Scientific Review Engineering and Environmental Sciences (2025), 34 (4), 398–416

Sci. Rev. Eng. Env. Sci. (2025), 34 (4) https://srees.sggw.edu.pl

ISSN 1732-9353 (suspended) eISSN 2543-7496 DOI 10.22630/srees.10421

Received: 30.04.2025
Accepted: 25.11.2025

Muhammad Umar ALI
Mateusz GRYGORUK✉
Warsaw University of Life Sciences – SGGW, Centre for Climate Research, Poland

Hydrological analysis of the Oder droughts for the period 1950–2022 in the context of the 2022 river disaster

Keywords: trend analysis, low flow, Poland, water management

Introduction

History has demonstrated how susceptible places on Earth are to severe and prolonged droughts, which can harm the environment, society, and economy. The growing population, increased demand for water due to irrigation and industrial uses, and global warming have all increased awareness of our susceptibility to drought. In many regions of the world, the frequency and severity of drought have increased due to climate change (Tallaksen & van Lanen, 2023). In terms of the number of people harmed and the financial cost, drought is one of the most damaging natural disasters (Van Loon, 2015). According to the United Nations Convention to Combat Desertification report, by 2030, an estimated 700 million people will be at risk of displacement due to drought (UNCCD, 2022).

Such is the case of one of the European rivers – the Oder. Among the many worrying pictures of the impact of severe droughts across Europe, July and August 2022 were the times when, unexpectedly, about 249 tons of dead fish were

✉mateusz_grygoruk@sggw.edu.pl

retrieved from the waters of the Oder, according to the report of the 'Polish Team for the Situation on the Oder' (Zespół ds. Sytuacji powstałej na rzece Odrze) (Kolada, 2022). Toxins produced by the algae species *Prymnesium parvum* caused the mass extinction of aquatic life. This situation resulted from the accumulation of unfavorable factors (atmospheric, hydrological, and nutrient concentrations), which led to an algae bloom in the waters of the Oder (Absalon et al., 2023). A key factor that enabled the proliferation of this species was the high salinity of the Oder during this period, likely due, at least in part, to discharges of industrial wastewater with a high salt content, such as from mining activities. Other contributing factors included the drought and the resulting low water levels, which reduced dilution and flow, as well as hydromorphological modifications to the river. A combination of meteorological conditions, including prolonged periods of high temperatures and a lack of precipitation, as well as human activities such as water extraction and altered land use, contributed to the hydrological alterations observed during this event. This incident highlighted the Oder system's vulnerability to severe weather and underscored the need for enhanced water resource management and effective drought protection measures. This study aims to conduct a comprehensive hydrological analysis of the Oder, with a particular focus on the catastrophic events that occurred in 2022. The overall goal of this paper was to reveal the trends and specifics of droughts along the Oder in its upper, middle, and lower courses, providing background for the analysis of the 2022 drought, which is suspected to remain one of the leading causes of the Oder disaster. The specific objectives of this paper were (1) to analyze and reveal the drought criteria expressed by the average value of the annual lowest discharges of the Oder in three different water gauging stations: Chałupki (upper course of the Oder), Połęcko (middle course of the Oder), and Gozdowice (lower course of the Oder); (2) to calculate and analyze durations of droughts in the three listed gauging stations; (3) to calculate trends of droughts, with a special focus on their changing lengths and discharge deficits; and (4) to analyze the 2022 drought as a possible trigger of the extensive *Prymnesium parvum* bloom and related exposure of the aquatic ecosystems of the Oder to the toxic enzyme prymnesine, produced by the blooming *Prymnesium parvum*.

Materials and methods

The Oder (Fig. 1) is one of the largest rivers in Central Europe. It originates in the Oder Mountains (Oderské Vrchy), at an elevation of around 634 m a.s.l., and spans approximately 854 km, making it Poland's third-longest river and a major

Ali, M. U., Grygoruk, M. (2025). Hydrological analysis of the Oder droughts for the period 1950–2022 in the context of the 2022 river disaster. *Sci. Rev. Eng. Env. Sci.*, *34* (4), 398–416. DOI 10.22630/srees.10421

waterway in the region (Sługocki & Czerniawski, 2023). The Oder river basin spans 118,938 km², covering three countries: Poland (86%), Germany (9%), and the Czech Republic (5%). The river basin has a population of approximately 16 million (2015), with 50.4% of the area being agricultural farmland (Joint Research Centre [JRC], 2020).

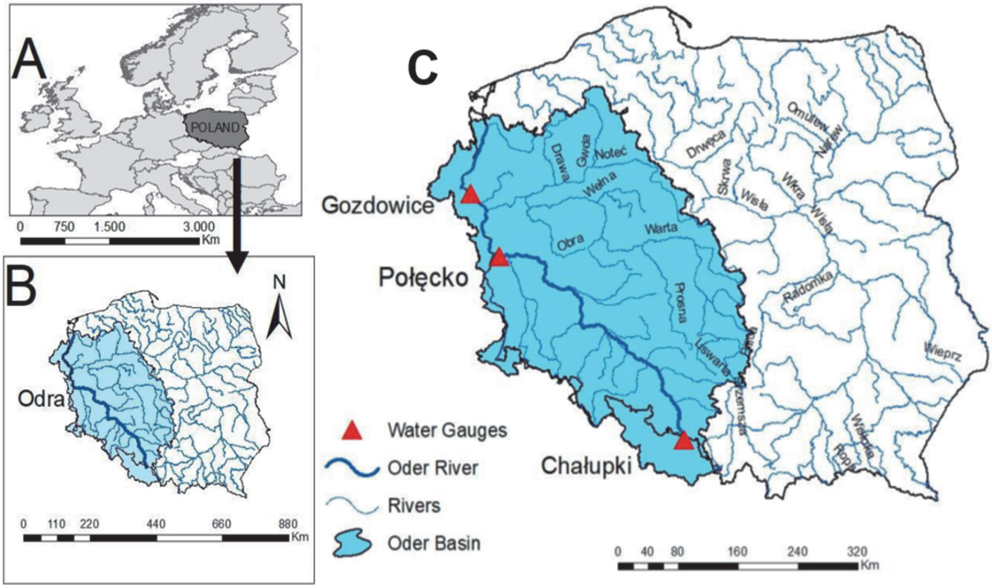

FIGURE 1. Location of the Oder river basin in Poland
Source: own work.

The Oder is primarily a lowland river with a hydrological regime characterized by a mix of pluvial and groundwater, and its catchment area covers approximately 33% of Poland. Its mean annual flow ranges from 41 $m^3 \cdot s^{-1}$ in the upper course to 535 $m^3 \cdot s^{-1}$ near the river mouth (Wrzesiński, 2021). The channel slope drops from 0.7% close to the border between Poland and the Czech Republic to 0.38% in the middle course, 0.25% in the lower course, and 0.04% at the mouth of the river (Absalon et al., 2023). The Oder river basin has a moderate climate, with notable seasonal fluctuations in temperature and precipitation. Winters are usually cold, with average temperatures ranging from −1°C to −5°C, while summers are temperate to warm, with average temperatures ranging from 18°C to 25°C (Sayegh & Żabnieńska, 2019). The basin receives an average of 500 mm of rainfall annually in the lowlands and over 1,200 mm in the higher regions (Graf & Wrzesiński, 2020). The average discharge at the river's mouth is approximately 574 $m^3 \cdot s^{-1}$; however, it may vary depending on seasonal and meteorological circumstances. The river flow usually reaches its maximum in the spring and early summer due to snowmelt from the Sudetes and Carpathian Mountains, as well as increasing precipitation. At certain times, the flow rate in the middle and lower sections of the river exceeds 1,000 $m^3 \cdot s^{-1}$ (Kreienkamp et al., 2021).

In this study, daily discharge data are analyzed based on river discharge data retrieved from the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB). In the first step, the lowest annual discharges were selected for each of the three water gauges for every year of analysis. Next, the average of these yearly values for each gauging station was calculated as a criterion for drought occurrence, referred to as the average low discharge, hereafter referred to as the average annual minimum flow (SNQ). It was calculated as an arithmetic average of the lowest annual discharges recorded in the Oder at each of the three gauging stations analyzed over the period 1950–2022. In the next step, river discharge hydrographs (daily discharge values) were analyzed to extract the days when daily discharges were lower than the SNQ value in each of the three gauges analyzed. This analysis allowed us to extract all the droughts (daily discharge lower than the assumed threshold discharge SNQ). The analysis included trend analysis using the Mann–Kendall test, a non-parametric method employed to detect trends in time series data (Shah & Kiran, 2021). It is beneficial for hydrological data where assumptions of normality may not hold (Zhou et al., 2020).

Results

The lowest annual discharges of the Oder (Fig. 2) are decreasing the most steeply in Gozdowice and Połęcko. In Chałupki, we can see that the SNQ was recorded at 4.22 $m^3 \cdot s^{-1}$ in 1954, while the highest was 22.1 $m^3 \cdot s^{-1}$ in 2010. Over the period from 1950 to 2022, the SNQ of Chałupki was 9.72 $m^3 \cdot s^{-1}$. With a p-value of 0.9922, Chałupki shows no significant trend in the long-term lowest discharges. This implies that Chałupki's low-flow conditions have stayed mostly constant over time. On the other hand, in Połęcko, the lowest annual discharge was 53.1 $m^3 \cdot s^{-1}$ in 2015, and the highest was 194 $m^3 \cdot s^{-1}$ in 1977. The SNQ of Połęcko over the period 1950–2022 was 106 $m^3 \cdot s^{-1}$, and the p-value for Połęcko was 0.8975, also indicating no significant trend. This implies that low-flow conditions at the station have fluctuated over time without showing any signs of permanent alteration. In Gozdowice, the lowest discharge was 124 $m^3 \cdot s^{-1}$ in 2015, and the highest SNQ

Ali, M. U., Grygoruk, M. (2025). Hydrological analysis of the Oder droughts for the period 1950–2022 in the context of the 2022 river disaster. *Sci. Rev. Eng. Env. Sci.*, *34* (4), 398–416. DOI 10.22630/srees.10421

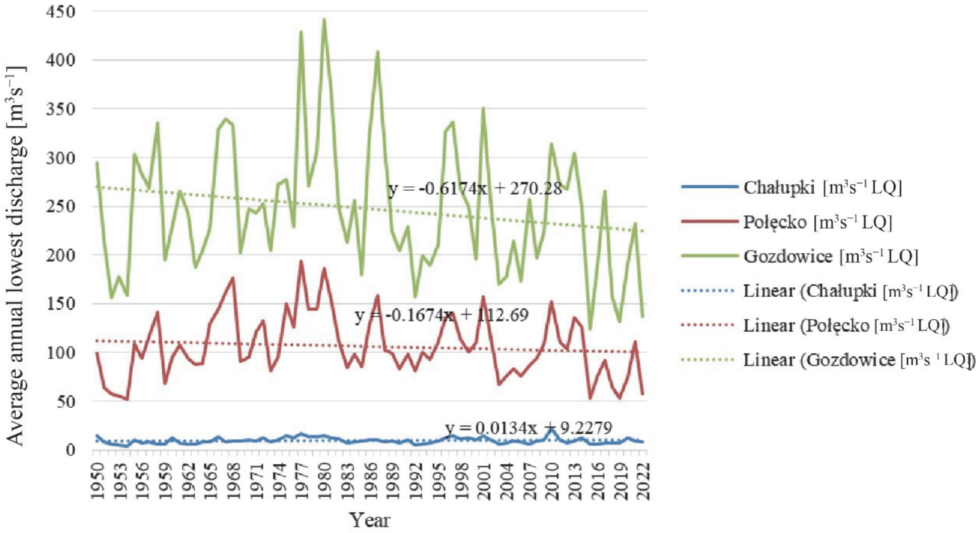

FIGURE 2. Lowest annual discharges of the Oder at three water gauging stations in the period of 1950–2022

Source: own work based on data of the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB).

was 441 $m^3 \cdot s^{-1}$ in 1980. The SNQ of Gozdowice over the period 1950–2022 was 247 $m^3 \cdot s^{-1}$. Like the other stations, the *p*-value of Gozdowice, which is 0.9563, shows no significant pattern in the lowest discharges over time. The lowest monthly discharges of the Oder in Chałupki generally show an increasing trend (Fig. 3). However, in April, May, June, July, and August, the lowest monthly discharges appear to be decreasing, whereas in January, February, March, and October, they are increasing. However, the trends are not statistically significant. The steepest decreasing changes of the lowest monthly discharges were recorded in June and September, while the steepest increasing tendencies of the lowest monthly discharges of the Oder in Chałupki were recorded in November and December. Overall, the lowest monthly discharges occur in summer and spring, and the highest in winter and autumn. On the other hand, the lowest monthly discharges of the Oder in Połęcko have generally been decreasing (Fig. 4). In the April to August period, the lowest monthly discharges appear to be decreasing; however, there is a slight increase in January, February, and March. Significant trends are found from April to August. The pronounced trends in spring and summer months underscore the impact of prolonged dry periods, which can potentially lead to reduced river discharge and exacerbate drought conditions.

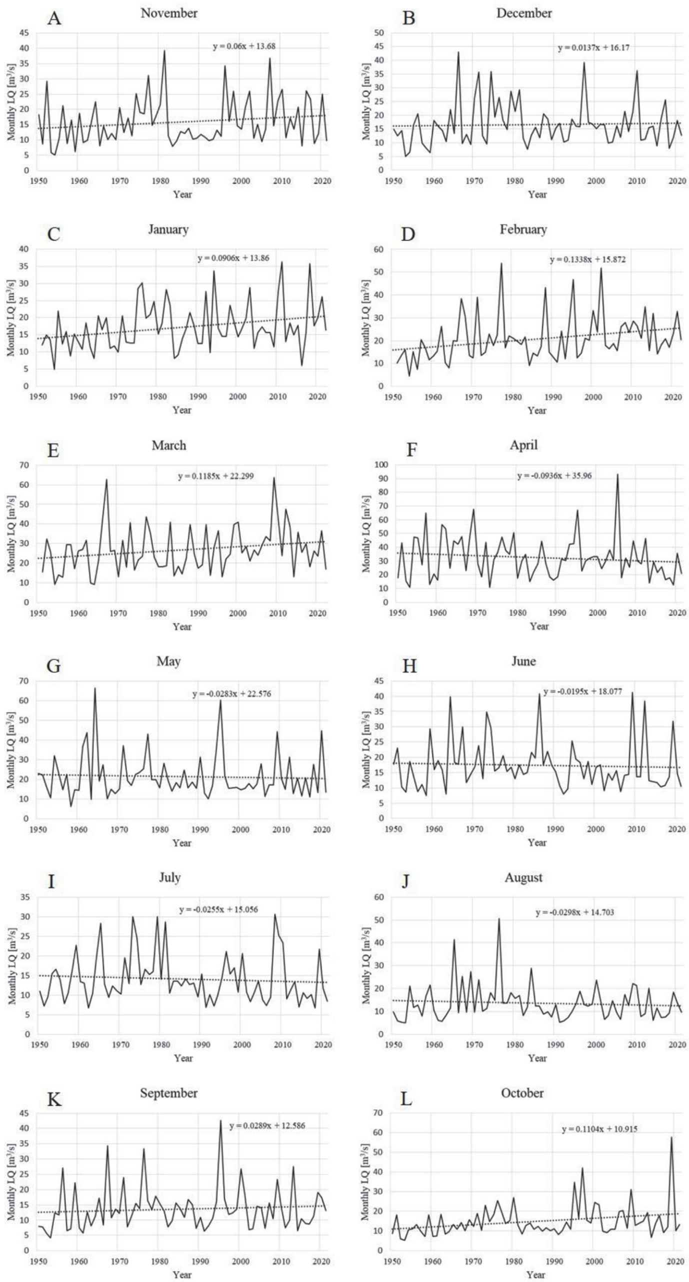

FIGURE 3. Lowest monthly flows of the Oder in Chałupki in the period of 1950–2022

Source: own work based on data of the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB).

Ali, M. U., Grygoruk, M. (2025). Hydrological analysis of the Oder droughts for the period 1950–2022 in the context of the 2022 river disaster. *Sci. Rev. Eng. Env. Sci.*, *34* (4), 398–416. DOI 10.22630/srees.10421

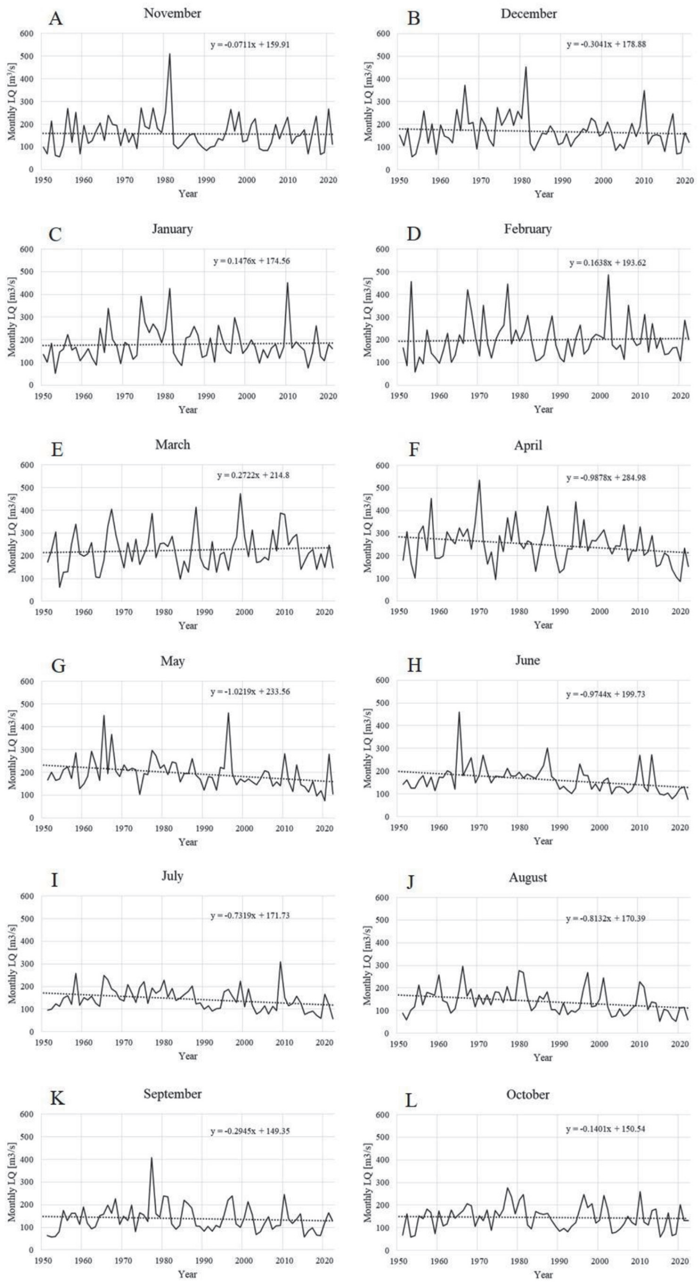

FIGURE 4. Lowest monthly flows of the Oder in Połęcko in the period of 1950–2022

Source: own work based on data of the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB).

Depending on the particular months, the graph displays both growing and declining patterns in the lowest monthly flows. These patterns suggest that various factors may be influencing the river's flow near Połęcko, including seasonal precipitation patterns, temperature fluctuations, and water management practices. Overall, the lowest monthly discharges are becoming lower in summer and spring. Similarly, in Gozdowice, increasing and decreasing trends are observed (Fig. 5). In January, February, and March, it appears that the lowest monthly discharges are increasing; however, in the other months from April to September, the lowest monthly discharges are decreasing. However, the trends are not statistically significant. In Gozdowice, like in Połęcko, declining trends throughout the summer months signify a rise in the intensity of low discharge intervals, which is associated with drought conditions. These results highlight the Oder's susceptibility to reduced discharge at critical times, which may impact downstream water availability and the health of the ecosystem. The monthly lowest discharge data from several months across the three water gauges show notable trends. According to the Mann–Kendall test results, the significant value is $p = 0.05$. The p-values below indicate notable and statistically significant trends. The resulting p-values are presented in Table 1. From the analysis, we can see that the strongest trends are observed in Chałupki in January ($p = 0.019$), February ($p = 0.001$), and October ($p = 0.032$). These patterns could indicate a worsening of the winter and late fall droughts, which would impact water availability during these months. In Połęcko, significant trends are observed in April ($p = 0.032$), May ($p = 0.001$), June ($p = 0.0002$), July ($p = 0.003$), and August ($p = 0.003$). The effects of prolonged dry spells are highlighted by the patterns in spring and summer, which can result in decreased river discharge and exacerbate drought conditions. On the other hand, the noteworthy patterns in Gozdowice for May ($p = 0.007$), June ($p = 0.002$), July ($p = 0.015$), and August ($p = 0.008$) support Połęcko's findings. Over the period analyzed, the average duration of the Oder drought in Chałupki was 22 days (daily discharge was lower than the SNQ of 9.72 $m^3 \cdot s^{-1}$). Droughts at this gauging station lasted a total of 1,586 days (6.03% of the analyzed period) (Fig. 6). The majority of droughts occurred in August and September. The fewest number of droughts was recorded in January and February.

Ali, M. U., Grygoruk, M. (2025). Hydrological analysis of the Oder droughts for the period 1950–2022 in the context of the 2022 river disaster. *Sci. Rev. Eng. Env. Sci.*, *34* (4), 398–416. DOI 10.22630/srees.10421

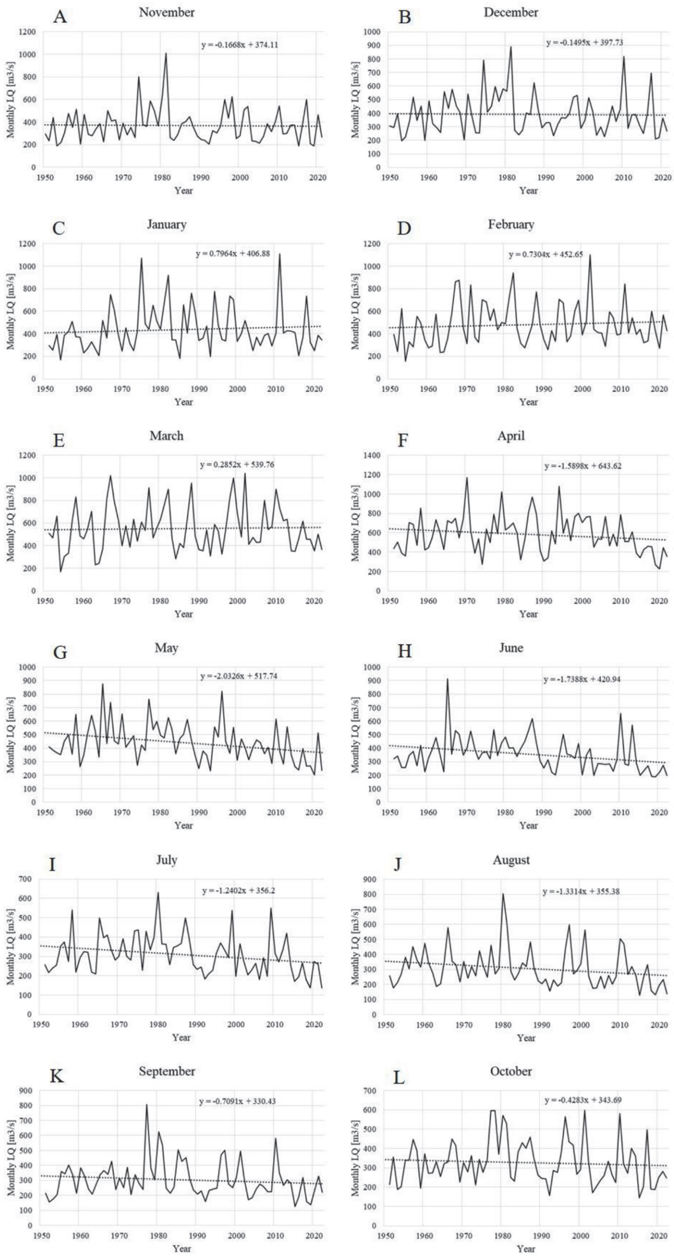

FIGURE 5. Lowest monthly flows of the Oder in Gozdowice in the period of 1950–2022

Source: own work based on data of the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB).

TABLE 1. *p*-values of the Mann–Kendall test for the lowest monthly discharges of the Oder in a particular month over the period of 1950–2022

Water gauge	Month											
	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT
Chałupki	0.071	0.506	0.019	0.001	0.054	0.181	0.553	0.159	0.184	1.000	0.199	0.032
Połęcko	0.710	0.388	0.797	0.384	0.669	0.032	0.001	0.0002	0.003	0.003	0.326	0.617
Gozdowice	0.770	0.548	0.509	0.384	0.984	0.145	0.007	0.002	0.015	0.008	0.210	0.338

Note: The blue background indicates a statistically significant increasing trend in average annual minimum flow (SNQ), while the red background indicates a statistically significant decreasing trend in SNQ.

Source: own work.

Over the period analyzed, the average duration of the Oder drought in Połęcko was 29 days (daily discharge was lower than the SNQ of 106 $m^3 \cdot s^{-1}$). Droughts at this gauging station lasted a total of 2,076 days (7.9% of the analyzed period) (Fig. 6). The majority of droughts occurred in August and September. The fewest number of droughts was recorded in January and April. Over the period analyzed, the average duration of the Oder drought in Gozdowice was 36 days (daily discharge was lower than the SNQ of 247 $m^3 \cdot s^{-1}$). Droughts at this gauging station totaled 2,584 days (9.8% of the total period analyzed) (Fig. 6). The majority of droughts occurred in August and September. The fewest number of droughts was recorded in January and May. It was revealed that the number and duration of droughts increase along the course of the Oder.

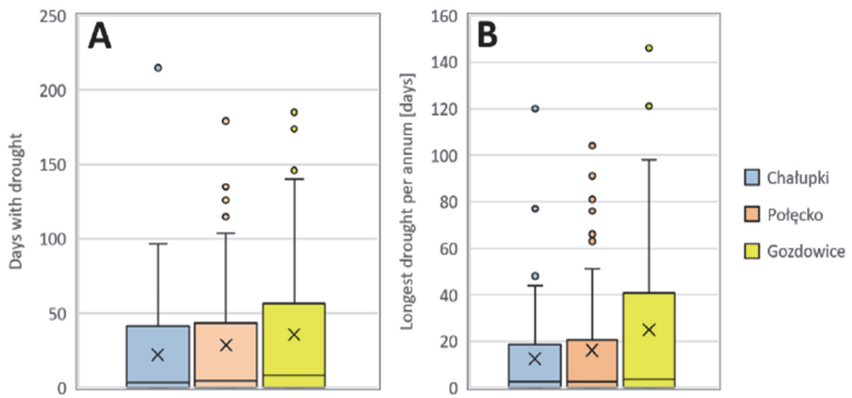

FIGURE 6. Distribution of droughts in three gauging profiles analyzed: A – the number of days of drought; B – the duration of the longest drought per annum

Source: own work.

Ali, M. U., Grygoruk, M. (2025). Hydrological analysis of the Oder droughts for the period 1950–2022 in the context of the 2022 river disaster. *Sci. Rev. Eng. Env. Sci.*, *34* (4), 398–416. DOI 10.22630/srees.10421

Over the period analyzed, the average duration of the Oder drought in Chałupki was 22 days (daily discharge was lower than the SNQ of 9.72 $m^3 \cdot s^{-1}$). Droughts at this gauging station lasted a total of 1,586 days (6.03% of the analyzed period) (Fig. 6). The majority of droughts occurred in August and September. The fewest number of droughts was recorded in January and February. Over the period analyzed, the average duration of the Oder drought in Połęcko was 29 days (daily discharge was lower than the SNQ of 106 $m^3 \cdot s^{-1}$). Droughts at this gauging station lasted a total of 2,076 days (7.9% of the analyzed period) (Fig. 6). The majority of droughts occurred in August and September. The fewest number of droughts was recorded in January and April. Over the period analyzed, the average duration of the Oder drought in Gozdowice was 36 days (daily discharge was lower than the SNQ of 247 $m^3 \cdot s^{-1}$). Droughts at this gauging station totaled 2,584 days (9.8% of the total length of the analyzed period) (Fig. 6). The majority of droughts occurred in August and September. The fewest number of droughts was recorded in January and May. It was revealed that the number and duration of droughts increase along the course of the Oder. Analysis of the durations of droughts on the Oder suggests that their dynamics differ when comparing the upper, middle, and lower courses of the river. In Chałupki, the number of days with drought is decreasing, suggesting that the inflow of water to Poland from the Czech Republic, along with the course of the Oder, is not subject to a significant increase in drought depths and frequencies. This indicates that the frequency of drought days has decreased over time in this area, which is defined as a daily discharge that is less than the SNQ value. The statistical significance trend is validated by the *p*-value of 0.0093 (Table 2), significantly below the significance level of 0.05. This suggests that the observed decline in drought days is statistically significant and not due to random chance. A similar situation is observed when analyzing the durations of the most extended annual droughts in Chałupki. At Chałupki, the most significant yearly drought durations likewise exhibit a decreasing tendency, indicating that the longest drought each year has been getting shorter over time. The *p*-value is 0.0021 (Table 2), indicating strong statistical significance. Improved mitigation strategies or modifications to weather patterns that reduce prolonged periods of dryness in this area may be associated with shorter drought durations. In the decade of 1950–1960, the longest recorded drought lasted for nearly 120 days, whereas in the most recent years, droughts longer than 40 days occur seldom.

TABLE 2. *p*-values of the Mann–Kendall tests for several days of drought at a particular gauging station and the longest annual drought at a specific gauging station

Profile	Number of days of drought		Longest drought	
	trend	p	trend	p
Chalupki	decreasing	0.0093	decreasing	0.0021
Polecko	increasing	0.5855	increasing	0.7792
Gozdowice	increasing	0.6032	increasing	0.7481

Note: The red background represents the statistical significance of the trend.

Source: own work.

The 2022 Oder drought appears to be unique when compared to other historical droughts. In Chałupki, over the period from 1 March 2022 to 30 September 2022, there were 11 days with drought (river discharge lower than 9.72 $m^3 \cdot s^{-1}$) (Fig. 7A). Discharge deficit (the amount of water required to balance the momentary discharge of the Oder to the threshold discharge SNQ) of the Oder in Chałupki in this period was positive and reached 228.7 Mm^3, meaning that over this period, water resources of the catchment of the Oder could be used to balance the drought. Most of the time, river discharges of the Oder were higher than the drought threshold used in this study. In Połęcko, over the period from 1 March 2022 to 30 September 2022, there were 0 days with drought (river discharge lower than 106 $m^3 \cdot s^{-1}$) (Fig. 7B). Discharge deficit (the amount of water required to balance the momentary discharge of the Oder to the threshold discharge SNQ) of the Oder in Połęcko in this period was positive and reached 3,371 Mm^3, meaning that over this period, water resources of the catchment of the Oder could be used to balance the drought. Most of the time, river discharges of the Oder were higher than the drought threshold used in this study. In Gozdowice, over the period from 1 March 2022 to 30 September 2022, there were 204 days with drought (river discharge lower than 247 $m^3 \cdot s^{-1}$) (Fig. 7C). Discharge deficit (the amount of water required to balance the momentary discharge of the Oder to the threshold discharge SNQ) of the Oder in Gozdowice in this period was negative and reached 1,898 Mm^3, meaning that over this period, water resources of the catchment of the Oder were not enough to balance the drought. Most of the time, river discharges of the Oder were higher than the drought threshold used in this study.

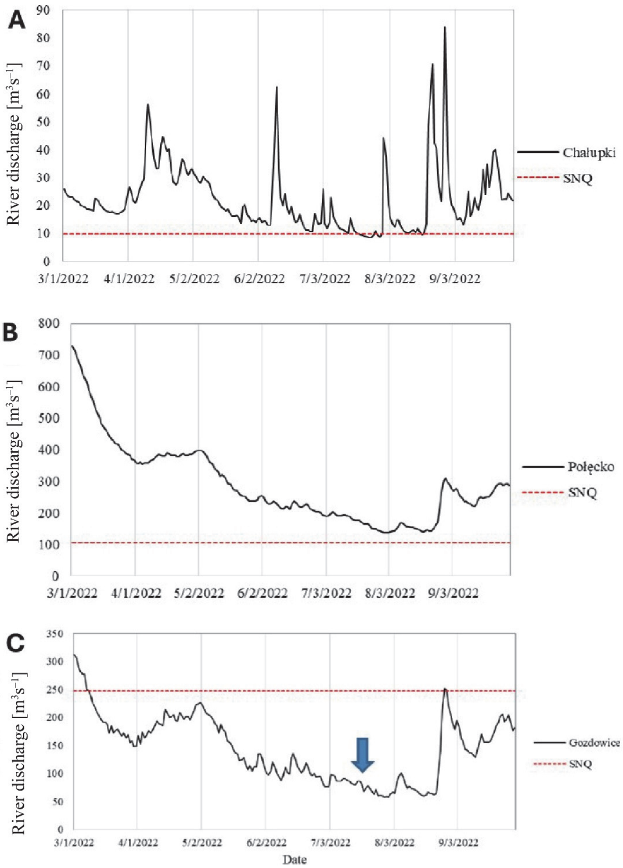

FIGURE 7. Discharge of the Oder in Chałupki (A), Połęcko (B), and Gozdowice (C) in the period from 1 March 2022 to 30 September 2022 (The arrow in Figure 7C represents the time when the Oder disaster occurred; SNQ – average annual minimum flow)

Source: own work based on data of the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB).

Discussion

Droughts in the middle and lower reaches of the river present several visible trends, including an increase in their duration, particularly during critical summer droughts. This reflects the regional trend in Europe (Parry et al., 2012), which revealed that, similar to the results presented in this study, summer droughts have increased in duration and discharge deficits over the last five decades. However, comparing the presented patterns to the former studies on droughts in Poland, it appears that the revealed trends in the durations of summer droughts in the middle and lower Oder are significantly larger than those previously reported (Przybylak et al., 2020). As documented, the 2022 drought became increasingly severe along the course of the Oder, particularly in its middle and lower reaches. These results highlight the Oder's susceptibility to decreased discharge during critical periods, which may impact the downstream water supply and ecological health. The statistical analysis reveals significant declining patterns in the monthly lowest discharge statistics, especially in the spring and summer. These patterns indicate that the drought has been worsening over time, which may have contributed to the Oder disaster in 2022.

The lowest yearly discharges at each site fluctuated, but the p-values did not show any noticeable long-term patterns. This result suggests that the general hydrological behavior of the Oder in terms of low flow has remained steady over the past few decades, despite brief fluctuations caused by droughts and other hydrological events. This is especially important because rising water demands and climate change have led to significant volatility in the flow of several European rivers (Blöschl, 2022). The seasonal examination of drought events, on the other hand, shows a different picture. All three stations are particularly vulnerable to drought in the late summer and early autumn months (from July to September), with August being the highest month for drought at Chałupki, Połęcko, and Gozdowice. However, in the downstream stations of Połęcko and Gozdowice, the changes are most noticeable, where droughts happen more frequently and stay longer. This pattern aligns with previous research, which demonstrates that the combined effects of land development, precipitation variability, and water extraction typically cause downstream river sections to experience greater hydrological stress (Sperna Weiland et al., 2021). While comparing the upstream station (Chałupki) with the downstream station (Gozdowice), this study found that the intensity and frequency of droughts are higher downstream. This finding is consistent with earlier research that suggests lower reaches of rivers are more vulnerable to water shortages due to a combination of natural and anthropogenic factors (Blauhut et al., 2022). This means that since downstream areas are more severely affected by drought, future attempts to manage water resources should concentrate more on them. Low water levels lead to multiple changes in aquatic ecosystems (Stubbington et al., 2024). In such a case, the reported disaster in the Oder region in 2022 (Szlauer-Łukaszewska et al., 2024) could have been induced by the specific drought that occurred that year. The beginning of the catastrophe

Ali, M. U., Grygoruk, M. (2025). Hydrological analysis of the Oder droughts for the period 1950–2022 in the context of the 2022 river disaster. *Sci. Rev. Eng. Env. Sci.*, *34* (4), 398–416.
DOI 10.22630/srees.10421

(12 July 2022) corresponds to the lowest water levels recorded over the discussed 2022 summer drought, so the lack of coincidence of these two phenomena is highly unlikely. The 2022 drought event – the primary focus of this study – falls within a broader pattern of increasing drought occurrences in Europe, a consequence of climate change. Research shows that in recent decades, Europe has seen more frequent and intense droughts. This is primarily due to rising temperatures, altered precipitation patterns, and increased evaporation (Moravec et al., 2021). Similar patterns can be observed in the Oder data, particularly from July through September, when decreased rainfall and warmer temperatures typically result in reduced river flow. Despite the Oder's generally consistent hydrological regime, seasonal drought patterns have worsened in recent years, particularly in areas downstream. This validates the results of Eini et al. (2023), who noted a comparable increase in drought severity in Poland, particularly in areas with high water demand and significant agricultural activities. The findings highlight the fact that, despite the river's total flow not declining significantly, seasonal hydrological stress is rising, which may have more negative effects on ecosystems, agriculture, and water supplies. There are several parallels and gaps between the results of this study and other relevant research conducted on the Oder and similar rivers in Europe. For example, Raczyński and Dyer (2024) found that, similar to the patterns seen in the Oder, low-flow periods are occurring increasingly often in numerous European rivers throughout the summer. On the other hand, the Oder seems to have resisted significant long-term changes in its lowest discharges. In contrast, different rivers, including the Rhine and Danube, have demonstrated more notable long-term variations in flow as a result of climate change. Perhaps this is due to the region's improved water management techniques and the Oder's unique geography. Drought patterns at Połęcko and Gozdowice align with research on the Elbe and Vistula, which has demonstrated comparable downstream escalated situations of drought effects (Piniewski et al., 2022). The results underscore the need for improved water management plans and adaptable methods to mitigate the impacts of droughts and ensure long-term access to sustainable water supplies (Sutanto et al., 2019). Drought deficits revealed for the lowest course of the Oder for the 2022 summer drought (more than 1.8 Mm^3 of water) were much higher than any reasonable reservoir could mitigate. Therefore, future actions aimed at mitigating droughts on the Oder should be based on catchment-scale solutions that can store as much water as possible in the landscape, preferably anticipating the need for restoration of aquatic and wetland ecosystems.

Conclusions

This study examined long-term drought patterns and hydrological conditions in the Oder from 1950 to 2022 using daily discharge data from three gauging stations (Chałupki, Połęcko, and Gozdowice). We identified spatial and temporal trends in drought along the river. Although the lowest annual discharges at all three stations fluctuated, the statistical analysis performed showed no statistically significant long-term trends, indicating that the river's overall low flow capacity has remained stable over the past several decades. However, we revealed a clear increase in drought frequency during summer months, particularly from July to September, with August consistently being the most drought-prone month across all stations. This fulfills the goal of characterizing drought patterns and highlights the increasing hydrological stress during critical warm months. A comparison of the stations revealed that downstream sections of the river experience more frequent and longer droughts than the upstream station at Chałupki.

This spatial variation suggests higher vulnerability downstream, likely due to cumulative upstream water withdrawals, increased human activity, and reduced inflows, addressing the goal of assessing regional differences in hydrological behavior. The analysis of the 2022 drought revealed that extremely low discharges and prolonged drought periods – particularly at Gozdowice – significantly contributed to the environmental disaster that occurred later that year. While hydrological drought may not have been the sole factor, the severe flow reduction likely worsened water temperature, nutrient levels, and algal blooms, acting as a key trigger. This aligns with understanding how drought conditions influenced the 2022 crisis.

Overall, the findings indicate that although the Oder has maintained long-term discharge stability, the increase in seasonal drought events reflects rising sensitivity to climate-related hydrological stress. These results offer valuable insights into drought dynamics in Central European river systems and underscore the need for enhanced adaptive water management, transboundary cooperation, and hazard mitigation strategies, particularly in downstream regions where risks are greatest. Future efforts should focus on enhancing water retention, ecological restoration, and coordinated emergency planning to strengthen resilience against extreme droughts and prevent similar ecological crises.

Acknowledgments

The results presented in this paper were developed in the form of a master's thesis defended at the Faculty of Civil and Environmental Engineering of the Warsaw University of Life Sciences – SGGW, authored by Muhammad Umar Ali, and supervised by Mateusz Grygoruk.

References

Absalon, D., Matysik, M., Woźnica, A., & Janczewska, N. (2023). Detection of changes in the hydrobiological parameters of the Oder River during the ecological disaster in July 2022 based on multi-parameter probe tests and remote sensing methods. *Ecological Indicators*, *148*, 110103. https://doi.org/10.1016/j.ecolind.2023.110103

Blauhut, V., Stoelzle, M., Ahopelto, L., Brunner, M. I., Teutschbein, C., Wendt, D. E., Akstinas, V., Bakke, S. J., Barker, L. J., Bartošová, L., Briede, A., Cammalleri, C., Kalin, K. C., De Stefano, L., Fendeková, M., Finger, D. C., Huysmans, M., Ivanov, M., Jaagus, J., …, & Živković, N. (2022). Lessons from the 2018–2019 European droughts: A collective need for unifying drought risk management. *Natural Hazards and Earth System Sciences*, *22*(6), 2201–2217. https://doi.org/10.5194/nhess-22-2201-2022

Blöschl, G. (2022). Three hypotheses on changing river flood hazards. *Hydrology and Earth System Sciences*, *26*(19), 5015–5033. https://doi.org/10.5194/hess-26-5015-2022

Eini, M. R., Ziveh, A. R., Salmani, H., Mujahid, S., Ghezelayagh, P., & Piniewski, M. (2023). Detecting drought events over a region in Central Europe using a regional and two satellite-based precipitation datasets. *Agricultural and Forest Meteorology*, *342*, 109733. https://doi.org/10.1016/j.agrformet.2023.109733

Graf, R., & Wrzesiński, D. (2020). Detecting patterns of changes in river water temperature in Poland. *Water*, *12*(5), 1327. https://doi.org/10.3390/w12051327

Joint Research Centre [JRC]. (2020). Fact sheet: Oder River basin. https://water.jrc.ec.europa.eu/pdf/oder-fs.pdf

Kolada, A. (ed.) (2022). *Report of the team for the situation arising on the Oder River. The basis for further research – Odra.* Institute of Environmental Protection – National Research Institute. https://ios.edu.pl/projekt/prezentacja-wnioskow-ze-wstepnego-raportu-zespolu-ds-sytuacji-na-rzece-odrze/

Kreienkamp, F., Philip, S. Y., Tradowsky, J. S., Kew, S. F., Lorenz, P., Arrighi, J., Belleflamme, A., Bettmann, T., Caluwaerts, S., Chan, S. C., Ciavarella, A., De Cruz, L., Vries, H. de, Demuth, N., Ferrone, A., Fischer, M., Fowler, H. J., Goergen, K., Heinrich, D., …, & Wanders, N. (2021). Rapid attribution of heavy rainfall events leading to severe flooding in Western Europe during July 2021. *World Weather Attribution*. http://hdl.handle.net/1854/LU-8732135

Moravec, V., Markonis, Y., Rakovec, O., Svoboda, M., Trnka, M., Kumar, R., & Hanel, M. (2021). Europe under multi-year droughts: How severe was the 2014–2018 drought period? *Environmental Research Letters*, *16*(3), 034062. https://doi.org/10.1088/1748-9326/abe828

Parry, S., Hannaford, J., Lloyd-Hughes, B., & Prudhomme, C. (2012). Multi-year droughts in Europe: Analysis of development and causes. *Hydrology Research*, *43*(5), 689–706. https://doi.org/10.2166/nh.2012.024

Piniewski, M., Eini, M. R., Chattopadhyay, S., Okruszko, T., & Kundzewicz, Z. W. (2022). Is there a coherence in observed and projected changes in riverine low flow indices across Central Europe? *Earth-Science Reviews*, *233*, 104187. https://doi.org/10.1016/j.earscirev.2022.104187

Przybylak, R., Oliński, P., Koprowski, M., Filipiak, J., Pospieszyńska, A., Chorążyczewski, W., Puchałka, R., & Dąbrowski, H. P. (2020). Droughts in the area of Poland in recent centuries in the light of multi-proxy data. *Climate of the Past*, *16*(2), 627–661. https://doi.org/10.5194/cp-16-627-2020

Raczyński, K., & Dyer, J. (2024). Changes in streamflow drought and flood distribution over Poland using trend decomposition. *Acta Geophysica*, *72*(4), 2773–2794. https://doi.org/10.1007/s11600-023-01188-0

Sayegh, M., & Żabnieńska, A. (2019). Characteristics of Oder river water temperature for heat pump. *E3S Web of Conferences*, *116*, 00071. https://doi.org/10.1051/e3sconf/201911600071

Shah, S. A., & Kiran, M. (2021). Mann-Kendall test: trend analysis of temperature, rainfall and discharge of Ghotki feeder canal in district Ghotki, Sindh, Pakistan. *Environment & Ecosystem Science*, *5*(2), 137–142. https://doi.org/10.26480/ees.02.2021.137.142

Sługocki, Ł., & Czerniawski, R. (2023). Water quality of the Odra (Oder) River before and during the ecological disaster in 2022: a warning to water management. *Sustainability*, *15*(11), 8594. https://doi.org/10.3390/su15118594

Sperna Weiland, F. C., Visser, R. D., Greve, P., Bisselink, B., Brunner, L., & Weerts, A. H. (2021). Estimating regionalized hydrological impacts of climate change over Europe by performance-based weighting of CORDEX projections. *Frontiers in Water*, *3*, 713537. https://doi.org/10.3389/frwa.2021.713537

Stubbington, R., England, J., Sarremejane, R., Watts, G., & Wood, P. J. (2024). The effects of drought on biodiversity in UK river ecosystems: Drying rivers in a wet country. *WIREs Water*, *11*(5), e1745. https://doi.org/10.1002/wat2.1745

Sutanto, S. J., Weert, M. van der, Wanders, N., Blauhut, V., & Lanen, H. A. J. van (2019). Moving from drought hazard to impact forecasts. *Nature Communications*, *10*(1), 4945. https://doi.org/10.1038/s41467-019-12840-z

Szlauer-Łukaszewska, A., Ławicki, Ł., Engel, J., Drewniak, E., Ciężak, K., & Marchowski, D. (2024). Quantifying a mass mortality event in freshwater wildlife within the Lower Odra River: Insights from a large European river. *Science of The Total Environment*, *907*, 167898. https://doi.org/10.1016/j.scitotenv.2023.167898

Tallaksen, L. M., & Lanen, H. A. J. van (2023). *Hydrological drought: processes and estimation methods for streamflow and groundwater.* Elsevier.

United Nations Convention to Combat Desertification (2022, May 11). *World "at a crossroads" in drought management, up 29% in a generation and worsening, says UN*. UNCCD. United Nations Convention to Combat Desertification. https://www.unccd.int/news-stories/press-releases/world-crossroads-drought-management-29-generation-and-worsening-says-un

Van Loon, A. F. (2015). Hydrological drought explained. *WIREs Water*, *2*(4), 359–392. https://doi.org/10.1002/wat2.1085

Wrzesiński, D. (2021). Flow regime patterns and their changes. In M. Zeleňáková, K. Kubiak-Wójcicka & A. M. Negm (Eds), *Management of water resources in Poland* (pp. 163–180). Springer International Publishing. https://doi.org/10.1007/978-3-030-61965-7_9

Zhou, Z., Shi, H., Fu, Q., Li, T., Gan, T. Y., & Liu, S. (2020). Assessing spatiotemporal characteristics of drought and its effects on climate-induced yield of maize in Northeast China. *Journal of Hydrology*, *588*, 125097. https://doi.org/10.1016/j.jhydrol.2020.125097

Summary

Hydrological analysis of the Oder droughts for the period 1950–2022 in the context of the 2022 river disaster. The study aims to analyze the droughts of the Oder from 1950 to 2022 at three water gauge profiles located in the upper (Chałupki), middle (Połęcko), and lower (Gozdowice) reaches of the Oder. The subject of the analysis was the temporal variability of the lowest annual and monthly flows of the Oder, the durations of lows characterized by a flow lower than the adopted threshold criterion (average annual minimum flow, SNQ), and the trends of their changes in the analyzed period. We identified decreasing trends of the lowest annual river flows in the middle and lower reaches of the Oder. The lowest monthly flows of the Oder exhibit statistically significant trends in the months of April–September (Połęcko) and May–September (Gozdowice). The summer drought of 2022 was exceptionally long and severe (the discharge deficit amounted to more than 1.8 Mm^3 in the Gozdowice profile) and is unlikely to be reduced to the SNQ level through any existing or planned reservoir. Changes in the drought indicators occur as a result of the course of hydrological processes taking place in the Polish part of the Oder basin.