histogram of all crosswind components of the leeway fitted with a normal distribution

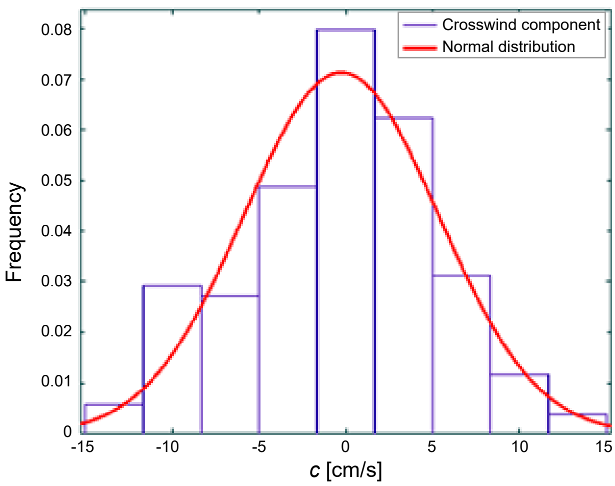

Figure 11. Histogram of the crosswind components of the leeway for wind speeds from 3.3 m/s fitted with a normal distribution

not require rejection of the null hypothesis at the 5% significance level which stated that the crosswind components of the leeway at the wind speeds from 3.3 m/s come from a population with a normal distribution in which $\mu = -0.26$ and $\sigma = 5.59$.

To summarize, the mean of the downwind components of the leeway was approx. 16 cm/s. In turn, the mean of its crosswind components was approx. 0 cm/s. This might mean that the crosswind component of the leeway of the drifter could be also neglected.

Conclusions

The properties of the leeway of water masses moving in the regions of the Świnoujście–Szczecin fairway have been analyzed. A method to decompose the leeway into its downwind and crosswind components has been used, and *in-situ* experiments were conducted to establish these components. As both the downwind and crosswind components of the leeway are required, e.g., to compute the trajectory of SAR objects, simple linear regression coefficients are a preferred method to parameterize the leeway of SAR objects. Moreover, this study may assist in the safe maneuvering of ships in the Świnoujście–Szczecin fairway region and may serve as a support for providing navigational assistance.

The linear relationships between the wind speeds and the leeway components have been investigated and established for the Świnoujście–Szczecin fairway regions for two groups of the wind speeds: medium (3.3–5.5 m/s) and higher (5.5–9.8 m/s). No relationship was observed for weak winds (0–3.3 m/s). Most likely, factors other than the wind speed significantly affected the speed of the leeway of the drifter in such a case. Furthermore, the error terms were estimated to establish errors in the downwind and crosswind components of the leeway.

The deployment of drifters allowed the generation of statistical parameters on the leeway flow for the Świnoujście–Szczecin fairway regions. The histograms of the leeway speeds, the leeway components, and the wind speeds were also presented. The analysis of the leeway allowed the conclusion to be drawn that for regions of the Świnoujście–Szczecin fairway, the leeway speeds were usually higher than 10 cm/s and typically higher than other regions of the Szczecin Lagoon. For the medium wind speeds, the drifter often diverged slightly on the left side, but at higher wind speeds, it often diverged a slightly to the right side. In turn, the direction of the movement of the water masses is in a good agreement with the movement direction of the air masses passing through the Szczecin Lagoon area. This arises from the small values of the crosswind components of the leeway which almost equal the leeway speeds and the downwind components of the leeway.

In the future, to increase the sample size, additional *in-situ* experiments are planned for the waters of the Szczecin Lagoon. A larger dataset will most likely increase the values of the correlation coefficients and decrease the errors of the regression functions and probability distributions. At weak wind speeds, an analysis of the impact of factors other than the wind on the leeway of the drifter is also planned in consecutive studies.

Acknowledgements

This research has been achieved under research project No. 1/S/INM/18 financed with a subsidy from the Ministry of Science and Higher Education for statutory activities. Furthermore, the authors would like to thank the Institute of Meteorology and Water Management (IMGW) for sharing the data on wind parameters for the meteorological stations in Trzebież and Świnoujście ("The source of data is the Institute of Meteorology and Water Management – National Research Institute", "The data of the Institute of Meteorology and Water Management – National Research Institute have been processed"). The authors would like to thank Mr. Andrzej Armiński for his assistance in performing the *in-situ* experiments in the waters of the Szczecin Lagoon.

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