

Effects of record extension and statistical methods on dam reliability – insights from the Stronie Śląskie failure

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Abstract: This paper investigates the effects of methodological choices and the extension of hydrological records on extreme discharge estimates and dam safety, drawing on the 2024 failure of the century-old Stronie Śląskie dam in Poland. It is based on long-term precipitation and discharge records from eight precipitation and seven gauging stations in the Biała Łądecka River basin (in the Sudetes Mountains) and neighbouring catchments. To isolate the effects of record extension, three periods ending in 1984, 2023 and 2024 are analysed. The series were tested for homogeneity, independence, stationarity and trends using a set of non-parametric tests. Extreme-value distributions were fitted by maximum likelihood following two sets of Polish guidelines (including the so-called event alternative method). Discharges at the ungauged dam cross-section were estimated by regional regression and extrapolation. No statistically significant monotonic trends were detected in hydrological data. Nevertheless, extending the series – by 40 years or by a single flood event – led to substantial increases in design discharge for low exceedance probabilities, and wider confidence intervals. The choice of probability distribution can change control flood estimates several-fold and shift the dam's overtopping probability from levels typical of high-consequence structures to those below the lowest reliability class. The results indicate that periodic hydrological re-evaluation of existing dams is essential and that clearly defined methods for estimating extreme flows are needed to establish consistent safety targets and responsibilities and prompt timely spillway upgrades.

Keywords: 2024 flood, dam reliability, design flood, hydrological trends, statistical methods, Stronie Śląskie dam failure

INTRODUCTION

The design of hydraulic structures and flood protection measures requires estimates of annual maximum discharge at a specified exceedance probability ($Q_{\max,p}$) and, in some cases, annual maximum daily precipitation ($P_{\max,p}$). For dams and levees, $Q_{\max,p}$ is a key parameter in assessing hydraulic safety, particularly overtopping risk. In the case of earth embankments, overtopping is usually equivalent to failure, which is the likely mechanism of the 2024 failure at Stronie Śląskie, Poland. Design discharges for hydraulic structures in Poland are determined for the probabilities specified in the Regulation of the Minister for the Environment of 20 April 2007 (Rozporządzenie, 2007). The first nationwide guidelines describing the $Q_{\max,p}$ calculation methods entered into force in 1968 (CUGW, 1967). However, at present, Poland has no uniform, coherent regulations in this area, and there is no consensus on which of the competing methods is most appropriate (Węglarczyk, 2015).

A methodology for estimating $Q_{\max,p}$ (Banasik *et al.*, 2020) was prepared specifically for the flood risk management plans (FRMPs) required under the Floods Directive (Directive, 2007). The FRMPs include flood hazard maps for dam-failure scenarios, currently covering 26 large reservoirs in Poland and updated every six years. For this relatively small group of dams, the Floods Directive, rather than technical or construction regulations, requires periodic reassessment of some aspects of failure risk. Other structures are not subject to such requirements, and there is therefore essentially no legal basis for regular assessment of their hydraulic safety. At the same time, the internal guidelines of the Technical Dam Control Centre (Pol.: Centrum Technicznej Kontroli Zapór IMGW-PIB) on dam-condition assessment (Sieński and Śliwiński, 2020, p. 11) state that “periodic verification of the adopted design flood discharges is required and, where necessary, modification of reservoir operation rules or modification of outlets and spillways”. The Centre is statutorily responsible for state-owned damming structures in importance classes I and II.

The evolution of flood risk over time has become a topic of public debate, especially after major floods and dam failures. International experience shows that dam safety is affected by ageing infrastructure, land development and climate change. Over the last century, approximately 30% of all dam failures were due to overtopping, while the proportion of dam failures during floods exceeding design levels has risen in recent decades (Lompi *et al.*, 2023; Hou *et al.*, 2024). Many dams were designed under the assumption of stationarity and for much lower levels of exposure. For example, in Canada, approximately half of all dams are over 50 years old, and seven of the ten most costly floods recorded between 1980 and 2019 occurred after 2010 (Islam *et al.*, 2024). Projected increases in extreme precipitation suggest that future spillway capacity may be underestimated, even in regions where no clear signal of change is detectable so far (Lompi *et al.*, 2023). Urbanisation and population growth have increased both the consequences of floods and the hydraulic loads on downstream structures, while conventional stationary approaches to design-flood estimation are being challenged (Xie *et al.*, 2021).

This paper aims to illustrate, from an engineering perspective, how both the safety of hydraulic structures and perceptions of that safety are affected by: (1) the choice of method for estimating $Q_{\max,p}$ and (2) the extension of measurement records and possible trends in hydrological data. To this end, a case study of the Stronie Śląskie dam and its neighbouring catchments is presented. On 15 September 2024, the dam failed during a record flood on the Morawka River, as described by Radzicki *et al.* (2025). The results are interpreted within the regulatory framework of Polish hydraulic engineering. Their implications for the design, operation, and safety assessment of existing dams and levees are discussed.

After a disaster, discussion often turns to negligence, errors or inevitability. Such hindsight bias can oversimplify complex failures. This paper instead asks: “What lessons can be drawn from the Stronie Śląskie disaster for assessing the hydraulic safety of dams and levees?”

MATERIALS AND METHODS

HYDROLOGICAL DATA

The analysis includes annual maximum daily precipitation and annual peak discharges from selected stations of the Institute of Meteorology and Water Management (IMGW) in Poland (IMGW-PIB, no date a; IMGW-PIB, no date b) – Figure 1. Data from the Czech Raškov gauging station were also included (average daily flows in that case; GRDC, 2025).

Three time frames were defined: from the start of measurements to 1984, 2023 and 2024. The first two allow changes over approximately 40 years to be assessed, while the 2024 series shows the effect of a single extreme event on the analysis. Missing discharge data from the Łądek-Zdrój station for 1961–1970 were infilled using a regression relationship with the Żelazno station. Some series do not meet the minimum sample-size requirement ($N \geq 30$). They were retained because they are not central to the analysis, although their quantitative representativeness is limited.

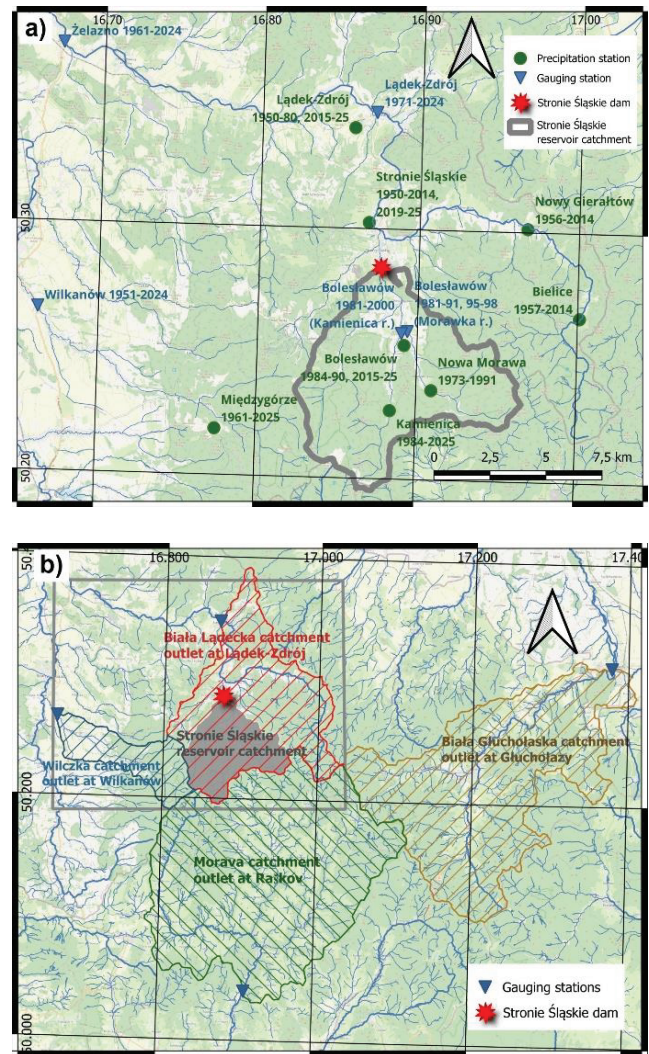


Fig. 1. Map of the Stronie Śląskie reservoir catchment and its neighbourhood: a) relevant gauging and precipitation stations, showing their periods of operation, b) boundaries of analysed catchments; source: own elaboration based on Mapa Hydro (IMGW-PIB, no date c) for station locations and OpenStreetMap for the base map

STATISTICAL METHODS

Various methods can be used to estimate annual maximum discharges ($Q_{\max,p}$) and annual maximum daily precipitation ($P_{\max,p}$) with a specified exceedance probability (p). The analysis draws on two Polish documents: the guidelines of the National Water Management Authority (KZGW) for the FRMPs (Banasik *et al.*, 2020), hereafter the “KZGW guidelines”, and the 1999 IMGW document (Ozga-Zielińska, Brzeziński and Ozga-Zieliński, 1999), hereafter the “IMGW guidelines”. These two documents differ in several respects, including the recommended probability distributions, homogeneity and stationarity tests, and goodness-of-fit tests. The methods comprise statistical frequency analysis and regional formulae. The IMGW guidelines require splitting the flood series into two genetic types: snowmelt (winter, December–March) and rainfall (summer); this approach is therefore termed the event alternative method.

The homogeneity of the measurement series was tested using the Mann–Kendall test (significance level $\alpha = 0.05$), in line with the KZGW guidelines. In accordance with the IMGW

guidelines, the Grubbs–Beck test was used to detect outliers ($\alpha = 0.10$); the runs test assessed independence ($\alpha = 0.05$); the Kruskal–Wallis rank-sum test assessed stationarity ($\alpha = 0.05$); and Spearman’s rank correlation coefficient assessed trends in the mean and variance ($\alpha = 0.05$). Trend line slopes were estimated using Theil–Sen linear regression, which is insensitive to outliers, and expressed as changes relative to the long-term mean.

$P_{\max,p}$ was estimated by assuming a log-normal distribution and assessed using the Kolmogorov λ_K test ($\alpha = 0.05$), in line with KZGW guidelines. Under the same guidelines, $Q_{\max,p}$ was estimated using Pearson III (recommended), log-normal, and Weibull distributions, verified with the λ_K test – an approach largely unchanged since 1967. For ungauged catchments, a regional regression equation and extrapolation are recommended.

The IMGW guidelines permit four distribution types for $Q_{\max,p}$: gamma, log-normal, Weibull, and log-gamma. The lower bound is varied and selected using the minimum Kolmogorov distance criterion. Fit is checked using Pearson’s χ^2 test ($\alpha = 0.05$), and the best-fitting distribution is selected using the Akaike information criterion.

Distribution parameters were estimated by maximum likelihood in each case. In the $Q_{\max,p}$ and $P_{\max,p}$ analyses, the upper bound of the 84% one-sided confidence interval was determined.

HYDROLOGICAL ANALYSES AT THE STRONIE ŚLĄSKIE DAM

The $P_{\max,p}$ analyses used mean rainfall in the Stronie Śląskie reservoir catchment (Thiessen polygon method). Estimates of $Q_{\max,p}$ were made using indirect methods, as the catchment is ungauged. The first approach extrapolated from the Łądek-Zdrój gauge (Eq. 4.10, KZGW guidelines, Banasik *et al.*, 2020, p. 67). The catchment-area ratio requirement was not met, although the catchments have similar shapes and land cover. The second method, considered most appropriate under the KZGW guidelines (Eq. 5.9, Banasik *et al.*, 2020, p. 82), uses the regional regression equation. In this approach, $Q_{\max,1\%}$ depends on $P_{\max,1\%}$, while the remaining quantiles are derived from a Pearson III distribution. The parameters and their sources are listed in Supplementary Table S1.

From the fitted $Q_{\max,p}$ distributions, the design (Q_d) and control discharge (Q_c) were estimated in compliance with the Regulation of the Minister for the Environment of 20 April 2007 (Rozporządzenie, 2007), assuming that the Stronie Śląskie dam belonged to importance class III (PGWWP, 2024). Interestingly, the recommended exceedance probabilities p have not changed since 1967 (CUGW, 1967). Available sources were used to estimate the “critical” discharge (Q_{crit}), defined as the discharge leading to overtopping and failure. This estimate relies on simplifying assumptions, such as neglecting the reservoir’s flood attenuation. The exceedance probability of Q_{crit} was then calculated.

RESULTS

VERIFICATION OF MEASUREMENT SERIES

The results of the verification of the data series are provided in Tables S2 and S3. Five stations showed an increasing tendency in annual maximum daily precipitation ($P_{\max}$), while three showed

a decreasing tendency. In the Stronie Śląskie reservoir catchment, the trend was slightly upward. However, none of the trends was statistically significant – the time series are considered homogeneous. The tests did not indicate a significant change in precipitation patterns over time. In one case (Bielice), the runs test indicated a clustering of dry or wet years. At some stations, precipitation values in 1997 and 2024 are statistical outliers – with very low probability of occurrence. These observations require careful assessment because they strongly affect distribution fitting.

Among the seven stations, five showed a decreasing trend in annual maximum discharges ($Q_{\max}$), while the only increasing trend was found in a very short series. None of these trends was statistically significant. Data from the Łądek-Zdrój gauging station, used extensively in the following sections, had a Theil–Sen regression slope of effectively zero.

Discharge values are influenced not only by precipitation magnitude but also by its spatial and temporal distribution, hydraulic infrastructure and catchment land use. Snowmelt flows are less directly linked to high daily precipitation totals, as they depend on snow cover and air temperature as well. Because climate change disproportionately affects winter weather in Poland, a shift might be expected in the snowmelt series. The tests, however, did not identify a statistically significant change.

Some test results indicate non-randomness (runs and rank-sum tests), suggesting that in some series low or high discharges may cluster during dry and wet periods (particularly at the Wilkanów station, possibly due to the upstream Międzygórze dam). Overall, the measurement series in the region show no statistically significant heterogeneity or non-stationarity, including those from the Łądek-Zdrój station. The watercourses analysed are typical mountain streams, with rainfall floods clearly dominant over snowmelt floods.

The subsequent analysis requires a representative discharge at Łądek-Zdrój during the 2024 flood. The post-failure peak, estimated at more than $1,000 \text{ m}^3 \cdot \text{s}^{-1}$ (Kledyński, 2025), cannot be used for this purpose. The flow rate prior to the disaster was analysed by Stodolak and Bednarek (2025). They reported that the water level of the Biała Łądecka stream at Łądek-Zdrój in 2024 was about 15 cm higher than in 1997 (380 and 365 cm, respectively), with a discharge of approximately $460 \text{ m}^3 \cdot \text{s}^{-1}$ ($425 \text{ m}^3 \cdot \text{s}^{-1}$ in 1997). A discharge of $455 \text{ m}^3 \cdot \text{s}^{-1}$ was reported by Kledyński (2025) and Radzicki (2025) and was adopted here. By contrast, official data indicate $675 \text{ m}^3 \cdot \text{s}^{-1}$ and a water level of 515 cm, but the basis of these figures and whether they refer to conditions before or after the dam failure are unclear.

ANNUAL MAXIMUM DAILY PRECIPITATION

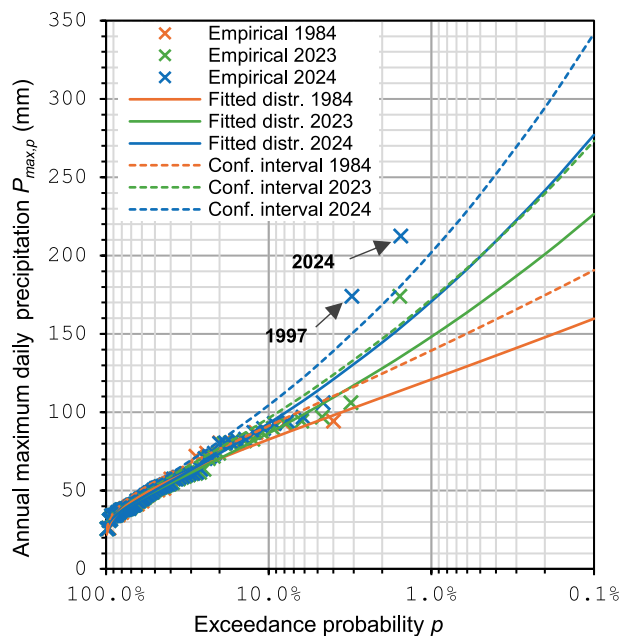
Selected $P_{\max,p}$ estimates are listed in Table 1, and the $P_{\max,p}$ curves for the Stronie Śląskie reservoir catchment are shown in Figure 2. Further results are available in Table S4.

Between 1984 and 2023, $P_{\max,p}$ increased at four of the five stations and decreased at one. The increase in annual maximum daily precipitation ranged from 6% (Nowy Gierałtów) to 38% (Stronie Śląskie), and by 23% in the reservoir catchment area. Adding the extreme year 2024 to the series increased $P_{\max,1\%}$ in the Stronie reservoir catchment by 15% and at the Kamienica

Table 1. Estimates of annual maximum daily precipitation ($P_{\max,p}$) for measurement series covering different years

Station	Until year	$P_{\max,p}$ precipitation (mm) of probability p		
		10%	5%	1%
Kamienica	2023	90.1	108.6	158.1
	2024	101.6	127.6	202.6
Międzygórze	1984	82.6	98.8	142.4
	2023	90.4	115.2	191.9
	2024	93.7	120.5	203.6
Stronie Śląskie	1984	74.8	80.7	91.4
	2023	83.4	96.2	125.7
	2024	85.4	98.8	129.8
Stronie Śląskie reservoir catchment	1984	82.6	94.4	120.9
	2023	86.6	103.7	148.2
	2024	92.9	113.8	170.7

Source: own study.

**Fig. 2.** Annual maximum daily precipitation ($P_{\max,p}$) curves for the Stronie Śląskie reservoir catchment; conf. = confidence; source: own study

station by as much as 28%, where a record daily total of 254 mm was recorded in 2024. The fitted log-normal distributions visually matched the empirical distributions, except for the two outliers (years 1997, 2024). The Kolmogorov test did not reject any of the $P_{\max,p}$ distributions.

The analysis shows the strong influence of extreme events on the distribution at low probability levels. The reliability of these measurements, obtained under particularly difficult field conditions, is critical. Based on projections from 2023, the precipitation value in the reservoir catchment in September 2024 (212 mm) corresponds to a probability of $p \approx 0.14\%$. Including the 2024 data raised this probability to $p \approx 0.38\%$.

ANNUAL MAXIMUM DISCHARGES

The empirical distribution of $Q_{\max,p}$ in Łądek-Zdrój (up to 2023), alongside various fitted $Q_{\max,p}$ distributions, is shown in Figure 3. The IMGW guidelines result in a hybrid distribution; however, for simplicity, only the distribution name corresponding to rainfall floods is given here, as rainfall floods clearly dominate at low p values. Table 2 presents the results according to

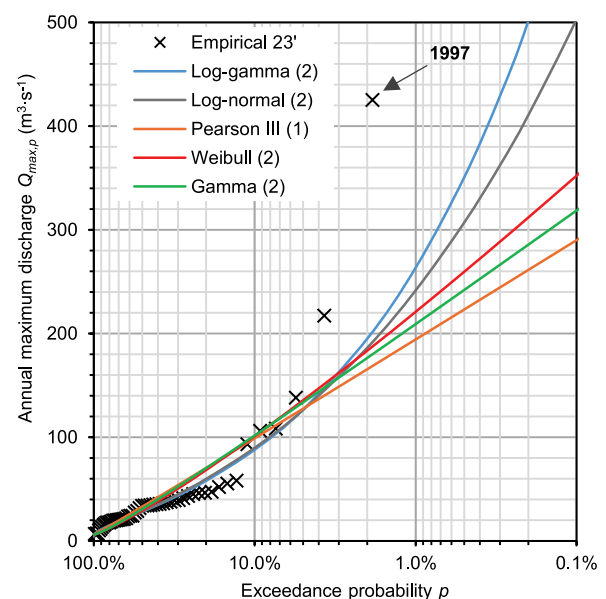
Table 2. Estimates of annual maximum discharge ($Q_{\max,p}$) for series covering different years, IMGW guidelines

Station	Until year	Distribution type	$Q_{\max,p}$ ($\text{m}^3 \cdot \text{s}^{-1}$) of probability p		
			1%	0.5%	0.1%
Głucholazy	1984	G	337	388	506
	2023	LN	529	704	1,273
	2024	LG	843	1,282	3,237
Łądek-Zdrój	1984	LG	159	195	304
	2023	LG	264	351	649
	2024	LG	382	542	1,167
Wilkanów	1984	G	41	49	79
	2023	LG	65	92	196
	2024	LG	91	137	338
Żelazno	1984	G	291	339	451
	2023	LN	457	623	1,183
	2024	LG	790	1,279	3,777
Stronie Śląskie ¹⁾	1984	LG	75	92	143
	2023	LG	124	165	306
	2024	LG	180	255	549

¹⁾ Dam cross-section, extrapolation from the Łądek-Zdrój station (multiplier 0.471).

Explanations: G = gamma, LN = log-normal, W = Weibull, LG = log-gamma.

Source: own study.

**Fig. 3.** Annual maximum discharge curves at the Łądek-Zdrój station up to 2023; fitted distributions (1) according to the KZGW guidelines, (2) according to the IMGW guidelines; source: own study

the IMGW guidelines. Further details are given in Supplementary Table S5.

The area enclosed between the extreme curves shows the uncertainty band. Weibull, Pearson type III, and gamma distributions are similar (Fig. 3) and all were rejected in Pearson's χ^2 test in this particular case. The other two distributions differed markedly from these three in the rare-event range, while fitting the empirical distribution better (consistent with results from other stations). The Kolmogorov test rejected distributions in only five of 45 cases, as it is insensitive to discrepancies in the cumulative distribution function at low exceedance probabilities. The best-fitting distribution could be identified unambiguously using the IMGW guidelines – e.g., the log-gamma function in Figure 3.

Between 1984 and 2023, the $Q_{\max,p}$ values at each station increased sharply in the low p range. The increase in $Q_{\max,1\%}$ ranged from 25% (Raškov) to 66% (Łądek-Zdrój). Including 2024 produced further increases, up to 73% in Żelazno. The lower the exceedance probability p , the greater the relative increase in $Q_{\max,p}$ after extreme events and the greater the uncertainty. In some cases, the best-fitting distribution type changes as the record was extended (cf. Tab. 2) – a phenomenon described as “tail wagging” and criticised by Węglarczyk (2015). In these analyses, including or excluding the log-gamma distribution fundamentally affected estimates of $Q_{\max,p}$. This distribution has the heaviest tail, which is particularly consequential in the safety analysis of dam structures.

The IMGW guidelines specify that the standard error of a quantile should not exceed 20% of its value – a very restrictive criterion in this case. For example, the best-fitting distribution at the Głucholazy station (1951–2023) had an excessively large error even for the $Q_{\max,10\%}$ quantile. Excluding such quantiles would render most distributions effectively useless for the design of spillways and outlets (cf. Tab. S5).

DISCHARGES AT THE STRONIE ŚLĄSKIE DAM CROSS-SECTION

Based on the $P_{\max,1\%}$ values (Tab. 1), the following discharges at the dam cross-section were estimated: $Q_{\max,1\%,84} = 81 \text{ m}^3\cdot\text{s}^{-1}$, $Q_{\max,1\%,23} = 101 \text{ m}^3\cdot\text{s}^{-1}$, and $Q_{\max,1\%,24} = 118 \text{ m}^3\cdot\text{s}^{-1}$ (for 1984,

2023, and 2024, respectively). The probability exceedance curves for $Q_{\max,p}$ obtained using this method (regional regression) and extrapolation (cf. Tab. 2) are shown in Figure 4.

The $Q_{\max,p}$ distributions obtained using the two methods differ substantially for rare events. Even the $Q_{\max,1\%}$ estimates, which in principle should be similar, diverge over time (Fig. 4). In these analyses, $P_{\max,p}$ appeared to increase more slowly than $Q_{\max,p}$. The log-gamma distribution provided the best fit to the empirical distribution and produced a steep curve.

The design discharge (Q_d) and control discharge (Q_c) for the Stronie Śląskie dam are summarised in Table 3. These values were calculated using the curves in Figure 4; the log-normal distribution under the KZGW guidelines was included for comparison.

All calculation methods indicate that the Q_d and Q_c discharges have increased significantly, raising questions about how the structure's reliability has changed over time. The Stronie Śląskie dam should be capable of passing the control discharge Q_c whilst maintaining structural safety. Based on records ending in 1984, 2023 and 2024, Q_c was estimated at 120–150, 180–280, and 210–530 $\text{m}^3\cdot\text{s}^{-1}$, respectively. As the observation record lengthened, the uncertainty band widened – a counterintuitive result – and the discrepancy between methods reaches a factor of approximately 2.5. In structural design, such ambiguities are typically resolved by adopting conservative values; however, it is debatable whether this approach is warranted here, because it conflicts with general hydrological recommendations.

The “critical” discharge (Q_{crit} , defined above) could be estimated by hydraulic modelling of the reservoir–spillway system, which was beyond the scope of this study. The surface spillway overflowed in 1997, but the dam itself did not (Archiwum Stronie, 1997), with a discharge at Łądek-Zdrój of 425 $\text{m}^3\cdot\text{s}^{-1}$ (7 July 1997). The adopted discharge at this station in 2024 (455 $\text{m}^3\cdot\text{s}^{-1}$), the year of failure, extrapolated to the dam cross-section, equals 214 $\text{m}^3\cdot\text{s}^{-1}$. Rainfall–runoff modelling by Kokoszka (2025) yields a similar peak value of 236 $\text{m}^3\cdot\text{s}^{-1}$. At the same time, Polish Waters stated (PGWWP, 2024) that the structure was designed for 70–80 $\text{m}^3\cdot\text{s}^{-1}$ and unchanged since

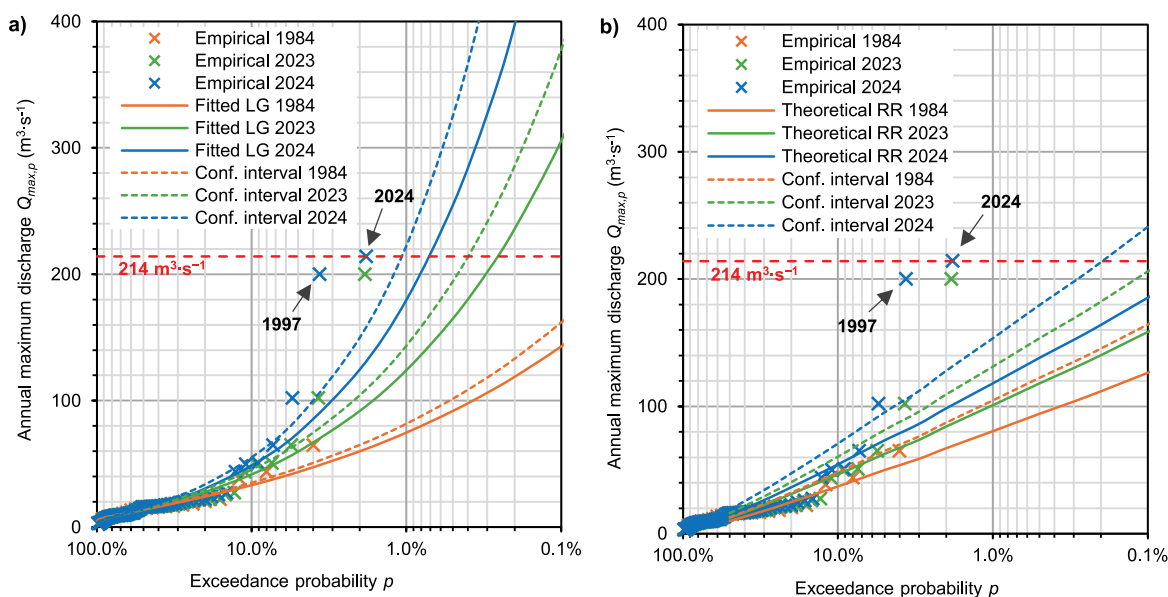


Fig. 4. Annual maximum discharge curves at the Stronie Śląskie dam: a) log-gamma (LG) distributions, b) regional regression (RR); 214 $\text{m}^3\cdot\text{s}^{-1}$ = benchmark value; source: own study

Table 3. The design discharge (Q_d) and control discharge (Q_c) for the Stronie Śląskie dam (dam importance class III)¹⁾

Type of discharge	Probability p	$Q_{\max,p}$ discharge ($\text{m}^3\cdot\text{s}^{-1}$), data until year			Estimation method
		1984	2023	2024	
Q_d	0.5%	94	118	138	regional regression equation
		73	150	227	extrapolation – log-normal
		92	165	255	extrapolation – log-gamma
$Q_c^{2)}$	0.2%	146	182	213	regional regression equation
		117	275	458	extrapolation – log-normal
		133	286	530	extrapolation – log-gamma

¹⁾ Estimates based on the regional regression equation and extrapolation with log-normal and log-gamma distributions.

²⁾ The mean estimation error at the 84% confidence level was added (as required for a mountain stream).

Source: own study.

1908, while the discharge in 2024 allegedly reached $320 \text{ m}^3\cdot\text{s}^{-1}$. This figure was not adopted here, as the statement was issued only a few days after the event and did not specify the estimation method. In light of this evidence, a more conservative value of $Q_{\text{crit}} = 214 \text{ m}^3\cdot\text{s}^{-1}$ was adopted instead (shown in Fig. 4). The aim is to illustrate general trends rather than provide an exact estimate, as the latter would require additional studies. Approximate exceedance probabilities of Q_{crit} are listed in Table 4. Their relative change was particularly strong during the period 1984–2023, ranging from fivefold to 170-fold.

Table 4. Estimated exceedance probability of the critical discharge (Q_{crit}) at the Stronie Śląskie dam cross-section, depending on the method and period of analysis

Until year	Exceedance probability (%) of $Q_{\text{crit}} = 214 \text{ m}^3\cdot\text{s}^{-1}$		
	regional regression	log-normal	log-gamma
1984	0.002	0.001	0.02
2023	0.01	0.17	0.26
2024	0.04	0.6	0.7

Source: own study.

Addressing this hydrological challenge is critical to ensuring the long-term reliability of the structure. This is especially relevant for long-lived facilities such as dams, where the magnitude of governing hydraulic loads is inherently uncertain and may increase over time in ways that are difficult to predict or control. The results in Table 4 can be considered in the light of Eurocode 0 (PN-EN 1990:2004), Annexes B and C. For new structures, consequence class CC3, the target reliability index is $\beta = 5.2$, corresponding to an annual probability of structural failure $p_f \leq 10^{-7}$. For the Stronie Śląskie dam, the annual overtopping probability in 2023 lay between 10^{-4} and $2.6\cdot 10^{-3}$, which is comparable to the structural reliability requirements set for new structures in the lowest consequence class CC1 and over an entire 50-year service life ($\beta = 3.3$). It must be stressed that the results listed in Table 4, based on simplified assumptions, illustrate relative changes in reliability rather than provide realistic absolute values.

DISCUSSION

Increasing estimates of annual maximum daily precipitation ($P_{\max,p}$) and annual maximum discharge ($Q_{\max,p}$), despite apparent stationarity in the hydrological data, may indicate an increase in the intensity or frequency of extreme events, while mean annual precipitation and discharge may even be decreasing. The tests used may not yet be sensitive enough to detect such changes. Alternatively, the dataset may be growing while the underlying distribution remains unchanged, especially given the uncertainty about the distribution type. Finally, the occurrence of several major floods between 1984 and 2024 may be due to chance, reflecting the random nature of hydrological phenomena and lacking any underlying trends. A comparison of topographic maps from the 1980s with current maps indicates marginal changes in land cover in the Stronie Śląskie reservoir catchment.

Estimates of design discharge (Q_d), control discharge (Q_c) and exceedance probability p , all critical to dam and levee safety, are subject to considerable uncertainty and vary significantly as measurement series are extended. Nevertheless, specific values must be adopted for hydraulic design. Procedures for determining key actions, such as wave loading, ice loading and hydrodynamic pressure, are not clearly specified in Polish regulations; they were covered by the now-withdrawn standard BN-67/8811-01. This study shows that design flood estimation methods are also ambiguous.

Structural design requires critical safety decisions. The wide range of admissible approaches – including distribution types, parameter estimation methods, and goodness-of-fit tests – and the resulting discretion in selecting design floods raise concerns. In the present analysis, using the log-gamma distribution instead of the recommended Pearson III distribution increased Q_c several-fold. This highlights an important advantage of the IMGW guidelines (Ozga-Zielińska, Brzeziński and Ozga-Zieliński, 1999), which provide unambiguous outcomes despite using statistical tools of disputed validity. Their authors gave a clear rationale for the proposed solutions, which nevertheless prompted a critical response (Kaczmarek, 2000). Many years later, the selection of statistical methods in hydrology remains unresolved in Poland, with no official public guidelines, despite clear objectives (Węglarczyk, 2015). From an engineering standpoint, standardising the methodology for estimating $Q_{\max,p}$

would help establish clear performance requirements for new and existing hydraulic structures and clarify design responsibilities. Setting exceedance probability (p) limits alone is clearly insufficient. Consistently applying well-defined procedures over time enables practitioners to accumulate experience, draw lessons from past errors, and refine the rules accordingly.

Uncertainty associated with model selection, represented by the band between extreme curves (cf. Fig. 3), is only one source of uncertainty. The study reveals several practical issues, including interruptions in the data series and changes in the locations of precipitation stations (Fig. 1). The low density of river gauging stations necessitates the use of indirect methods for discharge estimation. In this study, the options are regional formulae, now considered obsolete (Węglarczyk, 2015), or extrapolation from relatively distant existing stations. Moreover, gauges are often damaged during major floods, significantly reducing the accuracy of critical measurements. Even with long data series of 50–70 years, the uncertainty quantified for the fitted distributions is significant (Figs. 2, 4). The upper bounds of the 84% confidence interval for $Q_{\max,p}$ quantiles are listed in the supplementary materials (Tab. S5).

The need to develop improved flood estimation methods is not unique to Poland. Contemporary approaches include stationary at-site and regional frequency analyses, like those used in this study, which are still common in most countries (Islam *et al.*, 2024). In response to climate change, non-stationary methods have also gained popularity, in which distribution parameters vary with factors such as land use or climate (Xie *et al.*, 2021; Barbhuiya, Ramadas and Biswal, 2023). The probable maximum flood approach is applied to extreme-risk situations, though storms exceeding the “maximum” threshold have been observed, prompting the incorporation of climatic trends into this approach (Kao, DeNeale and Watson, 2019; Herbozo *et al.*, 2022). More recently, machine learning and remote sensing have become important approaches to improving the accuracy and spatial coverage of flood predictions (Kumar *et al.*, 2023).

For example, in 2025, the German Association for Water, Wastewater and Waste (DWA) issued an extension (DWA, 2025) to the guidelines by DVWK (1999), which must be used in design practice. Example applications and dedicated calculation software were also developed. DWA seeks to utilise as much available data as possible, using a statistical approach similar in principle to the event alternative method in the IMGW guidelines (Ozga-Zielińska, Brzeziński and Ozga-Zieliński, 1999). Several genetic types of floods are considered, with more than one event per year included in the analyses. The guidelines use a wide range of tools, selecting among five probability distributions and three parameter estimation methods based on goodness-of-fit tests and information criteria. In contrast, the two cited Polish guidelines include regional formulae based on data collected before 1980 and some statistical methods that have not changed much since 1967.

The Stronie Śląskie dam could not formally have been required to pass the 2024 critical discharge ($214 \text{ m}^3\text{s}^{-1}$), based on the KZGW guidelines (Banasik *et al.*, 2020), even accounting for the data up to 2023. However, if the extrapolation method were applied instead of the recommended regional regression equation, the estimated Q_c for 2023 would clearly exceed Q_{crit} . The dam would then fail to meet basic civil-engineering safety requirements, even assuming perfect technical condition. This would necessitate urgent reconstruction to improve reliability, given the

severe consequences of failure and the extended service life (which increases the overall probability of failure). At the same time, this example raises methodological questions, including whether the very poor fit of the Pearson type III $Q_{\max,p}$ distribution obtained by regional regression to extrapolated data would justify a different estimation method.

The analysis demonstrates that periodic review of hydrological data relative to a dam’s discharge capacity is essential to assess its actual hydraulic safety. One example is the 2004 initiative by the Italian authorities requiring a reassessment of the hydraulic safety of all large dams, the average age of which is currently around 70 years (Murano, 2025). In 2024, an additional requirement was introduced to perform such an assessment whenever a discharge exceeds either two-thirds of the spillway capacity or $Q_{\max,0.5\%}$. In more than 20% of cases, such an assessment led to a decision to modify the dam.

Hydrological re-evaluation can form part of a broader risk assessment, including the consequences of failure (and thus the importance class). The need to assess breach consequences for more structures within the flood risk management plans (FRMPs) was highlighted in the 2025 report of the Committee on Water Science and Water Management of the Polish Academy of Sciences (Pol.: Komitet Nauk o Wodzie i Gospodarki Wodnej Polskiej Akademii Nauk) (Walczykiewicz *et al.*, 2025). Current Polish regulations, however, provide limited grounds for repeated analysis, as the dam’s importance class is formally fixed at the time of construction or reconstruction, along with design discharges. As a result, a structure may be considered compliant with safety requirements on paper, even when its actual reliability has long been inadequate. Ensuring structural reliability should be viewed as an ongoing process, not a one-time achievement.

CONCLUSIONS

No statistically significant monotonic trends were observed in the analysed series of maximum precipitation and discharge in the Biała Łądecka and neighbouring catchments. Some series showed clustering of dry and wet years.

Despite the apparent absence of nonstationarity, extending the time series led to sharp increases in the annual maximum daily precipitation ($P_{\max,p}$) and annual maximum discharge ($Q_{\max,p}$) estimates in nearly all cases. Even adding a single (albeit extreme) year can raise $Q_{\max,1\%}$ by 73%. As a result, the hydraulic safety of the century-old Stronie Śląskie dam had deteriorated over decades (even if it had been in perfect technical condition), which contributed to the 2024 failure.

Periodic re-evaluation of dam hydraulic safety is an essential strategy for managing this risk. This should include recalculating design flood discharges and considering structural modifications.

The various discharge estimation methods yield substantial discrepancies. For the Stronie Śląskie dam, $Q_{\max,1\%}$ increased by 53% when a different indirect estimation approach was applied. Hydrological computations should therefore follow clearly defined, mandatory, and unambiguous methods that are periodically reviewed, updated as necessary, and publicly accessible – consistent with standard practice in civil engineering. On the basis of this study and international experience, significant shifts in future precipitation and flooding patterns can be expected, which should be considered when choosing design flood estimation approaches.

SUPPLEMENTARY MATERIAL

Supplementary material to this article can be found online at: https://www.jwld.pl/files/Supplementary_material_71_Krysiak.pdf.

CONFLICT OF INTERESTS

The author declares that there is no conflict of interests.

DATA REPOSITORY

Additional research data are available at Research Data Repository under <https://repo.pw.edu.pl/info/researchdata/WUT26868c11688d465b973f9c06e39a0bc7/>, including data series verification results, estimated distribution parameters, goodness-of-fit test results, and information criterion values.

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