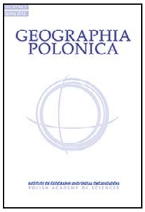

Geographia Polonica
2026, Volume 99, Issue 1, pp. 99-120
https://doi.org/10.7163/GPol.0319

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EXTENSIVE FLOODS IN SOUTH-WESTERN POLAND: SYNOPTIC DRIVERS, UPPER AIR ENVIRONMENT AND ASSOCIATED IMPACTS

Sławomir Sulik[1,2] • Szymon Walczakiewicz[3,2] • Małgorzata Świątek[3] • Oliwier Sahm[4]

[1] Department of Meteorology and Climatology, Faculty of Earth Sciences and Spatial Management
Nicolaus Copernicus University
Lwowska 1, 87-100 Toruń: Poland
e-mail: sulik@umk.pl (corresponding author)

[2] Skywarn Poland
Warsaw: Poland

[3] Institute of Marine and Environmental Science
University of Szczecin
Mickiewicza 16, 70-383 Szczecin: Poland
e-mails: szymon.walczakiewicz@usz.edu.pl • malgorzata.swiatek@usz.edu.pl

[4] Faculty of Earth Sciences and Spatial Management
Nicolaus Copernicus University
Lwowska 1, 87-100 Toruń: Poland
e-mail: 319581@stud.umk.pl

Abstract

The main research aim was to determine changes in synoptic conditions during rainfall incidents that led to catastrophic flood events in south-western Poland in 1997, 2010 and 2024. The synoptic analysis was based on data from the ERA5 (ECMWF – European Center for Medium-Range Weather Forecasts) reanalysis containing information on such variables as atmospheric pressure, geopotential, moisture content or direction and speed of air flow in the lower troposphere. The study also includes information on hydrological conditions on the rivers covered by the gauge stations (IMGW-PIB), specifying the height of the exceedance of the alarm condition and the number of days. As a result of the analysis, it was found that the spatial distribution and accumulation of precipitation caused by the migration of the low-pressure system from over the Gulf of Genoa was significantly influenced by the blocking high. The presence of a jet stream and atmospheric fronts associated with forming shallow lows within the main low baric center was also a supporting factor. In addition, the elevated sum of accumulated precipitation associated with the 2024 rainfall incident again signals a problem related to the rapid warming of the Mediterranean Sea, affecting the overall sum and distribution of precipitation in Europe.

Keywords

flood • precipitation • severe weather • climate change • Poland

Introduction

The effects of climate change are hitting our daily lives. The effects of the changes include, for example, extreme weather events, which can be observed since the middle of the 20th century. One such extreme is flooding, which is causing increasing losses (Alfieri et al., 2016, Winsemius et al., 2015). The acceleration of the hydrological cycle, due to higher temperatures, causes more extreme rainfall accumulations. A statistically significant increase in flood risk is observed in most world regions (Alfieri et al. 2016). Flood risk is also fostered by processes associated with increasing levels of urbanization (Kundzewicz et al., 2010). Societies are trying to adapt to changing conditions by various means to minimize flood losses. This is also done by individual European countries (Wiering et al., 2017), which is generally a more advanced process in the northwestern parts of the continent than in the southern and eastern parts (Paprotny et al., 2025). Analyses of flood risk conducted on a global scale, indicate its strongest increases in southern, central and western Europe, as well as in the USA and many parts of Asia (Alfieri et al., 2016).

The frequency of extreme high precipitation is also increasing in northern Europe and Alpine regions, and it is even higher than in central Europe (Bednar-Friedl et al., 2022). The phenomenon itself is not new in Poland, the first documentation of such situations can be found as early as in the chronicles of Jan Długosz from the 15th century. A characteristic period for the occurrence of floods in Poland is July-August, when increased activity of the Azores high can be observed, which favors the formation of rain clouds Nimbostratus and Cumulonimbus (Matuszko, 2018) In addition, at this time we can distinguish "urban flooding", "flash floods", which covers small areas and watercourses, but is particularly destructive in highly urbanized areas. These types of floods are hard to predict by their suddenness (Morawski, 2022). During this period, the average precipitation in southwestern Poland even reaches more than 600 mm this is equal to the average for annual precipitation in the country (Tomczyk et al., 2022). However, when analyzing the losses that floods have brought, it can be seen that these phenomena have intensified over the past three decades. As an example, we can take the economic devastation caused by the Great Water of 1997, which brought almost 4 times the losses of other floods of the second half of the 20th (Ciepielowski, 1999).

In Europe, the upward trend in flood losses is unfortunately much greater than population and economic growth (Kundzewicz et al., 2010). It is projected that by the end of the 21st century, the socio-economic impact of river floods will increase by an average of 220% in Europe due to climate change, not taking into account other adverse factors (Alfieri et al. 2015) and it should be noted that, for example, between 1870 and 2016, Europe's population increased by 130%, urban area by more than 1000% and wealth by more than 2000% constant prices (Paprotny et al., 2018), which influences the increase in material losses in flood events. The occurrence of flood events is also facilitated by land use change, altered farming practices, increased impervious surfaces, straightening of riverbeds and narrowing of riverbeds, which limit space for water drainage (Sabelli, 2023). 56% of the 1564 floods recorded during this period were flash foods, i.e. river floods lasting less than 24 hours, 39% were typical river floods, 4% were coastal floods and 1.5% were floods of mixed origin – floods caused by a co-occurrence of storm surge and high river flows (Paprotny et al., 2018).

The main objective of the study carried out was to identify the common features linking the synoptic conditions that led, consequently, to flooding in the southwestern part of Poland. For this purpose, the synoptic situation, thermodynamic and kinematic conditions and the hydrological situation were analyzed in detail in connection with precipitation.

Study area and big floods

The analysis covered synoptic flood conditions in the upper and partly middle Odra River basin, i.e. in the Sudetes, their foothills, and the Silesian Lowlands. Floods in this area are a common phenomenon, e.g., in the Kłodzko Valley and in the catchment areas of some left-bank tributaries of the Odra, such as the Bóbr, Kaczawa, Bystrzyca, and Ślęża, the flood risk index (WZP calculated as the ratio of the maximum reliable flood MWW minus the safety limit flow to MWW: (MWW – Qgr) MWW-1) is above 0.9 (Dubicki et al. 2005, Kasprzak 2010). The largest floods occur in summer, with about 75% of floods on the Oder recorded between June and August (Dubicki, 1972), most of them in July and August (Dubicki et al., 2005, Müller et al., 2009).

The causes of flooding in the upper Odra river basin are extensive, intense, and prolonged (lasting 2-3 days or even longer) precipitation and the timing of this precipitation in different parts of the upper Odra river basin and the order in which water flows into the receiving water body from higher-order basins (Dubicki et al., 2005). The formation of intense and abundant rainfall in this area is facilitated by the inflow of moist air masses and the orographic barrier formed by the Sudetes and Beskids (Tokarczyk et al., 2021). The slope of the hillsides, the permeability of the subsoil, and the land cover are also important factors. The height of the flood wave is increased by the restriction of the river bed width due to the construction of flood embankments (Kasprzak, 2010) and the development of mountain streams, changes in land use, and the construction of hydrotechnical structures that alter the hydrological regime of rivers and, consequently, the propagation of flood waves in the longitudinal profile of their valleys (Tokarczyk et al., 2021).

The highest rainfall in southwestern Poland comes from the Izera Mountains (Kasprzak, 2010), where, on the Czech side of the mountains, near the border with Poland, a Sudetes record daily precipitation total of 345.1 mm was recorded on July 29, 1897, at the Nová louka station (Brázdil et al., 2005). Exceptionally heavy rainfall also occurs in the Śnieżnik Massif (Wrona, 2008). Systematic meteorological and hydrological observations (of river water levels) conducted since the early 19th century indicate that floods occurred on the upper Oder and its tributaries before 1997 in the following years: 1813, 1829, 1854, 1880, 1902, 1903, 1958, 1965, 1970, 1972, 1977, 1981, and 1985. The events of 1903 and 1854 were considered the largest floods on the Oder River until 1997. In the period after World War II, the largest flood occurred in 1977 (Jelonek et al., 2021). Dangerous rainfall floods also occurred later, of course. One of them took place in southwestern Poland in August 2006. It was caused by rainfall lasting as long as five days, which could not be absorbed by the ground due to its dryness caused by a four-week long period of drought, and caused alarm levels to be exceeded on the Bóbr, Kwisa rivers and their tributaries (Kasprzak, 2006). On the tributaries of the Oder River that drain mountainous areas, summer rainfall floods occur very frequently. For example, on the Nysa Kłodzka and Bóbr Rivers, summer floods occur every year or every 2 to 3 years, with the exception of 1987 -1997 in the Nysa Kłodzka catchment area and 1986-1991 in the Bóbr catchment area (Dubicki et al., 2005). The Nysa Kłodzka River is a particularly dangerous river, causing not only floods in the Kłodzko Valley after heavy rainfall in the surrounding mountain ranges, but also in the upper middle Odra Valley, supplying it (the Odra) with enormous amounts of water (Dubicki, 1972, Dubicki et al., 2005).

This paper analyzes the synoptic and circulation conditions of three particularly dangerous floods that occurred in 1997, 2010, and 2024.

The flood in the summer of 1997 was a nationwide flood, the largest in the Polish territories both in terms of hydrology, as measured by the extent and maximum water levels and flows, and in terms of material losses, which, in addition to Poland, also affected the Czech Republic and Germany (Kundzewicz, 2005). The floods were the result of two waves of intense and torrential rainfall occurring on July 4-10 and July 15-23 (Kundzewicz et al., 1999). The magnitude of the July 1997 surges on the Odra River from its sources to Slubice, i.e., at most of the Odra River water gauges (in the upper and almost all of the middle reaches of the Odra River), exceeded the maximum recorded water levels. The largest of these occurred at the Svinov cross-section in the Czech Republic (387 cm). Water levels defined as absolute maxima were also exceeded on the Nysa Klodzka River and its tributaries – in Bystrzyca Kłodzka by as much as 248 cm. Absolute maxima were also exceeded in the upper reaches of the Oława River, the Kaczawa River and on the Bóbr River in Jelenia Góra (Dubicki, 1997). Flooding also affected, albeit to a much lesser extent than the Odra River basin, the foothill region of the Vistula River basin (Drezińska & Kruszewski, 1997). In Poland, 2592 towns and cities were flooded during the flood, 1362 of them completely, an area of 665,000 hectares was under water, 480 bridges were destroyed and 245 damaged (Kundzewicz et al., 1999).

The floods of May and June 2010 were not as threatening as those of 1997. The sources of danger in the Odra River basin were its right-hand tributaries, especially in the upper section – up to Opole, as well as the Widawa River (Wrocław region – middle course) and the Warta River, the mouth of which is the border between the middle and lower courses of the Odra (Jelonek et al., 2011). The immediate cause of the first culminating wave on the Odra River and its right tributaries was caused by precipitation in the second decade of May and the second in late May and early June (Szalińska et al., 2021). As a result of the merging of the upper Odra and Ostravice rivers, a wave was formed, which reached a record high of 650 cm at Chałupki on the border between Poland and the Czech Republic, at the Olza water gauge the state exceeded 912 cm and at Racibórz-Miedonia 903 cm, where the zone of average water levels ranges from 147 to 296 cm (Szalińska et al., 2021). In 2010, flooding also occurred in the Vistula River basin – primarily precipitation waters flowing from mountainous areas caused increases in water levels on the Vistula's mountainous tributaries and an increase in water levels in the upper reaches of the river, most notably in Sandomierz (the

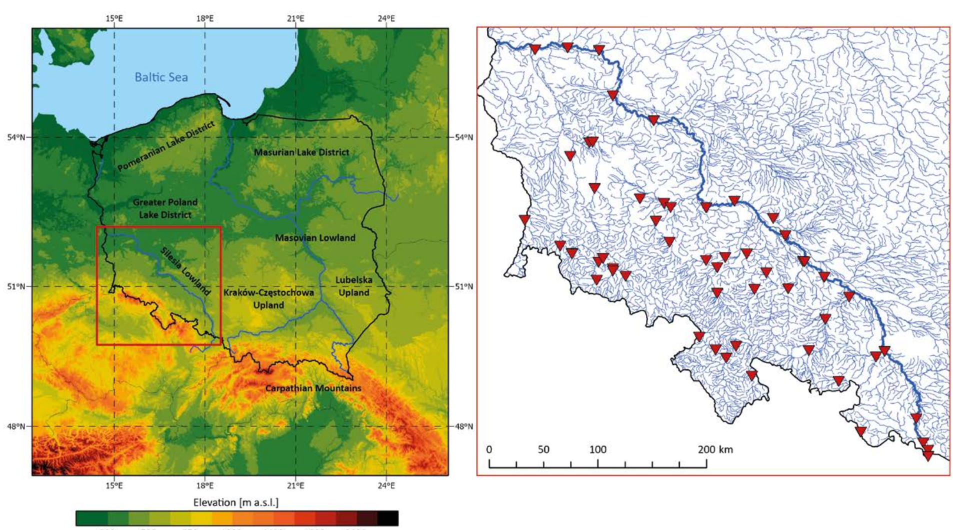

Figure 1. Hypsometric map of Poland and border countries based on Shuttle Radar Topography Mission Global Coverage (SRTM3; Farr et al. 2007). Red panel denotes hydrographic network with IMGW-PIB gauge stations (red triangles) used in study

mouth of the San River – the end of the upper reaches of the Vistula), where it reached 437% of normal in May. A total of 156% of the outflow norm in May and 343% of the outflow norm in June flowed into the Baltic Sea from the Odra River basin, while 236% and 314%, respectively, flowed from the Vistula River basin.

Flooding in September 2024 essentially occurred in Poland in the upper and central parts of the Odra River basin. In the Vistula River basin, minor exceedances of the alarm condition occurred at only 4 stations and in the Odra River basin at 67 stations (Pawelec et al., 2024). This aspect further outlines the problem of climate change, which is transforming.

Database and methodology

Various types of data were collected and analyzed to determine the synoptic and atmospheric circulation conditions that led to catastrophic flooding in areas of southwestern Poland in 1997, 2010 and 2024. The main database resource was the ERA5 product of ECMWF (European Center for Medium-Range Weather Forecasts). Climate reanalysis combine past observations with models to generate consistent time series of multiple climate variables (Hersbach et al., 2018). ERA5 is the latest reanalysis product by ECMWF, providing many atmospheric levels in hourly resolution. This product allows analysis of a variety of factors at 137 isobaric levels with a resolution of 0.25 x 0.25 on an hourly interval. Atmospheric reanalysis are developed on the basis of combining meteorological models with observations made at synoptic stations, while data gaps are filled on the basis of knowledge of the applicable laws of physics. Information on air temperature, water temperature, moisture content, spatial distribution of atmospheric pressure, wind speed and direction or geopotential height was taken from the resources of ERA5 databases. Measurements conducted at aerological stations are most often conducted at 00 and 12 UTC. Unfortunately, some measurements made via radiosondes are not available due to at least bad weather conditions or error in measurement time. ERA5 data were also used in the reconstruction of the state of the atmosphere in the vertical section. The thundeR package (Taszarek et al., 2023) of the R programming language was used for this purpose (R Core Team 2024[1]). These reconstructions are done on the basis of estimating the most probable atmospheric conditions based on meteorological reanalysis. In addition, information on wind speed and direction at heights of 0-12 km AGL was taken by visualizing the data on a hodograph. In the given study, it was also necessary to determine the direction of the inflow of air masses on the given days. For this task, data on the backward trajectories of air particles based on NCEP data were used using the SplitR library for the Hysplit model (Stein et al., 2015).

Table 1. Characteristics of ERA5 reanalysis data used in research

Data type	Grid
Horizontal grid spacing	0.25° × 0.25°
Projection	Latitude-longitude
Temporal resolution	Hourly
Horizontal coverage	Poland, Europe
Timeframe	05-10.07.1997 14-18.05.2010 13-16.09.2024
Total grid points	500,195
Latitude extent	30°–66°
Longitude extent	-15°–45°

The magnitude of flooding in July 1997, May 2010 and September 2024 was determined on the basis of water levels on the days when alarm levels were exceeded at individual stations in the Odra River basin, in Poland. The value in effect for a given post at the time of preparation of this study, i.e. in February 2025, was considered to be the alarm level. Posts where the exceedance of the alarm condition during the flood in September 2024 amounted to at least 1m were taken into

[1] https://www.r-project.org/

account, except for the water gauge posts Wrocław-Rędzin and Krosno Odrzańskie on the Odra due to the non-existence of these water gauges in 1997 and 2010, Głuchołazy and Biała Nyska on the Biała Głuchołaska due to the lack of determination of the value of the alarm condition, and Nowogród Bobrzański on the Bóbr due to the absence of this post in 1997 and the lack of exceedance of the alarm condition in 2010. Data from 1997 and 2010 were taken from an online database published by the Institute of Meteorology and Water Management – National Research Institute. Since the September 2024 data had not been verified and posted in the online public database by the time of preparation of this study, operational data from IMGW-PIB posted in "Bulletin of the National Hydrological and Meteorological Service. September 2024." It should be mentioned that a large part of the maximum water levels, especially during the 1997 flood, were determined only by estimation due to the flooding of water gauges and difficult access to the river, on the basis of leveling – marked water traces, which manifests itself in the dissimilarity of the values reported by various summary studies prepared by IMGW-PIB (Dubicki, 1997; Jelonek et al., 2011). Apart from the Oder River, special attention was paid to the rivers that were very dangerous due to flooding – Nysa Kłodzka and Bóbr, for which the number of water gauges made it possible to determine the changes in the exceeding the alert level depending on the kilometer of the downstream.

Results

Synoptic patterns

The system of baric centers plays a key role in the question of circulation of air masses. In the cases analyzed, the initiation of large-scale rainfall on the territory of Poland was undoubtedly associated with an extended deep high-pressure center over western Europe. At the same time, another high-pressure center was located in the northeastern part of Europe. Especially in 2010 and 2024, an area of reduced pressure with a low pressure center over Poland (2010) or Romania and Hungary (2024) is visible. In addition, systems of atmospheric fronts in the form of undulating atmospheric fronts with fragments of occlusion were associated with low pressure systems (Fig. 2) The inability of the low located over a fragment of Central Europe to migrate was mainly due to the presence of the previously mentioned high pressure systems.

The initiation of large-scale precipitation events was also initiated by circulation factors during the examined time intervals. At that time, portions of air with different characteristics flowed over the area of Poland. During the large-scale precipitation initiated on July 5, 1997, a consistent direction

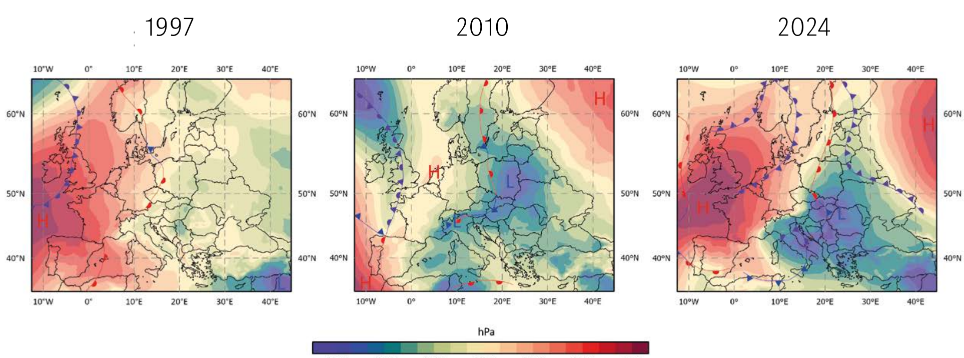

Figure 2. Mean sea level pressure (shaded) and atmospheric fronts (lines) during precipitation events initiation at 1200 UTC on July 05 (1997), May 14 (2010) and September 13 (2024) for Europe. L (blue) denotes low pressure system and H (red) denotes high pressure system. Derived from ERA5 database

of air inflow at the levels of 750 and 1500 m AGL stands out, while the contribution of tropical-type air coming from over the Sahara Desert is also visible. May and 2010 are mainly the main contribution of tropical air from over the Mediterranean. The precipitation that occurred in September 2024 was mainly associated with the inflow of air of polar-marine origin at 750 and 1500 m AGL and moist air from the Atlantic Ocean (Fig. 3A). During all three analyzed precipitation incidents, an impressive thermal gradient was evident at the 500 hPa isobaric level. The lowest air temperature occurred in the belt from the southern tip of Norway to the southern part of France. At the same time, in the south of the continent in the Mediterranean, the air temperature was significantly elevated (Fig. 3B). The visible low-pressure trough also at the same altitude perfectly illustrates the formation of the center of the low-pressure center over western Italy in 1997 and 2024. During the 2010 incident, the low-pressure center was characterized by a shallower form and a location closer to the borders of Spain.

In the case of extreme weather phenomena, the speed of air movement also plays an important role. Many times in convective phenomena, their potential can be intensified by the jet stream flow. Effectively separating two different air masses, the horizontal jet stream often dictates synoptic conditions. In the case of the synoptic cases analyzed, a meandering airstream was evident over the European area (Fig. 4A). Especially in September 2024, the jet stream effectively intensified the persistence of the low pressure center and the distribution of transported moisture deposits. In all cases, too, a uniform spatial distribution of the water vapor contained in the air can be observed. A scenario related to the separation of humid and cool polar-maritime air along with hot and humid air on the eastern side of the continent can then be observed. At the same time, due to the greater heat capacity of the air of tropical origin, the masses located on the eastern and southern parts

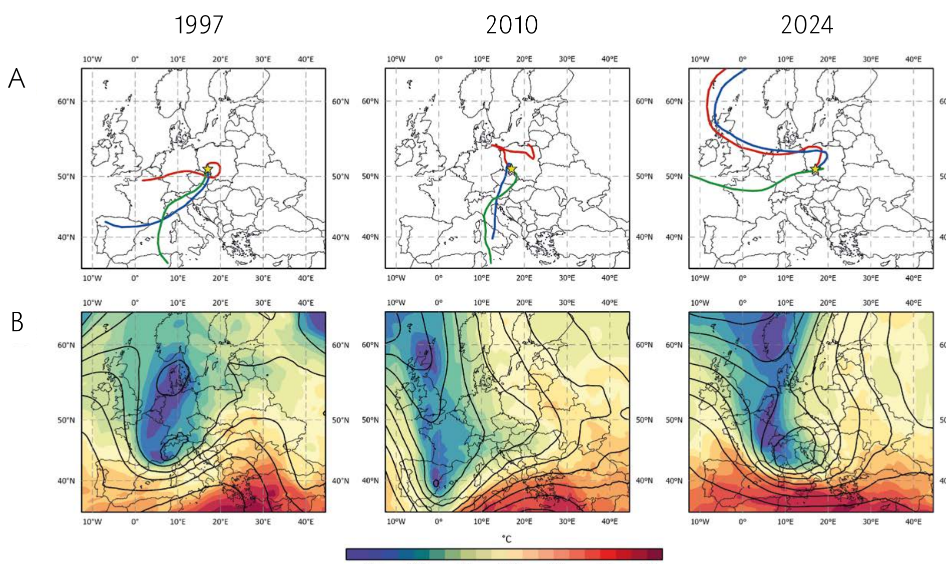

Figure 3. A – Backwards trajectories ending lines during precipitation events initiation at 1200 UTC on July 05 (1997), May 14 (2010) and September 13 (2024) for Europe. Red line denotes 750 m AGL level, blue line denotes 1500 m AGL level and green line denotes 2500 m AGL level. The star symbol denotes location for model sounding presented in upper air section. B – 500 hPa air temperature (shaded) and geopotential height (contour) for same date-time interval. Data derived from Hysplit model based on Global Forecast Model and ERA5

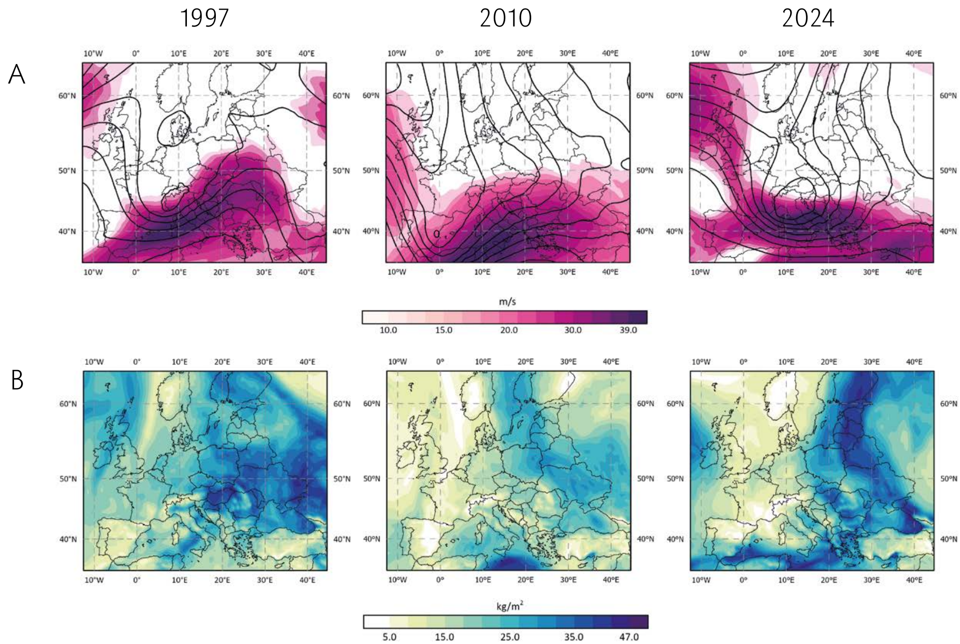

Figure 4. A – 200 hPa wind speed (shaded) and geopotential height (contour) at 1200 UTC on July 05 (1997), May 14 (2010) and September 13 (2024) for Europe. B – Total column water vapor for same date-time interval. Data derived from ERA5 database

of Europe were more abundant in moisture, which, combined with cyclonic circulation, contributed to prolonged rainfall over eastern Europe (Fig 4B). An additional factor leading to the intensification of precipitation timing was the blocking of further migration of the low-pressure center by highs in the eastern and western parts of Europe.

Upper air section

An extremely important role in weather forecasting is played by upper air maps. A stratigraphic curve containing values of temperature, AGL altitude and corresponding values of wind speed in the 0-16 km AGL profile contains information on thermodynamic conditions. During the 1997 precipitation incident, a slight atmospheric instablity was evident in the profile slightly below 1 km AGL to about 6 km AGL characterized by simultaneous weak airflow. Importantly, higher up because from the isobaric height of 300 hPa to about 200 hPa the presence of stronger airflow was marked, signifying the presence of a meandering jet current. In the case of the 2010 incident, a very low-suspended condensation level with an early cut-off level is evident (Fig. 5B), while at the same time there is relatively weak movement of air particles at 0-16 km AGL. The stratigraphic curve from the 2024 precipitation incident is very similar to that of 2010 (Fig. 5C). The overlap of air temperature values with the dew point temperature in the 0-4 km AGL section can be seen, which led to strong condensation in this section of the profile. On the other hand, the air flow at 200-300 hPa was similarly shaped, signifying the renewed presence of the jet stream over the south-western part of Poland.

As for the atmospheric kinematic conditions during the first day with precipitation that contributed to the floods, the 1997 and 2024 incidents stand out. In the case of July 5, 1997, a relatively weak flow was evident at

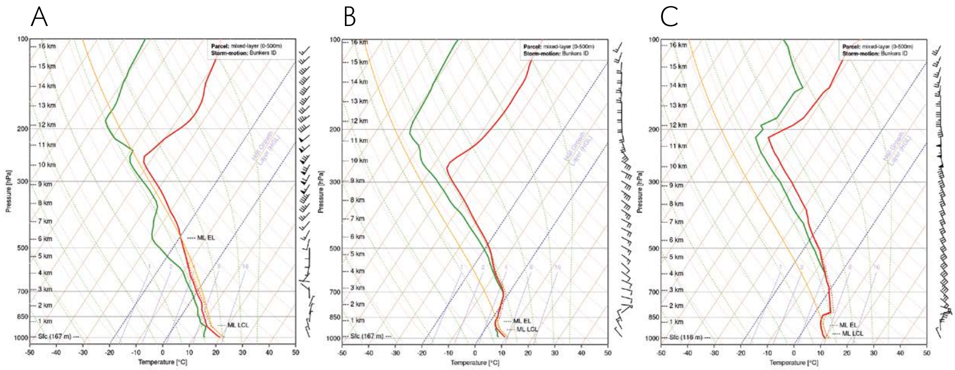

Figure 5. Skew-T diagram at 1200 UTC for Wroclaw. A – July 05 (1997), B – May 14 (2010), C – September 13 (2024). Computed from sigma-level ERA5 database

0-3 km AGL characterized, however, by a high wind twist. As the altitude increased, the wind speed increased while changing direction up to an altitude of 9 km AGL. The peak value of the airflow at an altitude of 12 km AGL reached 20 m·s^{-1} (Fig. 6A). During the initiation of precipitation on May 14, 2010, moderate kinematic conditions were marked. The wind speed in the 0-12 km AGL profile did not exceed 20 m·s^{-1}. The weak airflow resulted in the possibility of rainfall accumulation over a longer time interval. Autumn precipitation initiated on September 13, 2024 was characterized by high dynamism in the studied profile. Elevated values of wind speeds reaching up to 30 m·s^{-1} in the upper range and variable direction are evident throughout the profile. Once again, an intensification of wind speeds at 9-12 km AGL is also evident (Fig. 6C).

Precipitations

The spatial distribution of precipitation during the three floods was mainly cumulative in the southern part of Poland (Fig. 7). In 1997, the highest precipitation totals were recorded in the Odra River basin, in its upper reaches. The most rain (more than 200 mm) fell in the area from the Sudetic Foreland and the southern part of the Silesian Lowlands to the western part of the Western Beskids. In addition, increased precipitation can be seen in central Poland, reaching about 100 mm. The highest precipitation during the 1997 floods in Poland was recorded at the meteorological station belonging to IMGW in Raciborz – 244 mm. In the Czech Republic, the station in Praděd recorded 455 mm. However, during the 2010 floods, the spatial distribution of precipitation was more shifted to the east compared

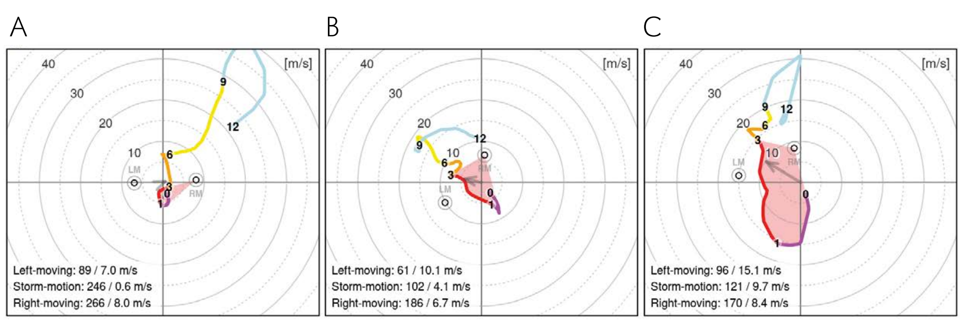

Figure 6. Hodograph diagram at 1200 UTC for Wroclaw. A – July 05 (1997), B – May 14 (2010), C – September 13 (2024). Computed from sigma-level ERA5 database

to 1997.The highest precipitation totals (200-300 mm) occurred in the area of the Western Beskids, the western part of the Carpathian Foothills and the belt of the Subcarpathian Basins. Most of the precipitation occurred in the Vistula River basin, but it also covered part of the Odra River basin. The meteorological station in Straconka (a district of Bielsko--Biala) recorded a rainfall of 221.1 mm (City Hall of Krakow, Report after the floods of May and June 2010). In contrast, the 2024 flood was characterized by rainfall concentrated in southwestern Poland, particularly in the Sudetes (Sudetic Foreland and Klodzko Basin). Precipitation in the higher parts of the mountains exceeded 350-400 mm / 4 days. On the summit of Śnieżnik (Poland), the station before it stopped working recorded precipitation of 396.7 mm. According to data from the RainGRS system belonging to the IMGW, precipitation at the same location was 472 mm. In the Czech Republic, the station in Rejvíz recorded precipitation of 516.7 mm.

In the case of all three analyzed floods, the beginning of the formation of the low-pressure system occurred in the Ligurian Sea region, more precisely in the Gulf of Genoa (Fig. 8). Initially, the route of all the lows followed the path of the Vb low mapped by van Bebber (van Bebber, 1891) – the low from the Ligurian Sea moved northeastward in Europe. The center of the 1997 low between July 5 and 6 traveled a distance of more than 2100 km, which resulted in a movement speed of about 89 km·h^{-1} (Fig. 8 – 1997). The route covered regions from the Gulf of Genoa through the Po Valley, the eastern part of the Alps, the western part of the Carpathians to the Polesia. Then, on July 6-9, the center of low pressure slowed down to about 30-35 km·h^{-1} and began to be almost stationary, within Ukraine and Belarus. Initially during this period, the system turned southeast and moved over Podolia. Then it made a turn to the north, northwest (NNW) into the region of central Belarus to return over the area of central Ukraine again. Finally, the low moved northeast to the region of the Central Russian Highlands (southwestern Russia). During the 1997 flood, the low covered a distance of more than 5300 km with an average speed of about 44 km·h^{-1}. During the 2010 flood, the center of the low moved slightly slower compared to 1997, but the route in the first four days (May 14-17, 2010) was almost identical to that traveled by the low between May 5 and July 6, 1997 (Fig. 8 – 2010). Between May 16 and 17, the center of the low turned more eastward into the Volyn Highlands region. In the final stage, the low moved in an east-southeast direction (ESE) with a speed of about 38 km·h^{-1} over central

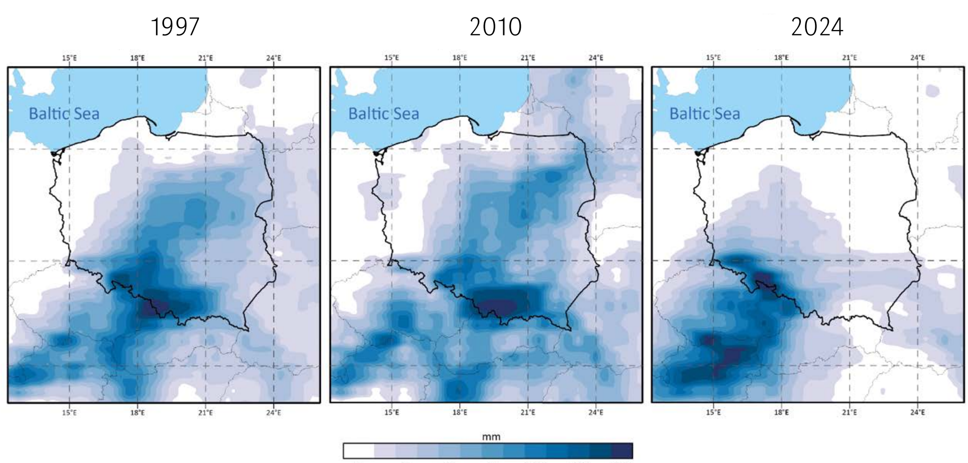

Figure 7. Spatial diversity of atmospheric precipitation during flood events. Total precipitation amounts computed from ERA5 database

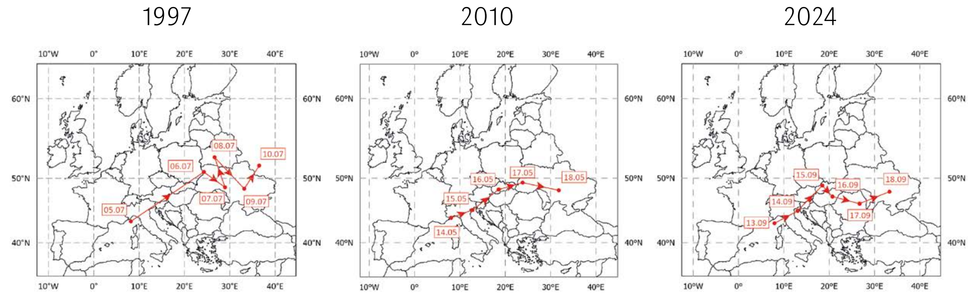

Figure 8. Path reconstruction of the low baric center causing the flood events. Computed based on ERA5 database

Ukraine. In 2010, the center of the low traveled a distance of less than 2900 km with an average speed of approx. 30 km·h^{-1}. A similar situation to that of 1997 and 2010 occurred during the 2024 flood. The low from over the Gulf of Genoa moved at an average speed of about 27-36 km·h^{-1} to the northeast into the region of the Western Carpathians (borderland of the Czech Republic and Slovakia) (Fig. 8 – 2024). Then, between September 15 and 16, the speed of movement decreased to about 15 km·h^{-1} and the direction changed to the southeast. The center of the low then reached over the Great Hungarian Plain from where in the next two days (September 16-18) its route changed direction to the east passing through the area of the Transylvanian Highlands – northern Romania (September 16), northern areas of the Black Sea Plain (September 17) to central Ukraine (September 18). In total, during the 2024 flood, the low covered a route of more than 3300 km with an average speed of approx. 30 km·h^{-1}. It is noteworthy that the second stage of the route, between September 15 and 18, 2024, is closer to the Vd type of low's routes determined by van Bebber.

Hydrology

The highest exceedances of the alarm levels were observed in the upper reaches of the Odra River at the Krzyżanowice station, where they amounted to 454 cm (Fig. 9A), and on the Nysa Kłodzka, where the exceedance of the alarm level was 419 cm in Kopice and 390 cm in Kłodzko (Fig. 11A and B). High water levels also occurred on the Bóbr River – in Żagań the maximum exceedance of the alarm condition was 349 cm (Fig. 10A and B). The maximum water levels on the upper and middle Odra (up to Słubice) were usually close to the values of 1997 and 2010 (Fig. 9A), the alarm levels, however, lasted much shorter, especially on the middle section from Ścinawa to Nietków, where the alarm levels in 1997 and 2010 were exceeded for about a month (exactly on average 30.8 days and 32.6 days, respectively) and in 2024 on average for 12 days (Fig. 9B). Based on the data published by IMGW-PIB, it can be concluded that, in general, during all floods, as the flood moves downstream, the length of the flood wave becomes longer and two periods of several days of exceeding the alarm level merge into one long one.

In addition to the Odra River, flood surges in September 2024 also occurred in its basin, mainly in the catchments of the Nysa Kłodzka, Bystrzyca (Fig. 11), Kaczawa and Bóbr (Fig. 10), which are direct tributaries of the Odra River. While all of the water gauging stations in the Odra River basin where alarm levels were exceeded by at least 1 m were also exceeded during the 1997 flood, alarm levels were not exceeded at the majority of stations (except for the Odra River itself) in 2010, specifically 24 out of 43 analyzed (Fig. 10 and 11). In the Nysa Kłodzka catchment, where in 2024 exceedances of the alarm condition were even approx. 4 m (Fig. 11B), in 2010 exceedances of the alarm condition were

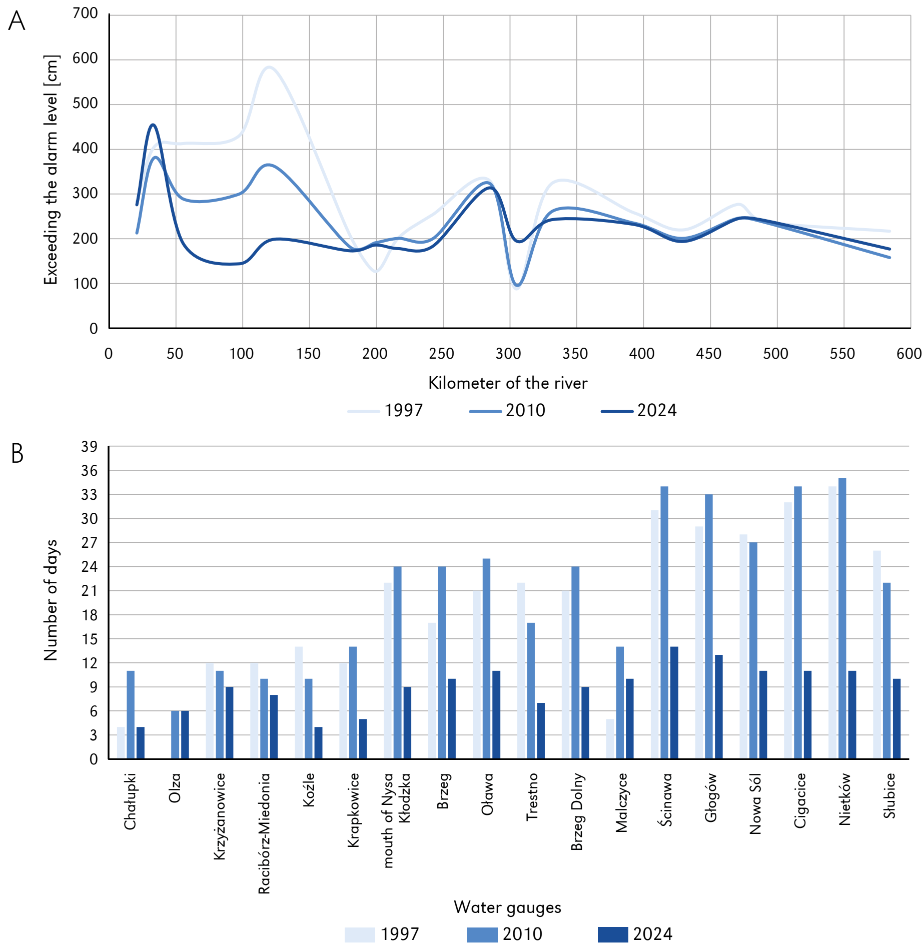

Figure 9. The magnitude of exceedance of the alarm condition depending on the km of the Odra River downstream counted from its source (A) and the number of days with exceedance of the alarm condition at water gauges (B) on the Odra River during the 1997, 2010 and 2024 floods, in the part of the river where the exceedance of the alarm condition in September 2024 was at least 100 cm

observed only at one water gauge (out of 9 in the catchment), at the mouth of the river to the Odra (Fig. 11A and B).

At the mouths of the Nysa Kłodzka River (in Skorgoszcz) and the Bóbr River (in Stary Raduszec) into the Odra, the alarm levels lasted the longest – in Skorgoszcz 26 days in 1997, 30 in 2010 and 13 in 2024 (Fig. 11C), and in Stary Raduszec 24 days in 2010 and 12 in 2024 (in 1997 measurements had not yet been made; Fig. 10C). In 2010 and 2024, alarm levels were exceeded for much shorter periods than in 1997 – in May and June 2010 it was an average of 6.2 days in the Odra River basin (except for the Odra River) (counting only stations where alarm levels were exceeded), in 2024 – 5.3 days and in 1997 – 10.2 days, the longest on the Nysa Kłodzka River and its tributary, the Biała Lądecka River (an average of 14.1 days; Fig. 11C).

Discussion

The precipitation and humidity situation across Europe is constantly changing. Extreme situations such as prolonged droughts or

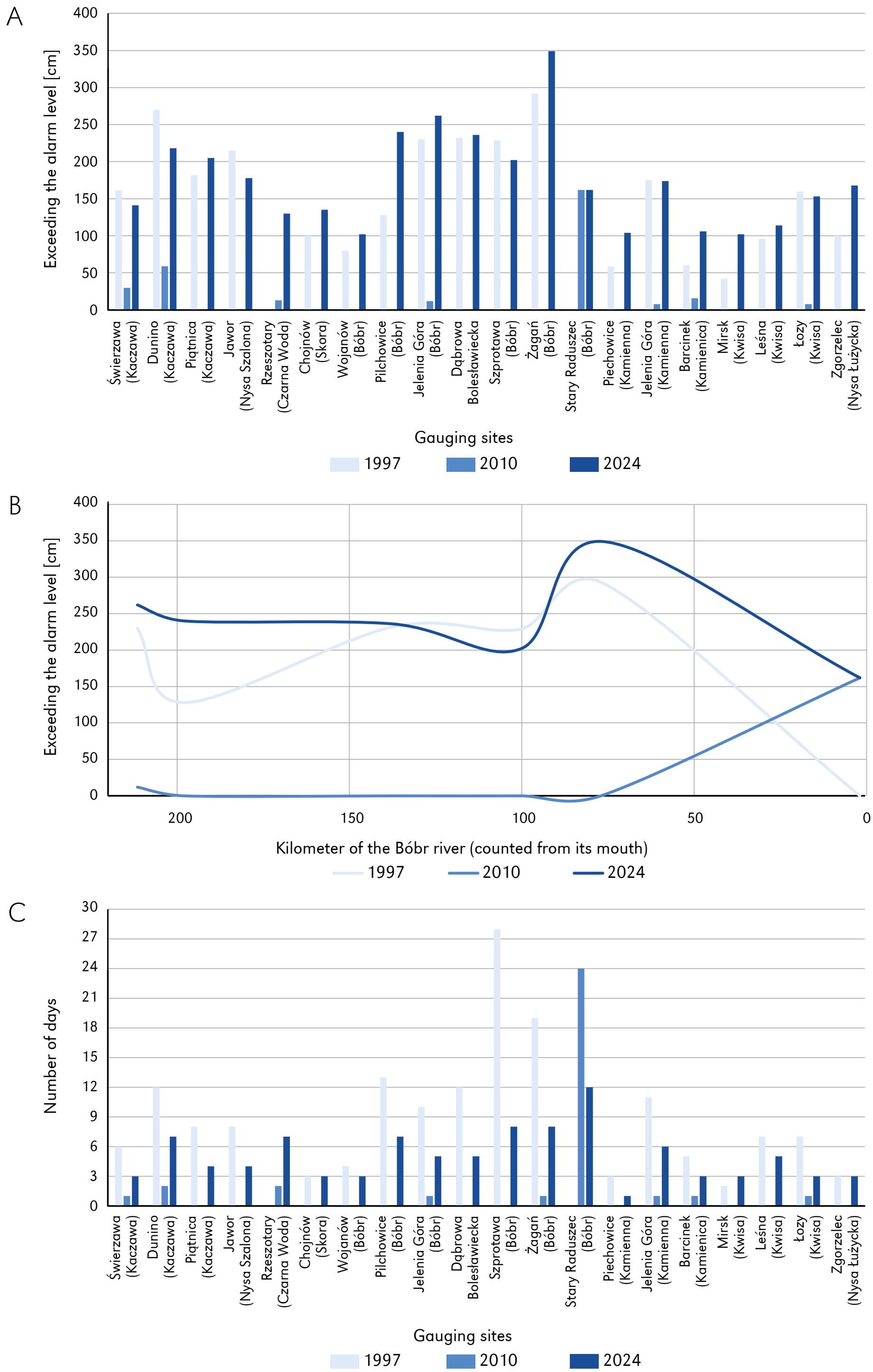

Figure 10. The magnitude of the exceedance of the alarm condition on the rivers of the Kaczawa and Bóbr basins (A), the magnitude of exceedance of the alarm condition on the Bóbr River, depending on the km of the downstream, counted from the mouth (B) and the number of days with exceeded alarm condition (C) on the rivers of the Kaczawa and Bóbr basins (Odra River basin) during the 1997, 2010 and 2024 floods at water gauges where the exceedance of the alarm condition in September 2024 was at least 100 cm

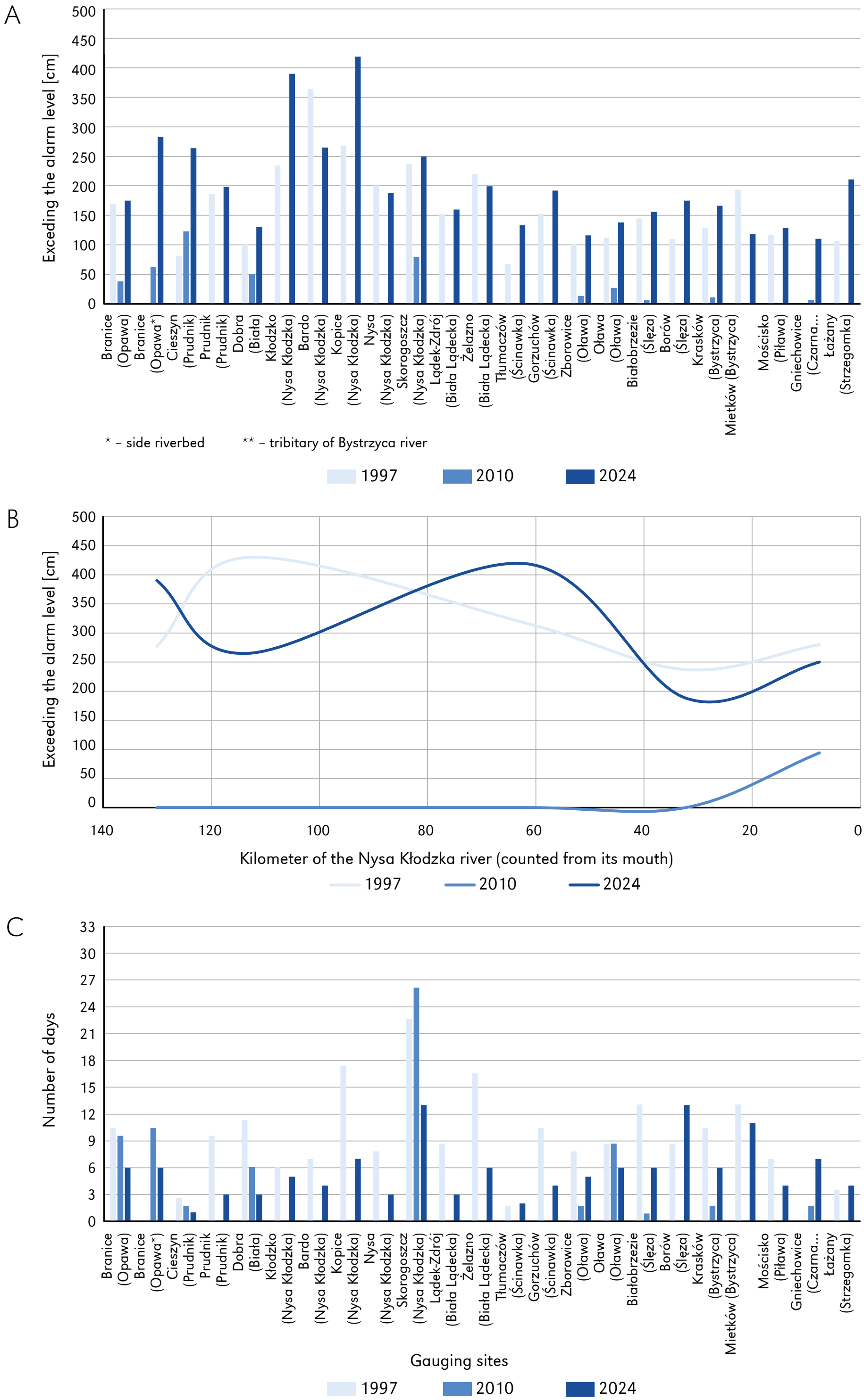

Figure 11. The magnitude of the exceedance of the alarm condition in the Odra River basin, outside the Kaczawa and Bóbr catchments (A), the magnitude of exceedance of the alarm condition on the Nysa Kłodzka River, depending on the km of the downstream, counted from the mouth (B) and the number of days with exceeded alarm condition (C) in the Odra River basin, outside the Kaczawa and Bóbr catchments, during the floods of 1997, 2010 and 2024, on which the exceedance of the alarm condition in September 2024 was at least 100 cm

precipitation can be experienced with increasing frequency. The Earth's atmosphere and the seas and oceans are inextricably linked, so if the values of one variable change, the others will also change. The situation under discussion mainly concerns the relationship of ocean and sea temperatures to precipitation totals in a given area. On the basis of water temperature anomalies, it is possible to make a preliminary assessment of regions likely to be affected by floods or droughts.

Extremely high precipitation most often occurs in Central Europe during cyclonic troughs over Central Europe. Absolute precipitation maximums are associated with a synoptic situation causing an inflow of air masses from the W-NW-N-NE sector, with very heavy precipitation most often caused by a cyclonic system with an inflow of air from the northeast (Ustrnul & Czekierda, 2001). Absolute maximum precipitation at measuring stations in southern Poland usually occurs when the center of the high is located over northwestern Europe and southern Poland is within the low, under the influence of air masses flowing from the N-NE-E sector (under N-NE-E advection of the cyclonic type). This baric system is responsible for most of the floods in the 20th century (Ustrnul & Czekierda, 2001), including the flood of 1997 (Niedźwiedź, 1999). During both the floods in July 1997 and May 2010, air from the Mediterranean Sea flowed into southern Poland at an altitude of 4000 m a.g.l. (Świątek, 2013). A similar direction of air mass advection contributing to flooding in Poland, in accordance with the path of the Vb van Bebber low-pressure system (van Bebber, 1891), was also indicated by Kundzewicz et al. (2005) pointed to a similar direction of air mass advection contributing to flooding in Poland, in accordance with the Vb van Bebber low-pressure system track (van Bebber 1891), while Kyselý and Beranová (2008) noted the impact of advection from the Mediterranean Sea on flood conditions in the Czech part of the Odra River basin. Ulbrich et al. (2003 a, b) also found that the extremely high rainfall totals causing summer floods in Central Europe are caused by the "Vb-Track" situation, when a low-pressure system from the Gulf of Genoa moves over Central Europe. Although climate change contributes to a decrease in Vb-track density (Vb-track situation), on the other hand, climate warming increases the likelihood of Vb situations causing exceptionally heavy rainfall in Central Europe, leading to floods (Kundzewicz et al., 2005). Wrona (2008) stated that, in addition to low-pressure systems moving to Poland along the Vb route, intense precipitation in the upper and middle Odra River basin is favored by a low-pressure trough with a cold atmospheric front moving from the Atlantic Ocean; a stable, highly vertically developed high-pressure system centered over Scandinavia or northwestern Russia; the flow of cool polar-maritime or Arctic air over Poland during the warm part of the year; and the occurrence of a low-gradient area of low pressure over Europe, causing the activation of a mostly quasi-stationary atmospheric front within its range. Synoptic situations associated with southern circulation are more conducive to higher precipitation intensity than zonal circulation, and the greatest flood risk in southwestern Poland is caused by the movement of a low-pressure system from southern Europe along the van Bebber's Vb route (Wrona, 2008).

As with El Nino and La Nina phenomena, which shape weather in Europe especially in the cooler half of the year, the Mediterranean plays a large role. Along with the global increase in air temperature, an increase in the temperature of surface waters including, in the main, seas and oceans is also recorded. This is a serious problem significantly affecting the waters of the Mediterranean Sea, which has become the fastest warming sea in the world (WWF, 2021). With 1.4 °C higher water temperature, the Mediterranean Sea is considered as a climate change hotspot, warming faster and more intensely than other parts of the world (Kubin et al., 2023). On August 15, 2024, the record for average daily sea surface temperature of 28.9 °C was broken. The previous record had been set a year earlier, which indicates the pace of progressive change. Also noteworthy are smaller areas of the Mediterranean Sea, which are warming at an alarming rate reaching 5°C above the average temperature of 1991-2020. We are talking about the part of the Tyrrhenian Sea in the section Genoa, Corsica, Sicily. The increase in the temperature of the water of this body of water is negatively affecting not only the organisms living under the water but also to a large extent what happens on the surface. For example, a study by Kotroni and Logouvardos (2016) positively assessed the impact of increased water temperature in the Mediterranean Sea on convective phenomena especially in autumn. The rate of warming in the Mediterranean can be determined as 0.35 °C per decade (Shaltout & Omstedt, 2014). However, it is not ruled out that in the following years the annual increase will be even higher which may lead to more frequent extreme events not only in the near Mediterranean. The increasingly warmer waters of the Mediterranean will be the perfect "fuel" for cyclones forming over the Gulf of Genoa (Fig. 12). The influence of increased water temperature of the Mediterranean Sea and the Black Sea on the intensity of precipitation was also noted by the authors of the study in the subject of three floods that occurred in the Prut and Siret catchment area (Romania and Moldova). Floods in the area in question occurred in 2008, 2010 and 2020 and were directly related to the advection of warm and humid air from the Mediterranean and Black Sea (Ionita & Nagavciuc, 2021). One of the most crucial aspects for the most intense rainfall and associated accumulations is effective rainwater management. Similar to the 1997 flood, the 2024 flood incident affected a similar area of southwestern Poland. The problem of river regulation or urbanization in terms of issued building permits in areas particularly vulnerable to such events is marked at this point. Over the past 30 years, areas located at a considerable distance from watercourses are strongly changing in terms of use. Regulation of rivers and simultaneous "shortening" of the actual length of rivers is still a current problem not only in the European area. This consequently leads to flooding in the area of the regulated sections (Wang et al., 2024). In the end, all possible means should be used to effectively manage rainwater in the form of retention and use of water later.

Conclusions and final remarks

The September 2024 flood in central Europe was another example of increasing flood surges in Europe caused by extremely intense precipitation (Winsemius et al., 2015, Alfieri et al., 2016). It was definitely not an isolated or surprising case in Europe (Paprotny et al., 2024). It occurred in Poland in areas identified by studies as particularly predisposed to such phenomena (Borowska-Stefańska et al., 2021). It appeared after a long period of drought, as in the Czech Republic in August 2002. (Brázdil et al., 2006) and in May 2023 in northern Italy (Barnes et al., 2023), where drying of the ground compacted the soil making it difficult for rainwater to infiltrate into the ground. The flooding described in the paper was the result of the most typical cause in central Europe, which is very intense rainfall lasting several days (longer than the typical flooding in southern Europe; Paprotny et al., 2018). What is not entirely typical, however, is the period of flood occurrence – in this part of Europe, such precipitation floods are more likely to occur in summer than in September (Paprotny et al., 2018). Like the August 2023 flood in Slovenia (Bezak et al., 2023), the analyzed event was caused by the collision of cool air masses from over the North Atlantic and warm and humid ones moving with the baric low from over the Mediterranean Sea.

This study presents the synoptic conditions conducive to the occurrence of prolonged rainfall which consequently led to flooding mainly in area of south-western Poland. The research material was divided into three rain-flood incidents, which occurred successively in 1997, 2010 and 2024. As a result of the analysis conducted on synoptic and hydrological conditions, the following conclusions listed below were found:

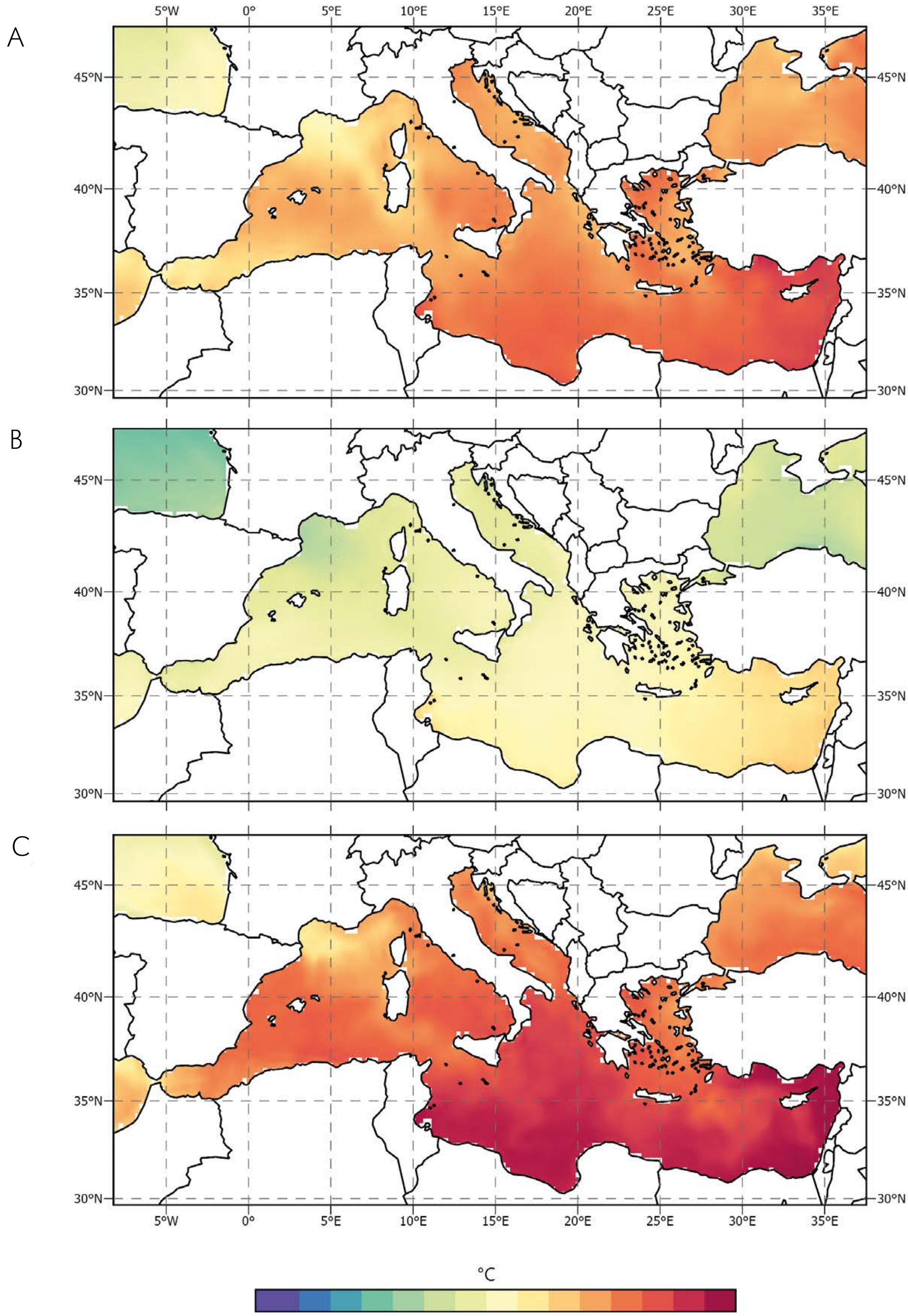

Figure 12. Mediterranean Sea water temperature for A – July 1997, B – May 2010 and C – September 2024. Data derived from ERA5 database

- Large-scale precipitation was associated with a low-pressure center forming near the Gulf of Genoa,
- Undulating atmospheric fronts were the initiating factor of the prolonged rainfall,
- Prior to the initiation of the precipitation, the close area of Poland was marked by a distinct flow of cold air from the north of the continent,
- The persistence of the low-pressure center and its route was assisted by the jet stream current present during the periods studied,
- The duration of the precipitation depended on the rate of movement of the low-pressure center and, at the same time, the degree of development of the present highs, effectively blocking the possibility of further migration of the lows from west to east,
- Precipitation causing flooding in the southwestern area lasted continuously for 5 to 6 days,
- During all three precipitation incidents investigated, precipitation values exceeding 300 mm were recorded across Poland,
- Convective type precipitation was an additional factor compounding the precipitation totals in 2024,
- The 2024 incident was also characterized by significantly elevated water vapor content in the air and the fact that the analyzed flooding took place in autumn, where air temperatures are much higher than in previous years,
- The amount of theoretical precipitation associated with the low-pressure center forming around the Gulf of Genoa may be influenced by the temperature of the Mediterranean Sea.

As climate change continues to progress, it is reflected in increasingly violent manifestations of the state of the weather. Understanding the conditions under which dangerous atmospheric phenomena form will allow us to better forecast and give us a slight advantage in preparing for a given scenario in the event of an unavoidable disaster. After all, every year around the world we will experience areas affected by drought or extreme flooding. This is why effective forecasts play such an important role, as well as the topic of responsible water management, including its storage for consumption or drainage to prevent flooding. Flooding in the Czech Republic and Poland was, unfortunately, not unique to Europe in the fall of 2024.

The research carried out is extremely important because of the need to understand the morphology of strongly extended low pressure systems of Mediterranean origin. Of note, in addition to the ability of the Genoese low to transport large deposits of moisture, is the barometric blockage causing flooding in this area of Europe. An example is the scenario from July 2025, where, despite the appearance of the Genoese low, the pre-predicted rainfall and consequently its accumulation could be another tragic flood incident in the area of Eastern Europe. Therefore, the next stages of the study should focus not only on the presence of the Genoese low but, more importantly, on the potential route, duration and magnitude of rainfall totals generated in a specific area. This will allow faster response and appropriate action to protect health, life and property.

Availability statement

Datasets analyzed during the current study are available in the ECMWF and IMGW-PIB database. These datasets were derived from the following public domain resources: https://cds.climate.copernicus.eu/datasets?q=era5, https://danepubliczne.imgw.pl/

Acknowledgement

Co-financed by the Polish Minister of Science under the "Regional Excellence Initiative" Program for 2024-2027 (RID/SP/0045/2024/01).

Editors' note:
Unless otherwise stated, the sources of tables and figures are the authors', on the basis of their own research.

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Article first received • 25 June 2025
Article accepted • 2 February 2026