In: *Prediction and Reduction of Diffuse Pollution, Solid Emission and Extreme Flows from Rural Areas – case study of small agricultural catchment* (ed. by K. Banasik, L. Øygarden & L. Hejduk), 27–46. Wydawnictwo SGGW, Warszawa – PL, 2011.

2

Analysis of low flow characteristics and drought frequency in agricultural catchments

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Introduction

Definition of drought and drought types

The occurrence of droughts is a natural feature of the climate of Poland. This is especially troublesome for agricultural areas in the growing season. In small agricultural catchments, especially in lowland areas, which have a fundamental significance for the natural environment and the economy, securing the required amount of water for agricultural use in a period of water deficiency is an important problem. As drought is such a common phenomenon, it needs to be monitored and forecasted, and its intensity needs to be assessed in order to lessen its effects on the economy, society and environment. However, due to the complexity of the processes involved, both Polish and world literature lack a universal definition of the phenomenon of drought. In practice, many methods and indicators are used to define the occurrence of drought. They are mostly based on the elements of the water balance: precipitation, evapotranspiration, runoff, as well as on the values of river flows and levels of ground water.

The definition which encompasses most of the parameters was created recently by a team of researchers gathered in the project: Flow Regimes from International Experimental and Network Data (FRIEND), Low Flow & Drought Group. The definition states that drought is a constant phenomenon with a regional reach, characterized by deviation from standard conditions for precipitation, soil moisture, the location of the ground water table and river flows (Tokarczyk 2008).

There are three stages, which may be distinguished in the drought phenomenon: atmospheric drought, soil drought and hydrological drought (Dębski 1970). Factors influencing the development of the particular types of droughts and their interaction are presented in Figure 2.1.

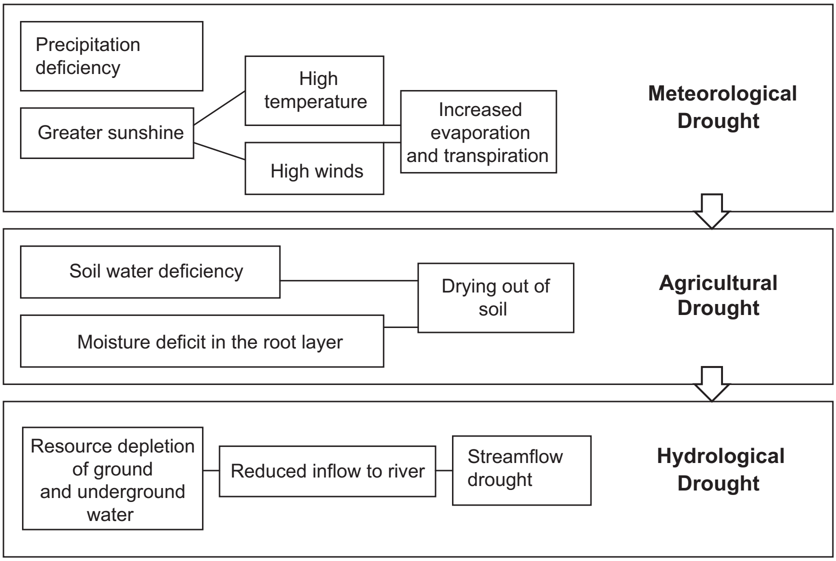


FIGURE 2.1. Factors influencing the development of meteorological, soil and hydrological drought in the summer half-year (modified after National Drought Mitigation Center 2006) http://drought.unl.edu/whatis/concept.htm

During the growing season, a long-lasting lack of precipitation causes atmospheric drought. If a lack of precipitation persists and is accompanied by high insolation and evaporation, the next stage of a soil drought follows.

As a consequence of evaporation from soil and plant transpiration, the gravitational water resources, and then the water resources related to mineral grains, are depleted and result in soil desiccation, so that soil moisture decreases below the critical value. During soil drought, there is a deficiency in water needed to fulfill the requirements of particular plants, cultivated at a particular place and time, and in this case, an agricultural drought is often said to occur. Prolonged lack of precipitation causes depletion of water resources in the saturated zone. Groundwater recharge of rivers decreases, and streamflow droughts (summer droughts) occur, which are also called as low flows. Literature indicates that streamflow droughts in rivers are identified as hydrological droughts. Smaller rivers, recharged by less extensive aquifer zones, might dry in this period causing the death of biological life in these water courses.

Streamflow droughts, caused by lack of surface- and groundwater inflows, can also occur in the winter period (winter droughts). Temperatures below zero cause accumulation of precipitation in the form of a snow layer on the surface and terminate groundwater inflow as a consequence of pronounced freezing of the substratum. Winter drought is independent from surface retention of the catchments and from the amount of accumulated snow. The rate of drought intensification depends on the speed of river freezing and on the formation of ice dams (Zielińska 1964).

The extent of negative influence of drought on agriculture depends on the period and location of its occurrence. According to Łabędzki (2006), the reaction of plants to drought depends on the species and the growth stage, as well as on the type of soil type in which they are being cultivated. Summer droughts have a negative influence on the potato crop and on the second regrowth of meadow sward and fodder field crops. Early spring and autumn droughts are usually a cause of a reduced winter crop. Spring droughts may affect the first regrowth of the meadow sward and decrease pasture productivity. Soils of the ground-water type, as well as of the rainfall-ground-water type, are particularly subject to the negative consequences of lowering the ground water table during hydrological drought. This is because capillary rise plays a very important role for vegetation, as water deficiency in the rhizosphere can be partly or even completely replenished through capillary rise from deeper layers (Ciepielowski et al. 2003). A consequence of the occurrence of catastrophic droughts is a significant decrease in grain and root crops, lack of fodder, increasing food prices, problems in conducting basic agrotechnical procedures (winter crop sowing, potato harvest) and in water supply for domestic and agricultural use, as well as fire in valuable forest areas and wetlands.

Droughts in Poland and in Europe

The areas of Poland, which are especially predisposed to the occurrence of drought and the final stage of hydrological drought, are found in the interfluves of the central Odra river, the central Warta and the central Vistula, where the specific discharges from the basin are the lowest in the whole country at below 1 $l \cdot s^{-1} \cdot km^{-2}$ (Figure 2.2). According to Łabędzki (2006), one of the driest regions in the country, characterized by frequent occurrence of droughts with extreme long periods without precipitation, is the whole central, northern-western and central-eastern part of Poland. Furthermore the central lowland area is where the threat of drought is the greatest. Over 70% of the meadows and pastures of Poland are located in areas with a rainfall deficit, but the consequences of this deficit are to a large extent compensated by capillary rise of shallow ground waters. Meadows and pastures located on soils of low quality, classified as 3z, are at especially high risk of reduced habitat productivity. In central and northern Poland, nearly all meadows and pastures of average and low quality are located in areas of medium or large water deficits (Stuczyński and Dębicki 2006). According to Kundzewicz et al. (2010), agriculture on the Polish Lowland is especially affected by the occurrence of increasingly frequent and more severe droughts. The highest duration of summer drought is characteristic for rivers in the Południowobałtyckie Lake District (Wielkopolskie and Chełmińsko-Dobrzyńskie lake District) in the Północnopodlaska Lowland, which is located in the River Narew basin. Regions which are mostly threatened by the occurrence of winter droughts are the Sudety, the Karpaty mountains and

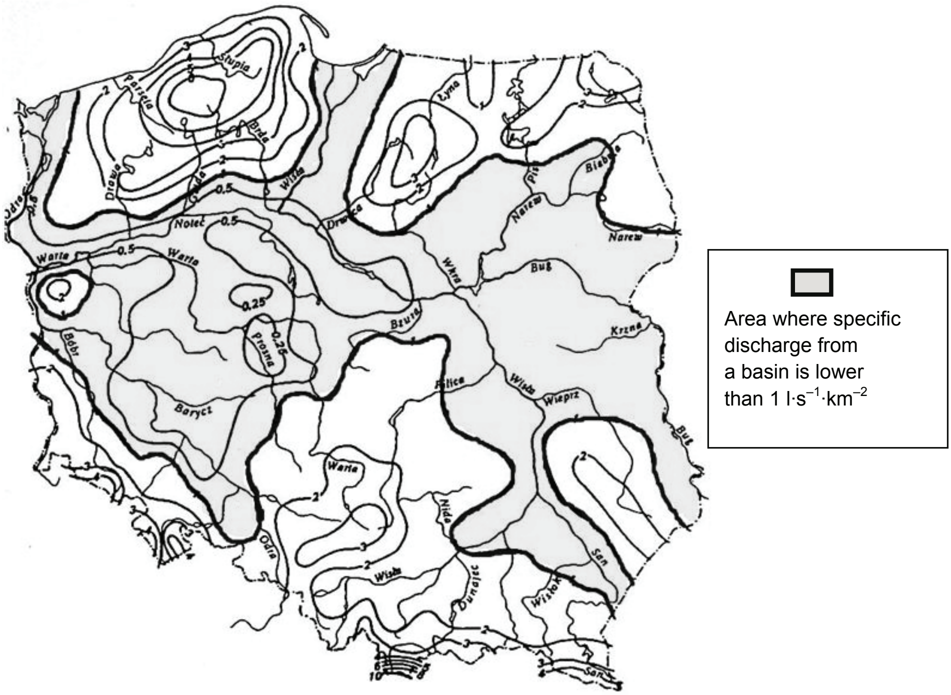


FIGURE 2.2. Area particularly threatened by occurrence of hydrological drought, where the specific discharge from a basin (q) is lower than $1\ \mathrm{l \cdot s^{-1} \cdot km^{-2}}$ (modified after Stachý 1987)

the Śląsko-Łużycka Lowland, as well as the eastern part of Poland, including Roztocze, Polesie and the Północnopodlaska Lowland (Farat et al. 1995; Kowalczak 2004; Kaznowska and Ciepielowski 2006).

Analysis of drought occurrence in Poland in the years 1988–2010 was undertaken by Kaznowska and Ciepielowski (2006) on the basis of the calendar (Table 2.1) prepared by Fal (2004) and completed with the data from the last years and revealed that years with droughts are often grouped in several-year cycles. The cycles last for mostly two or three years. The longest dry period took place in the 20th century, when from 1947 to 1954 droughts occurred sequentially, and there were streamflow droughts for five years from 1950 to 1954 in rivers over most of Poland. Six years with streamflow droughts occurred between 1951 and 1960, five in the period 1961–1970, none in the decade of 1971–1980, four between 1981 and 1990 and three in the years 1991–2000, with a particularly catastrophic drought in1992, which in August involved practically the whole country. In the decade 2001–2010, there were five years with hydrological droughts, which affected in 2003 and 2006 significant parts of Poland. According to research by Lorenc et al. (2008), the period from 1982 to 2006 was characterized by permanent drought with only two 4-year and 5-year periods, when droughts did not occur in the larger part of Poland.

TABLE 2.1. Calendar of droughts and streamflow droughts for Polish territory. Grey – years characterized by a large coverage of streamflow droughts in the country (after Fal 2004, after Kaznowska and Ciepielowski 2006)

Period	Years with streamflow droughts									
988–1500	988	1121	1332	1376	1455	1457	1459	1461	1463	1469
	1471	1472	1473	1479	1494	1500				
1501–1600	1516	1530	1531	1532	1534	1536	1538	1540	1545	1551
	1552	1553	1559	1561	1567	1575	1580	1584	1590	
1601–1700	1648	1652	1653	1661	1665	1666	1668	1678	1679	1680
	1681	1682	1684	1686	1690	1693	1696			
1701–1800	1702	1706	1707	1708	1715	1718	1719	1733	1739	1740
	1742	1745	1748	1749	1775	1783	1790	1794	1797	1800
1801–1900	1802	1807	1811	1817	1818	1821	1822	1832	1826	1827
	1828	1830	1831	1833	1834	1835	1841	1842	1846	1847
	1848	1853	1855	1862	1863	1874	1876	1889	1892	1893
	1895	1898	1899							
1901–2000	1901	1904	1911	1913	1920	1921	1925	1928	1929	1930
	1934	1943	1947	1948	1949	1950	1951	1952	1953	1954
	1959	1961	1963	1964	1969	1970	1983	1985	1989	1990
	1992	1993	1994							
2001–2010	2002	2003	2005	2006	2008					

The analysis of drought frequencies in Poland conducted by Mager et al. (2000), based on daily-recorded water levels in the period of 1891–1950 and flows from 1951–1995 has shown that the frequency of years with hydrological drought within Poland was larger in the last 45 years (year with drought every 3,2 years) than in the whole analyzed period (year with drought on average every 4,0 years). These results confirm research conducted by Sadowski (1991) who, having analyzed the frequency of drought occurrence in particular centuries, has concluded that drought takes place in Poland on average every 4–5 years.

According to Łabędzki (2006), in the last 25 years droughts in Poland have been occurring more often, they are also more intense and involve larger regions of the country. Based on systematic observations from the last fifty years, it can be concluded that within Poland the occurrence of drought periods is intensifying. According to Kundzewicz et al. (2010), as a result of progressing climate change, the problems of satisfying water requirements of Polish agriculture might be deteriorating due to possible changes in water balance and the nature of rural areas. Water shortage, despite a local increase of annual precipitation, will increase due to two factors. A large increase in air temperature will cause intense evapotranspiration in the winter period, which will prevent the restoration of soil moisture in this period. Furthermore, a possible slight increase of average rainfall during summer and the significant increase in evapotransporation will cause higher water requirements in agriculture.

Intense droughts which occur in Poland also concern other European countries. In the 20th century, many of the European tributaries suffered droughts in the 1980s and in the 1990s, as in Poland. Relatively short, but intense hydrological drought took place in 1983. In the period from July to November streamflow droughts with a significant reduction in runoff took place in many European countries, from Sweden to Slovenia, which are situated in a region stretching from 10° E to 15° E longitude. Towards the end of November, drought was also evident in rivers of western Great Britain, as well as central and eastern Europe, up to 30°E (Stahl 2001). The 1989/1990 drought generated long and significant water deficits. During the summer of 1989, the drought encompassed south-western Europe (Spain, France, Great Britain), as well as Denmark and the northern part of Germany. In Poland, hydrological drought occurred mainly in the Warta River basin, whereas in July 1990 drought affected as much as 45% of the area of Poland. Also in Europe, as a consequence of a dry winter, the hydrological drought of 1989 continued during the summer of 1990. In southern Europe, the south-western part of Great Britain, and central Europe, the streamflow drought of 1990 lasted from April to May, and in western and northern Europe, as well as in its central part, it occurred in August and in September, when lowest flows were recorded (Farat et al. 1995; Stahl 2001). Spain was especially affected by drought in the 1990s, with significant occurrences in the period of 1992–1995 and in 1999. In 2000, the drought that occurred in Bulgaria, the Czech Republic, Germany, Hungary, Romania, Turkey and in the western Balkans cost a total of 0.5 billion Euro (Demuth 2009).

The first decade of the 21th century brought further droughts in Europe. In this period, there were local as well as regional droughts. Catastrophic drought took place in 2003 in Austria, Belgium, Bulgaria, the Czech Republic, France, Germany, Greece, Hungary, Italy, the Netherlands, Norway, Poland, Portugal, Romania, Switzerland, Sweden, Great Britain and the Western Balkans, and its cost was about 12 billion Euro. In total, the drought of 2003 affected over 100 million people and one third of the European Union. In 2005 and in 2006, drought affected large parts of central, western and southern Europe. In 2007, drought occurred in Greece, Moldavia and south-western Europe, and in 2008 Portugal and Spain were affected (Demuth 2009). During the drought in 2007 there were over 3, 000 fires in Greece, which destroyed over 10,000 farms (Kundzewicz and Jania 2007). In 2010, a drought in the summer period plagued some areas in Russia, Ukraine and Kazakhstan, and caused disastrous fires. In Russia, over 22, 000 farms have been affected by drought. Thirty percent of the sown area was destroyed in the affected regions (Karpiuk 2010).

The work of Stahl et al. (2010) contains analysis of sequences of daily flows from many years in a large area of Europe, taking into account the most recent hydrological drought from 2003. Trends in daily discharges were investigated for 441 small catchments (< 1000 km^2) of nearly natural character in 15 European countries in the period of 1962–2004. For some of the water-gauges, sequences of daily flows were longer and began in 1932, 1942 or 1952. The catchments described in this study represent various regions of Europe characterized by specific hydrological regime and water balance. The analysis defined linear trends of annual and monthly flows, as well as low flows in the summer period and the time of their occurrence. Negative trends were found for annual flows in the southern and eastern regions of Europe, and mostly positive trends for other regions of Europe, particularly in countries of the northern latitudes. In case of monthly average discharge from the period 1962–2004, trend analysis showed a clear increase in discharges during winter for most of the study catchments. The transition from positive to negative trend (decrease of monthly average discharge values) was observed in the month of April, and in August this change occurred over most of Europe (Figure 2.3). Analysis of low flows showed a decreasing trend for a significant part of the analyzed regions of Europe, which is characterized by the presence of the lowest monthly flows in summer. However, trends differ for catchments where flow minima occur in the summer as well as in the winter period. The authors concluded that the study results were similar to the results of national and regional studies.

A significant decrease of annual flows in the second part of the 20th century for southern Europe but an increase in the northern part, especially in the winter period, was also revealed from a study of annual flows in the periods of 1900–1970 and 1971–1998, which was included in the second report of the European Environment Agency (EEA) in 2009. However, in the case of hydrological droughts (streamflow droughts

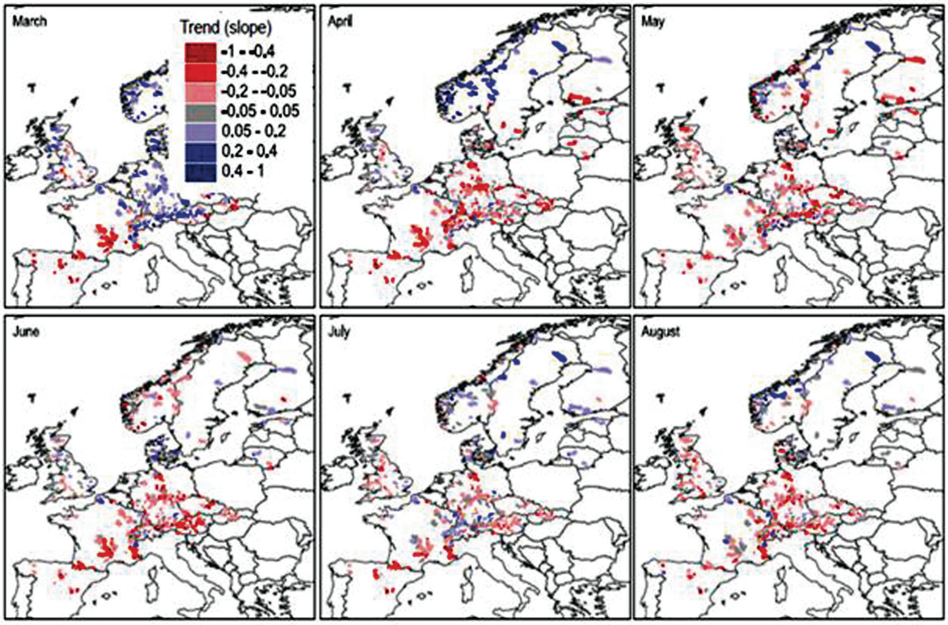


FIGURE 2.3. Trends in monthly streamflow for the period 1962–2004 for selected months (March, April, May, June, July, August) (Stahl et al. 2010)

and groundwater droughts) of the 20th century, it is difficult to unambiguously determine the direction of changes (Lanen van et al. 2007). In the 21th century, droughts have occurred frequently in Europe (2003, 2005–2008, 2010), but these have affected many countries in various climatic zones in some years but have been much more restricted in others., and it is not possible to conclude that droughts have become worse in recent years because studies are influenced by the length of the observation period (Demuth 2009).

According to predictions of future climate, the duration of dry seasons (periods without precipitation or with precipitation significantly below the average value) is expected to increase globally, as is the duration of dry and hot periods, which will accelerate the occurrence of water stress even more due to intensification of evaporation (Kundzewicz et al. 2010). Forecasts of climatic change for Europe in the years 2070–2099, prepared on the basis of results obtained from climatic models using the A2 scenario, indicate a probability of more severe and more common droughts in the future are the following countries: Spain, Portugal, Italy, the northern coast of France, the south coast of Great Britain, and southern Ireland are thought to be particularly threatened by an increasing occurrence of drought (MICE 2005). For Poland, a more frequent occurrence of streamflow droughts, which will lead to water deficits in significant areas of the country, are forecasted to occur by as soon as the first half of the 21th century (Kaczmarek 1997).

Materials and methods

Characteristics of the study area

The Zagożdzonka catchment is situated in the strip of the Central Polish Lowlands in the vicinity of Radom, in the region where, according to Farat et al. (1995), droughts are the most frequent. Zagożdżonka is a left tributary to the Vistula river, and its catchment area at the Płachty Stare gauging station is 82,4 km^2. The average slope of the main streams range from 2,5 to 3,5‰, and their valleys are narrow and shallow (Byczkowski et al. 2001). The catchment of Zagożdżonka has an agricultural character. Almost half of the catchment is composed of arable lands, which occupy 47,5% of the hydrologically active area of the catchment, i.e. the part which contributes to the creation of direct runoff and production of suspended sediment, while forests cover 40,5% of the area, and pastures some 11,5%. Sandy soils are the dominant type of soil (Hejduk and Banasik 2002). For the catchment area, the average annual rainfall determined from the years 1963–2007 is 605 mm, whilst the average for the 6-month summer period is 385 mm, with variation from just over 223 mm in 1988 to 759 mm in 1974 (Kaznowska and Banasik 2009).

Truncation level and drought characteristics

Drought is a period of continuing low stages and low flows in river, caused by long-term shortage of precipitation and intensive evaporation (summer droughts) or long-lasting temperatures below zero (winter droughts). Despite extensive Polish and world literature devoted to this issue, there is no clear definition based on the genesis of the phenomenon. Drought can therefore be defined only by convention (Ozga-Zielińska 1990).

The most commonly used definition is based on the recognition of drought as period of flows equal to, or lower than, the truncation level of drought. A method which consists in extracting drought periods from daily-recorded hydrographs using the assumed truncation value is called in literature the threshold level method (TLM). The method was first adapted for hydrology by Yevjevich (1967), and propagated and developed by hydrologists from the Low Flow group cooperating in the international FRIEND IHP – UNESCO (Flow Regimes from International Experimental and Network Data) project. A result of the cooperation is a publication „Hydrological Drought" edited by Tallaksen and Lanen (2004), which includes a comprehensive review of methods to assess streamflow droughts, which are identified with hydrological drought. The choice of threshold level depends on the purpose of the study. For its determination, hydrological, economic and ecological criteria are used. In the literature, there is a number of values of characteristic flows used to determine droughts, which include SNQ (mean value of the minimum annual flow), WNQ_{let} (maximum value of the minimum summer flow), and $Q_{70\%}$, $Q_{80\%}$ and $Q_{90\%}$ (discharges with a determined probability of occurrence). For the purpose of the study, two discharges were chosen for the threshold level of drought, namely the value $Q_{90\%}$ taken from the flow duration curve, which is 0,087 $m^3 \cdot s^{-1}$ and the SNQ value which is 0,078 $m^3 \cdot s^{-1}$. Both of these values were investigated for the gauging station of Płachty Stare, in a 45-year period (1963–2007).

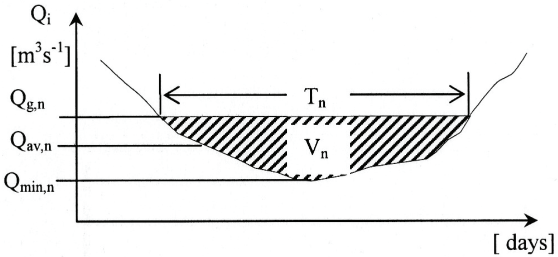
Hisdal et al. (2004) proposed $Q_{90\%}$ as being useful for extracting information on drought from daily hydrographs, whereas SNQ is frequently used for drought assessment on a national scale in Poland (Farat et al. 1995; Mager et al. 2000; Kowalczak 2004; Tomaszewski 2007). However, although there is a long tradition of using SNQ in hydrology, it is still an imperfect characteristic. The value refers practically exclusively to one day, as usually the value of minimal annual flow (NQ) occurs once a year. In agriculture, taking into consideration plant management based on soil moisture character, a single day does not really matter, and it is longer periods without precipitation that are crucial (Byczkowski and Banasik 1993).

As an additional criterion for drought identification from daily hydrographs, a minimum drought length with flows below the threshold values was employed. In Polish studies minimum drought lengths of 1, 5, 10 and 20 days have been used (Zielińska

1964; Farat et al. 1995; Mager et al. 2000; Kowalczak 2004; Kasprzyk 2002 and 2005; Głogowska 2005; Kaznowska and Ciepielowski 2006; Tomaszewski 2007; Tokarczyk 2008).

In order to avoid dependency between two successive droughts, events which were at least 5 days apart from one another were distinguished as separate phenomena (Zelenhasić and Salvai 1987). In isolated cases, this approach was replaced by the method of Kasparek and Nowicky from the Institute of Hydrology, Wallingford (UK), involves separating independent droughts by comparing the size of their deficits with the volumes of outflow above the truncation level between the periods of drought in question.

The input data for streamflow drought assessment were daily hydrographs of flows for hydrological years (from 1 November to 31 October). Droughts were described by the minimum flow, the average flow, and the duration and the volume of water deficit expressed by the area between the hydrograph line and the assumed threshold level (Figure 2.4). The parameters were determined using the Nizowka2003 model (Jakubowski and Radczuk 2004).



T_n – duration of drought [days]
$Q_{g,n}$ – threshold level of drought [in $m^3 \cdot s^{-1}$]
$Q_{min,n}$ – minimum discharge of drought [in $m^3 \cdot s^{-1}$]
$Q_{av,n}$ – av. discharge of drought [in $m^3 \cdot s^{-1}$]
V_n – volume deficit's of drought [thousand m^3]

FIGURE 2.4. Parameters of streamflow drought

To assess the severity of drought in the years 1963–2010, the following characteristics were used:

$$T_{av,n} = \frac{\sum T_{ni}}{\sum n_i} \tag{1}$$

where:

$T_{av,\,n}$ – average duration of drought (days),
n_i – number of droughts occurrences in the study period,
Tn_i – summed number of days, when droughts occurred in the examined period (days).

$$V_{av,n} = \frac{\sum V_{ni}}{\sum n_i} \tag{2}$$

where:
$V_{av,\,n}$ – the average volume of drought deficit (10^3 m^3),
$\sum V_{ni}$ – the sum of drought volumes in the study period (10^3 m^3).

Additionally, characteristics describing maximum values of the analyzed parameters of the particular droughts in the study period were determined:
$T_{\max,\,n}$ – maximum drought duration in the study period (days),
$V_{\max,\,n}$ – maximum volume of drought deficit in the study period (10^3 m^3).

Average drought intensity in the study period was also calculated as the quotient of the volume deficit and the number of days with drought flows (Kasprzyk 2002). This characteristic indicates how much the deficit in the outflow falls for one day of drought.

$$I_{av,n} = \frac{\sum V_{n_i}}{\sum T_{n_i}} \tag{3}$$

where: $I_{av,\,n}$ – average drought intensity (10^3 m^3·day^{-1}).

The value was converted to a percentage of average annual runoff.

Results and discussion

During the period 1963–2010, 33 streamflow droughts were identified for the Zagożdżonka catchment using the *SNQ* value as the threshold, and a further nine droughts were recognized if the $Q_{90\%}$ was used. All of the droughts occurred in the summer half year. A lack of winter droughts has also been identified for other rivers in the Central Polish Lowlands. Studies by Farat et al. (1995), Głogowska (2005), Kaznowska and Ciepielowski (2006), Tomaszewski (2007), in which droughts were identified with a minimum length of 5, 10 or 20 days and were truncated on daily hydrographs with $Q_{90\%}$ or *SNQ* discharge values, have shown that in the second half of the 20th century, no winter droughts were recorded in the Wilga and Ner catchments, whereas in the Bzura, Pilica and Prosna catchments only a small number of such droughts were observed.

The typical period of drought occurrence in the study area according to the Polish Hydrological Atlas (Stachy 1987), lasts from June to August. Similar results were obtained for Zagożdżonka. Months with the highest frequency of drought occurrence are, in order, August, July, June and September. The beginning of the drought period identified with truncation by *SNQ* is usually in July (most cases), June or August, and less frequently May. In the case of droughts defined by $Q_{90\%}$, the drought period begins usually in June, commonly can be earlier in May, or later in July or August. The end of drought periods usually occurs in September or August, but in rare cases, the period of drought lasts longer, for example throughout the first or second half of October, as in: 1964, 1988, 1991 and 2009. In terms of frequency and duration, summer droughts are the dominant type.

In Zagożdżonka, the average duration of drought is 34 and 39 days for the *SNQ* and $Q_{90\%}$ truncation levels, respectively (Table 2.2). Similar results were obtained for other rivers in Central Polish Lowlands (Bzura, Pilica, Warta, Prosna) where average duration of drought in period 1951–1990 was from 30 to 50 days, using *SNQ* as the truncation level with daily hydrographs (Kaznowska, Ciepielowski 2006).

TABLE 2.2. Characteristics of droughts in the Zagożdżonka river at the Płachty Stare gauge in the multi-annual period 1963–2010

Truncation level Q_{gn} ($m^3 \cdot s^{-1}$)	Characteristics of droughts									
	$\sum n_i$	$\sum Tn_i$	$T_{av,\,n}$	$T_{\max,\,n}$	$V_{av,n}$	$V_{\max,\,n}$	$I_{av,\,n}$		$Q_{\min,\,n}$	
	–	dni/days			tys. m^3/th.m^3			%	$m^3 \cdot s^{-1}$	date
$Q_{90\%}$	41	1584	39	151	71	376	1,85	0,021	0,02	30 August 1992
SNQ	32	988	34	141	47	265	1,60	0,018	0,02	30 August 1992

Symbols according to the formulae (1) to (3).

For Zagażdżonka, the length of 30% of all droughts identified by a truncation level of $Q_{90\%}$ is from 10 to 20 days, while 15% of droughts last between 20 and 30 days, and nearly 50% have a duration of over one month (and half of these are longer than two months). For the *SNQ* truncation level, the average duration of drought is shorter (Table 2.2). Duration of almost half of these droughts is between 10 and 20 days (47%), while 38% comprise droughts lasting for over 30 days, and within this group, half are again longer than two months. Droughts of longer than two months were identified in: 1963, 1964, 1983, 1989, 1992, 1994, 2003 and 2008. Except for 1998, these were years when hydrological droughts were recorded extensively within Poland (Table 2.1).

The longest drought in Zagożdżonka lasted for about 150 days. It started at the end of May 1964 and ended in October (Figure 2.5, Table 2.2). The deficit volume was the largest in the whole study period and amounted to 376×10^3 m^3 for the $Q_{90\%}$ truncation level and 265×10^3 m^3 for *SNQ* (Table 2.2). The deficit of drought from 1964 comprised 13% of the sum of all drought deficits identified by threshold level $Q_{90\%}$ and 15% of those identified by the truncation discharge *SNQ* (Figure 2.6).

The deficit of the maximum drought comprised 3–4% of the average annual runoff in the study period. According to Kasprzyk (2002), the largest drought deficits in

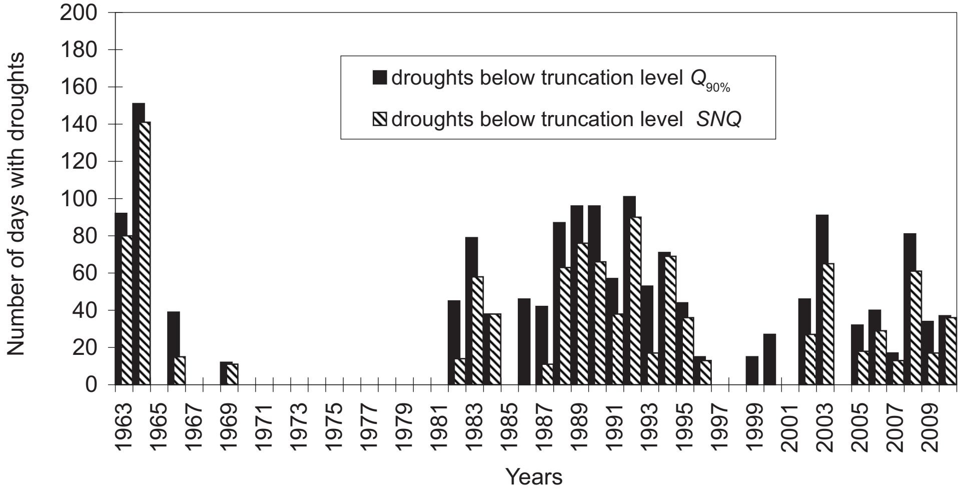


FIGURE 2.5. Number of days with streamflow droughts at the Płachty Stare gauging station in the multi-annual period 1963–2010

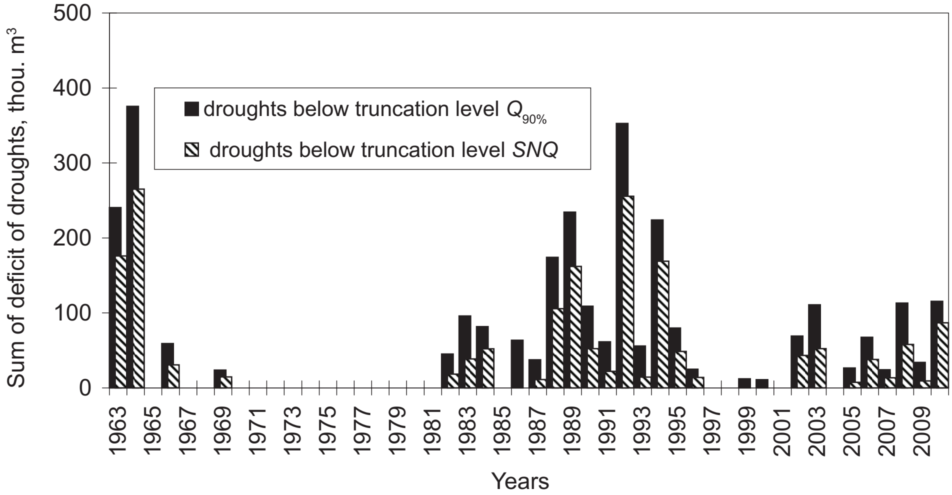


FIGURE 2.6. Deficits of streamflow droughts at the Płachty Stare gauging station in the multi-annual period 1963–2010

relation to average annual runoff in Poland are characteristic of agricultural catchments, particularly those located in the western region of the Mazovian Lowland, as is the case for the Zagożdżonka river.

Drought intensity from 1964, understood as the amount of drought deficit (the volume of runoff) for one day of its duration, was larger than the average drought intensity ($I_{av,n}$) determined for the period of 1963–2010 (Table 2.1). The intensity of drought from 1964 amounted to 1.88 and 2.49 × 10^3 m^3 for truncation levels *SNQ* and $Q_{90\%}$, respectively. However, investigation of drought intensity in Zagożdżonka for the period 1963–2007 (Kaznowska and Banasik, 2009) showed that the drought from 1964, although it lasted the longest and was characterized by the largest volume of water deficit, was not the most intense. Droughts with the highest intensity took place in 1992 and in 1994 (Figure 2.7). In 1992, two droughts occurred. The first had a short duration from the turn of May and June, while the second began at the end of June and ended in September. The sum of drought volume deficit from 1992 was smaller than the volume deficit of the drought from 1964 by only a few percent (Figure 2.6). The average intensity of drought expressed as per cent of average volume of annual runoff was the largest in the study period and amounted to 0,033 and 0,040% for droughts with truncation levels *SNQ* and $Q_{90\%}$, respectively (Figure 2.6). In 1994, one drought was observed, which lasted from the end of June until September for about 70 days, and its intensity was 0,036% for $Q_{90\%}$ and 0,028% for *SNQ* (Figure 2.6). Intensity of droughts from 1992 was about 80% higher than average intensity of those in the period 1951–2010, which was 0,018% and 0,021% for threshold levels *SNQ* and $Q_{90\%}$, respectively for (Table 2.2).

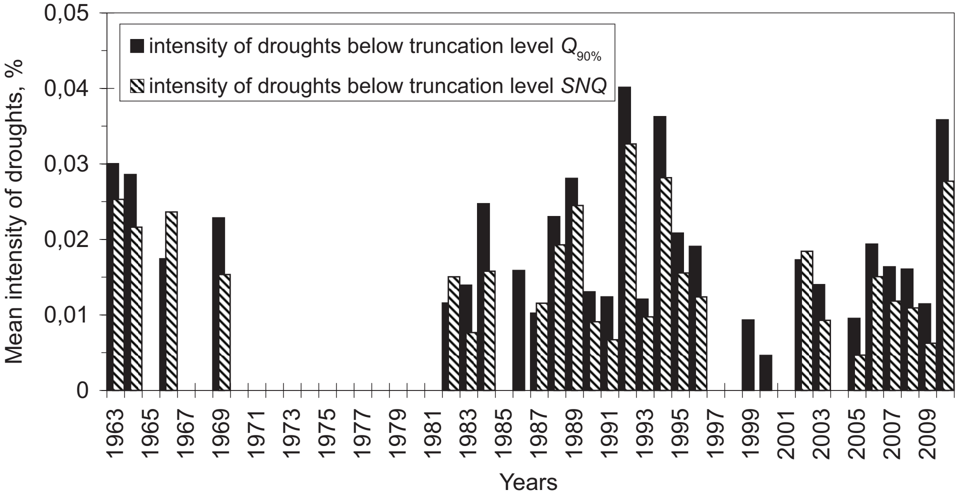


FIGURE 2.7. Mean intensity of streamflow droughts at the Płachty Stare gauging station in the multi-annual period 1963–2010

Also two droughts in July and August of 2010 were characterized by high intensity, which was nearly as high as that in the drought in 1994. The average intensity was 0,028% and 0,035% for the *SNQ* and $Q_{90\%}$ thresholds, respectively (Figure 2.7). Even though the summed length of droughts from 2010 was similar to the average value from the multi-annual period and amounted to 36 and 37 days for the *SNQ* and

$Q_{90\%}$ thresholds, respectively (Figure 2.5), the summed deficit of both droughts was higher than the average value from the multi-annual period ($V_{av,n}$) by 62% and 85%, respectively for drought determined by SNQ and $Q_{90\%}$ threshold levels.

The first drought of 2010 was especially intense and its minimum flow amounted to 0,028 $m^3 \cdot s^{-1}$ on 23 July, and the average discharge during the drought was 0,05 $m^3 \cdot s^{-1}$ and was one of the lowest observed on record. During the drought from June to September 1992, the lowest discharge on record of 0,024 $m^3 \cdot s^{-1}$ was observed on the 30 August. The average discharge in the 1992 drought was 0,04 $m^3 \cdot s^{-1}$ and was also the lowest value recorded in the study period.

Głogowska (2005) obtained very similar results for average drought intensity in the Wilga agricultural catchment, which like the Zagożdżonka catchment is also located in the Mazovian Lowland. In the period 1979–2002, the average drought intensity of the Wilga at the Oziemkówka gauging station was 0,018% using the $Q_{90\%}$ truncation level.

Years with droughts in the Zagożdżonka catchment can be grouped into cycles, including two-year cycles (1963–1964, 1999–2000, 2002–2003), three-year cycles (1982–1984) and many-year cycles (1986–1996 – 10 years, 2005–2010 – 6 years). During 1963–2010, three periods characterized by the occurrence of droughts can be observed (Figures 2.5, 2.6, 2.7). The first is 1963–1969 when the droughts were characterized by declining frequency and intensity. The second is 1982–1996, when droughts occurred nearly every year and reached the highest intensity of the study period and values of the largest deficits are close to the maximum recorded in 1964. In the third period of 2002–2010, droughts occurred in every year except 2004, but deficits and intensities were lower and only summed duration times reached similar values to those of the first two periods. However, 2003 saw a catastrophic hydrological drought in Poland and 2010 had a short but severe and very intensive drought. In 2003, the drought in the Zagożdżonka catchment defined by with the $Q_{90\%}$ and SNQ truncation levels reached deficits of 110,9 × 10^3 m^3 (56% higher than the average deficit of 71 × 10^3 m^3 from the study period) and 52,4 × 10^3 m^3 was higher by only 10% than the study period average of 47 × 10^3 m^3.

Periods of streamflow droughts in the Zagożdżonka catchment were compared by Kaznowska and Banasik (2009) with sums of precipitation in half-year summer periods from 1963–2007. It was found for 1963–1969, when droughts were the largest, dry and average half- year periods were dominant over humid ones. In the period 1982–1996, which had high intensity droughts, precipitation was low and never reached 90% of the annual average precipitation of the summer 6-month period, so that dry and very dry periods were dominant. Drought was absent in the period from 1970 to 1981 which was characterized by wet and very wet summer periods (precipitation reached 110% of that in the average drought from the multi-annual period), with the exception of 1971 and 1979, which were very dry. Kaznowska and Banasik

(2009) have also noted that in the period 2002–2007 droughts did not reach a significant size with respect to intensity and deficit volumes, even though summer precipitation totals were smaller in this period than in 1963, 1992 and 1994 when the largest droughts of the 20th Century were recorded. This was thought to reflect a stronger influence of physical and geographical (retaining capacity of the catchment) than climatic factors on drought occurrence. However, previous studies have varied regarding which factors have the strongest influence on drought, investigating the role of physical and geographical factors in shaping the hydrological. For example, a study by Kasprzyk (2005) of droughts in Central Europe (Poland, Czech Republic, Slovakia) in small and medium-sized catchments (100–600 km^2) suggested the characteristics of the substratum (lithology, water-bearing capacity, retention capacity), affect the degree of drought intensity, but climatic factors (precipitation, water balance) have the dominant influence on drought development. In contrast, Dynowska (1976) stressed the dominant importance of geological structure, compared with climate, through the effect of groundwater recharge in small catchments. During droughts, rivers are recharged only by groundwater and if a catchment is underlain by permeable rocks with significant water-bearing capacity, the degree of river recharge by groundwater will be high. However, Dynowska (1971) also states that climate shapes the frequency of drought occurrence throughout the year, and determines the time of their occurrence by the amount of water that is introduced into the cycle.

Summary

The area of Europe often experiences strong droughts. Research conducted in Poland and in Europe on the basis of historical sources and long-term hydrometeorological observations also highlights their perennial character. According to studies by Lorenc et at. (2008), the period from 1982 to 2006 was characterized in Poland by permanent drought with only two 4–5 –year periods when drought did not occur in the larger part of the country. In the first decade of the 21st century, the drought of 2003 was the most severe and affected one third of the EU area. Water stages in many Polish rivers decreased to historical minima, and the summer in Europe was the warmest on record (Mierkiewicz and Sasim 2005; Demuth 2010).

Further droughts followed in: 2005, 2006, 2007, 2008, 2009 and 2010 in various regions of Europe. Severe droughts and associated forest fires were common in southern and eastern part Europe, especially in the Mediterranean region. According to Kundzewicz et al. (2010), extreme hydrological phenomena, such as droughts and floods, have become more devastating in many regions of the world. In recent years, a sequence of large-scale droughts have been recorded, with much lower than average precipitation and heatwaves, which caused strong evaporation.

Agricultural areas are especially endangered by the occurrence of drought. Currently in Europe, the use of water for agricultural is stable, but at an high level. However, throughout the last two decades the use of water in agriculture in Europe has increased (EEA 2009), making it more vulnerable to droughts and water deficiencies. According to EFA (2009), the increase in drought frequency in southern Europe will cause a decrease in water available for irrigation and may limit agriculture in some regions. In Poland as little as ca. 0,5% of arable land requires irrigation, but a possible increase in water deficit as a result of climate change may strengthen an already increasing trend in irrigation development. This may be the case especially because irrigation in Poland is used as an intervention and as protection against temporary water deficiency (Łabędzki 2006 and 2009).

It is desirable to forecast changes in the intensity of extreme phenomena, such as hydrological and associated streamflow droughts for small catchments with as natural characteristics as possible both in Europe and in Poland. Such catchments should have a relatively long period of hydrometeorological observations and should be representative of definite hydrological regimes and water balances. Analysis of daily hydrographs from the Zagożdżonka catchment in the period 1963–2010 has enabled an assessment of drought in a small agricultural water course of the Mazovian Lowland in the Polish Lowland, an area which, according to Kundzewicz et al. (2010), is especially prone to the occurrence of more frequent and more severe droughts. The analysis has confirmed that hydrological droughts occur here frequently, often forming cycles which last many years. They are typical of the summer period, mostly the months of July and August, and last not much more than a month. The results obtained in the present study are compatible with those found in other investigations of the Mazovian Lowland.

Regarding increases in drought frequency and intensity over recent years, it was noted that from 1982 to 2010, droughts with defined by the $Q_{90\%}$ threshold level occurred in almost every year (except 1985, 1997, 1998, 2001 and 2004). In the first decade of the 21st century, droughts occurred in 2002, 2003 and from 2005 to 2010. However, the duration and scale of deficit in these events did not exceed the average values for the period from 1963–2010, except for the drought in 2003.

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