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Threshold Values of Extreme Hydrometeorological Events on the Polish Baltic Coast

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Abstract: The main aim of this study is to determine the threshold values for extreme sea and weather events on the Polish Baltic coast. The study is based on daily hydrometeorological data on the sea level; air temperature and atmospheric precipitation collected between 1965–2014 from six coastal sites (Świnoujście; Kołobrzeg, Ustka, Łeba, Hel, and Gdynia/Gdańsk). Threshold values for the occurrence of extreme events (with a probability of 10% and 95%, and a return rate of once every 10 years) and exceptionally extreme events (with a probability of 1% and 99%, and a return rate of once every 100 years) were determined using probability distribution and quantile analysis. Hydrometeorological absolute extremes were also determined. The methodology used to determine these extreme events and the time-space analysis of hydrometeorological extremes reveal significant geohazards for the functioning of the Baltic coastal zone, including the erosion of coastal dunes and cliffs and the destruction of technical infrastructure.

Keywords: extreme events; threshold values; probability; hydrometeorological conditions; Baltic coast

1. Introduction

It is expected that global warming will continue in the 21st century. In countries around the Baltic Sea, climate change and sea level rise have been studied since at least the 1990s [1,2]. In the Baltic Sea region, global warming is likely to be higher than the global average. Global warming will be accompanied by an increase in precipitation in the winter and uncertainty of weather changes in the summer, with a high probability of a high frequency of droughts in the southern zone of the region. The forecasted atmospheric changes will also be accompanied by an increase in the sea level and its temperature. Hydrometeorological changes will affect the natural environment, for example, marine biogeochemistry and coastal erosion [3]. Climate changes and physical properties of the sea favor the occurrence of extreme hydrometeorological events. The functioning and transformation of the natural environment in the coastal zone are especially determined by extreme hydrometeorological events. Extremely high storm surges and atmospheric precipitation intensify hydrological and geomorphological processes (including storm floods and mass movements). Extreme weather events therefore pose a significant threat to the natural environment and human activity. On the Polish Baltic coast, the greatest geohazards are storm floods. The frequency thereof is rising, causing significant economic losses across long stretches of land [4].

Literature contains neither a uniform definition of extreme events nor a methodology for their designation [5–10]. Extreme weather events are most often determined using probability characteristics [11–13]. The extreme characteristics of meteorological, hydrological, and geomorphological events include threshold values whose probability of being exceeded is lower than 10%, thus with a return period of once per decade. Exceptionally extreme weather events are considered those with a probability of less than 1%, thus with a return period of once per century. Probability characteristics are often used to estimate threats to hydrotechnical infrastructure in the coastal zone. Also used to determine extreme events is the quantile method, which most often accounts for threshold values using percentiles 5% and 95% [14–16]. Regardless of the methodology employed to determine extreme weather events (whether probabilistic or quantile), the events must be assigned absolute maximums and minimums.

The main aim of this study is to determine the threshold values for extreme sea and weather events (in terms of sea level, air temperature, and atmospheric precipitation) on the Polish Baltic coast. This paper presents absolute values of hydrological and meteorological conditions, as well as threshold values for extreme weather events calculated using the probabilistic method (for return period) and quantile analysis (for frequency of occurrence).

Aside from their scientific significance, extreme hydrometeorological events have a utilitarian significance. Extreme thermal and precipitation conditions, as well as high sea level, are the main determinants of geomorphological changes in the sea coastal zone (sometimes with disastrous and irreversible consequences). Exceeding the threshold values defining extreme hydrometeorological events may pose a significant threat to the functioning of the coastal zone. Therefore, the determination of threshold values and return periods for extreme events is important for various areas of human activity, especially those related to the protection, management, and development of the coastal region.

2. Materials and Methods

The research area was the Polish Baltic coast (about 500 km long), where there are two basic types of shoreline: dunes and cliffs. The dune coastal zone, which covers around 85% of the coast, has been forming since the wane of the last glacial period, i.e., the beginning of the Holocene. It consists of sand barriers (spits) that separate coastal lakes from the sea, and proglacial wetlands made up of dunes of varying origin and height (2–30 m). The cliff coastal zone, which covers around 15% of the coast, was formed during the Pleistocene Epoch and is a type of high coastline (up to 95 m). It is made up of glacial clays accumulated by the continental glacier in the form of head moraines, as well as fluvioglacial loams and sands accumulated mainly in the form of bottom moraines. Poland's Baltic coastal zone is home to coastal islands (e.g., Wolin and Uznam), peninsulas (e.g., Hel), bays (e.g., the Bay of Pomerania and Bay of Gdańsk), and lagoons (e.g., the Szczecin and Vistula lagoons). Sections of the coast near the Szczecin and Vistula lagoons are floodplains and areas of organic accumulation. According to the Köppen classification system, the South Baltic coast is in a temperate zone with a humid, continental climate; warm summers; and an even distribution of rainfall in all seasons. In the last half-century, in the research area, the average annual air temperature was 8.3 °C and the average annual rainfall was around 605 mm. A statistically significant increase trend was observed in the mean annual air temperature of 0.3 °C/10 years. There was no statistically significant tendency for atmospheric precipitation [17]. The Atlantic climate and the sea have an important influence on the climate of the region, which is manifested in frequent cloud cover, increased humidity, and increased wind speed. Most notable are winds from the N-W sector, which most frequently cause a rise in sea level and wind waves. Storm surges most frequently occur during cyclonic circulations from the direction: Northwest 20.6%, West 18.3%, and North 12.7% [18]. In winter, the Polish coast is usually on the warm side of the jet stream which, during positive NAO (North Atlantic Oscillation), causes warming, increased precipitation, and strong winds. In summer, the influence of the subtropical high-pressure system is important, which causes more extreme thermal conditions. The Polish Baltic coast can therefore be classified as a modern marine climate [19].

Daily data from a 50-year homogeneous measurement series (1965–2014) were used to determine the threshold values for extreme hydrometeorological events. The data included average, maximum, and minimum air temperature; total atmospheric precipitation; and average and maximum sea level. Meteorological data (from meteorological stations in Świnoujście, Kołobrzeg, Ustka, Łeba, Hel, and Gdynia) and sea level data (from mareographical stations in Świnoujście, Kołobrzeg, Ustka, Hel, and Gdańsk) were obtained from the Institute of Meteorology and Water Management in Warsaw (Figure 1). In Poland, the Baltic High System (BHS) applies, which accounts for long-term observations of average sea level using the Kronstadt sea gauge. The estimated difference between the system based on the Normaal Amsterdams Peil (NAP) and the BHS is around 15 cm (the Kronstadt system is higher). Although Poland uses a high system based on the Kronstadt sea gauge (zero level = −508 cm), the registration and recording of sea levels is based on the NAP (zero level = −500 cm). This is why the sea gauges do not need to be adjusted [20]. In order to obtain a reference to the 0.00 NN ordinate, it would be necessary to reduce the sea-level values presented in this paper by 500 cm. An analysis of the average sea levels in the Polish Baltic coast in 1965–2014 showed a rate of increase of about 2 mm per year. This dynamic is similar to that found for the global average increase of the sea level, which was estimated to be 1–2 mm per year [21].

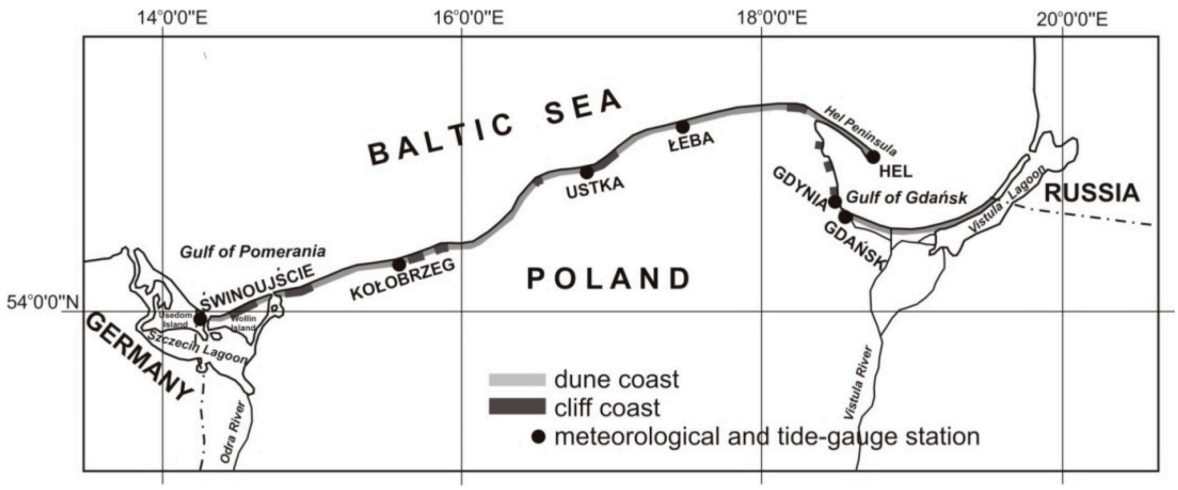

Figure 1. Research area and locations of meteorological and mareographical stations in the coastal zone of the Polish Baltic.

The definitions and criteria for determining extreme weather events are based on global research [22–24]. The following criteria were used in this study:

- Absolute extreme. The highest or lowest value that has been empirically evidenced for a given meteorological and hydrological event.
- Extreme event. Values close to the absolute extremes for a given meteorological and hydrological event, whose probability of being exceeded is lower than 10%, i.e., the chances of their occurrence (or "return period") is at most once every ten years. In quantile terms, extreme threshold values were designated using percentiles 5/100 and 95/100.
- Exceptionally extreme event. Values close to the absolute extremes for a given meteorological and hydrological event, whose probability of being exceeded is lower than 1%, i.e., the chances of their occurrence (or "return period") is at most once every hundred years. In quantile terms, exceptionally extreme threshold values were designated using percentiles 1/100 and 99/100.

For the probabilistic approach, the following procedure was used to determine extreme events: verification of the completeness and homogeneity of data (using Alexandersson's homogeneity test); adjustment of the theoretical distribution to empirical distribution (using the Kolmogorov − Smirnov test); and determination of the probability density distribution from the cumulative probability density function. This study specifies the threshold values for hydrometeorological events with a return period of 1 year P(X) 100%, 5 years P(X) 20%, 10 years P(X) 10%, 50 years P(X) 2%, 100 years P(X) 1%, 500 years P(X) 0.2%, and 1000 years P(X) 0.1%. Return periods were determined by the following formula [12].

The probability of the threshold values being exceeded was estimated from the inverse probability density function. Calculations were made in Easy Fit Professional (Version 5.6, MathWave Technologies, Washington, DC, USA).

3. Results

In the coastal zone of the Polish Baltic, the average annual air temperature from 1965–2014 ranged from 7.9 °C in Łeba to 8.6 °C in Świnoujście. Annually, on average, the most precipitation occurred in Ustka (704.2 mm) and the least in Świnoujście (535.7 mm). The average sea level ranged from 501.0 cm in Świnoujście to 509.6 cm in Gdańsk. The eastern coastal region is therefore cooler and more humid, and has a higher sea level than the western coastal region.

3.1. Absolute Extreme

The absolute values of thermal and precipitation extremes in the Baltic coastal zone are low compared to those recorded further away from the coast. The highest absolute maximum air temperature (38.0 °C) was recorded in Kołobrzeg (10 August 1992), and the lowest (33.7 °C) in Hel. The lowest absolute minimum air temperature ranged from −25.0 °C in Łeba (6 February 2012) to −18.7 °C in Hel. The highest absolute amplitude of air temperature (≥60 °C) occurred in the central part of the coastal zone (Ustka and Łeba), and the lowest (<55 °C) in the eastern part (Hel and Gdynia). The absolute values for average daily air temperature followed a similar pattern. The daily precipitation efficiency in the coastal zone is fairly low. The highest daily efficiency was recorded in the middle of the coastal zone, especially near Ustka and Łeba (141.0 mm, 24 July 1988). In the western (Świnoujście and Kołobrzeg) and eastern (Hel and Gdynia) coastal zone, the maximum daily precipitation was less than 90 mm. The absolute extreme of the maximum sea level was 661 cm in Świnoujście (4 November 1995), which was higher than the average sea level by 1.6 m. The highest average daily sea level was recorded at around 620 cm at bay stations in Świnoujście (Zatoka Pomorska) and Gdańsk (Zatoka Gdańska). The maximum average daily sea level was about 620 cm, which was higher than the average sea level by around 1.1 m. The absolute minimum of the average sea level on the entire Baltic coast was lower than the average level by 1.0–0.7 m (Table 1).

The absolute extremes presented in Table 1 occurred once in the 50-year period studied. The occurrence of such events in the future (especially maximum sea level and atmospheric precipitation) could have catastrophic consequences for human activity and the natural environment.

Table 1. Absolute extremes of air temperature (°C), atmospheric precipitation (mm), and sea level (cm) in the Polish coastal zone of the South Baltic (1965–2014). AGL: About ground level.

Place	Maximum Air Temperaturę at 2 m AGL	Mean Air Temperaturę at 2 m AGL		Minimum Air Temperaturę at 2 m AGL	Precipitation	Maximum Sea Level	Mean Sea Level	
	Max	Max	Min	Min	Max	Max	Max	Min
Świnoujście	37.4	27.7	−16.5	−22.2	76.6	661	624	401
Kołobrzeg	38.0	28.1	−16.5	−21.9	85.2	644	618	401
Ustka	37.8	29.8	−16.1	−22.2	94.2	636	611	428
Łeba	37.2	28.4	−16.5	−25.0	141.0	-	-	-
Hel	33.7	26.0	−14.6	−18.2	77.1	620	604	431
Gdynia	35.0	27.2	−16.0	−18.7	82.1	-	-	-
Gdańsk	-	-	-	-	-	644	620	436

3.2. Extreme Events—Probabilistic Analysis

When using the probabilistic method to determine extreme threshold values, it was very important to match the theoretical distribution to empirical distribution (by selecting the best theoretical distribution from among the 40 available in Easy Fit 5.6 Professional). Matches were indicated by the statistically significant (significance level $p < 0.001$) lowest value of the Kolmogorov − Smirnov (K − S) test (Table 2), which was additionally confirmed by the lowest Corrected Akaike Information Criterion (AIC_C).

For data on daily air temperature, the best match was the Error (Exponential Power) Distribution, which has the following parameters and functions of cumulative distribution and probability density:

k—shape parameter; σ—scale parameter (standard deviation); μ—location parameter (mean); z—standardized value; Γ—scale parameter.

$$F(x) = \begin{cases} 0.5\left(1 + \frac{\Gamma_{|c_0 z|^k}(1|k)}{\Gamma(1|k)}\right) & x \geq \mu \\ 0.5\left(1 - \frac{\Gamma_{|c_0 z|^k}(1|k)}{\Gamma(1|k)}\right) & x < \mu \end{cases} \quad (1)$$

$$f(x) = c_1 \sigma^{-1} \exp\left(-|c_0 z|^k\right) \quad (2)$$

$$c_0 = \left(\frac{\Gamma(3|k)}{\Gamma((1|k))}\right)^{1/2} \quad c_1 = \frac{k c_0}{2\Gamma(1|k)} \quad z \equiv \frac{x-\mu}{\sigma} \quad (3)$$

For data on daily atmospheric precipitation, the matching of distributions and the subsequent determination of threshold values for a specific return period were heavily flawed. This is why data for maximum daily precipitation in all months from 1965–2014 were taken into account. The best match was the Log-Gamma Distribution, which had values of $p = 0.59$ and $K - S = 0.108$. The probability of daily precipitation for a given return period estimated later for this distribution indicated values that could possibly occur (Table 3). The Log-Gamma Distribution has the following parameters and functions of cumulative distribution and probability density:

α—continuous parameter (α > 0); β—continuous parameter (β > 0).

$$0 < x < \infty \quad (4)$$

$$F(x) = \frac{\Gamma_{\ln(x)/\beta}(\alpha)}{\Gamma(\alpha)} \quad (5)$$

$$f(x) = \frac{(\ln(x))^{\alpha-1}}{x\beta^{\alpha}\Gamma(\alpha)} \exp(-\ln(x)|\beta) \quad (6)$$

For daily data on the sea level, the best match was the Generalized Logistic Distribution. This distribution has the following parameters and functions of cumulative distribution and probability density:

k—shape parameter; σ—scale parameter (standard deviation > 0); μ—location parameter (mean); z—standardized value.

$$1 + k\frac{(x-\mu)}{\sigma} > 0 \quad \text{for } k \neq 0 \quad (7)$$

$$-\infty < x < +\infty \quad \text{for } k = 0 \quad (8)$$

$$F(x) = \begin{cases} \frac{1}{1+(1+k\,z)^{-1/k}} & k \neq 0 \\ \frac{1}{1+\exp(-z)} & k = 0 \end{cases} \quad (9)$$

$$f(x) = \begin{cases} \frac{(1+k\,z)^{-1-1/k}}{\sigma\left(1+(1+k\,z)^{-1/k}\right)^2} & k \neq 0 \\ \frac{\exp(-z)}{\sigma(1+\exp(-z))^2} & k = 0 \end{cases} \quad (10)$$

$$z \equiv \frac{x-\mu}{\sigma} \quad (11)$$

Table 2. Matching theoretical distributions to empirical data (using the K − S test) on thermal conditions, precipitation conditions, and sea level in the Polish coastal zone of the South Baltic (1965–2014).

Place	Hydrometeorological Conditions					
	Maximum Air Temperature	Mean Air Temperature	Minimum Air Temperature	Precipitation	Maximum Sea Level	Mean Sea Level
	Statistical Distribution					
	Error (Exponential Power) Distribution			Log-Gamma Distribution	Generalized Logistic Distribution	
Świnoujście	k = 3.91 σ= 8.19 μ = 11.95 K − S = 0.021 p < 0.001	k = 3.39 σ= 7.18 μ = 8.62 K − S = 0.033 p < 0.001	k = 2.42 σ = 6.72 μ = 5.70 K − S = 0.042 p < 0.001	α = 70.59 β = 0.048 K − S = 0.108 p = 0.590	k = 0.10 σ = 11.55 μ = 506.46 K − S = 0.015 p < 0.001	k = 0.05 σ = 10.78 μ = 499.80 K − S = 0.015 p < 0.001
Kołobrzeg	k = 3.50 σ = 7.98 μ = 11.67 K − S = 0.025 p < 0.001	k = 3.17 σ = 7.12 μ = 8.34 K − S = 0.039 p < 0.001	k = 2.30 σ = 6.68 μ = 5.34 K − S = 0.044 p < 0.001	α = 127.11 β = 0.028 K − S = 0.123 p = 0.429	k = 0.10 σ = 12.01 μ = 507.11 K − S = 0.014 p < 0.001	k = 0.06 σ = 11.06 μ = 500.73 K − S = 0.013 p < 0.001
Ustka	k = 3.35 σ = 7.97 μ = 11.36 K − S = 0.031 p < 0.001	k = 3.14 σ = 7.08 μ = 8.20 K − S = 0.036 p < 0.001	k = 2.30 σ = 6.75 μ = 5.41 K − S = 0.041 p < 0.001	α = 89.93 β = 0.040 K − S = 0.090 p = 0.797	k = 0.09 σ = 11.98 μ = 508.11 K − S = 0.017 p < 0.001	k = 0.05 σ = 11.13 μ = 502.18 K − S = 0.018 p < 0.001
Łeba	k = 3.74 σ = 8.01 μ = 11.22 K − S = 0.031 p < 0.001	k = 3.31 σ = 7.12 μ = 7.92 K − S = 0.038 p < 0.001	k = 2.16 σ = 6.82 μ = 4.61 K − S = 0.041 p < 0.001	α = 87.05 β = 0.040 K − S = 0.101 p = 0.672	-	-
Hel	k = 5.58 σ = 8.08 μ = 11.30 K − S = 0.027 p < 0.001	k = 4.47 σ = 7.07 μ = 8.24 K − S = 0.031 p < 0.001	k = 3.12 σ = 6.64 μ = 5.52 K − S = 0.037 p < 0.001	α = 72.66 β = 0.049 K − S = 0.066 p = 0.975	k = 0.09 σ = 12.15 μ = 508.28 K − S = 0.015 p < 0.001	k = 0.042 σ = 11.15 μ = 503.29 K − S = 0.020 p < 0.001
Gdynia	k = 4.30 σ = 7.81 μ = 11.28 K − S = 0.023 p < 0.001	k = 3.75 σ = 7.23 μ = 8.51 K − S = 0.031 p < 0.001	k = 2.87 σ = 6.97 μ = 6.00 K − S = 0.039 p < 0.001	α = 83.83 β = 0.041 K − S = 0.094 p = 0.758	-	-
Gdańsk	-	-	-	-	k = 0.07 σ = 12.17 μ = 513.45 K − S = 0.018 p < 0.001	k = 0.02 σ = 11.64 μ = 508.29 K − S = 0.019 p < 0.001

Analysis of the probability density function revealed potential threshold values for thermal-precipitation conditions and sea level for the expected return period (Table 3, Figure 2). Threshold values for extreme events are determined by a 10% probability (once every ten years), and for exceptionally extreme events, by a 1% probability (once every hundred years). For maximum air temperature (T_{max}), the highest values were recorded in Ustka in the central coastal area (10% = 33.2 °C, 1% = 35.5 °C), and the lowest in Hel in the eastern coastal area (10% = 30.0 °C, 1% = 31.3 °C). For minimum air temperature (T_{min}), the highest values were recorded in Łeba (10% = −18.1 °C, 1% = −21.6 °C), and the lowest in Hel (10% = −13.1 °C, 1% = −15.3 °C). For average daily air temperature (T), the highest threshold values were recorded in Kołobrzeg (10% = 28.2 °C, 1% = 30.5 °C), and the lowest in Hel (10% = 25.7 °C, 1% = 27.2 °C). The range of air temperature threshold values between stations was <50%. For atmospheric precipitation (P), the highest threshold values were recorded in Hel (10% = 58.9 mm, 1% = 96.7 mm), and the lowest in Świnoujście (10% = 49.8 mm, 1% = 80.5 mm). The spatial variation of extreme threshold values for atmospheric precipitation in the Polish coastal zone is <20%. For the sea level, the highest threshold values were recorded in Kołobrzeg (maximum sea level H_{max} 10% = 660.1 cm, 1% = 731.0 cm; and average daily sea level H 10% = 617.0 cm, 1% = 661.0 cm), and the lowest in Gdańsk (maximum sea level H_{max} 10% = 648.9 cm, 1% = 703.5 cm; and average daily sea level H 10% = 612.3 mm, 1% = 644.7 cm). The spatial differences between extreme threshold values for sea level are very small, and do not exceed 5%.

In the Polish Baltic coastal zone, spatial variation between threshold values for extreme hydrometeorological events were recorded. The highest probability values for thermal extremes and sea level were recorded in the western part of the zone (Świnoujście, Kołobrzeg), and for atmospheric precipitation, in the central part of the zone (Ustka, Łeba), as shown in Table 2.

Table 3. Probability of extreme hydrometeorological events in the Polish coastal zone of the South Baltic (daily data from 1965–2014).

Place	**Parameter**	**P(X) [%]**									
		0.1	**0.2**	**0.5**	**1**	**2**	**5**	**10**	**20**	**500**	**100**
		T [Years]									
		1000	**500**	**200**	**100**	**50**	**20**	**10**	**5**	**2**	**1**
Świnoujście	T_{max}	36.7	36.2	35.6	35.0	34.5	33.7	33.1	32.4	31.3	30.5
	T	31.9	31.5	30.8	30.2	29.6	28.8	28.2	27.4	26.4	25.5
	T_{min}	−21.0	−20.2	−19.2	−18.4	−17.5	−16.3	−15.4	−14.4	−12.9	−11.8
	P	117.2	105.4	90.8	80.5	70.8	58.6	49.8	41.1	29.0	1.0
	H_{max}	817.0	787.6	752.0	727.0	703.9	675.8	656.3	638.1	616.0	600.6
	H	686.4	673.3	656.7	644.5	632.7	617.7	606.7	596.1	582.5	572.6
Kołobrzeg	T_{max}	37.1	36.6	35.9	35.3	34.7	33.8	33.1	32.3	31.2	30.2
	T	32.3	31.8	31.1	30.5	29.8	29.0	28.2	27.5	26.3	25.4
	T_{min}	−22.1	−21.3	−20.2	−19.4	−18.5	−17.2	−16.2	−15.1	−13.6	−12.3
	P	101.1	93.4	83.6	76.4	69.3	60.0	53.0	45.7	34.8	1.0
	H_{max}	820.5	791.3	755.9	731.0	707.9	679.7	660.1	641.7	619.4	603.7
	H	711.3	695.4	675.5	661.0	647.2	629.7	617.0	604.9	589.6	578.6
Ustka	T_{max}	37.4	36.9	36.1	35.5	34.8	33.9	33.2	32.3	31.2	30.2
	T	32.2	31.6	30.9	30.3	29.7	28.8	28.0	27.3	26.1	25.2
	T_{min}	−22.4	−21.6	−20.5	−19.6	−18.7	−17.4	−16.3	−15.3	−13.7	−12.5
	P	129.3	117.3	102.3	91.6	81.3	68.3	58.7	49.1	35.4	1.0
	H_{max}	786.0	762.0	732.5	711.5	691.8	667.4	650.2	634.0	614.0	599.8
	H	707.6	692.5	673.4	659.5	646.1	629.2	617.0	605.2	590.3	579.5
Łeba	T_{max}	35.9	35.5	34.8	34.3	33.7	32.9	32.2	31.5	30.4	29.5
	T	31.3	30.8	30.1	29.6	29.0	28.1	27.5	26.7	25.6	24.7
	T_{min}	−24.7	−23.8	−22.6	−21.6	−20.6	−19.2	−18.1	−16.9	−15.2	−13.8
	P	120.3	109.2	95.2	85.3	75.7	63.6	54.7	45.8	33.1	1.0
Hel	T_{max}	32.3	32.0	31.6	31.3	30.9	30.4	30.0	29.5	28.8	28.2
	T	28.3	28.0	27.5	27.2	26.7	26.2	25.7	25.2	24.4	23.7
	T_{min}	−17.1	−16.5	−15.8	−15.3	−14.7	−13.8	−13.1	−12.4	−11.3	−10.5
	P	142.2	127.5	109.4	96.7	84.7	69.7	58.9	48.4	33.8	1.0
	H_{max}	801.6	775.7	743.8	721.3	700.2	674.2	656.0	638.8	617.7	602.9
	H	692.3	679.3	662.7	650.5	638.6	623.5	612.5	601.7	588.0	577.9
Gdynia	T_{max}	33.9	33.5	32.9	32.5	32.0	31.4	30.8	30.2	29.3	28.6
	T	30.8	30.4	29.8	29.3	28.8	28.0	27.4	26.8	25.8	25.0
	T_{min}	−18.8	−18.2	−17.4	−16.8	−16.1	−15.1	−14.3	−13.4	−12.2	−11.2
	P	117.1	106.1	92.4	82.6	73.3	61.5	52.8	44.1	31.8	1.0
Gdańsk	H_{max}	767.7	747.2	721.8	703.5	686.1	664.4	648.9	634.2	615.8	602.6
	H	678.8	668.3	654.8	644.7	634.8	621.9	612.3	602.8	590.4	581.3

These theoretical values for the probability of hydrometeorological events (Figure 2, Table 3) are highly varied in comparison to the empirical absolute extremes (Table 2). For maximum and minimum air temperature (T_{max} and T_{min}), the absolute extremes had a theoretical return period of once every 500 years (Kołobrzeg, Ustka, Gdynia) and once every 1000 years (Świnoujście, Łeba, Hel).

For average temperature (T), the absolute extremes had a theoretical return period of once every 5 years (Świnoujście, Kołobrzeg, Gdynia), once every 10 years (Hel), once every 20 years (Łeba), and once every 50 years (Ustka). For atmospheric precipitation, the absolute extremes had a theoretical return period of once every 20 years (Hel), once every 50 (Świnoujście, Gdynia), once every 100 years (Ustka), once every 200 years (Kołobrzeg), and once every 1000 years (Łeba). For maximum sea level (H_{max}), the absolute extremes had a theoretical return period of once every 2 years (Hel), once every 5 years (Kołobrzeg, Ustka, Gdańsk), and once every 10 years (Świnoujście). For maximum average sea level (H), the absolute extremes had a theoretical return period of once every 5 years (Ustka, Hel), once every 10 years (Kołobrzeg, Gdańsk), and once every 20 years (Świnoujście).

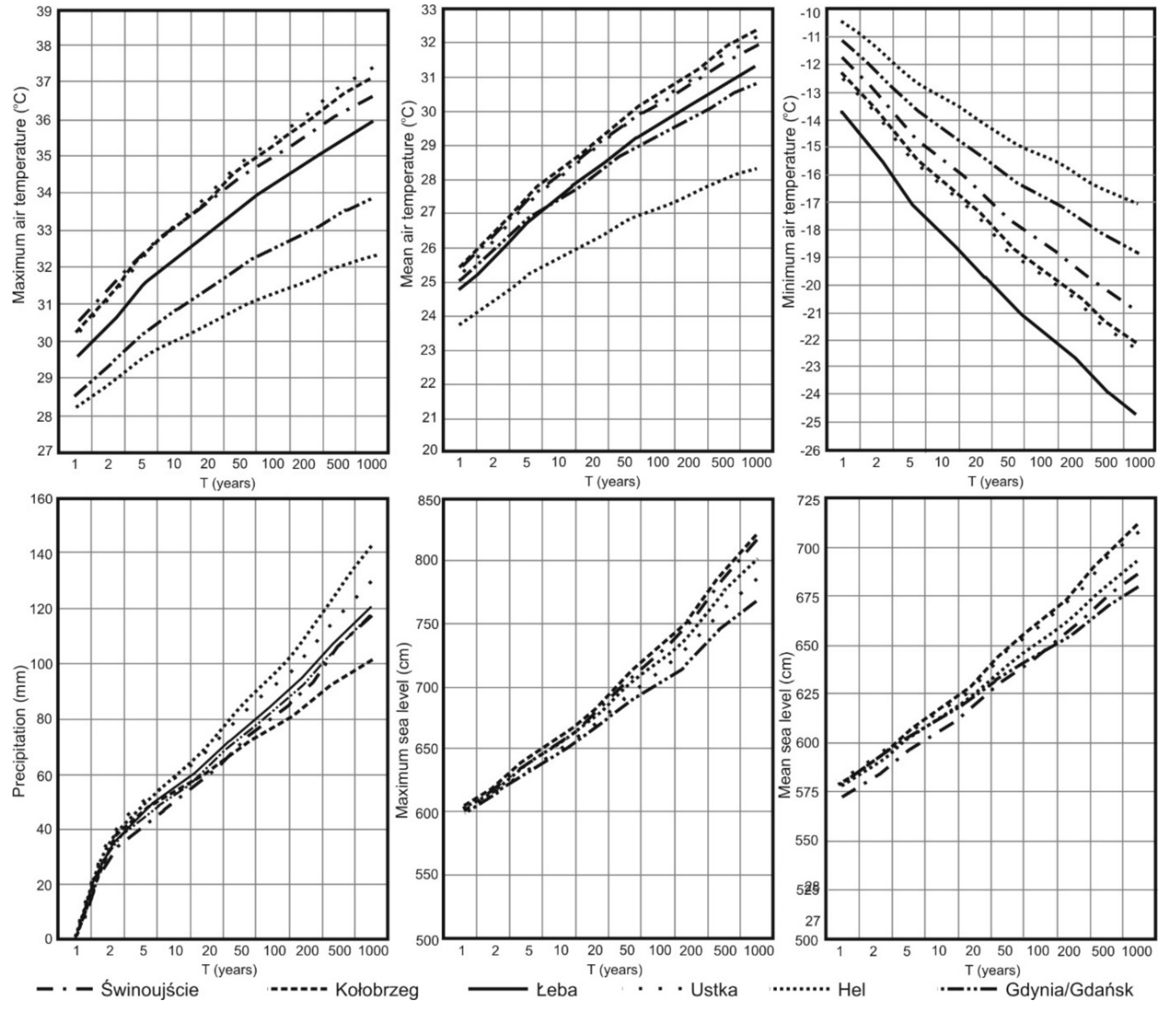

Figure 2. Threshold values for the probability (return period) of extreme hydrometeorological events in the Polish Baltic coastal zone.

The occurrence of extreme hydrometeorological events with a 10% probability in the Polish Baltic coastal zone is marked by high episodicity and randomness (Figure 3). For the period from 1965–2014, no statistically significant tendency for the increase or decrease in the occurrence of extreme events can be determined. The least common were days on which the sea level was extremely high—there were only three, 12 years apart (in 1983, 1995, and 2012). More common was extremely high atmospheric precipitation, which occurred on 22 days, the greatest concentration of which was in 1991–1993, and 2010–2012. Most common were extreme thermal events, especially maximum and minimum air temperature (49 and 67 days, respectively). Exceptional was 1987, in which there were 11 extremely cold days (T_{min}). Then, in 2010, there was an exceptional number of extremely hot days (T_{max}), i.e., five.

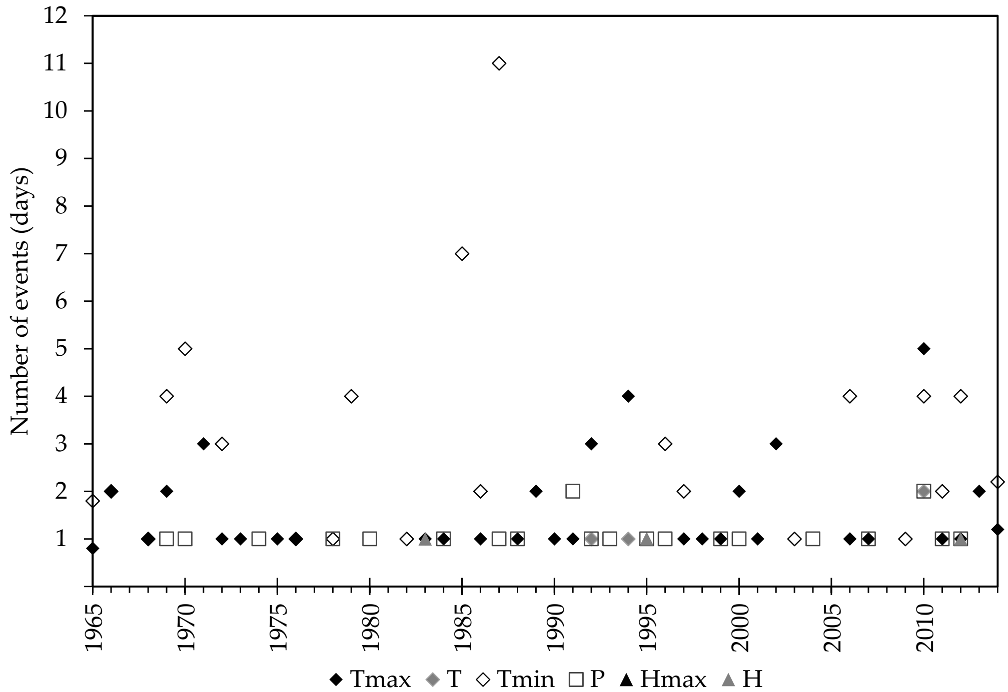

Figure 3. Occurrence of extreme hydrometeorological events with a 10% probability in the Polish Baltic coastal zone (collectively).

3.3. Extreme Events—Quantile Analysis

Quantile analysis (Table 4) determines the threshold values for the occurrence of extreme events in reference to empirical data using percentages 1%, 5%, 95%, and 99%. In probabilistic analysis, theoretical threshold values for extreme hydrometeorological events are much higher than in quantile analysis, resulting in the episodic occurrence of extreme events with long return periods. In quantile analysis, threshold values are lower, and extreme events occur much more frequently than in probabilistic analysis. For example, for the 95th percentile, they concern 5% of the data set (900–1000 cases in the 50-year collection of hydrometeorological data). Quantile analysis is therefore more helpful than probabilistic analysis for the study of time trends and spatial variability. Due to its much higher frequency of extreme events, quantile analysis enables the determination of a statistically significant linear trend in the 50-year period (Figure 4).

For the Polish Baltic coastal zone, analysis revealed a statistically significant (significance level $p < 0.05$, correlation coefficient $r > 0.3$) positive trend in the occurrence of extreme events (95%), air temperature, and sea level (Figure 4). For average air temperature, as well as maximum and average sea level, analysis revealed an increase in the number of events to three every 10 years. For maximum air temperature, the increase was lower, i.e., to two days every 10 years. For the quantile analysis, the annual numbers of extreme thermal events ranged as follows: from 10 in 1977 and 1980 to 45 in 2006 for maximum temperature; from 70 in 1977 to 48 in 2006 for average temperature; and from 1 in 1977 and 1990 to 52 in 1969 for minimum temperature. Extreme precipitation occurrences ranged from seven in 1975, 1982, and 2005, to 23 in 2002. Extreme maximum sea level occurrences ranged widely from three in 1966 to 67 in 1983.

Table 4. Extreme threshold values (percentiles 5/100 and 95/100) and exceptionally extreme threshold values (percentiles 1/100 and 99/100) of hydrometeorological events in the Polish coastal zone of the South Baltic (1965–2014).

Place	Percentile	Maximum Air Temperature at 2 m AGL [°C]	Mean Air Temperature at 2 m AGL [°C]	Minimum Air Temperature at 2 m AGL [°C]	Precipitation [mm]	Maximum Sea Level [cm]	Mean Sea Level [cm]
Świnoujście	1/100	−4.6	−7.7	−11.2	0.1	464	455
	5/100	−0.5	−2.9	−5.4	0.1	478	471
	95/100	24.7	19.4	15.8	12.0	548	535
	99/100	29.0	22.2	18.1	22.3	576	557
Kołobrzeg	1/100	−4.6	−8.2	−12.0	0.1	464	458
	5/100	−0.4	−3.2	−6.0	0.1	478	472
	95/100	24.2	18.9	15.3	13.0	550	538
	99/100	28.8	21.7	17.4	26.1	577	558
Ustka	1/100	−4.7	−8.2	−11.8	0.1	465	459
	5/100	−0.6	−3.1	−6.0	0.1	478	473
	95/100	24.3	18.8	15.5	13.8	550	539
	99/100	29.0	21.7	17.8	25.7	573	558
Łeba	1/100	−5.0	−8.4	−12.9	0.1	–	–
	5/100	−0.8	−3.5	−6.8	0.1	–	–
	95/100	24.1	18.6	14.9	13.5	–	–
	99/100	28.5	21.5	17.3	26.2	–	–
Hel	1/100	−4.8	−7.0	−9.9	0.1	464	460
	5/100	−1.0	−2.8	−5.0	0.1	478	474
	95/100	23.8	18.9	15.6	12.2	548	539
	99/100	26.9	21.3	17.9	23.6	570	556
Gdynia	1/100	−4.8	−7.5	−10.5	0.1	–	–
	5/100	−0.9	−3.0	−5.4	0.1	–	–
	95/100	23.2	19.4	16.4	12.4	–	–
	99/100	26.7	21.9	18.9	23.4	–	–
Gdańsk	1/100	–	–	–	–	468	463
	5/100	–	–	–	–	483	478
	95/100	–	–	–	–	555	545
	99/100	–	–	–	–	578	563

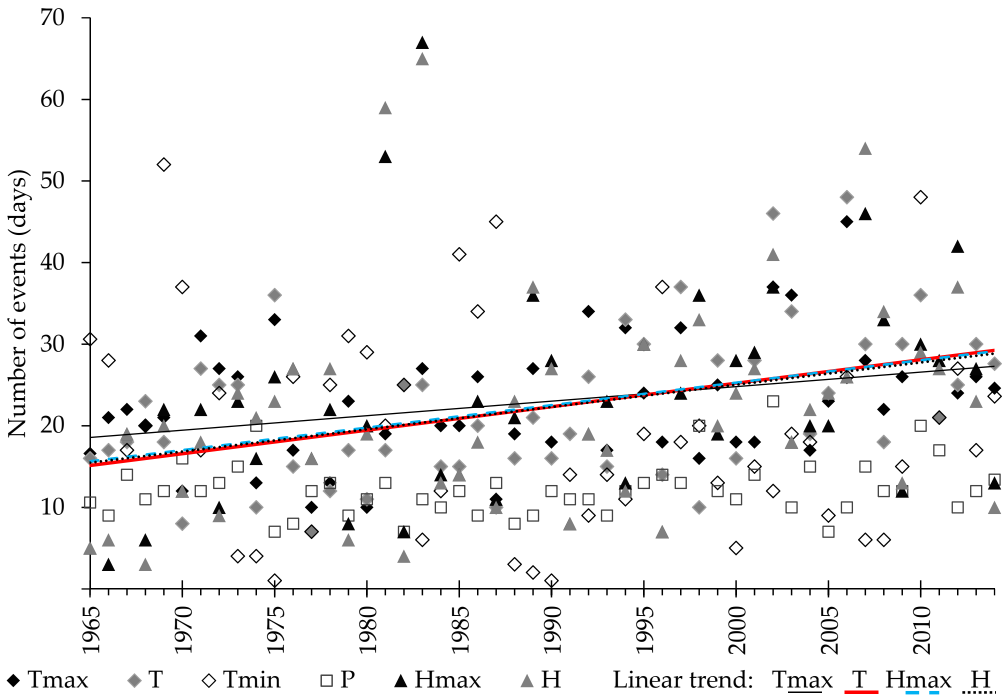

Figure 4. Occurrence of extreme hydrometeorological events in the Polish Baltic coastal zone.

Analysis of occurrence of extreme hydrometeorological events showed a high variability in time and space. In the whole coastal zone, the most extreme thermal events (over 100 cases in the five-year period) took place in the last three pentads (at the beginning of the 21st century) of the analyzed long-term period 1965–2104. This situation confirms the regularity of climate warming on the South Baltic coast. However, the occurrence of extreme precipitation and sea level was characterized by a large time-space heterogeneity. For example, a high frequency (over 50 days in the five-year period) of extreme rainfall events was recorded in Świnoujście in the last pentad (2010–2014) of the long-term period (1965–2014). On the other hand, in Ustka, the most extreme precipitation events were found in the periods 1969–1974 and 1995–1999. In the case of high sea level, the most extreme events (over 100 in the five-year period) occurred in the pentad 1980–1984 and the beginning of the twenty-first century (2000–2014) (Figure 5).

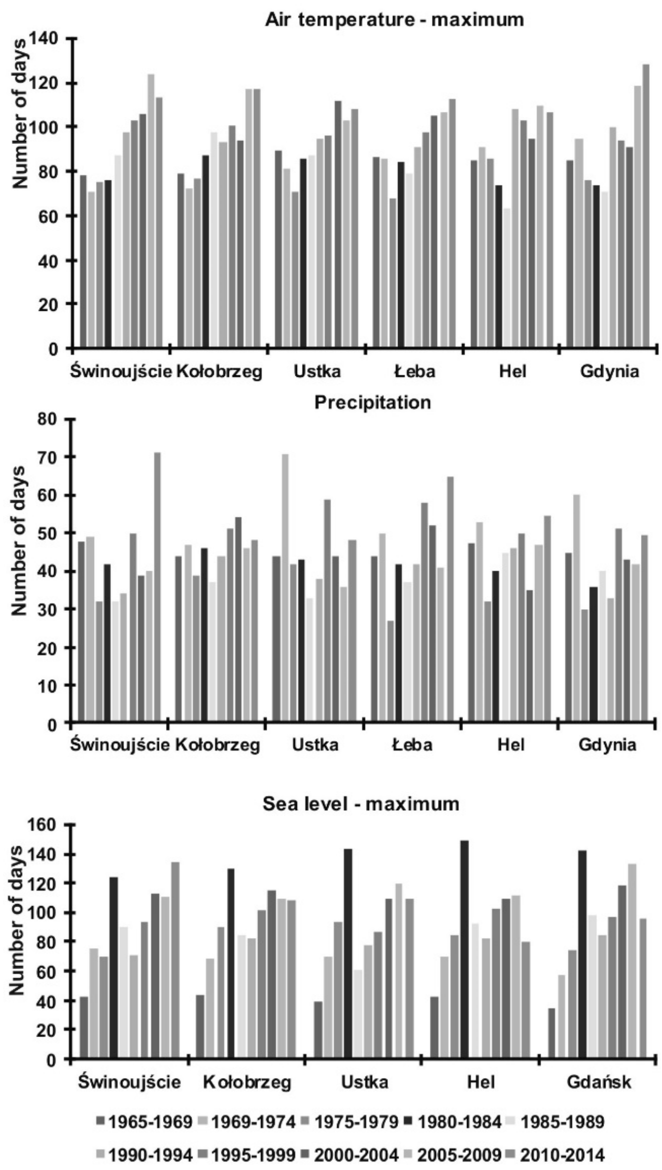

Figure 5. Temporal and spatial variability of the occurrence of extreme hydrometeorological events in the Polish coastal zone of the Baltic Sea.

4. Discussion

The methodology of separation, the threshold values for extreme events, and the temporal and spatial regularities of hydrometeorological conditions in this work are consistent with those in other works, especially those from the Baltic countries [9,13,25–31].

Certain quantitative discrepancies between threshold values may be a result of the theoretical distribution in the probability distribution analysis and the varied extent of input data. The Log-Gamma distribution for maximum monthly precipitation was similar to the gamma distribution for maximum monthly precipitation (i.e., $\geq$0.1 mm) for 1961–2010 [16]. For sea level, the best-suited theoretical distribution was the Generalized Logistic Distribution. In other works, the Gumbel Distribution is most often used [12,19]. The higher values of probability (excess) in this work were due to varying periods of input data and measurement intervals. This study analysed data from a uniform period (50 years, 1965–2014) measured at uniform daily intervals for each station (the number of entries for each hydrometeorological phenomenon at each station was ~18,250). In other works (e.g., [10]), the time period for sea level data varied (e.g., Świnoujście 1901–2006, Ustka 1948–2006) and the quantity of input data was significantly lower (mainly monthly data, e.g., Świnoujście < 1400 and Ustka ~800). The probability values for extreme sea levels obtained in this work were around 25 cm higher for a probability of 10% and 40 cm higher for a probability of 1% than those in other works on the probability of maximum seal levels in the South Baltic being exceeded [12,32]. The threshold values obtained for maximum sea level are realistic. For example, those with a probability of 0.1 (once per 1000 years) ranged from 2.68 (Gdańsk) to 3.21 (Świnoujście) meters above the average sea level (MAMSL). Similar sea levels with a 1000-year return period have been recorded in the Polish Baltic coastal zone, including 2.2 MAMSL on 13 November 1972 in Kołobrzeg [33], as well as in estuary sections of rivers during ice blockages, such as 2.67 MAMSL on 16 March 1956 in Wisła Świbno and 3.10 MAMSL on 21 March 1888 in Nogat [12].

Due to their probability and return period, extreme events rarely occur. This is why quantile analysis is more appropriate when using statistical methods, time decomposition, and extreme hydrometeorological event forecasting. It revealed an increase in the frequency of extreme sea level and air temperature events within the last 50 years. However, it did not reveal the same for atmospheric precipitation, which confirms that changes in precipitation, as well as in the number of days with extreme precipitation, are insignificant and spatially inconsistent [31,34]. Extreme hydrometeorological events occur at an especially high frequency during positive North Atlantic Oscillation (NAO). Deep, low-pressure centres from the Atlantic moving rapidly over the Polish Baltic coast are conducive to storm surges, effective atmospheric precipitation, and significant warming, especially in winter [35,36].

The extreme threshold values obtained using quantile analysis (e.g., of percentiles 5% and 95%) are similar to those obtained using the 3σ-rule, a common method for determining extreme events. The 3σ-rule can be used as a warning system for danger and abnormal hydro-meteorological conditions, preferably for normally distributed data. In this study, threshold values of the 95% and 99% percentiles (using the Generalized Logistic Distribution) for the maximum average sea level are very similar (+1% error) to values +2σ from μ and +3σ from μ (σ—standard deviation, μ—average). To determine the range of a specific data percentile for deviations of ±2σ and ±3σ from μ for thermal and precipitation data, specific distribution tables can be used (for temperature—Error (Exponential Power) Distribution, for precipitation—Log-Gamma Distribution). Nevertheless, the quantile classification used in this study to determine threshold values for extreme thermal and precipitation events is more appropriate than typical classifications based on the 3σ-rule.

Southern Baltic coasts are eroded during an extremely high sea level, especially during high storm waves and intense precipitation. Exceeding the set threshold values for medium and maximum sea level can be treated as a threat to extreme erosion of coastal dunes. An analysis of the correlation between the sea level and loss of coastal dunes in Poland has made it possible to define threshold values for potential erosion of the dune coast. Extreme values of sea level determined with the probabilistic method coincide with empirical studies favoring the erosion of coastal dune. Conditions during an average sea level of 602 cm and maximum of 636 cm are potentially beneficial to intensive erosion of the dune coast (>100,000 m^3) [18]. Thus, threshold values of the mean sea level > 596 cm and maximum sea level > 638 cm (Table 3) determined in this report based on the probabilistic method

(10% probability, once every ten years) constitute an important geoindicator for extreme erosion of dunes on the Polish coast of the Baltic Sea.

The threshold values for extreme mean sea level determined in the study (e.g., for Świnoujście 10% probability = 596 cm) are also a good indicator of cliff coast erosion (e.g., for the island of Wolin). Empirical cliff top recession rates studies in 1984–2014 showed that the statistically defined extreme sea level is responsible for significant transformation of the foot of the cliff and initiates mass movements [37]. This value is consistent with empirical research on coastal cliffs abrasion [38]. What is more, the thresholds for extreme precipitation, as defined in this paper, are a good indicator of the initiation of mass movements on the cliff coast. For example, the precipitation threshold value for Świnoujście is 49.8 mm with a probability of 10% (Table 3), which coincides with research on the impact of weather conditions on the dynamics of landslide processes on the shores of the Wolin Island, conducted in 2006–2009 by Winowski, et al. [38]. This author stated that the initiation of mass movements occurs when the daily sum of rainfall is higher than 40 mm, while for regular landslide processes, when daily rainfall is at least 60 mm.

Analyzing the 21st century Regional climate models (RCM) dealing with, among other things, changes in air temperature, precipitation, sea level, and storm surges, an increased frequency or crossing of thresholds for extreme hydrometeorological events in the Baltic Sea zone—set out in Table 3, may be expected in the nearest time. In the South Baltic region, the average annual air temperature is expected to increase in the 21st century by 2–3 °C, with an additional increase in atmospheric precipitation by 0–10% in the summer and 10–20% in the winter season [39]. It is also expected that the periods of heat will become more frequent and will last longer [40]. For the southern Baltic coast, most RCMs indicate an increase in frequent daily rainfall, both in winter and summer [41]. On the other hand, model simulations suggest a decrease in the number of days with atmospheric precipitation [42], which may increase the risk of long periods of drought [43]. It is predicted that in the 21st century, the sea level of the ocean will increase due to the loss of land ice masses and the thermal expansion of ocean water from 28 to 61 cm [44]. An absolute increase in sea level in the Baltic Sea is estimated at 80% of the global average [3]. For the south and south-west coast of the Baltic Sea, the estimated relative increase in the level would be particularly high, around 50–60 cm [45]. The hydrodynamic modeling performed assumes an increase of storm surges for the entire Baltic Sea in all seasons [46]. The size of the predicted increase in the case of long-term extremes by 5% or 10 cm is relatively small. Therefore, the absolute change of extremely high sea levels during storm surges will probably depend on the size of the average sea level change. This is particularly important for the Southern Baltic, where the largest increase in the average sea level is forecasted [47]. This will result in the increased erosion of dunes and cliffs and may contribute to damage to the coast's technical infrastructure (descent to the beach, technological conurbations, or existing bank fortifications).

5. Conclusions

Delimitation of threshold values for extreme hydrometeorological events in the Polish coastal zone of the Southern Baltic performed in the study allows for the following conclusions:

Threshold values were determined using the probabilistic method and quantile approach. The probabilistic method that captures the probability and return period of extreme events (10%, 1 time/100 years) is particularly useful for determining threshold values of extreme hydrometeorological events in the context of their impact on the dynamics of real geomorphological changes on the seacoast. Statistical threshold values of extreme sea level and atmospheric precipitation determined with this method are reflected in the empirical intensity of the erosion of coastal dunes and cliffs, e.g., an average daily sea level > 596 cm (10% probability) will generate the potential erosion of coastal dunes in the entire Polish coastal zone of the Baltic >100,000 m^3. Therefore, threshold values of hydrometeorological extremes determined by the probabilistic method are a good indicator of the risk of occurrence of erosion processes. On the other hand, the quantile approach due to a much higher frequency of events is very helpful for the time decomposition of the occurrence of extreme hydrometeorological events. It is then possible to determine the trend, cyclical, and seasonal variability of extreme hydrometeorological events. A positive trend (+3 days/10 years) of the occurrence of extreme events (95% percentile) as regards to air temperature and sea level was found.

Temporal and spatial diversity of threshold values of extreme hydrometeorological events was found in the Polish coastal zone of the Baltic Sea. The highest values of thermal extremes and sea level were found for the western part of the coast, in the Szczecin Pobrzeża region (Świnoujście and Kołobrzeg), and in the case of atmospheric precipitation in the central part of the coast, in the Pobrzeże Koszalińskie region (Ustka, Łeba). The eastern region, Gdańsk Coast, demonstrated the lowest threshold values of extreme hydrometeorological events. The most extreme hydrometeorological events occurred in the western region, on the Szczecinskie Coast, and the least in the central part of the coast, on the Koszalin Coast. Coasts of the Pomeranian Bay (Świnoujście and Kołobrzeg) and, to a lesser extent, Gdańsk Bay (Hel, Gdynia/Gdańsk), are the most threatened by the occurrence of extreme hydrometeorological events. The smallest threat occurs in the coastal zone of the open sea (Ustka, Łeba).

The beginning of the 21st century (2000–2014) had the highest frequency of extreme hydrometeorological events—average and maximum air temperature, as well as mean and maximum sea level. Such a situation is a manifestation of climate warming and sea level rise in the coastal zone of the South Baltic Sea.

Taking into account global and especially regional climate models prepared for the 21st century, one can expect an increase in the frequency of extreme hydrometeorological events in the near future (exceeding threshold values). This applies in particular to the maximum and average daily air temperature, daily sum of atmospheric precipitation, and maximum and average sea level.

Delimitation of extreme hydrometeorological events is significantly practical. Threshold values for seal level and thermal and precipitation events determine the extreme ranges of certain hydrometeorological conditions to which the economy should adapt. The threshold values presented in this study can be used to forecast changes in climatic and hydrological conditions in the Baltic coastal zone for the 21st century.

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