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Analysis of Performance of the Wind-Driven Pulverizing Aerator Based on Average Wind Speeds in the Conditions of Góreckie Lake

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Abstract: In the introduction to this paper, the characteristics of Góreckie lake and the construction and operation of the wind-driven pulverizing aerator are presented. The purpose of this manuscript is to determine the efficiency of the pulverizing aerator unit in the windy conditions of Góreckie Lake. The efficiency of the pulverization aerator depends on the wind conditions at the lake. It was necessary to conduct thorough research to determine the efficiency of water flow through the pulverization segment (water pump). It was necessary to determine the rotational speed of the paddle wheel, which depended on the average wind speed. Throughout the research period, measurements of hourly average wind speed were carried out. It was possible to determine the efficiency of the machine by developing a dedicated mathematical model. The latest method was used in the research, consisting of determining the theoretical volumetric flow rates of water in the pulverizing aerator unit, based on average hourly wind speeds. Pulverization efficiency under the conditions of Góreckie Lake was determined based on 6600 average wind speeds for spring, summer and autumn, 2018. Based on the model, the theoretical efficiency of the machine was calculated, which, under the conditions of Góreckie Lake, amounted to 75,000 m^3 per year.

Keywords: lake restoration; wind energy; savonius rotor; Podsiadłowski method

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1. Introduction

The eutrophication of surface waters is a natural and constantly progressing process [1,2]. This problem occurs not only on a local scale [3,4]; its occurrence is global [5–7]. Anthropogenic factors have a great impact on accelerating lake degradation [8]. These factors include tourism development, intensification of agriculture and an uncontrolled flow of domestic pollutants [9,10]. Climate changes cause some lakes to dry up and turn into swampy areas [5,11,12]. Rapid deterioration of water quality occurred in the 20th century, and in particular in the second half of it [13]. The causes and effects of lake eutrophication are widely described in limnological literature. Accelerated eutrophication processes are among the greatest threat to the biodiversity of the aquatic ecosystems [14]. Most of the lakes studied in recent years in Poland are characterized by an increased concentration of phosphorus ions and reduced transparency. Many recent publications indicate there is a deterioration of water quality in Poland [15–17] and around the world [18,19]. In order to improve water quality, many protective measures are necessary [20]. The most important include cutting off the biogens inflow and creating buffer zones separating arable fields [3]. Unfortunately, many lakes have already reached a high level of eutrophication, where the biological processes have been disturbed. This type of water reservoir has lost its self-restoration capabilities [21–23]. Therefore, it is necessary to introduce appropriate restoration methods. We can distinguish biological, chemical and mechanical restoration methods [24,25]. However, the best results are achieved by combining several methods, preferably non-invasive ones [20–22]. One of the mechanical methods supporting chemical restoration of surface water reservoirs is pulverization aeration with the use of wind-driven aerators (Podsiadłowski's method) [13,26].

The aim of this paper is to determine the theoretical efficiency model of the wind-driven pulverizing aerator, based on its technical parameters and data on average wind speeds in the analyzed period. This manuscript presents a new method for determining the flow efficiency of an aerator pulverization mechanism. The authors used hourly average wind speeds to build a mathematical model for the assessment of machine performance. The developed method can be used on other eutrophied lakes to plan the reclamation process. The disadvantage of the method is the necessity to modify the mathematical model to the individual lake conditions.

In 2013, Ryszard Konieczny [27] conducted an analysis of the pulverization aeration parameters. His main aim was to determine the nomograms for monitoring system operation parameters. The main question that the author considered was the monthly operating efficiency of the aerator pulverizing unit in Polish water reservoirs in individual months. The author [28] observed that the increase in the wind speed by one unit ($m \cdot s^{-1}$) corresponded to an average increase in the rotational speed of the paddle wheel by 3 $rev \cdot min^{-1}$, the range of the rotation of the paddle wheel was in the range of 4.1 to 24.4 $rev \cdot min^{-1}$, and the volumetric flow rate of water was in the range of 149.6 to 663.1 $m^3 \cdot day^{-1}$.

Podsiadłowski et al. [10] performed an analysis of the efficiency of the pulverizing aerator operation on Góreckie Lake. They showed that the efficiency of the pulverization aeration increased with the increase in the wind speed. According to the authors, the most significant increase in pulverization efficiency occurred at wind speeds of 4.2 to 5.2 $m \cdot s^{-1}$. The above dependence may result from the self-sealing effect of the rotor, which is associated with higher water volumetric flow rates [28]. Speeds above 5.2 $m \cdot s^{-1}$ lead to inhibition of aeration efficiency due to the limitation of the volumetric flow rate of water through the suction hoses.

Osuch et al. [20] presented the possibility of determining the volumetric flow rate through the pulverizing aerator unit in the windy conditions of a particular lake. They based findings on the author's method of maximum wind speeds. According to the obtained results, in the conditions of Góreckie Lake, the average monthly volumetric flow rate through the aerator pulverizing unit in 2018 was less than 8800 $m^3 \cdot month^{-1}$, which is comparable to the result obtained in this manuscript (8333 $m^3 \cdot month^{-1}$). Furthermore, Konieczny [28] emphasized the differences in the efficiency of the aerator pulverizing unit, which depends on the wind conditions of the reservoir, which can range from 5977.8 to 13,418.4 $m^3 \cdot month^{-1}$.

None of the above-mentioned studies of the efficiency of pulverizing aerator operation was based on average wind speeds. The approach to determine the course of pulverization presented in this manuscript seems to be an appropriate method of determining the efficiency of the aerator pulverizing unit in real conditions.

2. Pulverization Aeration Method

In 1995, the Institute of Agricultural Engineering at the Agricultural University in Poznan (currently, the Institute of Biosystems Engineering at the University of Life Sciences in Poznan) began research on the integrated technology of lake restoration. The core of the proposed method was a wind-driven pulverizing aerator (Figure 1), allowing degassing and simultaneous oxygenation of hypolimnion waters, and a mobile aerator to perform precise phosphorus inactivation in the water column [20].

Figure 1. Wind-driven pulverizing aerator—Góreckie Lake.

The pulverizing aerator, for discharging harmful gases of anaerobic decomposition of organic matter contained in bottom sediments, such as hydrogen sulfide, methane and ammonia, and for the simultaneous oxygenation of hypolimnion waters, uses only wind energy [10,20]. This is the cleanest energy available on Earth [29,30]. This type of aerator maintains moderate oxygenation in the bottom area in the range of 0–1 mg $O_2 \cdot dm^{-3}$ [21]. The advantage of moderate oxygenation over intensive oxygenation consists in limiting the mineralization of organic matter in bottom sediments, enabling nitrification and denitrification processes that result in the removal of nitrogen into the atmosphere, thus maintaining the positive redox potential at the sediment–water interface, which allows phosphorus retention. As a result, the nitrogen ammonium is oxidized to the form of N_2, enabling the annamox process to occur [20,27,28,31–36]. The pulverizing aerator uses only energy from a wind turbine (Savonius system) to drive the pulverizing unit. The aerator wind turbine allows the pulverizing unit to function at wind speeds above 2 $m \cdot s^{-1}$ [10]. The pulverizing unit (Figure 2) works on the basis of communicating vessels. It consists of two chambers (for suction, and pressure) and a paddle wheel (for pulverization). The wind-driven pulverizing aerators are fully mechanical and resistant to pollution deposited in the overlying area of the water that they work on [32,34]. The wind-driven pulverizing aerators can be equipped with coagulant dispensers, enabling the application of up to 25 kg of active substance per month. The drain valve of the coagulant dispensers can be controlled by drivers built on the basis of fuzzy logic and using water spray mass and liquid density [2,10,37].

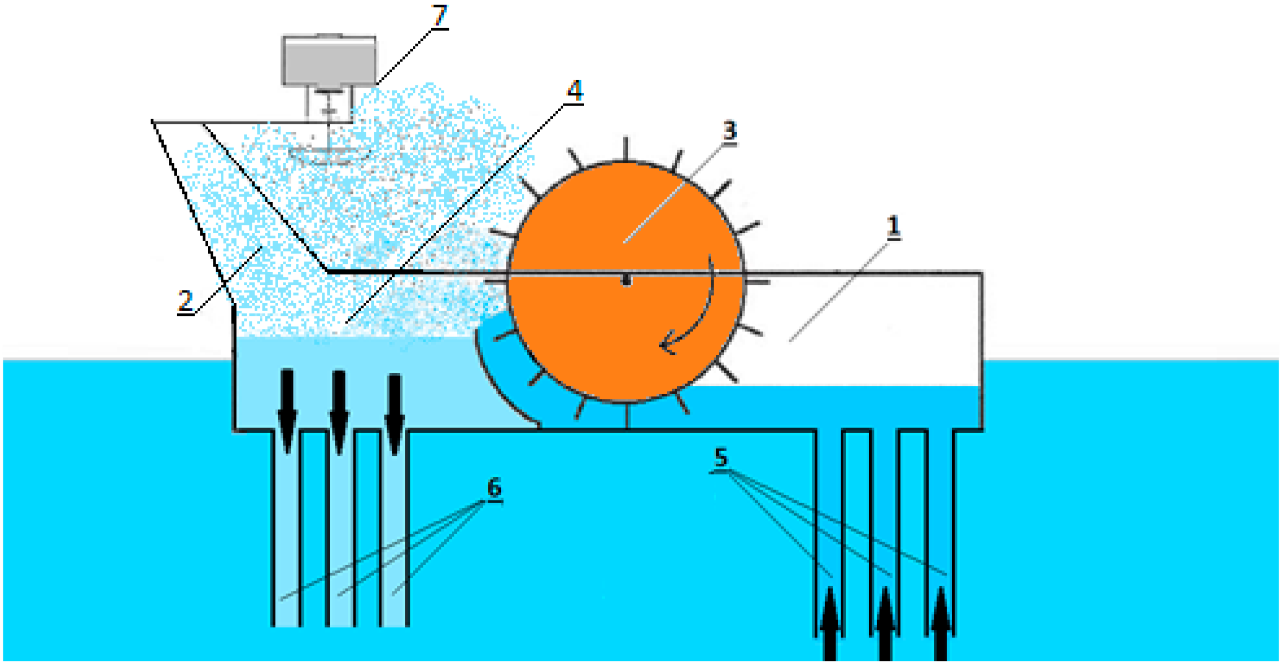

Figure 2. Pulverizing aerator unit. Designations: 1—suction chamber, 2—splash plate, 3—paddle wheel (for pulverization), 4—pressure chamber, 5—suction hoses, 6—pressure hoses, 7—coagulant dispenser.

3. Characteristics of Góreckie Lake

Góreckie Lake is located in the Poznan Lake District, in Wielkopolska Voivodeship. The area of water surface is 104.1 ha. The maximum depth of the lake is 17.2 m, with an average depth of about 9 m [38,39]. It is a glacial reservoir located in the central part of the Wielkopolska National Park, in the protection area, i.e., Nature 2000. There are two islands located in the lake area [20,40].

The lake is divided into two basins—south and northwest. The southern basin is characterized by steeply sloping banks and great depth. The second basin—the northwest one—is much shallower [39]. At present, the lake does not have a tributary, and the previously existing connection with Łódzko-Dymaczewski Lake has been dry for many years [20,40,41].

The first available information on the physico-chemical conditions of Góreckie Lake comes from the 1930s. At that time, research was carried out to determine water transparency during a time of intensive algae development. The results were very good, and the oxygen conditions were assessed as good in the whole lake water column [42].

A palace was built on the eastern shore of the lake in 1941, along with a complex of other utility buildings. One of the buildings was a sewage treatment plant. Waters from the treatment plant flowed directly into Góreckie Lake. After World War II ended, a preventorium for children suffering from tuberculosis was located in the building. Wastewater from the preventorium is considered one of the reasons for Góreckie Lake's accelerated eutrophication [43].

Despite cutting off the sewage inflow from the preventorium in the late 1980s, an increase in the trophy of the Góreckie Lake was noticed in the next decade. Another reason for the increase in the trophy of the lake was the presence of ever larger flocks of wild geese [20,41].

In 2008, there was a rapid deterioration of the condition of Góreckie Lake. Transparency water fell to 1.5 m [40,41].

4. Materials and Methods

Water flow efficiency was determined for all months of 2018, when the pulverization aeration was performed (March to November). This paper also presents water quality indicators for the water (oxygen content, electrolytic conductivity, pH, transparency, orthophosphate content, ammonium nitrogen content) of the analyzed reservoir. The study was conducted in 2018. A number of research tasks needed to be performed in order to achieve the aim of the work.

Physico-chemical parameters of water were monitored. In the lake's vertical profile, oxygen content and temperature were measured using a WTW Oxi 340i multi-parameter meter and CellOxi 325 oxygen probe. After connecting to the meter, the TetraCon 325 conductivity sensor was monitored for electrolytic conductivity, while pH values were read after connecting the SENTIX 41-3 electrode to the meter. Water transparency was measured using a Secchi disk. The water was taken with a scoop from the surface, 7 and 14 m deep. The collected water samples were analyzed in the laboratory for ammonium nitrogen and orthophosphates content using a Lovibond PC MultiDirect photometer.

Based on our measurements, the theoretical efficiency of the pulverizing unit during one rotation of the paddle wheel was determined according to Equation (1).

$$Q_r = O_c \cdot P_v \left[m^3\right] \tag{1}$$

where:

Q_r—theoretical efficiency of one pulverization wheel rotation;

O_c—pulverization wheel circumference;

P_v—area of the pulverization wheel blade.

Using Equation (2), the ratio of the wind turbine (Savonius type) bevel gear to the aerator pulverization unit was determined.

$$i_g = \frac{r_{wt}}{r_c} \tag{2}$$

where:

i_g—pulverizing aerator bevel gear ratio;

r_{wt}—wind turbine speed per unit of time;

r_c—number of pulverization wheel revolutions per unit of time.

In the next stage of work, a rotational speed model of the aerator pulverization wheel was determined, depending on the wind speeds, Equation (3). The model was determined using the Davis Instruments Vantage Vue DAV 6250EU weather station, based on research conducted from March to November of 2018. Using the weather station, the average wind speeds were determined in 1-minute periods, while counting the number of revolutions of the aerator wind turbine. The studies were carried out at average minute wind speeds in the range of 0–5 $\mathrm{m \cdot s^{-1}}$. Based on the collected results, an approximation equation was determined in the form of a second-degree polynomial.

$$v_m = y\ [RPM] \tag{3}$$

where:

v_m—the rotational speed of the pulverization wheel [RPM];

y—equation of a second-degree polynomial.

A detailed analysis of the wind speed within the aerator's range was carried out throughout the research period. Following, the average wind speeds were determined for each hour, every day of the month, starting from March and ending in November. This is the period of effective pulverizing aerator operation for the year, which excludes the winter period, when biological and chemical processes usually disappear [20]. The meteorological station saves wind speed data with the exact time of the measurement. Several dozens of such measurements were performed during each hour. Throughout the remainder of this manuscript, the average wind speeds for each full hour of operation of the pulverizing aerator are used.

Using Equation (4), the rotational speed of the pulverization wheel was determined for each hour of aerator operation in the analyzed period. The values were obtained after substituting into the approximation equations, in the form of a second-degree polynomial, the pulverization wheel rotational speed model v_m of obtained average wind speeds for each hour v_{avg}, and multiplying the obtained value by 60 (1 h—60 min).

$$v_h = 60 \cdot v_m \left[rev \cdot h^{-1} \right] \tag{4}$$

where:

v_h—rotational speed of the pulverization wheel ($rev \cdot h^{-1}$).

Then, using Equation (5), the theoretical volumetric flow rates through the aerator pulverizing unit were determined for each hour of the pulverization in the analyzed period.

$$q = v_h \cdot Q_r \left[m^3 \cdot h^{-1} \right] \tag{5}$$

where:

q—theoretical volumetric flow rate for one hour ($m^3 \cdot h^{-1}$).

According to Equation (6), volumetric flow rates in the aerator pulverizing unit were determined for each day of pulverization in 2018. The results were presented in monthly record sheets.

$$Q_{t_j} = \sum_{q_{ij}}^{24} q \left[m^3 \cdot day^{-1} \right] \tag{6}$$

where:

Q_{t_j}—theoretical volumetric flow rate per one day ($m^3 \cdot day^{-1}$);

i—hour {1, 2, 3, . . . , 24};

j—day of the month.

This paper also compares the theoretical volumetric flow rates in the aerator pulverizing unit for the individual months of the year. The distribution of wind conditions in individual months is very different. The comparison was made by comparing Q_t values.

Summing up the research and the analyses that were carried out, the theoretical volumetric flow rates for the entire season of the pulverization aeration were calculated for a total of 7 months of pulverizing aerator operation. The calculations were made in accordance with Equation (7).

$$Q = \sum Q_t \left[m^3 \cdot year^{-1} \right] \tag{7}$$

where:

Q—theoretical volumetric flow rate for the entire year ($m^3 \cdot year^{-1}$).

5. Results

Determination of the theoretical efficiency of the pulverizing unit during one rotation of the paddle wheel was possible thanks to the pulverization wheel measurements, where accordingly

- blade width is 0.061 (m);
- blade height is 0.082 (m);
- pulverization wheel diameter is 1.8 (m).

After substituting the above data into Equation (1), the value of the theoretical efficiency of one rotation of the paddle wheel Q_r in the pulverization unit is 0.028 (m^3).

In the further part of the work, using Equation (2), the ratio of the wind turbine bevel gear to the aerator pulverizing unit was determined. According to the measurements carried out, the gear ratio $i_g = \frac{1}{1}$. This means that both the wind turbine and the pulverization wheel work at the same rotational speed (not including losses on the belt transmissions connecting the wind turbine with the aerator main transmission and the aerator main transmission with the pulverization wheel, respectively).

The studies conducted in situ, using the weather station, and based on Equation (3), allowed the development of approximation equations in the form of a second-degree polynomial. The equation and the obtained results are shown in Figure 3.

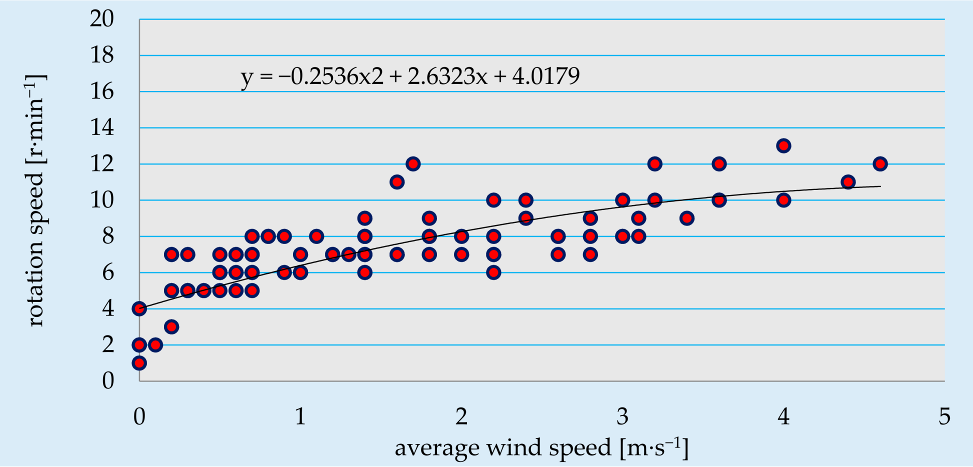

Figure 3. Rotational speed model of the aerator pulverization wheel in relation to average wind speed.

As shown in Figure 3, when the average wind speed was 0.5 m·s^{-1}, the pulverizing wheel rotated on average 5 times during 1 min. At an average wind speed of 3 m·s^{-1}, the pulverization wheel will rotate 10 times in 1 min.

The results of wind measurements obtained from the weather station (tens of thousands of results) were averaged for each hour of aerator operation in 2018. Sample results are presented in Table 1.

Table 1. Sample results of average hourly wind speeds.

	Average Wind Speed (m*s^{-1})					
Hourly Interval	**3 March 2018**	**4 April 2018**	**7 June 2018**	**28 August 2018**	**29 September 2018**	**29 November 2018**
0:00 a.m.–1:00 a.m.	0.399	0.555	0.857	0.488	0.149	1.097
1:00 a.m.–2:00 a.m.	0.559	0.536	0.746	0.451	0.724	1.294
2:00 a.m.–3:00 a.m.	0.488	0.941	0.520	0.492	0.698	1.354
3:00 a.m.–4:00 a.m.	0.430	0.797	0.725	0.381	0.721	1.418
4:00 a.m.–5:00 a.m.	0.531	1.053	0.685	0.316	0.781	1.248
5:00 a.m.–6:00 a.m.	0.574	1.116	0.696	0.318	0.916	1.365
6:00 a.m.–7:00 a.m.	0.732	0.887	1.438	0.361	1.464	0.968
7:00 a.m.–8:00 a.m.	0.952	1.764	2.482	0.312	1.612	1.114
8:00 a.m.–9:00 a.m.	1.507	1.620	3.342	0.724	1.451	1.102
9:00 a.m.–10:00 a.m.	1.870	1.301	2.759	0.615	1.761	1.254
10:00 a.m.–11:00 a.m.	1.534	1.405	2.553	0.701	1.942	1.164
11:00 a.m.–12:00 a.m.	1.129	1.423	2.297	0.887	1.897	1.487
0:00 p.m.–1:00 p.m.	1.250	1.354	2.442	0.821	1.891	1.547
1:00 p.m.–2:00 p.m.	2.366	2.638	2.558	0.951	1.839	1.624
2:00 p.m.–3:00 p.m.	1.403	3.454	2.060	1.216	1.761	1.247
3:00 p.m.–4:00 p.m.	1.556	3.590	2.587	1.600	2.231	1.258

Table 1. *Cont.*

	Average Wind Speed (m*s^{-1})					
Hourly Interval	**3 March 2018**	**4 April 2018**	**7 June 2018**	**28 August 2018**	**29 September 2018**	**29 November 2018**
4:00 p.m.–5:00 p.m.	1.280	3.710	2.105	1.467	2.287	1.698
5:00 p.m.–6:00 p.m.	0.954	4.342	1.932	1.612	2.474	0.888
6:00 p.m.–7:00 p.m.	0.651	4.011	1.752	1.441	1.861	0.924
7:00 p.m.–8:00 p.m.	0.646	3.535	1.766	0.758	1.876	1.214
8:00 p.m.–9:00 p.m.	0.849	4.117	0.926	0.651	1.210	0.964
9:00 p.m.–10:00 p.m.	0.639	4.504	0.428	0.875	0.845	0.824
10:00 p.m.–11:00 p.m.	0.587	4.909	0.688	0.561	0.712	0.634
11:00 p.m.–12:00 p.m.	0.708	3.691	0.409	1.834	1.411	0.417

The above values of the average hourly wind speeds were substituted to the approximation equations in the form of a second-degree polynomial for the determined model of rotational speed of the pulverization wheel. Then, using Equations (4)–(6), the theoretical volumetric rate of the pulverizing unit was determined for each day of pulverizing aerator operation in 2018. The results were presented in monthly record sheets accordingly. The obtained results of the theoretical daily efficiency in monthly statements were compared with each other. As shown in Figure 4, wind drive under the conditions of Góreckie Lake is a stable power source for the pulverizer aerator. In all months except September, the average monthly aerator capacity largely exceeded 8000 m^3.

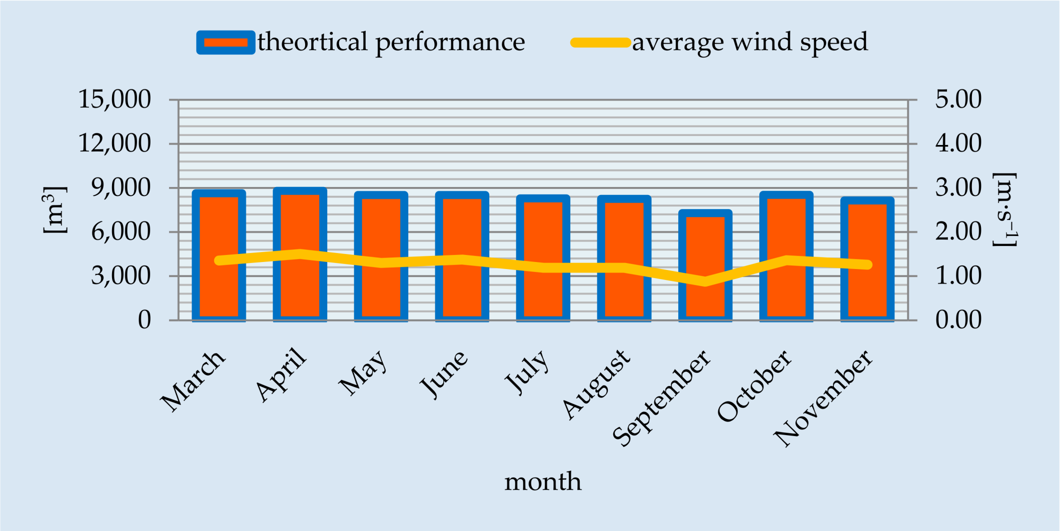

Figure 4. Volumetric flow rate in the aerator pulverizing unit in 2018.

In March, the pulverizing pulser of the aerator pumped over 8600 m^3. In April, the aerator capacity increased by over 200 m^3 throughout the month. It was the largest monthly aerator performance in 2018. The highest daily performance was recorded on the 7th day of the month. A slightly lower yield was obtained in May. Throughout the month, the aerator pumped approximately 8520 m^3 of lake water. The aerator performance in June was almost the same as in May. The difference in favor of June was almost 2 m^3 throughout the month. The highest capacity was obtained on the 10th day of the month and amounted to over 312 m^3. The average wind speeds in July were slightly lower than in previous months. This slightly affected the aerator's performance. In the whole month it amounted to less than 8300 m^3. In August, slightly more than 8250 m^3 flowed through the pulverization unit of the aerator. It was about 50 m^3 less than in the previous month. The smallest performance per month was recorded in September. At that time, only 7300 m^3 flowed through the aerator aeration unit. This result was worse than the best month (April) by about 1500 m^3. In October, the aerator performance increased. Over the entire month, it was just over 8500 m^3. This result is comparable with May and June. The wind conditions in November were not good either. This affected the aerator's performance—it was less than 8200 m^3 per month.

Summarizing the research and analyses carried out, the theoretical volumetric efficiency for the entire season of the pulverization aeration was calculated based on Equation (7)—in total for all nine 9 months of the pulverizing aerator operation. The theoretical efficiency of the water flow through the pulverizing unit in the conditions of Góreckie Lake in 2018 was over 75,000 (m^3).

6. Conclusions

Wind-driven pulverizing aerators can be successfully used in the windy conditions of a moderate climate. The average monthly efficiency of over 8300 (m^3) of pumped water allows the pulverization aeration method to be included into the sustainable methods of water reservoirs restoration. Purified water from harmful gases of anaerobic decomposition of organic matter and oxygenated with atmospheric air goes back to the overlying water area, which supports the intended biological purposes. This research formulated following conclusions:

1. Supplying the aerator with a wind turbine leads to a stable average monthly performance of the pumped lake water, which can significantly affect the planning of the reclamation process.
2. As the average wind speed increases, the volumetric flow rate through the pulverizing unit of the aerator also increases, and with it the efficiency of the pulverization and oxygenation of the bottom waters of the reservoir.
3. The method of assessing the efficiency of the wind-driven pulverizing aerator based of average wind speeds is suitable for determining the volumetric flow rate of the pulverizing unit, which can significantly facilitate the planning of restoration of water reservoirs.

Author Contributions: Conceptualization: A.O., E.O.; methodology: A.O., E.O.; software: A.O., S.P.; validation: S.P., E.O., A.O.; formal analysis: E.O., A.O.; investigation: E.O., A.O.; resources: A.O., E.O.; data curation: S.P., A.O.; writing—original draft preparation: E.O., A.O., P.R., S.P.; writing—review and editing: A.O., P.R.; visualization: A.O., S.P.; supervision: E.O., P.R.; project administration: E.O., P.R.; All authors have read and agreed to the published version of the manuscript.

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