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Extreme sea levels and floods: the case study of Klaipėda City, Lithuania

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Abstract
Klaipėda City is located in the Southeast Baltic Sea region, where sea level rise has been observed for decades. The Klaipėda Strait, which separates the Baltic Sea and the Curonian Lagoon, where the port is located, is also more prone to sudden extreme changes in water levels, usually caused by windstorms. Extreme sea level changes pose a threat to port operations, technical structures, city residents, buildings, and infrastructure. Fluctuations in sea levels also affect the water level of the Danė River, which enters the Klaipėda Strait and divides the city into two parts. Therefore, this study aims to determine the past extreme sea level events and their influence on floods in the Danė River within Klaipėda City from 1961 to 2022. For this, the impact of meteorological parameters caused dangerous sea level rises in the Klaipėda Strait, and the following rise of the Danė River was studied. The results show that the annual mean, annual mean maximum, and annual mean minimum water levels in the Klaipėda Strait increased from 1961 to 2022. Also, the number of events where the water level in the Klaipėda Strait was ≥100 cm in the Baltic Elevation System was increasing. The increasing frequency of extreme water level events in the Klaipėda Strait puts urban areas at greater risk from Danė River compound floods.

Keywords
Baltic Sea; Coastal river city; Extreme sea levels; Storm surges; Compound flood

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1. Introduction

Coastal cities are threatened not only by rising water levels but also by hydrometeorological extremes. Long-term sea level variations in the Baltic Sea are associated with vertical crust movements and climate change, which lead to global sea level rise. The Baltic Sea mean sea level rise (MSLR) rate was slightly higher than the global average (Weisse et al., 2021). Long-term measurements of mean sea level in the Baltic Sea show an almost statistically significant acceleration (Hünicke and Zorita, 2016). The assessment of long-term sea level changes highlights that the highest future flood risk is expected to occur at the eastern ends of the Gulf of Finland and the Gulf of Riga, as well as in the Gulf of Gdańsk (Meier et al., 2004). The annual mean water level maximum rise 1961–2005 is also recorded in the Gulf of Finland and the Gulf of Riga, near Klaipėda, and in the south-western Baltic Sea (Pindsoo and Soomere, 2020). Short-term water level fluctuations are determined by changing air pressure and the effect of wind on the sea surface (Kulikov et al., 2015). Both long-term and short-term fluctuations in water levels, due to the geographical features of the Baltic Sea, manifest themselves very differently in different regions and have an impact on extreme sea levels. Numerical simulations have shown that the response of extreme sea level to wind speed perturbations is more complex in the Baltic Sea to wind speed perturbations and that return levels are found to increase more where they are already high, for example in the Gulf of Finland (Hieronymus et al., 2018). According to Meier (2015), sea level rise is more likely to increase the Baltic Sea surge levels.

In recent decades, the intensification of the westerly circulation has led to more rapid sea level rise, an increase in storm surges (extreme sea levels), and a rise in the maximum annual sea level (Wolski and Wiśniewski, 2021). Extreme sea level rise is partially driven by the average sea level that has risen overall over the last 100 years (Weisse et al., 2014). Extreme sea level rise by the end of this century is also projected under RCP4.5 and RCP8.5 scenarios (Vousdoukas et al., 2016, 2017). Sea level extremes are strongly linked to variability and changes in large-scale atmospheric circulation (Weisse et al., 2021), with large seasonal to decadal fluctuations (Weisse et al., 2017). Some parts of the Baltic Sea may have experienced an increase in the intensity of storm surges in recent decades (Pindsoo and Soomere, 2020), which may be linked to long-term changes in storm tracks (Hünicke et al., 2015).

Extreme sea levels in the Southeast (SE) Baltic Sea are usually caused by storm surges. The number of storm surges increased steadily on various Baltic coasts between 1960 and 2010 (Wolski et al., 2014). Formation of the storm surges depends on three components: the volume of water in the respective basins of the Baltic Sea (the initial sea level prior to preconditioning an extreme event); the action of tangential wind stress within the given area (wind directions: whether they are shore- or seaward; wind velocities; and duration of wind action); and deformation of the sea surface by the mesoscale, deep low-pressure systems passing rapidly across the Baltic, which then generate seiche like variations of the sea level in the Baltic (Wolski et al., 2014). Wolski and Wiśniewski (2021) identified and characterized two main types of storm surges: a surge driven by wind and a surge driven by sub-pressure associated with an active low-pressure area. Moreover, the authors emphasized that if these two factors act together at the same time, a major storm surge can occur. Short-term sea level rises in the SE Baltic region are mostly associated with wind updrafts caused by storms and hurricanes (Stonevičius et al., 2010). Gräwe et al. (2019) simulations also showed that sea level rise in the East Baltic region is most sensitive to the wind effect when prevailing westerly winds push the water from west to east. Eastern Baltic coasts, including Lithuania, are vulnerable to extreme hydrological events caused by western air masses (Dailidienė et al., 2006; Wolski et al., 2016).

The long-term sea level rise in the Klaipėda Strait from 1898 to 2002 was 13.9 cm, which is attributed to climate change (Dailidienė et al., 2006). Klaipėda was the third fastest in sea level maximum increase from 1961 to 2005 (5–7 mm yr^{-1}) after the Gulf of Finland and the Gulf of Riga (Pindsoo and Soomere, 2020). The average water level in the Klaipėda Strait increased by 21 cm from 1902 to 2018 (Čepienė et al., 2022).

Rising sea levels due to climate change increase the likelihood of extreme water levels, putting coastal cities located at river mouths at risk of flooding (Kirezci et al., 2020; Rutgersson et al., 2022). Storm surges pose a threat to low-lying areas under the influence of low-pressure systems (Kowalewska-Kalkowska, 2021). Storm surge flooding is common in coastal river cities. The water level of the Oder River due to storm-driven flooding has been analysed most comprehensively in the Baltic Sea basin by Kowalewska-Kalkowska (2021) and Kowalewska-Kalkowska and Wiśniewski (2009). The water level of the Odra River has been found to rise as a result of storm surges caused by wind and baric waves, combined with a large-scale system of northerly and north-westerly winds (Kowalewska-Kalkowska and Wiśniewski, 2009). There is a lack of research on storm-driven flooding in Baltic Sea rivers. An analysis of compound floods often encompasses the impact of the storm surge on the occurrence of river flooding. The frequency of compound floods was revealed over north-western Europe from 1901 to 2014 (Ganguli and Merz, 2019). The eastern Baltic Sea coast is predicted to experience an increase in the probability of compound flooding (Bevacqua et al., 2019).

The aim of this study was to determine the occurrence and frequency of extreme sea level events and their impact on flooding in the Danė River in Klaipėda during the years 1961–2022. Klaipėda is a coastal city where the river and sea potential for compound flooding increases flood risk areas (Čepienė et al., 2022). Sites close to water bodies are becoming increasingly attractive for the development of new residential communities. However, further development of such places without considering the implications of climate change might make them more vulnerable to flooding. At the national level, the socio-economic losses caused by extreme hydro-meteorological events will then be higher. Sustainable spatial planning in flood risk areas requires knowing hazards and risks.

2. Study site, materials and methods

2.1 Study site

Klaipėda is a river city located on the southeastern coast of the Baltic Sea. The city experiences short-term variations in sea level due to the influence of westerly and south-westerly winds (Dailidienė et al., 2006, 2012; Gräwe et al., 2019; Wolski and Wiśniewski, 2021). Klaipėda city has a shoreline along the Curonian Lagoon and the Klaipėda Strait, which connects the lagoon to the Baltic Sea (Figure 1).The Klaipėda Seaport, a significant national asset, is situated along the Klaipėda Strait. The urban area of Klaipėda is geographically split by the Danė River, which flows into the Klaipėda Strait. The river is called Akmena-Danė from its origin in the Klaipėda Strait. The river in the urban area of Klaipėda has the name Danė, whereas outside the city territory, it is known as Akmena.

The Danė River is prone to compound floods, and in the center of Klaipėda, the short-term extreme rise of the water level in the Klaipėda Strait has the greatest impact on them (Čepienė et al., 2022). The magnitude of flooding in the city is determined by regional factors such as atmospheric circulation, westerly and south-westerly winds, short-term rises in the water level due to storm surges, and local factors such as the topography, the discharge of the Danė River, the riverbank type of reinforcement, and the protective measures in place.

The Klaipėda Strait has significant variations in water level, with a high amplitude of extreme fluctuations. According to Dailidienė et al. (2006), the amplitude in the

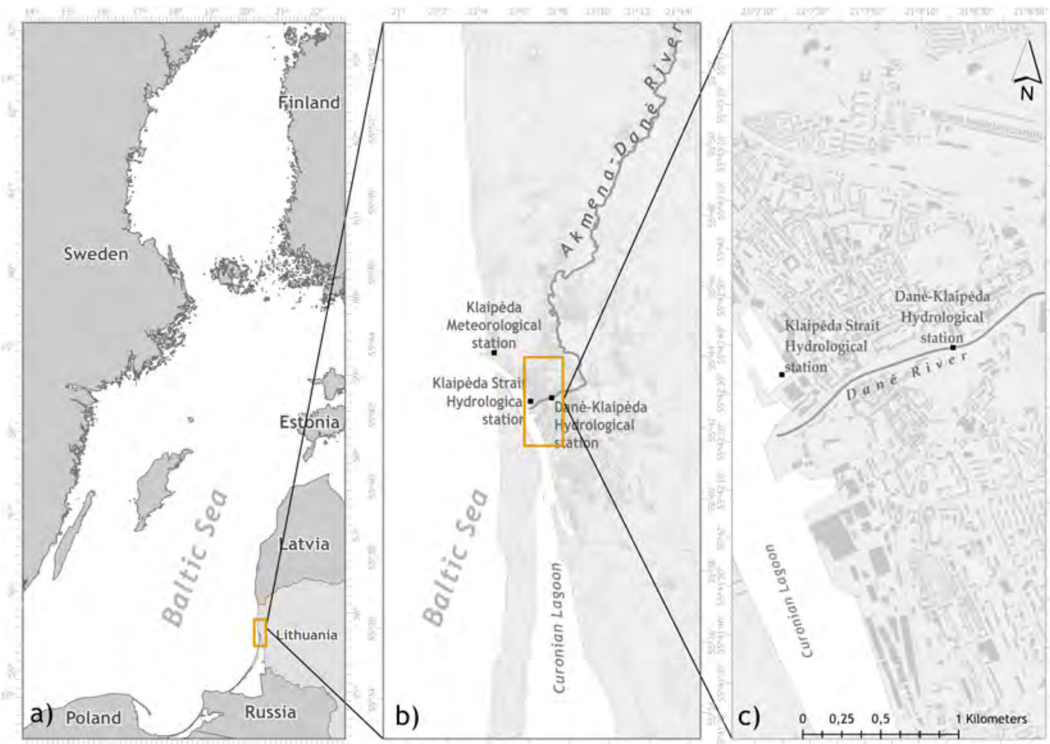

Figure 1. The study area: South-eastern part (SE) of the Baltic Sea (a); the Klaipėda Strait, which connects the Curonian Lagoon with the SE Baltic Sea and the Danė River (b); Klaipėda city (c).

years 1961–2002 displayed fluctuations ranging from a maximum observed value of 186 cm in 1967 to a minimum of −91 cm in 1984. The fluctuations in water levels pose a significant risk to the urban environment, including the city's infrastructure and the efficient operation of its port facilities.

A high water level event in the Klaipėda Strait is called a surge when the water level exceeds the 100 cm threshold in the Baltic Elevation System (BS) or when the water level exceeds the 600 cm threshold in the Lithuanian State Elevation System LAS07 (On Approval (...), 2020). A water level of 650 cm is considered to be a very high water level or an extreme event.

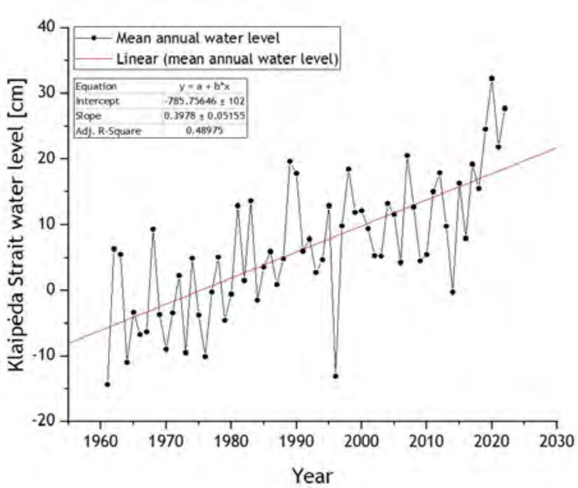

Figure 2. Klaipėda Strait mean annual water level (BS) trend, 1961–2022.

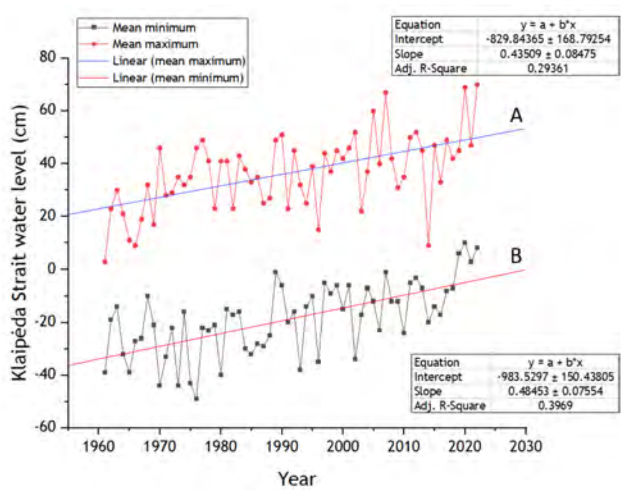

Figure 3. Annual mean water level maximum and annual mean water level minimum (cm, BS) trends in the Klaipėda Strait, 1961–2022.

2.2 Material and methods

The objective of this study was to analyse the impact of extreme and high sea level events on flood occurrences in the Klaipėda Strait. A study was carried out on the fluctuations in sea level, specifically the annual mean, annual mean maximum, and annual mean minimum water levels. This analysis was based on meteorological and hydrological monitoring data collected in the Klaipėda Strait for a period of 61 years (1961–2022). The Lithuanian Environmental Protection Agency and the Lithuanian Hydrometeorological Service are responsible for the hydrological and meteorological observation data. The study uses data from the Klaipėda Strait Hydrological Station since 1961, coinciding with the establishment of the Baltic Elevation System (BS) in Lithuania and other Eastern Baltic states. This BS is based on the tide gauge at Kronstadt (−500 cm). Sea level measurements in the Klaipėda Strait are conducted using a mareograph, which was later replaced by an automated water level measuring station that had data transmission capabilities. The analysis of Klaipėda Strait and the Curonian Lagoon data is based on hourly, daily, and monthly average, minimum, and maximum records. Trend analysis was used to identify long-term trends in water levels. The use of linear regression was applied to evaluate trends, while correlation analysis was used to investigate the relationship between various time series of hydro-meteorological indicators. The coefficient of determination R^2 (r-squared) of a linear regression characterizes the strength of the relationship. The significance of the regression equation is enhanced when the $R^2 > 0.25$ (Borradaile, 2003; Čekenavicius and Murauskas, 2004). The quantity R is equal to the Pearson correlation coefficient. The relationship between wind speed, atmospheric pressure, and changes in water level in the Klaipėda Strait was investigated using the Pearson correlation coefficient. Using the same correlation coefficient, the water levels of the Danė River in the city center and the Klaipėda Strait were correlated.

The research involved the selection of historical records from the archives to identify cases of high (100 cm (BS)) and extreme (150 cm (BS)) water level thresholds in the Klaipėda Strait. Six cases from the years 2000 to 2022 were selected for further analysis: (a) four cases when the water level reached the 130 cm threshold (BS), and (b) two cases when the water level reached the 150 cm threshold (BS). Data on sea level were compared with the meteorological situation. The meteorological data was obtained from the Klaipėda meteorological station, which is situated in close proximity to the Baltic Sea (Figure 1). The air pressure maps were obtained from the Meteorological Office, Bracknell, UK.

In order to assess the areas at risk, a flood exposure map was generated for the Danė River, specifically when the water level in the Klaipėda Strait reached 200 cm. This water level corresponds to a 1% probability of occurrence on average, indicating that such an event may occur once in 100 years and is considered a catastrophic water level (Environmental Protection Agency, 2018, 2020). This water level is relatively close to the extreme water level in the past. The map shows the geographical locations of residential areas, structures, and roadways that are susceptible to potential floods. The visualization was done with ArcGIS Pro.

In order to determine how an increase in sea level in the Klaipėda Strait would affect the compound floods of the Danė River, the water level of the river was analysed in the years 2020–2022. The water level of the Danė River in the city's center, about 1.3 kilometers away from the Curonian Lagoon, is monitored by the Lithuanian Hydrometeorological Service. Measurements started in 2008, although the collection of data for hourly water levels began just in 2018.

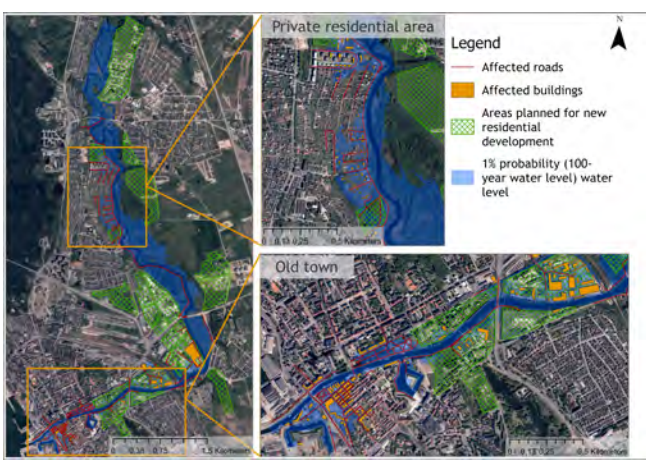

Figure 4. Flood scenario if the water level in the Klaipėda Strait were to rise 200 cm (BS) at the average annual maximum discharge of the Danė River (59 $m^3\ s^{-1}$).

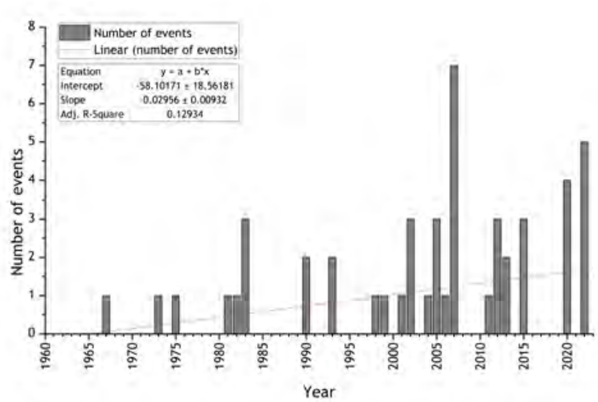

Figure 5. Number of events where the water level in the Klaipėda Strait were ≥100 cm (BS), 1961–2022 (n = 48).

3. Research results

3.1 Long-term water level variability in the Klaipėda Strait

The mean annual water level (Figure 2) as well as the annual mean water level maximum and annual mean water level minimum significantly increased from 1961 to 2022 (Figure 3). The Klaipėda Strait had a statistically significant increase in its mean annual water level, with a recorded rise of around 3.9 ± 0.05 mm per year^{-1} for the period 1961–2022 (Figure 2). In the same period the annual mean water level maximum rose on average by 4.3 mm year^{-1}, and the annual mean water level minimum -4.8 mm year^{-1} (Figure 3).

The increase in annual mean, maximum and minimum sea level in the study region can be explained by the global sea level rise, but also by the change in atmospheric circulation. The intensification of westerly atmospheric circulation is closely related to the increasing water level in the SE Baltic Sea. The study results show that the extreme flood events in the lower reaches of the Danė River rise are related to the changes and increase trends of the sea level in Klaipėda Strait.

3.2 Extreme water level events in Klaipėda Strait

The first case of water level reaching a threshold of 100 cm (BS) in 1961–2022 was recorded in 1967. With a recorded rise of 186 cm in water level, this particular example is often regarded to be the most extreme event in documented history. This rise can be attributed to the predominant north-westerly wind, with gusts as high as 40 m s^{-1} and an average daily speed of 15 m s^{-1}.

When developing predictions for the future, it is essential to consider both potential extreme and long-term water level rise in the Klaipėda Strait. Therefore, a water level of this magnitude might be considerably more extreme and damage the city's economy and social structure significantly. The extent of the damage is additionally affected by the development of port activities in recent decades, the proximity of public areas to the water, and the development of private residential areas that are at risk due to increasing water levels.

According to the presented case, Figure 4 illustrates the flood scenario in Klaipėda City, depicting the affected road network and buildings within the flood zone. This flood scenario does not correspond to the 1961 case but it is close to it. Although it Based on a previous study (Čepienė et al., 2022), the magnitude of the flood may be even higher when the effect of climate change is considered. This scenario assumes a water level increase of 200 cm in the Klaipėda Strait, coinciding with the average annual maximum discharge of the Danė River, which is recorded at 59 m^3 s^{-1}. In such a scenario, the Old Town and the private residential area in the northern part of the city would be most at risk. The severity of floods may be increased by the variability in the flow of the Danė River, which is directly influenced by precipitation patterns. The General Plan of Klaipėda City Municipality (2021) approves the

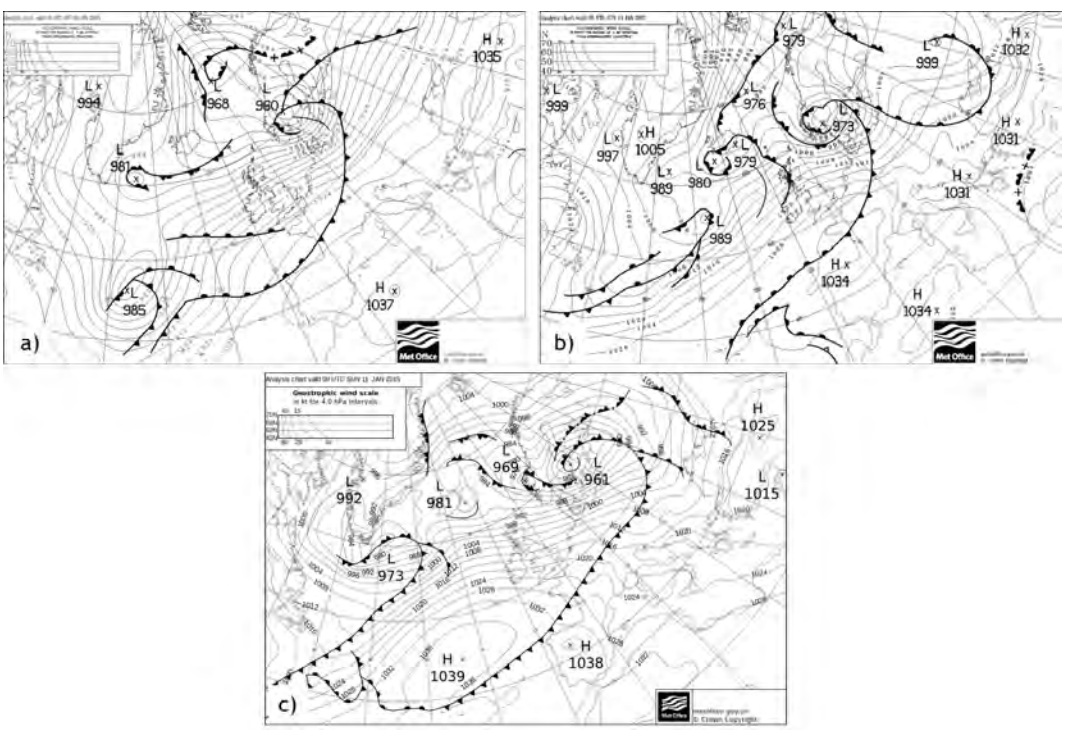

Figure 6. Weather maps: 8 January 2005, 18:00 UTC (a); 14 January 2007, 06:00 UTC (b); 11 January 2015, 00:00 UTC (c). Source: Meteorological Office, Bracknell, UK.

Table 1. Hydrological and meteorological parameters of the selected events in 2000–2022.

Date of storm event	Recorded Klaipėda Strait water level				Meteorological data				
	Max [cm]	Min [cm]	Amplitude [cm]	Daily average	Mean wind speed [m s^{-1}]	Maximum wind speed [m s^{-1}]	Mean wind direction	Atmospheric pressure. Maximum depth (P_{min}) at Klaipėda meteorological station level [hPa]	Duration (hours) of exceeding the mean sea level by 100 cm
29 January 2002	137	32	105	76	16.5	32	W	992.9 (time 00.00)	4
8 January 2005	154	48	106	70	8.4	28	SW	993.3 (time 21.00)	7
14 January 2007	143	57	86	91	10.10	29	SW	997.1 (time 9.00)	11
11 January 2015	137	48	89	96	12.00	29	W	978.2 (time 02.00)	9
12 March 2020	173	40	133	78	8.3	26	SW	988.1 (time 18.00)	6
19 February 2022	132	35	97	79	5.4	27	W	978.1 (time 05.00)	4

assignment of certain areas for residential development to reduce the migration of people to suburban areas. Some areas are situated within flood-prone zones, hence increasing the potential socio-economic harm in possible extreme situations.

Throughout the study period, 48 cases of water levels reaching 100 cm (BS) thresholds were recorded, including 34 cases between 2000 and 2022 (Figure 5). There were 5 cases when the water level exceeded thresholds of 150 cm, including the most extreme 18 October 1967 event, hurricane Anatol on December 4, 1999, hurricane Gudrun (Erwin) on January 8–9, 2005, and cyclone Laura on March 12, 2020. The water level in the Klaipėda Strait rose to 165 cm (BS) during hurricane Anatol, and there was a westerly wind blowing with an average speed of 19 m s^{-1} and a gust of 38 m s^{-1}, the mean atmospheric pressure was 979 hPa.

38 of the total events or the number of days where the water level rose over 100 cm (BS) took place in the winter, including 6 in December, 21 in January, and 11 in February. This is about 80% of all the occurrences. The recurrence of extreme water levels is typically related to the presence of robust cyclonic winds offshore of the Lithuanian shore, where the average wind velocities occasionally exceed 33 m s^{-1} (Vaidogas et al., 2011). There were 23 events where westerly and 17 cases where south-westerly winds were the predominant directions that raised the water level. Between 1993 and 2021, these wind directions including southerly winds were the most common along the Lithuanian coast (Šakurova et al., 2023). Notably, the strongest winds are observed during the winter season (Katinas et al., 2017).

In the study, events are defined as the number of days when the water level reaches the 100 cm (BS) threshold. The years 2007, 2020, and 2022 were characterized by a significant multitude of events. All the days when the water level rose in 2007 (11, 13, 14, 19, 20, 21, and 22 days) occurred in January. The water level exceeded 100 cm on the dates of February 25th, 26th, and 27th in 2020, with the highest recorded water level observed on March 12th. The water level exceeded 100 cm on the dates of February 17, 19, 21 and 25 in 2022. This observed increase in water level implies a potential increase in both the frequency and duration of these events.

The cases between 2000 and 2022, when the water level has reached 130 cm (BS) threshold, were chosen for additional analysis in this study. There were a total of 6 cases or 7 days, as during Hurricane Gudrun (Erwin) on January 8–9, 2005, when water level exceeded 100 cm on two consecutive days (Table 1). In every case the daily amplitude demonstrates that the peaks in water level are momentary. High water level ($\geq$100 cm) persists from 4 to 11 hours.

Deep low-pressure systems have an impact on the entire topography of the Baltic Sea, causing floods in some

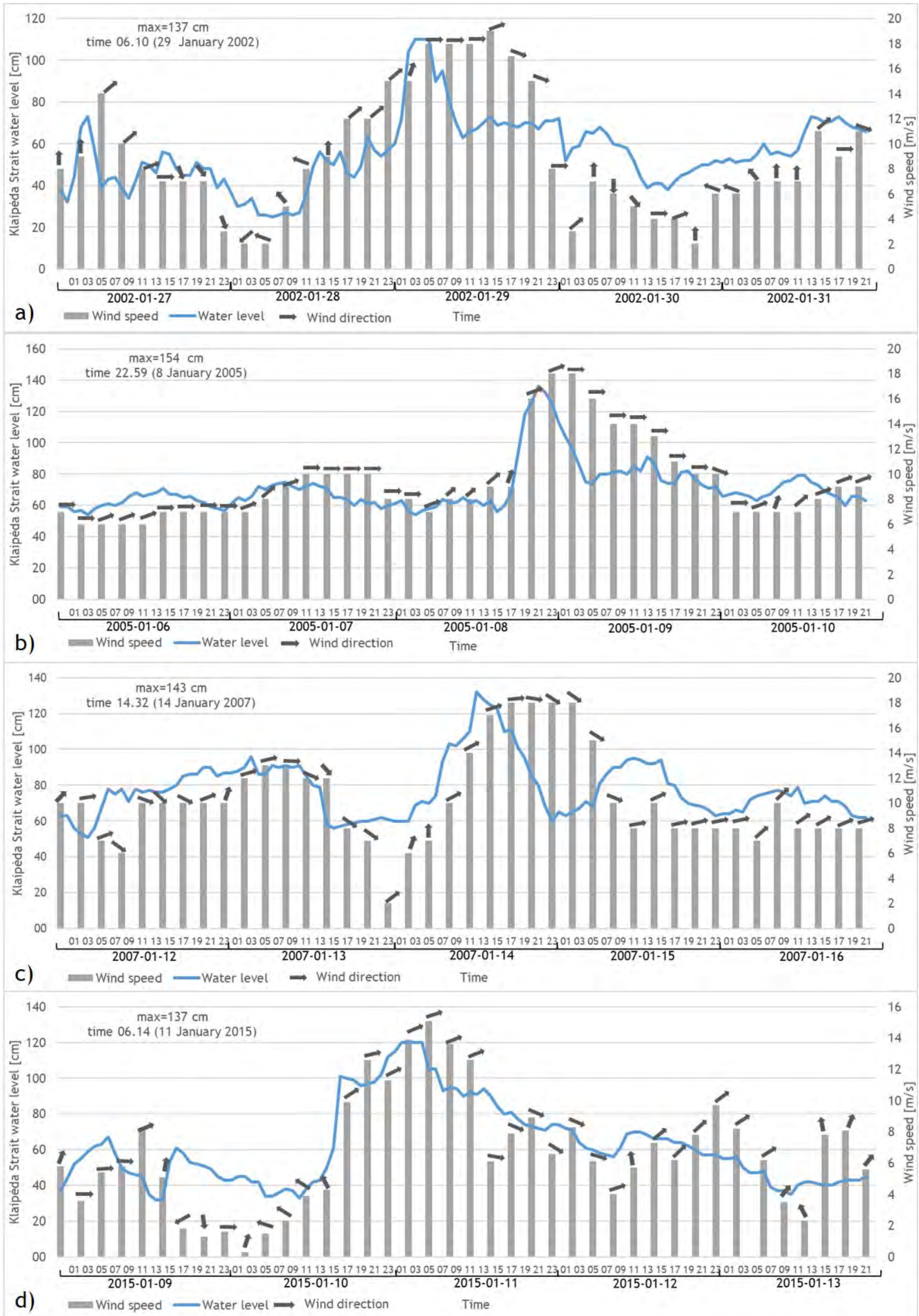

Figure 7. Changes in water level at Klaipėda Strait against the background of wind speed and direction: from 27 to 31 January 2002 (a); from 6 to 10 January 2005 (b); from 12 to 16 January 2007 (c); from 9 to 13 January 2015 (d).

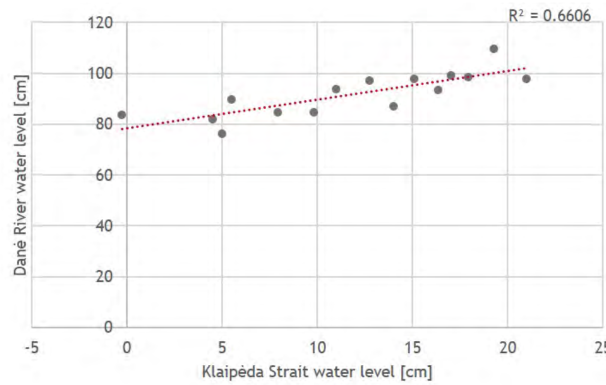

Figure 8. The relationship between mean annual water levels of the Klaipėda Strait and the lower reaches of the Danė River, 2008–2022.

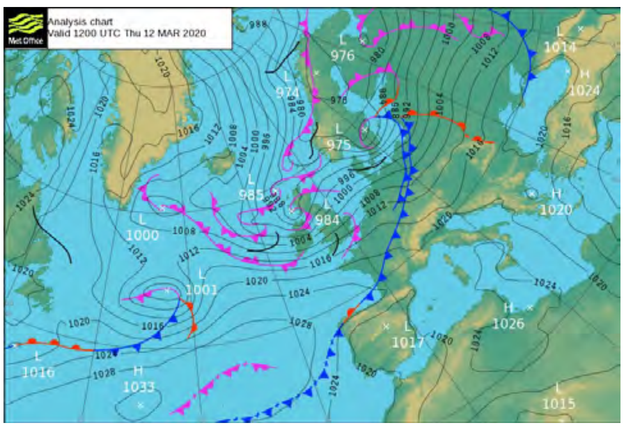

Figure 9. Weather map on 12 March, 12:00 UTC (14:00 local time). Source: Meteorological Office, Bracknell, UK.

areas and subsidences in others, which contribute to the development of sea level rise (Wolski et al., 2014). Extreme hydrometeorological events in Europe are linked with cyclones, as indicated by studies conducted by Owen et al. (2021) and Pepler and Dowdy (2021). The occurrence of peak water levels in the Klaipėda Strait and the lower reaches of the Danė River, as well as the occurrence of compound flooding in the city of Klaipėda, may primarily be attributed to the presence of intense winds accompanied by cyclonic circulations.

On January 29, 2002, during a storm, the Klaipėda meteorological station recorded a maximum air pressure depth of 992.9 hPa (Table 1). With an average wind speed of 16.5 m s^{-1} and gusts nearly reaching a catastrophic speed of 32 m s^{-1} (hurricane-force winds $\geq$32.7 m s^{-1}), the westerly wind direction was predominant in Klaipėda on that particular day. Due to weather conditions, the water level in the Klaipėda Strait rose to 137 cm (BS).

During the case of hurricane Gudrun (Erwin) on January 8–9, 2005, a group of deep atmospheric low-pressure systems connected to frontal systems resulted in the predominance of southwest and west wind fields over the Baltic Sea. Consequently, this meteorological phenomenon led to an increase in water levels in the Klaipėda Strait (Wolski et al., 2014). At the Klaipėda meteorological station, the recorded atmospheric pressure was 993.3 hPa, whereas a cyclone in southern Scandinavia reached a maximum depth of 960 hPa (Figure 6a). During the second day of the storm, the mean wind speed was 15 m s^{-1}, while the wind gusts reached an extreme speed of 28 m s^{-1}. A south-westerly wind blew on the first day and a westerly on the second. The occurrence of higher water levels in the Klaipėda Strait is influenced by intensified south-westerly winds, which in turn affect the rise of the Baltic Sea water off the south-eastern Baltic coast. Additionally, the Curonian Lagoon's waters are being pushed northward by south-westerly winds and toward the Klaipėda Strait. This leads to extreme water level rises in the Klaipėda Strait and thus in the Danė River. These meteorological conditions led to a significant increase in the water level in the Klaipėda Strait, exceeding 150 cm (BS). This rise in water level is considered an extreme event.

Maximum water levels in the Klaipėda Strait occurred on 14 January 2007, as a result of a low-pressure cyclonic system across southern Scandinavia (Figure 6b). Although the Klaipėda Strait reached a high water of 143 cm (BS) which is considered an emergency, the maximum winds (29 m s^{-1}) did not exceed hurricane levels.

On January 11, 2015, during the case of hurricane Felix (Figure 6c) a prevailing westerly wind with gusts reaching 29 m s^{-1} was observed over the southeast coast of the Baltic Sea. The height of the water level in the Klaipėda Strait was 137 cm (BS). This storm was not as powerful as previous storms and the damage to Lithuania's coastline was severe (Jarmalavičius et al., 2015).

Figure 7 illustrates how meteorological factors, such as wind speed and direction, affected the water level in the Klaipėda Strait during the hurricanes and storms in 2002, 2005, 2007 and 2015. The changes in water levels and the maximum levels observed in the Klaipėda Strait are dependent upon the speed and direction of the wind. Furthermore, the time in which the water level had its most significant increase coincided with the occurrence of the lowest atmospheric pressure.

Between the mean annual water levels of the Klaipėda Strait and the Danė River, a correlation coefficient (Figure 8) determined for the period 2008–2022 reveals a significant relationship ($R = 0.81$). As hourly meteorological and hydrological data have been available from 2011, allowing for more details case analysis, the last two cases will be analysed separately by integrating the Danė River water level data.

3.2.1 12 March 2020 event

The Klaipėda Strait reached a water level of 173 cm on March 12, 2020, which is over the extreme water threshold. When cyclone Laura, with a depth of 975 hPa, was

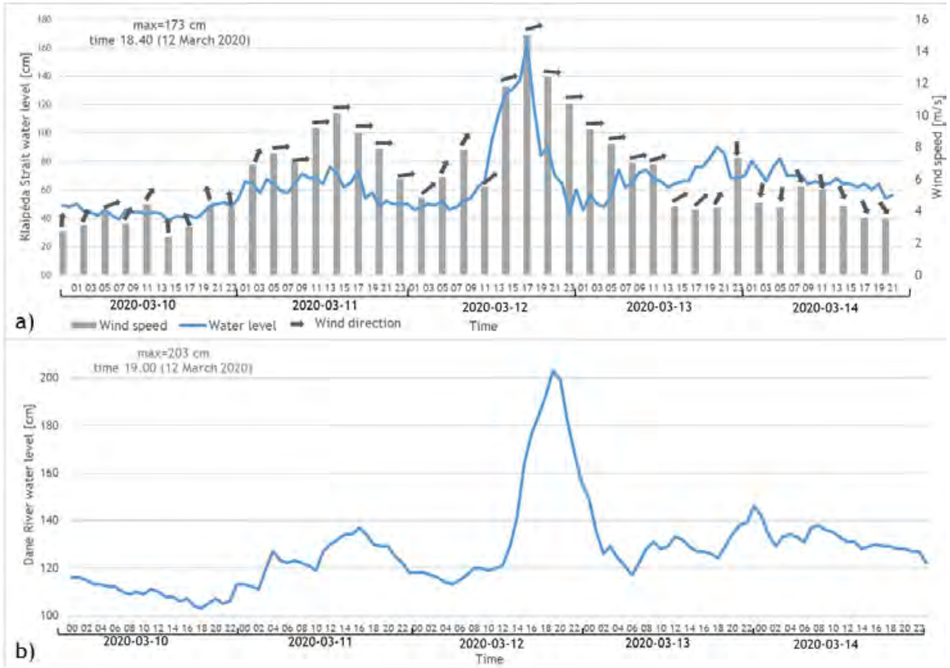

Figure 10. Changes in water level at the Klaipėda Strait against the background of wind speed and direction from 10 to 14 March 2020 (a); hourly water level of the Danė River in the centre of Klaipėda from 10 to 14 March 2020 (b).

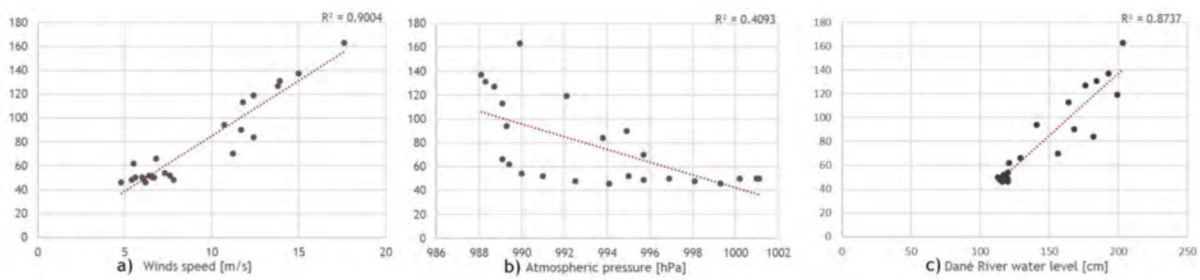

Figure 11. Relationship on 12 March between Klaipėda Strait water level (cm, BS) and: wind speed (a), atmospheric pressure (b), Danė River water level (c).

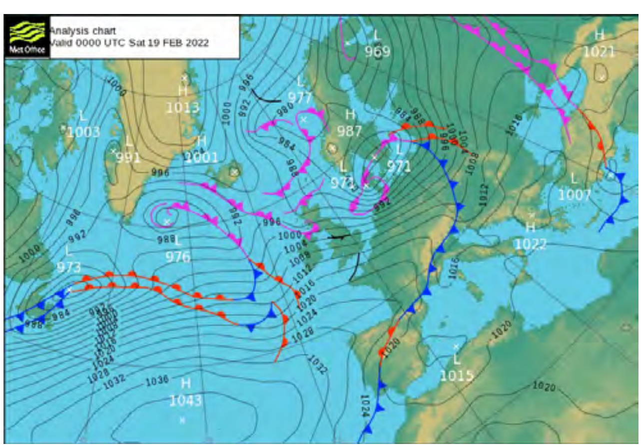

Figure 12. Weather map on 19 February, 00:00 UTC (02:00 local time). Source: Meteorological Office, Bracknell, UK.

over southeast Sweden at 14:00 local time, the lowest atmospheric pressure was recorded at 18:00 local time at 988.1 (Figure 9). The wind speed reached its maximum of 26 m s^{-1} in a westerly direction, occurring one hour after the minimum air pressure was recorded. Throughout the day, the average wind direction remained predominantly south-west. Simultaneously, the maximum water level in the Klaipėda Strait was observed.

The previous cases have demonstrated a strong dependence between the fluctuation of water levels in the Klaipėda Strait and both wind speed and direction. In this case, there is also a dependence between fluctuations in water level, wind direction and wind speed (Figure 10a and Figure 11a). The maximum increase in water level coincides with the recorded maximum wind speed, as well as the maximum water level in the lower reaches of the Danė River (Figure 10b). A south-westerly wind causes the

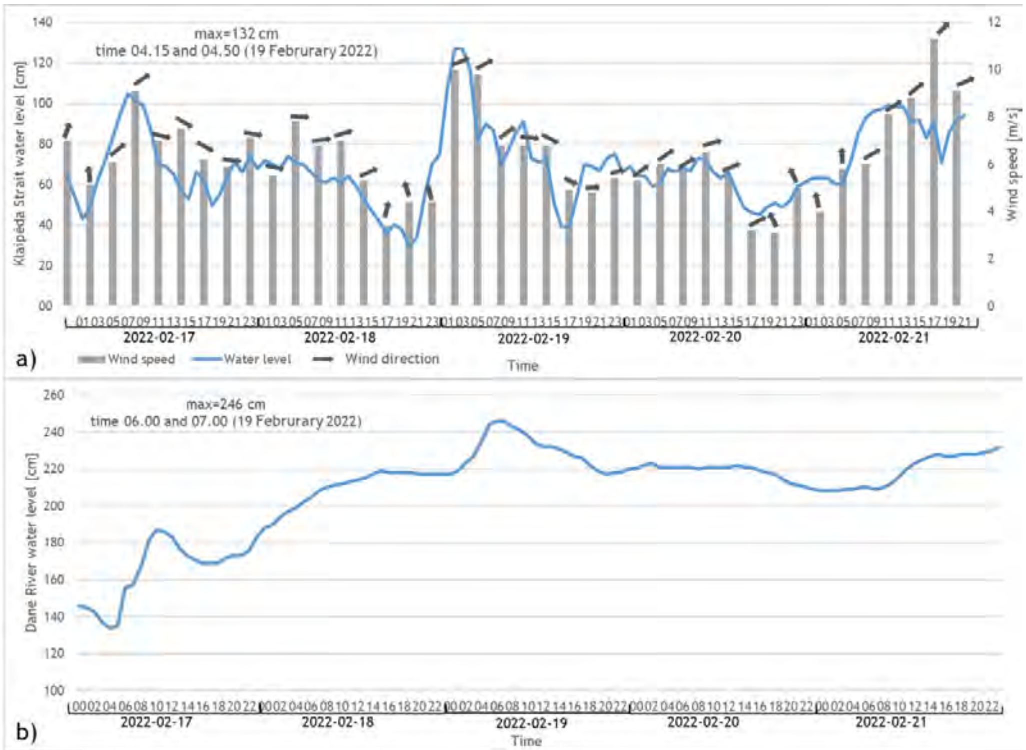

Figure 13. Changes in water level at the Klaipėda Strait against the background of wind speed and direction from 17 to 21 February 2022 (a); hourly water level of the Danė River in the centre of Klaipėda from 17 to 21 February 2022 (b).

water level to rise immediately. The water level decreases when the wind decreases and changes direction. The correlation between water levels in the Klaipėda Strait and wind speed is stronger compared to that with atmospheric pressure (Figure 11b).

A graph of hourly water level data for Danė River (Figure 9b) shows an obvious correlation between the water level of the river and the water level of the Klaipėda Strait. The calculated correlation coefficient ($R = 0.93$) indicates a significant relationship (Figure 10c) The maximum water level in the Danė River, measuring 203 cm, was recorded at 19:00 during the storm. This occurred 20 minutes after the maximum water level of 173 cm was observed in the Klaipėda Strait.

3.2.2 19 February 2022 event

In Klaipėda, February 2022 was a particularly stormy month. Stormy weather was caused by three storms: Dudley, Eunice and Franklin. During approximately one week, specifically from 16th to 21st February, a series of low-pressure systems passed through northwestern Europe and northern central Europe, mainly affecting the southern regions of Ireland and England, as well as northern Belgium, the Netherlands, the northern part of Germany, and the southwestern area of the Baltic Sea region (Mühr et al., 2022).

During the Eunice storm on 19 February, a storm surge formed in the Klaipėda Strait, resulting significant increase in water level by 132 cm (BS). At 05.00 local time, the Klaipėda meteorological station recorded the minimum atmospheric pressure of 978.1 hPa. Within the cyclone bar system, the lowest pressure recorded was 971 hPa at 00.00 UTC, located in the south-west Sweden (Figure 12). The pressure field and the steeper bar gradients show a predominance of stronger south-westerly winds in the south-eastern part of the Baltic Sea. The wind speed reached its maximum around 04:00 local time (02:00 UTC), coinciding with the greatest increase in water level in the Klaipėda Strait. This increase maintained until 05:00 (03:00 UTC).

From 17–21 February, the presence of cyclonic circulation in the Klaipėda Strait and the lower reaches of the Danė River resulted in the generation of maximum water levels and their predominance over an extended duration. The water level has reached the 100 cm threshold several times these days, with a peak of 132 cm observed on 19 February (Figure 13a). This rise and fluctuation in water levels was driven by three storms over Europe.

The Danė River had its highest increase in water level, measuring 246 cm, approximately 2 hours after the maximum water level of 132 cm observed in the Klaipėda Strait (Figure 13b). The highest water levels in the Danė River are caused by two factors: the increase in water level in the Klaipėda Strait and the duration of the strong westerly and south-westerly winds. These wind patterns contribute to the rise in water levels (Figure 14). The prolonged rise of the maximum water level of the Danė River (Figure 13b) is linked to a combination of factors. The prevalence of

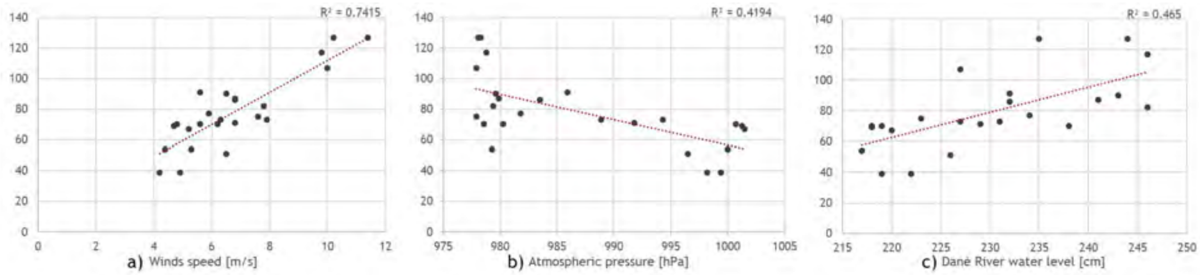

Figure 14. Relationship on 19 February between Klaipėda Strait water level (cm, BS) and: wind speed (a), atmospheric pressure (b), Danė River water level (c).

cyclonic circulation during the January–February 2022 period resulted in intensified precipitation. Additionally, an ongoing rise in sea level in the southeastern Baltic Sea, coupled with raised water levels in both the Curonian Lagoon and the Klaipėda Strait, compounded the situation.

On 19 February, flooding of the Danė River was observed throughout the entire territory of Klaipėda City. Pedestrian and bicycle paths, other recreational infrastructure, a part of the territory of the Klaipėda University Botanical Garden, and the steep bank of the meander had all been inundated. Some of these locations are 9 kilometers away from the Klaipėda Strait.

4. Discussion and conclusions

The water level rise in the Klaipėda Strait is being affected by climate change, which therefore amplifies the probability of maximum flooding occurrences in the port city of Klaipėda. In the region situated along the south-eastern coast of the Baltic Sea, there has been a consistent increase in sea levels at an average annual rate of 3.9 mm during the years 1961–2022. It is important to emphasize that both the annual mean water level maximum and annual mean water level minimum increased as well as the average annual water level. The increase in sea level is closely related to the changes in the atmospheric circulation patterns. It was assumed, that there is a strong correlation between the long-term variations of the winter North Atlantic Oscillation (NAO) index and the long-term annual mean sea level of tide gauges in the Klaipėda Strait and Curonian Lagoon. The correlation coefficient between these variables during the period of 1961–2005 ranged from 0.53 to 0.60, with 99% significance ($p < 0.01$) (Dailidienė et al., 2006). Furthermore, the relationship between the long-term changes in sea level and the winter NAO index was found to be stronger than the relationship between changes in air and water temperatures. Large-scale atmospheric circulation and the variations of the Baltic Sea's climate are known to be closely related (Hurrell et al., 2003; Omstedt et al., 2004; BACC I, 2008; BACC II, 2015). The frequency of air mass from west to east has increased, potentially impacting the magnitude of the sea level rise.

In recent decades, there has been a notable increase in the frequency of intense storms. For example, very high water levels were observed only 1–2 times per 50 years during the start of the 20th century, but in more recent decades, they have been seen every 5–7 years. The observed phenomenon can be attributed to the rise in regional storm activity and the increased occurrence of westerly wind (Dailidienė et al., 2012). The occurrence of increased water levels in the Klaipėda Strait and the lower reaches of the Danė River, as well as occurrence of compound floods in Klaipėda, can be attributed to the prevailing intense winds accompanied by cyclonic circulation. An increase in cyclonic circulation is noted during the cold season. Typically, the months of December to March exhibit an increased occurrence of intensified storms and increased occurrences of floods. During the study period 1961–2022, a total of 48 cases were recorded in which the maximum water level reached a high water level threshold of 100 cm BS. Of the total number of extreme water level rises, about 71% (34 cases) occurred between 2000 and 2022. The number of extreme water levels has increased since the beginning of the 21st century.

The results of the study indicate a correlation between the increase in water levels in the Klaipėda Strait and a corresponding increase in water levels in the lower reaches of the Danė River. Therefore, the rise in water levels caused by the storm has a significant influence on the occurrence of floods and amplifies the built-in vulnerability of the urban area. The research did not analyze the Danė River flow and its susceptibility to flooding in relation to precipitation patterns. However, it is important to note that historical records indicate a significant rise in the water level of the Danė River, approximately 2.5 meters, during the month of November in 2017, which can be explained by heavy precipitation events. The technical specifications of urban surface water collection systems had a major impact what happened. In the future, it is important to assess an integrated analysis of all the factors contributing to flooding and to identify vulnerabilities of the coastal community. This approach could help the adjustment to possible negative impact of storms in the future, assessing potential socio-economic losses, mitigating impacts, and reducing or avoiding socio-economic damage (Sinay and Carter, 2020).

With a changing climate, increasing recurrence and potentially higher magnitude of extreme events, it would be appropriate for coastal river communities to analyse multiple flood scenarios. This can help to adapt to potential threats in order to avoid socio-economic losses while planning and developing areas near water bodies. The two given case studies show the dependence between the water level of the Danė River and the fluctuations in the water level of the Klaipėda Strait. These fluctuations are affected by several variables such as wind speed, direction, and atmospheric pressure. However, the case study of 2022 shows the necessity for an integrated long-term adaptation strategy that involves thorough monitoring and studies to understand the factors contributing to the increase in water levels and the occurrence of floods in the Danė River.

When developing future scenarios to mitigate socio-economic risks for infrastructure and residential areas, it is essential to comprehensively assess several elements, including climate change, bank deformation, and the influence of hydrometeorological events on bank changes. Fast-moving low-pressure systems pose a threat to coastal cities as they cause deformation of the sea surface topography. Storm-generated surges and fluctuations in sea level are the result of wind forces and sea surface deformation caused by the baric field's characteristics (Wolski et al., 2014). Extreme hydro-meteorological events can change the coastline and cause coastal erosion, which is particularly relevant to seacoast settlements because they are designed to satisfy the needs of the local population and be used for recreation. The Danė River is no exception, with walking and cycling trails, leisure spaces, playgrounds, and various types of infrastructure. Future infrastructure developments must take coastal erosion caused by hydrometeorological factors into consideration because it may damage already-existing infrastructure. Storms in January and February 2022 damaged the Danė River bank in the city's northern part close to Klaipėda University's Botanical Garden, threatening the city's infrastructure. In the near future, it is planned to develop the recreational infrastructure and promote water tourism on the Danė River by installing recreational docks. It is important to assess possible fluctuations in water levels in order to ensure that the infrastructure to be developed is long-lasting and remains intact or less vulnerable to extreme hydro-meteorological events.

Previous studies (Čepienė et al., 2022) have shown that flooding in the northern part of Klaipėda is more influenced by the discharge of the Danė River, while the central part of the city is more at risk from rising water levels in the Klaipėda Strait. In the northern part of the city, next to the Danė River, there are private residential houses that are located in flood-risk areas. The riverbank remains in its natural state and there are no protective shoreline fortifications that preserve them from higher flooding. The city centre is rich in cultural heritage sites, buildings, and public infrastructure. All these tangible objects affected by flooding contribute to the economic damage. Social risk impacts are measured in terms of intangible impacts on coastal communities (risks to human health, life). Effective communication with the coastal communities is crucial for local authorities when developing flood risk mitigation programmes. It is the responsibility of these authorities to ensure that the development of flood risk management infrastructure corresponds to the needs and perceived significance of water bodies as expressed by the coastal communities (Quinn et al., 2019).

The potential effects of climate change should not impede the progress of urban development. Therefore, it is essential to consider all scenarios, identify the areas and communities that are most vulnerable to harm, and implement sustainable climate change mitigation initiatives. Although there exist a contentious debate on how much of human-induced climate change's influence on storms so far, climate models indicate that the phenomena of global warming may potentially result in a rise in the occurrence of severe hourly winds by middle of the 21st century (Vautard et al., 2019). Regions that are prone to fluctuations in water levels resulting from storm surges driven by intense winds will experience increased vulnerability. Klaipėda is no exception, with storm induced surges appearing more frequently in the Klaipėda Strait. The rise in water level in the Klaipėda Strait has significant effects on the city, particularly concerning the increased water level of the Danė River. Further research is needed for comprehensive investigations that integrate various hydrometeorological phenomena and their implications for flood-prone regions. Additionally, it is important to assess the efficacy of urban surface water collection systems. By considering the potential risks, the development and expansion of flood-prone areas in the context of climate change, thereby minimizing or mitigating potential losses to the maximum extent possible.

The main theses of this study:

- Annual mean water level, annual mean water level maximum and annual mean water level minimum are significantly increasing in the SE Baltic Sea region.

- The mean water level in the Klaipėda Strait continues to increase due to climate change. It increased by 4 mm year^{-1} in the study period (1961–2022).

- The frequency of events with water levels $\geq$100 cm (BS) in the Klaipėda Strait has been increasing from 1961 to 2022.

- The formation of compound floods in the lower reaches of the Danė River is determined by the rising water level of the SE Baltic Sea in the Klaipėda Strait. We therefore recommend that this climate change component be included in flood risk assessments in the lower reaches of rivers flowing into the sea.

Author contributions

Conceptualization, E.V.; methodology, E.V., I.D., A.B.; software, E.V. and G.P.; investigation, E.V., I.D., and A.B.; writing – original draft preparation, E.V.; writing – review and editing, I.D. and A.B.; visualization, E.V. and G.P.; supervision, I.D. All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare no conflict of interest.

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