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Odra River in Lower Silesia: probabilistic analysis of flood risk dynamics as part of sustainable development of water management

1. Introduction

One of the most common natural catastrophes in Poland are, undoubtedly floods. The uneven distribution of time and the areas of precipitation as well as climatic changes are contributing to the more and more often and violent occurrences of the maximum flow of rivers, which increases flood damage. Inadequate land management and the unjustified belief in the effectiveness of technical flood control measures can also contribute to flood damage.

The development of water management, including flood protection, should be carried out in a sustainable way by integrating social, environmental, and economic objectives. In flood protection, those measures that are least invasive to the natural environment should be used first; in particular, non-technical flood protection methods (e.g., flood risk assessment and management as well as the proper definition and management of flood plains). One of the bases for the sustainable development of water management is the preparation of models, which help us calculate the likelihood of maximum flow and identify areas most at risk of flooding. Based on these, the proper spatial policy and prevention of flood effects will be possible.

This article presents a probabilistic analysis carried out for the flood risk dynamics for a selected area of the Odra River basin. The authors based their risk dynamic assessment on the results of the distributions of the maximum values for a selected hydrological characteristic – the flow rate. Based on the daily flow data collected at a hydrological station on the Odra River in Malczyce from the years of 1994–2013, 30-day flow maxima were set individually for four 5-year periods. Then, a probabilistic model of maximum flow was developed based on these peaks for each 5-year period. The resulting models were used to estimate flood risks and for an analysis of the dynamics for the studied area.

2. Floods, their negative consequences, and risk of occurrence

In Poland, one of the most frequently occurring natural catastrophes (both locally and nationally) are floods. Their negative consequences are one of the barriers to economic growth. This barrier has a rather complex character resulting from various conditions and causes. The possibility of floods and the unpredictability of the phenomenon are external causes, which are largely unaffected by human nature. Total flood prevention is not possible. Most often, the size of the event is so large that it cannot be prevented by any available methods. It is not possible to forecast the occurrence of floods well in advance, which would allow for actions to minimize the negative consequences. Accurate forecasting is only possible a few days in advance. It is also believed that the size and frequency of floods will increase due to climate change.

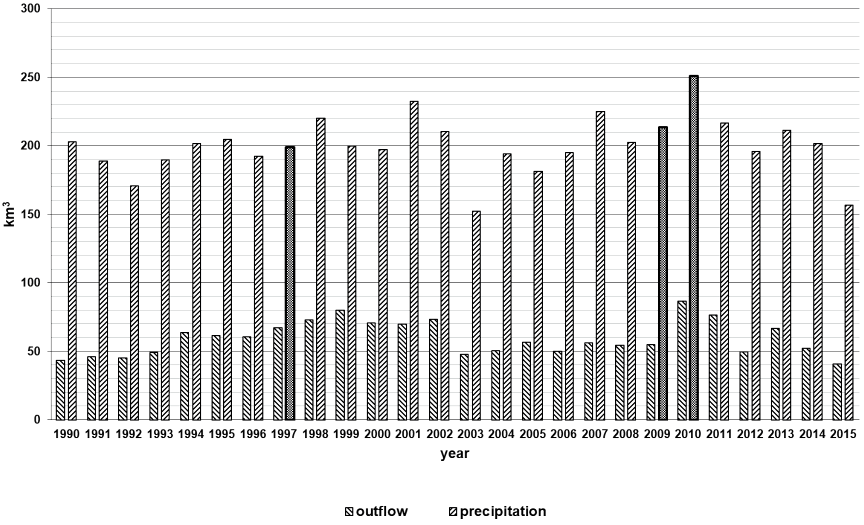

Figure 1. Precipitation and water outflow – 1990–2015

Source: own study based on www.stat.gov.pl

While the total precipitation has not changed significantly (Fig. 1), the number of days with high-intensity (often torrential) floods has increased (Nachabe and Paynter, 2001). According to numerous forecasts, these processes will intensify (Ustawa z dnia 18 lipca 2001...; IPCC 2007), and others. Several times (in 1997, 2010, and 2011), Poland has suffered catastrophic floods, resulting in significant structural and social damage. The losses resulting from the floods in 2010 in Poland totaled 12.5 billion PLN, of which private property losses accounted for nearly 2 billion PLN (Biedroń and Bogańska-Warmuz, 2012).

Human activity also contributes to increasing flood damage. The increasing scarcity of available space leads to increased use of any yet-to-be-developed areas. This shortage may be due to the following:

- landforms – narrow valleys, surrounded by steep slopes,
- flood hazard – floodplains,
- land use restrictions related to special protection areas, such as Natura 2000,
- existing buildings.

It seems that pressure for the further development of floodplains will increase. The development of floodplains may cause catastrophic damage. Particularly vulnerable to damage is the technical infrastructure, such as sewage treatment plants (Halama, 2012).

Not to forget that ecological awareness in Poland is still relatively low, there is also the lack of basic knowledge as well as the legacy of past beliefs and convictions. Due to these, people in Poland widely believe that safety and security issues are primarily in hands of the authorities. There is no obligation for individual insurance, and voluntary insurance is very often not obtained. After a flood, the expectation that the government and/or local authorities will provide compensation for flood damages is widespread.

Risk management is not easy to accept (Yen, 1988); therefore, the introduction and enforcement of land use restrictions of floodplains is rather difficult (Halama, 2013a). Chaotic local spatial planning and the frequent lack of restrictions seem to favor potential investors (Halama, 2016) who plan to develop floodplains.

Another factor contributing to the increase of flood damage is the immense and completely unjustified belief in the effectiveness of the technical methods of flood damage prevention. The lack of understanding that the risk of flooding cannot actually be eliminated is also problematic.

Flooding is generally unpredictable; however, it is possible to estimate flood risk depending on factors such as the following:

- location,
- hydrological conditions,
- terrain relief,
- occurrence of flood types.

According to the literature (Ciepielowski, 1999; Koncepcja przestrzennego zagospodarowania kraju..., 2012), the risk of flooding is high in southern and southwestern Poland (Fig 2). The catchment areas of the upper Vistula and Odra Rivers have often suffered catastrophic floods.

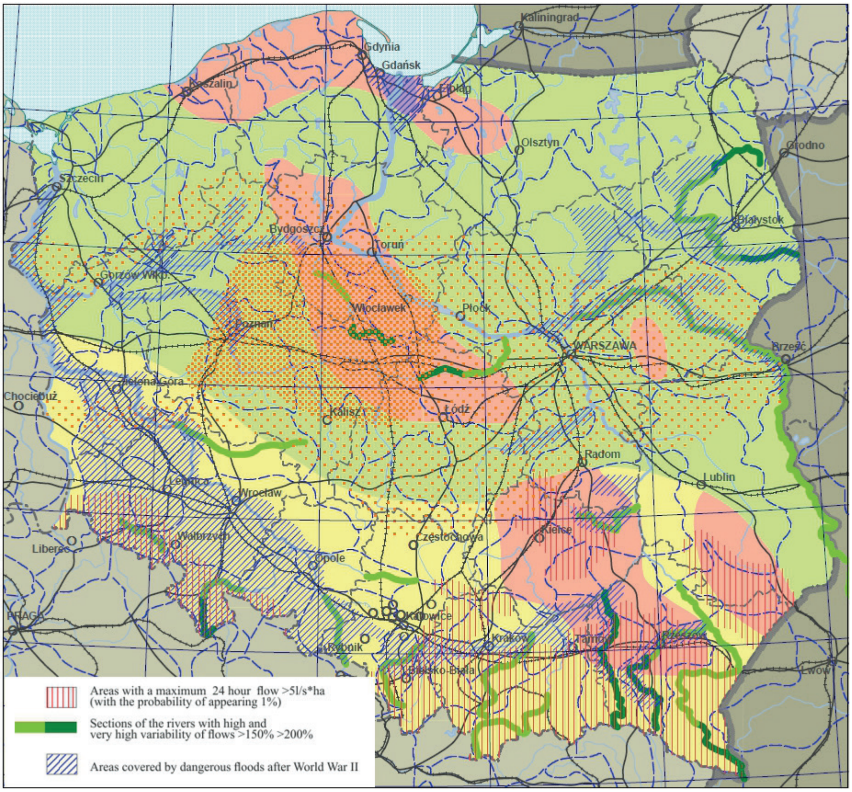

Figure 2. Regionalization of floods in Poland

Source: own study based on [24]

Since the risk of flooding cannot be completely removed, humans can only look to minimize its negative consequences. There are two main solution groups to reduce flood damages:

1. Technical solutions that affect the quantity and speed of surface water flow, such as the following examples:
   - construction of retention reservoirs and dry retention reservoirs,
   - increase of natural retention,
   - construction of flood embankments;
2. Non-technical solutions include the following:
   - flood risk assessment,
   - properly implemented spatial policy, where floodplains are included in local spatial development plans.

At present, the greatest controversies are caused by large-scale investments such as the construction of large retention reservoirs. The significant environmental impact, objections from ecological organizations, and the need for mass expropriation do not support such investments. An alternative to large reservoirs are small retention reservoirs (Halama, 2013b), but their numbers and pace of construction are not sufficient.

In sustainable water management, non-technical methods are slowly becoming the preferred method of flood protection. This is reflected in the legal system and the directions of its changes.

3. Sustainable development of water management

The origins of the policy of sustainable development trace back to the 1980s. The first significant document of international importance in this field was the so-called "Report Bruntland" (then called "Agenda 21"). Others then followed. In simple terms, sustainable development is a socio-economic development that integrates economic, social, and political activities. According to (Lorek, 2002), the aim is to preserve the environmental balance and sustainability of the natural processes and preserve the environment for the present and future generations.

In the many definitions of sustainable development (all cannot be presented here due to the limits of this article), there are a few common terms:

- sustainability – the need to maintain balance between economic growth and environmental protection,
- durability,
- self-sustainability – respect for natural resources makes further development and growth possible.

Sustainable development can also be seen as a set of socially superior objectives; among these, the most important are as follows:

- prosperity (material and social),
- justice,
- safety and security.

In its most developed form, sustainable development (understood as integrated order) is defined as the integration of five orders (Lorek, 2002):

- ecological governance,
- economic order,
- social order,
- spatial order,
- institutional and political order.

Ecological and environmental order is often combined and referred to as environmental-spatial order. This includes issues such as ecological spatial planning and flood protection (as part of water protection).

Sustainable development has also been defined in the Parliament Act of April 27, 2001 (Ustawa z dnia 27 kwietnia 2001 r. Prawo ochrony środowiska) (Uchwała nr 239 Rady Ministrów..., 2012). This should be understood as "such socio-economic development that integrates political, economic, and social activities, preserving the environmental balance and sustainability of basic natural processes". Sustainable development should ensure the ability to meet the basic needs of today's and future generations. The need to comply with the above rules is also stated in Article 5 of the Constitution of the Republic of Poland (as the superior law).

The principles of sustainable development have also been included in water management (which also includes flood protection). In recent years, there have been significant changes in the approach to flood protection caused by the accession of Poland to the European Union and the need to adopt EU law into Polish legislation.

The most important EU Directives whose implementation has caused changes in the approach to flooding protection are as follows:

– Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy (called the "water framework directive"),
– Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks (called the "flood directive").

The most important Polish legal acts regulating the planning and development of floodplains are as follows:

– Ustawa z dnia 18 lipca 2001 r. Prawo wodne (Dz.U., nr 115, poz. 1229, z późn. zmian.): in text "The Water Law Act";
– Ustawa z dnia 27 marca 2003 r. o planowaniu i zagospodarowaniu przestrzennym (Dz.U., nr 80, poz. 717, z późn. zmian.): in text "The Spatial Planning Law Act".

Replacing the traditional flood protection methods, they introduce "flood risk management." Previously, the preferred technical methods such as the construction of flood embankments or retention reservoirs are now being gradually replaced by flood risk management (in particular, in the spatial planning of floodplain areas). It is now required to prepare flood risk maps and maps of those areas at risk of flooding. The Water Law Act (Uchwała nr 239 Rady Ministrów..., 2012) places a greatest emphasis on the spatial development of river valleys or floodplains

[Art. 88k.] as a means of protecting people and property against floods. The technical measures only complement the preferred methods.

In areas with the highest risk of flooding, it is forbidden to perform construction work and other activities that impede flood protection or increase flood risk (e.g., the construction of buildings). Flood risk areas with a probability of 1% and 10% are areas of special flood risk for which the erection of buildings is prohibited (Uchwała nr 239 Rady Ministrów..., 2012).

For flood risk areas, it is required to coordinate the study of the spatial planning conditions and directions[1] (as well as local spatial development plans) with the relevant director of the regional water management board[2].

It is evident that flood damage protection under sustainable water management is presently focused on "moving people away" from water through flood risk assessment and proper local spatial planning. For this purpose, it is necessary to calculate the maximum flow as well as define those areas at risk of flooding.

4. Applications of probabilistic models for extreme values in environmental analysis

The use of statistical models and modeling techniques in determining and identifying environmental hazards is widely used in environmental engineering and is a popular tool for engineering in broad environmental management (Zwoździak, 2017).

The very rich and comprehensive bibliography of the literature on the theory of extreme value distributions and their applications consists of more than 1100 positions counting from the beginning of the 20th century until the beginning of the 21st century. There is no way to present them all, as it would require a separate multi-volume monograph devoted solely to the subject study. The vast amount of literature indicates the great interest in this field of science as well as its wide application; therefore, only selected items will be presented in this chapter that, in the author's opinion, had a significant impact on the development of the theory and are closely related to the issues raised in the article.

The first to use extreme values in studying floods was probably Fuller (Fuller, 1914). The systematic development of a general theory of extreme values, however, is associated with the work of Bortkiewicz, which concerned the distribution range in a random sample from a normally distributed population. This work is very important, since the author introduced and clearly defined the concept of distribution of the highest value for the first time here (Bortkiewicz, 1922).

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[1] Polish "studium uwarunkowań i kierunków zagospodarowania przestrzennego".

[2] Polish "dyrektor regionalnego zarządu gospodarki wodnej".

Gumbel first drew the attention of engineers and statisticians on the possibility of use the formal theory of extreme values for certain distributions that were previously regarded as empirical. He applied the distribution of extreme value to the analysis of streamflow in the US in 1941 (Gumbel, 1941). In the course of his research, Teodorovic acquired the observed frequencies of N(T), meaning the number of days during a period that was T days long when the water flow in the Greenbrier River in West Virginia exceeded 17,000 cubic feet. The period of his observation took 72 years (from 1896 to 1967). He then compared the observed the frequency with theoretical Poisson distributions. In the results, it could be seen that the discrete observations of N(T) for a studied river and a given climate can be very well modeled with Poisson distributions (Todorovic, 1979).

In the 1970s through the 1990s, many papers were written on the subject of applying elements of the extreme value theory to solve problems associated with floods. Pericchi and Rodriguez-Iturbe conducted research based on the data of the daily water flow in the Feather River in Oroville, California, USA. The data collected came from the years of 1902–1960.

From this data, they selected the annual flow peaks and fitted the Gumbel distribution to their empirical distribution. In addition to this, they proposed schedules in their work such as gamma (Person Type III), gamma-log (log – Pearson Type III), and log – normally for the analysis of selected peaks. The use of probability distributions for the flood frequency estimation was also illustrated in Greis and Wood's work (Greis and Wood, 1981). Rossi proposed a two-component extreme value distribution to analyze the frequency of flooding. At the end of the twentieth century (after the great flood that caused huge losses in the US Midwest), Hipel presented the use of extreme value theory in the analysis of flood events in his work. He presented a thorough analysis of emergency levels being exceeded over 100 years in the context of the flood of 1993.

In their article, Katz and His co-authors presented a comprehensive study using the distributions of extreme values on the hydrological data collected in Fort Collins, Colorado, USA (Katz et al., 2002). Engeland, Frigessi, and Hisdal presented the analysis of flood and drought risks using generalized extreme value distributions and Pareto. They conducted their research on data concerning the streamflow of the Ha River in southwest Norway (Engeland et al., 2005). In their work, Bordi and His co-authors analyzed the wet and dry periods in Sicily. For this purpose, they applied monthly rainfall maxima (Bordi et al., 2007). Yurtal et al. compared the method of maximum likelihood in their work to the weighted method of moments for estimating the parameters of the hydrological data distribution probability obtained from measuring stations on the Ceyhan River in southern Turkey (Dogan et al., 2010). After a great number of floods in the Czech Republic, Holičky and Sykora used log-normal distributions and Persona III in their research to estimate the flood risk for cultural heritage sites

(Holický and Sýkora, 2010). Nachabe and Paynter conducted their research using a generalized distribution of extreme values on hydrological data from selected lakes in southwestern Florida (Majewski and Walczykiewicz, 2012). In their studies, Chaibandit and Konyai analyzed the hydrological data obtained on a monthly basis from six stations on the Yom River. The study used the distributions of extreme values, normal distribution, and log-normal distribution as well as the return period method (Chaibandit and Konyai, 2012). In their studies, Arns et al. estimated flood risk by approximating the probability of achieving a certain water level in rivers (Arns et al., 2013). Charon et al. compared a very large number of probability distributions used to model wind speeds. The data came from nine meteorological stations in the United Arab Emirates (Charon, 2015).

One of the co-authors of this study has been conducting research on the probabilistic measurement of flood risk in Lower Silesian rivers since 2010. The results of these studies are presented in the following works: (Kuźmiński, 2012; 2013a; 2013b; 2013c; 2013d; 2013e; 2014).

Since 2015, the authors have been conducting research on the measurement of flood risk dynamics in the rivers of Lower Silesia using selected models of extreme value distributions. The results of these studies are presented in the following publications: (Kuźmiński et al., 2016a; 2016b; 2016c).

4.1. Maxima

We assume that the y_i observations are the maxima, that

$$y_i = \max\{x_{i1}, \ldots, x_{im}\}, \qquad i = 1, \ldots, n, \tag{1}$$

where x_{ij} may not be observable. In the case where x_{ij} are observable, the selection of certain maxima from certain sets *with m* number of elements is a form of selection of the upper extreme values from a data set. This method is called the block method or Gumbel method (Kuźmiński, 2013b).

The block maxima method requires defining the time horizon (the block) and calculating the maxima of the tested variable for the said horizon. Most commonly, blocks of one year, half a year, a quarter year, a month, or a shorter length of time are used depending on the research needs. For data in the form of hydrometric parameters, blocks of the mentioned above size are used. The block size cannot be too small to prevent the occurrence of the relationship between the maximum values of the neighboring blocks of time. A ten-day period is considered to be the minimum limit value of the size of the time block for which the independence of the neighboring maxima can be accepted (Engeland, 2005).

There can also be cases when, during long-lasting floods, the risk of the dependence even between the maxima of adjacent blocks of time may occur. In such situations when such a relationship between the variables under consideration occurs, it is necessary to apply the cumulative distribution of extreme values for dependent random variables for the analysis of the distribution of the maximum values.

At this point, one more fact deserves attention; namely, that observations ***yi*** are the embodiments of random variable M_m defined by the following formula:

$$M_m = \max\{X_1, \ldots, X_m\}. \tag{2}$$

In the studies conducted for the purpose of this article, a 31-day block was used (heretofore referred to as a "monthly block" for simplicity).

4.2. Probabilistic models of maxima values

In the probabilistic studies of maxima distributions for hydrometric data, it is suggested to first apply the Gumbel distribution, which is one of the three types of extreme value distributions (Ustawa z dnia 18 lipca 2001 ...). The 1983 report from the IACWD (US Interagency Advisory Committee on Water Data – Hydrology Subcommittee) recommends the Persona III distribution with the log-normal transformation for long-term data to predict flood events as well as the log-normal distribution.

According to the theorem concerning the types of extreme value distributions, the distributions of extreme values are described by one of three distribution functions from the family of extreme value distribution functions (Kuźmiński, 2013a).

Additionally, if random variable X has distribution function F, then random variable ($\mu + \sigma X$) has the distribution function where μ and $\sigma > 0$ are the parameters of position and scale, respectively. Combining the above two statements results in a very broad family of distribution functions for the extreme value distributions defined by the following formulas:

$$\text{Gumbel (EV0 or Type I)}: \; G_0(x) = \exp\left(-e^{-(x-\mu)/\sigma}\right), \; -\infty < x < \infty, \tag{3}$$

$$\text{Frechet (EV1 or Type II)}: \; G_1(x) = \exp\left(-\left(\frac{x-\mu}{\sigma}\right)^{-\alpha}\right), \text{ for certain } \alpha > 0, x > 0, \tag{4}$$

$$\text{Weibull (EV2 or Type III)}: G_2(x) = \exp\left(-\left(-\left(\frac{x-\mu}{\sigma}\right)\right)^{\alpha}\right), \text{ for certain } \alpha > 0, x \le 0. \tag{5}$$

Broadening the classic family of distribution functions of the extreme value distributions by the parameters of position and scale (as has been done and presented in Models (Biedroń and Bogańska-Warmuz, 2012; Bordi et al., 2007; Bortkiewicz, 1922)) significantly expands the spectrum of possibilities related to the modeling of the maximum value distributions of various random variables. Taking advantage of the parameterized distribution functions of the maximum value distributions, a theoretical distribution function that describes the distribution of the studied value of the maximum characteristic at a very large degree of compliance can be very precisely matched.

In the research that was conducted for this article, a tool in the form of an empirical distribution function was used to visualize the empirical distributions of the maximal values of specific hydrological characteristics.

Estimation methods and tests of significance

To estimate the parameters of the maximum value distributions from the family of distribution functions of the distributions described by Formulas (3), (4), and (5), the maximum likelihood method was applied for the purpose of our research. This method provides effective results in specific cases. These cases concur with the cases considered in (Kotz and Nadarajah, 2005). Parameter γ*estimator* exists for $\gamma > -1$, and for $\gamma > -0.5$, the variance has asymptotically normal distribution.

In order to verify the hypotheses concerning the compatibility of the studied empirical distributions with the selected theoretical distributions of the maximal values described in the paper, the following compliance tests were applied: chi-square, Kolmogorov–Smirnov, and Anderson–Darling tests.

In addition, within the family of distributions of extreme values described by Formulas (3), (4), and (5), the credibility quotient test is used to verify hypothesis H_0: $\gamma = 0$; i.e., that the tested distribution is better-described by the Gumbel distribution against an alternative hypothesis H_1: that the tested distribution is better tested by other distributions of this family. The test statistics for this test are described with the following formula:

$$T_{\mathrm{LR}}(x) = \frac{\prod_{i \le n} g_{\hat{\gamma},\hat{\mu},\hat{\sigma}}(x_i)}{\prod_{i \le n} g_{0,\tilde{\mu},\tilde{\sigma}}(x_i)} \tag{6}$$

from $(\hat{\gamma},\hat{\mu},\hat{\sigma})$ and $(\tilde{\mu},\tilde{\sigma})$ representing the sets of the maximal likelihood estimators in the EV0, EV1, and EV2 models described by Formulas (3), (4), and (5). Since the sets of the parameters are 2- and 3-dimensional, it is known that the test statistics have an asymptotically chi-square with one degree of freedom. Consequently, the *p*-value has the following formula:

$$p_{\mathrm{LR}}(x) = 1 - \chi_1^2(T_{\mathrm{LR}}(x)) \, . \tag{7}$$

The significance level is achieved with higher accuracy using Bartlett's adjustment, which consists of replacing the TLR test statistics with the statistics given by formula TLR / (1+2.8/*n*). In this case, the p-value has the following formula (Kuźmiński, 2013d):

$$p_{\mathrm{LR}}(x) = 1 - \chi_1^2(T_{\mathrm{LR}}(x)/(1+2.8/n)) \tag{8}$$

5. Analysis of flood risk dynamics – experimental

5.1. Hydrological data

In a study conducted for the purpose of this article, one particular hydrometric parameter was used – the flow measured in units of m^3/s (Bajkiewicz-Grabowska and Mikulski, 2011). The daily flow of the Odra River measured at hydrological stations located in Malczyce were collected for the study during the time period from January 1, 1994, through December 31, 2013 (which provides a sample size of $n = 7305$). The time horizon studied was divided into four periods with lengths of five years each: Period I spans the years of 1994–1998; Period II spans the years of 1999–2003; Period III spans the years of 2004–2008; and Period IV spans the years of 2009–2013.

Using the block method described in the previous section, the 30-day maxima were selected from the daily flow. With these assumptions, Formula (1) takes the following form:

$$y_i = \max\{x_{i1}, \ldots, x_{i30}\}, \qquad i = 1, \ldots, 60 \tag{9}$$

for the maxima of the tested data for each of the four periods.

5.2. Theoretical and empirical probabilistic models for maxima

To depict the empirical probability distributions of the 30-day maxima from the four studied periods, a commonly used tool in the form of an empirical distribution function was used. Additionally, the chart of the empirical distribution function for each period includes a distribution function of an optimally matched distribution of the theoretical maxima. These graphs are shown in Figure 1.

In the data from Period I (1994 through 1998), there is one maximum – $q_{\mathrm{VII},97} = 3020\ m^3/s$; this is from July 1997, when the historical flood of the Odra River basin took place. In the graph shown in Figure 3 for Period I, there is an empirical distribution function shown (which was removed without this observation). For comparison, Figure 4 shows a graph of an empirical distribution function for the data from Period I, including all of the maxima with the optimally matched theoretical distribution function.

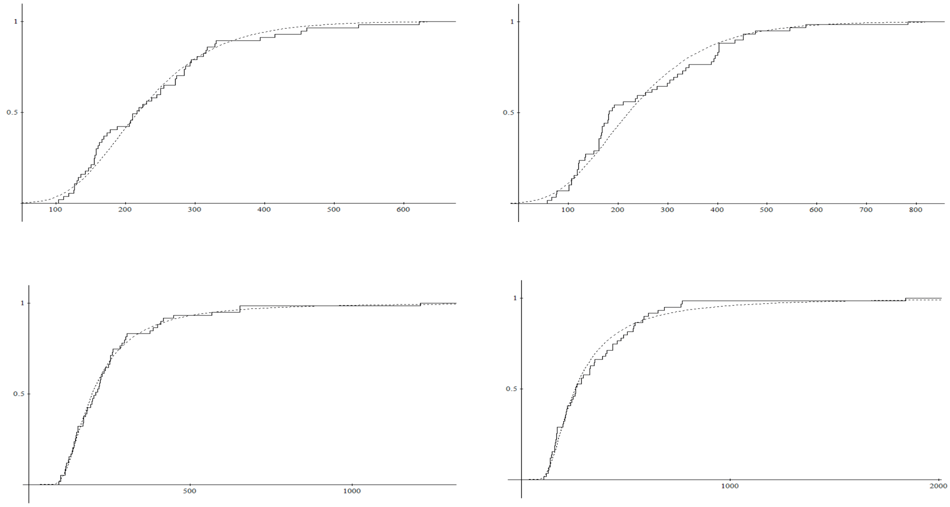

Figure 3. Empirical distribution functions of 30-day flow maxima distributions for data from Malczyce for Periods I-IV (solid line) and distribution functions for theoretical maxima distributions (dotted line). Period I – chart in upper left corner; Period II – chart in upper right corner; Period III – chart in bottom left corner; and Period IV – chart in lower right corner

Source: own materials

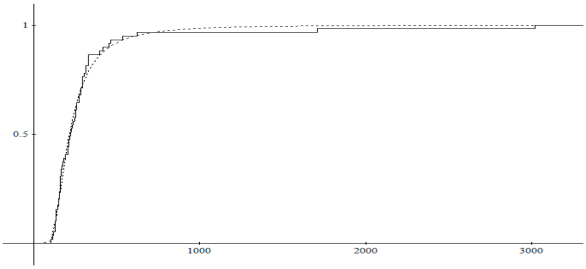

Fig. 4. Empirical distribution function of maxima distributions for Period I, including data from July 1997 (solid line) and distribution function of theoretical distribution

Source: own materials

By using the highest likelihood method, the parameters of the theoretical distributions optimally suited to the empirical distributions of the studied maxima for the four periods were estimated. In the case of Period I, the maxima distribution parameters excluding and including the observation of the $q_{\mathrm{VII},97} = 3020\ \mathrm{m^3/s}$ maximum were estimated (Tab. 1).

Table 1

Values of estimators of theoretical distribution parameters for flow maxima for studied periods

Periods	**Estimator values**
1994–1998 (excluding $q_{\mathrm{VII},\ 97}$)	$\hat{\mu}_I = 190.5 \quad \hat{\sigma}_I = 74.3$
1994–1998 (including $q_{\mathrm{VII},\ 97}$)	$\hat{\mu}_I = 0 \quad \hat{\sigma}_I = 183.5 \quad \alpha = 2.463$
1999–2003	$\hat{\mu}_{II} = 182.85 \quad \hat{\sigma}_{II} = 105.42$
2004–2008	$\hat{\mu}_I = 0 \quad \hat{\sigma}_I = 129.1 \quad \alpha = 2.824$
2009–2013	$\hat{\mu}_I = 0 \quad \hat{\sigma}_I = 215.2 \quad \alpha = 2.04$

Source: own materials

In the cases of Period I (excluding the $q_{\mathrm{VII},97}$ maximum observation) and Period II (the Gumbel distribution), the distribution function described by Formula (3) turned out to be the optimally suited distribution for the empirical distribution of the 30-day flow maxima. For Period I (including the $q_{\mathrm{VII},97}$ maximum observation) as well as Periods III and IV (Frechet distribution), the distribution function described by Formula: (4) turned out to be the optimally suited distribution.

The charts of the empirical distribution functions of the studied maxima for the periods under consideration along with the theoretical distribution functions of the respective distributions indicate the very good fit of the theoretical distributions (Figs. 1 and 2). In order to confirm the goodness of fit of the empirical distributions with the matched theoretical distributions resulting from a visual assessment of the given distribution function graphs, the following commonly used goodness of fit tests were performed: the Anderson–Darling and Kolmogorov–Smirnov tests. The results of the tests for the distribution in all of the analyzed periods in the form of the *p-value* shown in Table 2 confirm the very high goodness of fit of the chosen theoretical distributions with the corresponding empirical distributions.

Table 2

p-value values of compatibility tests for maxima distributions

Period	Test	
	KS	**A – D**
1994–1998 (excluding qVII, 97)	$p_v = 0.6208$	$p_v = 0.7998$
1994–1998 (including qVII, 97)	$p_v = 0.763$	$p_v = 0.8429$
1999–2003	$p_v = 0.6271$	$p_v = 0.5849$
2004–2008	$p_v = 0.9776$	$p_v = 0.9918$
2009–2013	$p_v = 0.6208$	$p_v = 0.7998$

Source: own materials

In addition, to confirm the validity of choosing the appropriate distributions of extreme values for the respective studied periods, a likelihood ratio test within the family of distributions of extreme values described with Formulas (3) through (5) was conducted (which was described in Section 3.4). The values of *p-value* calculated from Formula (8) are presented in the following table (Tab. 3).

Table 3

p-value values for likelihood ratio test in family for family of extreme value distributions

Periods	*p-value*
1994–1998 (excluding qVII, 97)	$p_v = 0.128$
1994–1998 (including qVII, 97)	$p_v = 0.000$
1999–2003	$p_v = 0.115$
2004–2008	p_v=0.000
2009–2013	$p_{v\,=}$ 0.000

Source: own materials

5.3. Risk assessment of flood risk during analyzed periods

This section consists of two main parts. In the first part, the flood risk measures will be calculated during the studied periods. The second part of the section contains an analysis of the dynamics of the examined risk.

Defining the concept of risk proves to be difficult each and every time; providing a clear and precise definition is impossible. Risk is defined on the basis of various branches of knowledge and theories, including economics, behavioral sciences, legal sciences, psychology, statistics, insurance, probability theory, and others. According to the authors, the following two definitions of risk are most suitable for determining flood risk: the first treats risk as the possibility or likelihood of loss (e.g., due to flooding (Jedynak, 2001), while the second assumes the risk to be the probability of a system failure or the failure of its p_f element, which may be equated with the flooding in particular cases (Ustawa z dnia 27 marca 2003...).

In this paper, the probability of exceeding a certain water flow level (q) by the maximal daily water flow from the time horizon assumed in the study was adopted as the measure of flood risk in the studied area based on the aforementioned two definitions. A time horizon of 30 days was chosen for the purpose of this study.

To measure the risk measure, the maximal water flow from the June 2010 flood (namely, $q_{VI,2010}$ = 1840 m^3/s) was chosen.

According to Formula (2), the maximum 30-day flow is a random variable denoted by $M30$. Table 4 presents the results of the calculations of the risk measures constituting the probability to exceed flow $q_{VI,2010}$ by random variable M_{30} for all of the studied periods.

Table 4

Measures of flood risk for Odra River in Malczyce

Periods	**Risk measure**		
	$P(M_{30} > q_{VI,2010})$	**dynamics indexes** $\mathbf{I_{t/t-1}}$	**percentile changes +/–**
1994–1998 (excluding qVII, 97)	0.0000002	–	–
1994–1998 (including qVII, 97)	0.003414655	–	–
II: 1999–2003	0.000001490	7.45	645
III: 2004–2008	0.000551176	369.1	3691
IV: 2009–2013	0.012475177	22.63	2163

Source: own materials

Additionally, Table 4 contains the indexes of the dynamics of changes in the flood risk over the period of 1994–2013. The results clearly show a strong upward trend of the risk. The flood risk during Period II increased by as much as 645% as compared to Period I; during Period III, it increased by 3691% in relation to Period II; and during Period IV, it increased by 2163% as compared to Period III.

6. Conclusions

Poland's water resources are characterized by uneven temporal and spatial distribution. In addition, climate change has contributed to the increasing occurrence of maximum flow in rivers. Inadequate land management and the unjustified belief in the effectiveness of technical flood control measures can contribute to flood damage. Sustainable water management should be implemented through the integration of social, environmental, and economic objectives.

The factors described in this paper include environmental protection requirements, while the appropriate planning serves to program and coordinate actions to achieve or maintain at least a good ecological status through the continuous improvement of environmental resources, taking into account measures to reduce flood risk in the Odra River basin. Sustainable development is, therefore, a set of orders such as natural, socio-demographic, economic, and spatial.

The activities aimed at achieving ecological and economic effectiveness apply when choosing the methodology of implementing planned environmental protection and flood risk management projects.

Flood protection measures should primarily use solutions that are least invasive to the natural environment, especially non-technical flood protection methods (e.g., flood risk assessment and management, the appropriate flood planning, and development). Undoubtedly, the basis for planning in water management is the preparation of models and, subsequently, determining the probability of the occurrence of maximum flow.

Three action instruments can create an integrated a flood safety system:

- investment engineering,
- economic engineering,
- financial engineering.

Investment engineering is not the only recipe for flood safety, as integrated investment, economic, and financial approaches altogether give a sense of security to the public in areas directly affected by floods as well as the adjacent areas. By applying a risk measure in the form of the probability of flood hazard, the interdependence between sustainable development and economic interest is taken into account.

The use of flood risk models can be similar to a classic cash flow strategy, using derivative instruments such as loans, subsidies, setting interest rates on loans, and insurance.

Using a probabilistic risk assessment, soft behavior can be followed by social behavior training to minimize flood damage.

The analysis of historical data based on the years of catastrophic flooding is not a measure or forecast related to the occurrence of subsequent floods. Using risk as a tool gives us the ability to plan anti-flood activities and, at the same time, allows us to secure the financial resources for liquidation. It is possible to plan the construction of adequate flood protection infrastructure in both hard and soft operations.

Probabilistic models of the maximum values for selected hydrological characteristics (maximum daily flow and daily water status) provide an effective tool for supporting the entire flood risk management process in the context of socio-economic consequences. Extreme value models were widely used for flood risk measurement and evaluation in the 20th century and still are in the 21st century (Fuller, 1914), (Todorovic, 1979), (Holický and Sýkora, 2010), and (Arns et al., 2013).

On the basis of selected probabilistic models, the flood risk measures in the form of the probability of exceeding certain values were calculated by the hydrological characteristics of Q (in m^3/s). Using the obtained risk measures in the four analyzed periods, its dynamics were analyzed. The results showed a very strong upward trend of this risk.n

Additionally, to illustrate the influence of the maximum flow of July 1997 (the historical flood date in Poland; i.e., qVII, 1997 = 1840 m^3/s for Period I), the risk measure was calculated based on a model whose parameters were estimated without observing the maximum of 1997. The same measure was calculated on the basis of a model estimated on the basis of a complete data set. Significant differences in the results shown in Table 4 show how the extreme observations exert on the model. In the flood risk dynamics analysis, the result obtained from the model without qVII 1997 was taken.

The widespread multidimensional flood models used in the United States and Europe are characterized by large computational space and extended analyses of the results. On the other hand, using a probabilistic measure of risk is undoubtedly a complement to global analyses and directions of flood control. Not only do both models complement each other, they can also be calibrated for data quality.

Reinforcing flood risk management plans and flood hazard maps into tools in the form of probabilistic flood risk measurements will allow for extensive spatial and temporal planning.

The analysis of risk dynamics allows for the timely updating of the planning documents described above.

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