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Severe floods in Nemunas River Delta

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Abstract. The river delta regions are usually most vulnerable to flooding due to small changes in terrain elevation and river – sea interaction. The trends of increased frequency of flooding and an increased duration of the high water events are evident in many regions. In this study, we analyse the most extreme (severe) flood events in the Nemunas Delta region of Lithuania. The study focuses on the causes of floods and their changes over 1926–2016. Analysing specific case studies and comparing them with related studies of other researchers, we present an original interpretation of the variability of flood parameters. The aim of the study is to demonstrate that the analysis of flood events must be based on the identification of the drivers of individual floods. This is especially true for the lower reaches and the delta regions of rivers situated within the North European Plain. Historically, an intense melting of snow appeared to be the main cause of severe flooding in this region. The results of this study, however, show that the situation has rapidly changed over the last 30 years and large areas can be flooded even if the snow water equivalent over the whole basin is relatively low.

Keywords *• extreme flooding • Lithuania • Nemunas River • severe water level*

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INTRODUCTION

Over the last few decades, river delta regions and other zones vulnerable to flooding have suffered from both an increased frequency of flooding and an increased duration of the high water events. It is assumed that residents in the affected areas are more or less adapted to the periodic flood events (for example, spring run-off floods), but they may not be prepared for non-seasonal floods that are beginning to occur due to the changing behaviour of the factors contributing to the floods.

It is very important to identify river sections that are potentially vulnerable to flooding, as well as to produce accurate hydrological forecasts in a timely manner in order to prevent and/or be adequately prepared for flooding. Analysis of past flood events and their key parameters makes it easier to understand the formation of extreme situations and to improve their modelling system. However, recent studies have shown that interpretations of flood-related statistical variables basically depend on the accuracy of the initial data (Koutsoyiannis 2013). Therefore, the initial data retrieved from long-term hydrological observations can be considered more important than the derived statistical flood parameters, as the original data may allow the application of the most appropriate methodology for understanding the cause-effect relationships between different flood characteristics.

The main objectives of this study are: the identification of the most extreme (severe) flood events in the lower reaches of the Nemunas River and its delta region; to determine the main causes of the flooding and the relevant characteristics of the river hydrological regime; and to understand the main conditions that influence the level of flooding. The long-term tendencies of these parameters can be considered very useful for flood prediction not only in the Nemunas River, but also in other rivers situated within Northern European floodplains. The research results are also considered to be relevant to the assessment of flood risks in other regions with similar hydroclimatic conditions.

Most studies focusing on the flood regime of European rivers analyse floods on large rivers with long-term availability of hydrological data. For example, analysis of Rhine River floods has highlighted the trends of maximum discharge that are typical of many European rivers (Glaser, Stangl 2003; Stahl *et al.* 2010; Bormann *et al.* 2011). The Rhine River long-term data series has helped to identify the suitability of various statistical methods for accurate estimation of individual flood parameters (Thieken *et al.* 2014; Toonen *et al.* 2016). Studies of the flood regimes in the Danube, Oder, Vistula, Elbe and Nemunas Rivers (Cyberski *et al.* 2006; Blöschl *et al.* 2013; Mudersbach *et al.* 2017; Stonevičius *et al.* 2017) have also considerably contributed to a better understanding of the flood regimes of European rivers. These studies have identified the causes of the floods in major European rivers, as well as their duration, dates and other characteristics. Flood statistics are used for the management of flood risk and its changes (Rojas *et al.* 2013; Francesch-Huidobro *et al.* 2016). The understanding of floods in large rivers can be transferred to smaller ones.

Researchers who model changes in river runoff (Sampson *et al.* 2015; Alfieri *et al.* 2015) emphasize the impact of climate change on flood characteristics. Flood parameters in a particular section of the river mostly depend on morphometric characteristics of the river valley and the river bed. Therefore, flood forecasting and risk management systems that are operational at national or regional levels should rely on information derived from various rivers with different hydromorphological parameters and hydrological regimes (Stonevičius, Valiuškevičius 2018). Studies of floods in river deltas (Vaikasas 2005) show that even a modest change in the shape of the channel cross-section and the distribution of current velocities (with the same water discharge) can have a significant impact on the scale of flooding. The availability of a long-term series of data is very important in accurate statistical flood analysis; therefore, observations from other regions are often used to extend the short-term series.

The Nemunas River is the largest river in Lithuania and annual floods in its lower reaches result in both inundation and losses. Most of the flood studies in this region include analysis of data from the Smalininkai gauging station that has operated since 1812. The first statistical analysis of long-term Nemunas flood data was conducted by J. Taminskas (2002), though Nemunas River flood analysis was also included into a special study on the hydrological regime of all Lithuanian rivers (Gailiušis *et al.* 2001). Additionally, the Smalininkai gauging station data were used in the analysis of processes occurring in the other river basins of the region (Reihan *et al.* 2012). The most comprehensive survey of the Nemunas flood regime in Lithuania was carried out during the first phase of the implementation of the European Union Floods Directive (EPA 2011).

With the Nemunas River usually ice-covered for part of the cold season, consequent ice jams are responsible for a significant proportion of the flooding events affecting the area. For this reason, Nemunas River flood analysis is usually carried out together with analysis of river water temperature and ice regime (Stonevicius *et al.* 2008; Dubra *et al.* 2013). Studies concerning the synoptic conditions during the spring run-off period (Stankunavicius *et al.* 2007) and the effects of climate change on the snow regime (Stonevičius *et al.* 2017) have revealed that the extent of the floods mostly depends on the intensity of the snowmelt in the lower reaches of the Nemunas River. Other authors analysed the impact of climate change on the runoff of Lithuanian rivers (Šarauskienė *et al.* 2017) through flood characteristics such as changes in seasonal and annual water balance. Regional studies carried out at the beginning of the 21st century (Latkovska *et al.* 2012) show that the timing of flood peaks in the Nemunas River (as in most Northern European rivers) has significantly changed. Floods tend to begin earlier and last longer, though the maximal river flooding extension during the spring run-off period is becoming smaller. These tendencies lead to discussions about the necessity of adaptation of the Lithuanian rivers to the changing conditions (Kažys *et al.* 2013; Korneev *et al.* 2015) and the preparation of new land management and water management plans (related to the problems caused by long-lasting floods). Some studies (Katutis, Rudzianskaite 2015) suggest that the extended inundation of the lower reaches of the Nemunas River is also able to affect river water quality and the soil chemical composition in the surrounding areas, as well as natural environment conditions within the delta region.

Research on floods and their impacts has become particularly popular around the world recently, though interpretations of the results of such statistical analysis appear to be quite diverse. Some authors examining an extremely long hydrological observation data series (Caporali *et al.* 2005; Koutsoyiannis 2013) argue that the number of severe floods in the 19th and 20th centuries is below the average of the last millennium. Additionally, some statistical indicators also show that the risk of flooding in Europe has declined over the last 100 years (Choryński *et al.* 2012). Moreover, statistical analysis of hydrological data shows periodical variation rather than coherent long-term trends in the regime (Montanari, Koutsoyiannis 2012). Similar results were obtained for the Nemunas River (Sakalauskiene 2003). Sometimes, this raises doubts about the use of deterministic models for the analysis of hydrological information, in particular about their ability to provide further tendencies of flood affecting processes in the context of climate change (Koutsoyiannis 2013).

Therefore, the original data of long-term hydrological observations are often considered to be more important than the statistical indexes and other derivative parameters as these allow the use of the most appropriate methodology for adaptation and help to find causal relationships between different characteristics. These data are considered to be useful for comprehensive analysis of the causes of flooding and allow the identification of the main factors affecting changes.

MATERIALS AND METHODS

Study area

The Nemunas River is situated in northern Europe and occupies part of the Baltic Sea catchment area. The length of the river is 937 km (the 4th longest river in the Baltic Sea region and 14th in Europe), and the area of the basin is 97,860 km² (the 3rd largest basin in the Baltic Sea region and 15th in Europe). The Nemunas River begins in the moraine highlands in central Belarus and then flows through the plains of Lithuania. Thereafter, the river enters the Curonian Lagoon, forming a fan-shaped delta (Fig. 1). The largest part of the basin is located in Lithuania (47.6%) and Belarus (46.4%), though 6% of the basin area is within the territories of Poland, Russia and Latvia. The dominant flow direction of the Nemunas River is from the southeast to the northwest, while the altitude of the river varies between 150–250 m in the eastern parts of the basin, 50–150 m in the middle reaches and below 50 m in the lower reaches. Of the total Nemunas River basin area, lakes occupy about 1.5%, while marshes occupy 15% and forests 21%.

The river basin is located in the northern part of the temperate zone. A more oceanic climate prevails in the western part of the basin, while a more continental in the eastern part. The mean January surface air temperature ranges from –3 °C in the western part to –9 °C in the eastern part, with the highest mean monthly temperature observed in July, this being from 17 °C to 19 °C, respectively. The mean annual precipitation amount within basin area ranges between 600–900 mm. The river hydrological regime reflects a mixed water balance: about 40% of the runoff consists of snowmelt water, about 25% of rainwa-

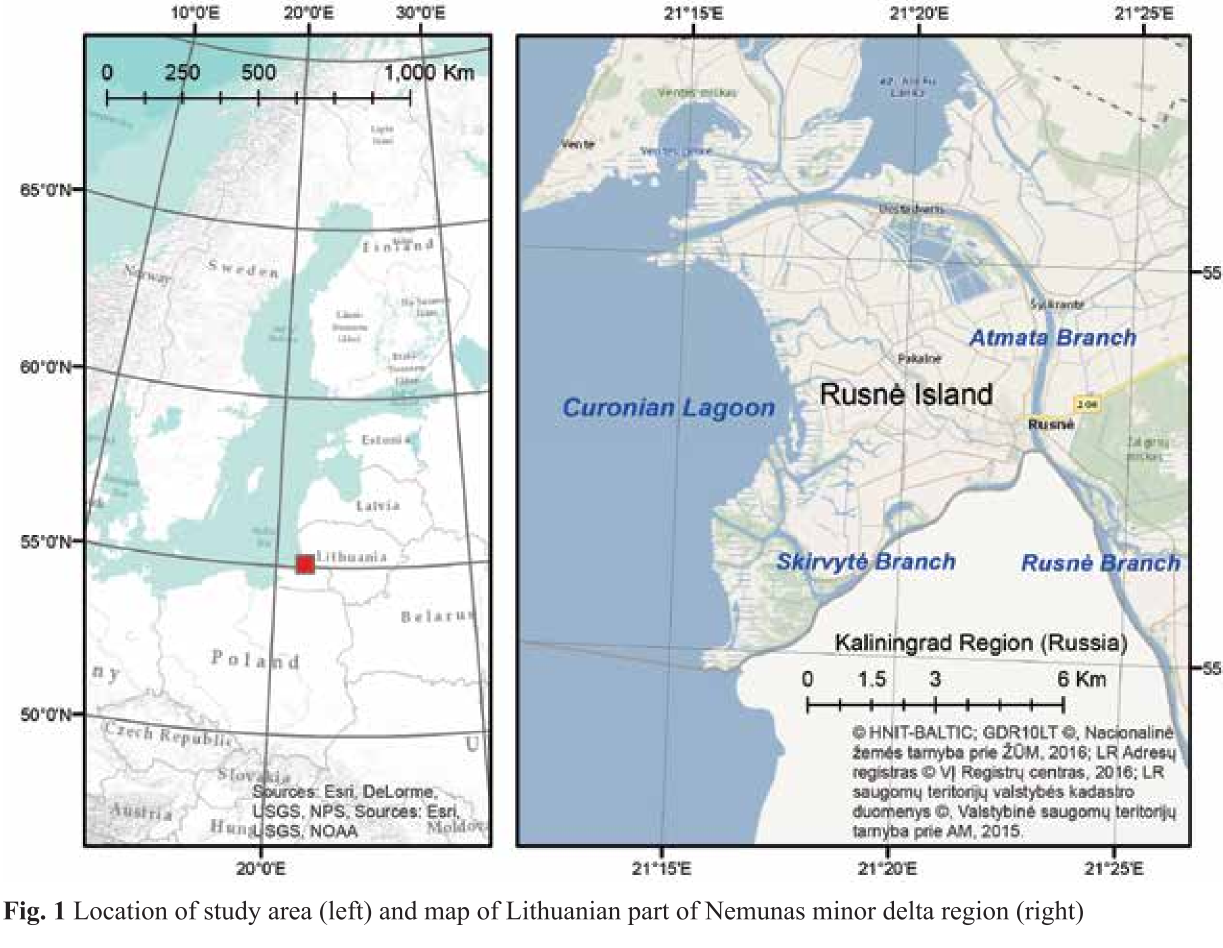

Fig. 1 Location of study area (left) and map of Lithuanian part of Nemunas minor delta region (right)

ter and about 35% of underground water. The mean annual discharge in the lower reaches of the Nemunas River (at the easternmost point of the delta) is about 600 m³/s, while this may increase by more than ten times during high water events (Gailiušis *et al.* 2001).

The Nemunas River Delta is an alluvial plain divided between Lithuania and Russia (Kaliningrad Region) near the Curonian Lagoon. The Nemunas River Delta is usually divided into the greater delta and minor delta regions. The total area of the greater delta is about 2000 km², while the area of the minor delta is about 600 km². The greater Nemunas Delta begins when the Nemunas River branches into two main branches: the Rusnė (to the right) and the Gilija (to the left). The minor delta begins with the split of the Rusnė distribute to the Atmata Branch (to the right) and Skirvytė Branch (to the left) (Fig. 1). The Atmata Branch and Skirvytė Branch surround the largest island of delta – Rusnė Island. In the Gilija Branch and on the left side of the Nemunas River, Rusnė Branch and Skirvytė Branch, the delta distributaries are enclosed by embankments, and therefore delta growth processes in this area are limited (Žaromskis 2013). Hazardous floods rarely occur in this part of the delta.

Annual floods occur on the right side of the minor delta (north of Rusnė Branch and Skirvytė Branch). In comparison to the left side, this riverbank is not adequately protected by embankments. Although overall rises in water level during floods in the minor delta are considerably lower than in other sections of the river, larger land areas may be inundated here due to a very low and flat terrain – more than 90% of the delta is at an altitude below 5 m, with some territories below sea level. The most frequently inundated part of the delta is situated at altitudes below 2 m above sea level.

About 80% of the annual runoff of the Nemunas River flows through the right distributaries of the delta. Annual runoff of 12.5 km³ flows into the Curonian Lagoon through the Skirvytė Branch and about 7.5 km³ through the Atmata Branch. This part of the delta is changing intensively: 5–20 t/ha of river sediments are deposited in this area each year during the spring run-off period. Additionally, most of the small delta branches have been canalised and many are truncated, not reaching the lagoon. Most rivers have oxbow lakes (Žaromskis 2013). There are polders between some branches. On the Lithuanian side of the Nemunas River Delta (where the territory is most commonly flooded), polders with artificially regulated water levels occupy over 40,000 ha.

Materials

In this study, we used observation data from two gauging stations: Smalininkai (at a distance of 112 km from the mouth of the Nemunas River) and Rusnė (at a distance of 13 km from the mouth of the Atmata Branch) located in the lower reaches of the Nemunas River. These two stations have the longest available time series of hydrological data for the lower reaches of the Nemunas River. Daily data of water level at the Smalininkai station have been available since 1812 and for the Rusne station since 1926. Smalininkai station observations also include water discharge measurements and manual observations of ice phenomena. The time series of Rusnė station data were interrupted during the Second World War, so there is a gap in the data between 1942 and 1949.

The Smalininkai gauging station is located upstream of the river delta (at a distance of 112 km from the mouth of the Nemunas River), though only a few tributaries contribute to the Nemunas flow volume downstream of the Smalininkai station – these accounting for about 15% of total flow. The area of the Nemunas River basin above Smalininkai is 81,200 km². The long-term mean discharge of the Nemunas River at Smalininkai is about 530 m³/s (~ 6.6 l/(s·km²)).

The Rusnė gauging station is located at one of the main branches of the Nemunas Delta – the Atmata Branch (at a distance of 13 km from the mouth of the Atmata Branch). The station data were used to represent the water level in the Nemunas River Delta. The gauge station's zero altitude is 1.53 m below mean sea level. The distribution of runoff volume into separate branches of the Nemunas River depends on short-term weather and environmental conditions (wind speed and direction, temporal locations of ice jams and channel dredging work schedules); therefore, water discharge at the Rusnė station is not observed. The Rusnė gauging station represents the water level in the large part of the delta because it is situated on the flat plain lowland.

In Lithuania, there are specific criteria for determining which floods are considered to be severe within river valley locations that often suffer from floods. As flooding can cause considerable damage across flat plain areas, it is operationally very useful to refer to water levels at certain gauging stations when determining the threshold for a severe flood. In the Nemunas River Delta, a severe flood is considered to be one in which the water level at the Atmata Branch near Rusnė exceeds 1.37 m above sea level (290 cm above the station's graph). This threshold is considered critical as the main road connecting Rusnė Island with the mainland will then be subject to flooding, thereby cutting off most of the Nemunas Delta area (on the Lithuanian side) from the mainland basin. In addition, the Nemunas Delta is a very uniform area, so the severe threshold defined for the Rusnė station is also critical across most of the delta branches and channels.

Methods

The hydrological regime of the lower reaches of the Nemunas River has been described using the Smalininkai and Rusnė gauge stations data for the periods 1812–2016 and 1926–2016, respectively. Classical statistical analysis methods were used for the data processing: we calculated monthly, seasonal (also hydrological seasons) and annual discharge and mean water level, as well as long-term means for both stations. The typical seasonal distribution of runoff, and its variation, has been determined by calculating the standard deviation of water discharge for every month.

A case study of the 2009–2010 winter–spring periods (from the beginning of November to the end of May) was chosen to reveal specific effects of different hydrometeorological factors on the Nemunas River Delta. This period was assumed to be typical because it very well reflects how the high water levels depend on the interaction of different factors. The analysis also includes meteorological data, namely snow depth and surface air temperature from 16 Lithuanian meteorological stations. These data were also averaged for different months and seasons (in the case of temperature) of the year. It was decided to not use spatial averaging methodology in this study as only part of the Nemunas basin area is within the territory of Lithuania and we had insufficient data for statistical parameters calculation from the Kaliningrad Region side.

For this research, we focused on cases of extreme high water levels at the Rusnė gauge station, i.e. when they exceeded 1.37 metres above sea level. Therefore, only those days (periods) that exceeded this threshold level were further analysed. The relationship between the maximum spring runoff flood in Smalininkai and the characteristics of extreme high water level periods in Rusnė was analysed for the periods 1926–1970 and 1971–2016. Changes in long-term flood regime were assessed estimating the average of water level maximums for different climatological periods (thirty years) and so analysing the seasonal variation of the water level maximums according to Smalininkai gauge station data. Finally, changes in the seasonal variation of the Rusnė extreme high water levels were determined together with defining the long-term change (shift) of dates of such high water levels for different climatological periods.

RESULTS

The main causes and characteristics of the spring runoff floods

The main cause of flooding in the lower reaches and delta of the Nemunas River is the runoff that forms during the spring snowmelt season (EPA 2011). Therefore, the absolute majority of floods in the Nemunas River (like in other Northern European rivers) occur in spring. In the period 1812–2016, there were only five cases where the maximum annual discharge in the Smalininkai gauging station was observed during summer or autumn and was completely unrelated to the snowmelt process. The fact that the Klaipėda Strait (connecting the Curonian Lagoon with the Baltic Sea) has a limited throughput also affects the floods of the Nemunas River Delta. The maximum discharge that can flow through the strait ranges from 1600 m³/s to 4000 m³/s (depending on wind and ice conditions). The maximum discharge of the Nemunas River during extreme flooding can reach up to 7000–8000 m³/s. Therefore, part of the water in such cases accumulates in the Curonian Lagoon and forces the water level to rise in areas closer to the mouth of the Nemunas River.

The spring flood is the most distinctive hydrological season in the lower reaches of the Nemunas River. The authors who studied the distribution of the Nemunas River runoff (Gailiušis *et al*. 2001) found that flooding caused by snowmelt in the lower reaches usually starts in the second part of March and lasts about 60 days. The Nemunas River discharge during spring run-off flood exceeds the mean annual value by approximately five times (more than 10 times in exceptional cases). In the March–May season, the mean monthly discharge standard deviation is much higher than during the rest part of the year (Fig. 2). Typical flooding in the delta is characterized by a sudden rise of water level – about 15 cm per day (mean intensity during the last five days preceding the peak). The recession of the flood wave is considerably slower (usually 1–5 cm per day) and takes much longer (the rising limb phase takes about 15 days and the recession limb about 45 days).

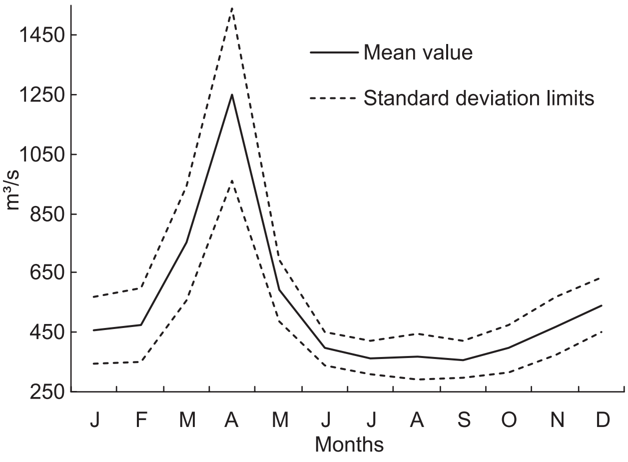

Fig. 2 Seasonal cycle of monthly mean discharge (black line) and standard deviation limits of monthly mean discharge (gray lines) in the Smalininkai gauging station from 1812 to 2016

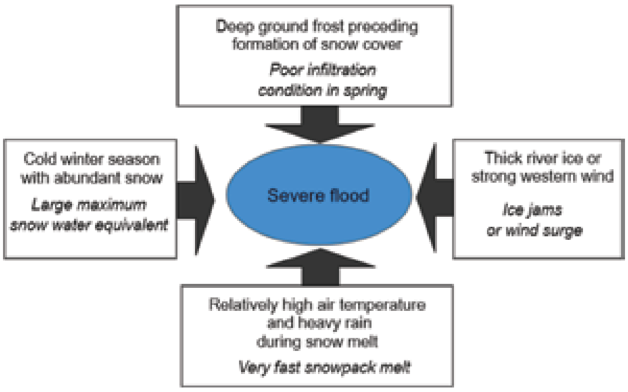

Fig. 3 The environmental conditions that favour severe flood formation in the Nemunas River and the main processes that affect the flood (in italic)

Large-scale spring flooding usually occurs when the river's water level is rising not only because of increased runoff during the snowmelt period, but also due to additional causes. Previous studies (Taminskas 2002; EPA 2011) have revealed that floods which have a significant impact on the inhabitants of surrounding territories and infrastructure in the Nemunas River have formed due to a specific complex of conditions (Fig. 3). During ordinary spring flooding, the water level rise at Smalininkai does not exceed 5 cm per day and at Rusnė 10 cm per day, but during severe floods the water level at Smalininkai may increase about 8–10 cm per day and at Rusnė about 20–30 cm per day.

Studies relating to the largest 20th century floods in the Nemunas Delta (Januškis, Sabaliauskas 1971; Rainys 1973; EPA 2011) argue that the probability of the formation of severe floods often depends on the location where the river ice cover starts to breakup. The probability of severe flooding significantly increases if the Curonian Lagoon is still ice-covered when the flood wave arrives in the lower reaches of the Nemunas River.

The case of 2010 spring flood

A typical situation of severe flood in the Nemunas Delta region occurred in the winter 2009/2010 (Fig. 4). This case demonstrates the essential mechanisms for the formation of severe floods in the Nemunas Delta, so we analyse it here in more detail. Although the maximum flood runoff in the Nemunas River over the last 30 years has been similar to or higher than that in spring 2010, the water level in delta region during this period has never risen higher than in the case of 2010. This situation illustrates the importance of a complex interaction between various factors affecting an extremely high water level. At the end of December 2009, the water level in the Nemunas River at the Rusnė station was mostly influenced by the snowmelt rate within the river basin. As the surface air temperature exceeded 0 °C, the snowmelt process started and the river's water level also increased, reaching a peak within 5–10 days. The river water level then declined as periods of prevailing negative temperatures occurred within the basin. A similar situation was observed at the end of February and the beginning of March – at this time, the snowmelt rate was mostly affected by rain events rather than by variation of surface air temperature. The most intense snowmelt in the Nemunas River basin was observed in the eleven-day period from the 19th of February to the 1st of March. The snowmelt water reached the river delta on the 1st of March, this marking the beginning of the spring runoff flood. On this particular day, the water level at the Rusnė gauging station started to rise rapidly. The second stage of rapid increase in water levels was observed from the 19th of March, when ice jams blocked several localities in the lower reaches and the delta region (Fig. 4). This second-high water level rise however was preceded by a short-term decline from 13th of March when ice jams started to form upstream from the delta (though a decline in discharge was not observed). On the 19th of March, the ice jam moved downstream and the water level started to rise. Within a few days, new ice jams appeared in the distributaries of the minor delta and caused the record high rate of water level rise (about 17.5 cm per day) from the 22nd to 28th of March. This example seems to be a good illustration of the importance of additional factors contributing to the formation of a severe flood.

Leading factors affecting lowland flooding can be verified by analysing the relationship between the highest water discharges at the Smalininkai station and the severe flood duration in the Nemunas River Delta – i.e. the number of days that the water level

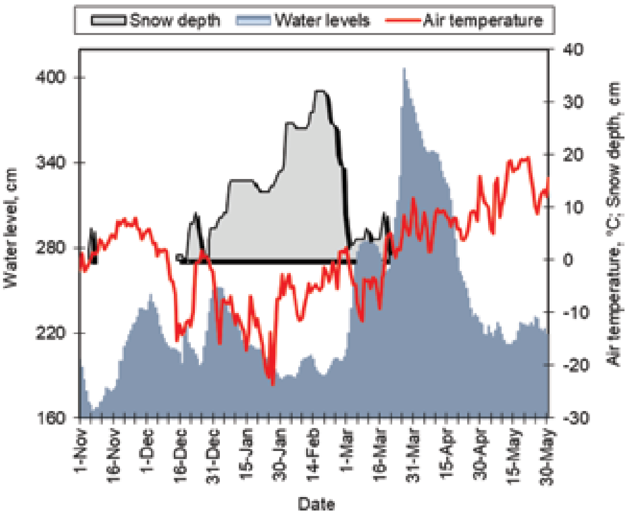

Fig. 4 The hydrograph of the Nemunas River water level in winter 2009/2010 and the following spring flood at Rusnė, as well as the mean snow cover depth and the mean surface air temperature in Lithuania

exceeds the 1.37 m above sea level threshold in the Rusnė station. The correlation coefficient between these parameters over a long-term period is 0.67. This allows us to conclude that in the case of small snowmelt water volumes, other factors are unlikely to result in an exceptionally extended river flood.

Changes in factors for spring runoff floods

According to the Rusnė gauging station data, there were 111 recorded severe flood events (that lasted more than one day) in the Nemunas River Delta from 1926 to 2016. All these events could be characterized by the water level exceeding the 1.37 m above sea level threshold. It is also necessary to take into account the fact that there are no data about floods between years 1942 and 1949. The mean frequency of severe floods when such conditions lasted several consecutive days was 1.11 per year in 1926–1970, while this parameter increased to 1.54 in the later period of 1971–2016. At the same time, the length of individual cases has become shorter. Results of previous studies (EPA 2011; Latkovska *et al*. 2012) show that such tendencies are also similar in smaller Lithuanian rivers, as well as in rivers of neighbouring countries.

The total number of severe water level days has increased in recent years: there were only 12 cases where severe water levels were observed for more than 20 days per year in 1926–1986, whereas such cases have been recorded approximately every third year in the last 30 years (Fig. 5a). In some years, this parameter could even exceed 40 days per year, while 2013 saw a record 61-days severe flooding. With short breaks between, the extremely high levels of flooding in 2013 were divided into three periods: from 3rd to 28th of January, from the 2nd to 23rd of February and from the 8th to 30th of March.

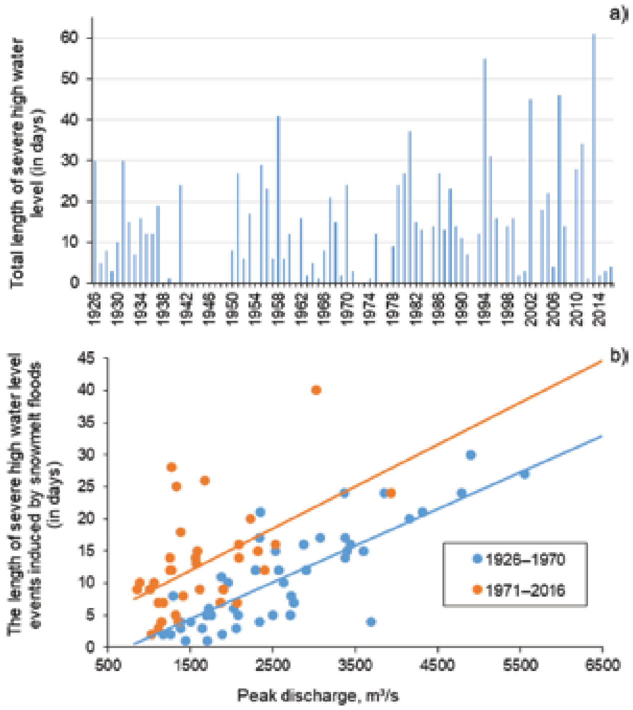

Fig. 5 The dynamics of the total number of days with severe water levels at the Rusnė gauging station in 1926–2016 (a) and the relationship between the peak discharge in the Nemunas River at the Smalininkai gauging station and the duration of severe water level in the Nemunas River at the Rusnė gauging station for the spring flood periods in 1926–1970 (blue dots) and 1971–2016 (orange dots) and the corresponding best fitting lines (b)

The number of days with extreme high water levels in the Nemunas River Delta has increased during the last hundred years, while river runoff has decreased over the same period. The maximal values of discharge decreased by about 18 m³/s per year at the Smalininkai gauging station over the 1926–2016 period and the mean annual discharge by about 1 m³/s per year.

These facts evidence that the typical flood parameters as well as the main factors influencing flood formation have changed. For instance, a typical ten-day length severe spring runoff flood might be initiated with approximately 2500 m³/s discharge in the period of 1926–1970, while a flood of the same length between 1971 to 2016 is characterized by 1000–1500 m³/s discharge (Fig. 5b). This confirms that the severe flood drivers have changed in the Nemunas River Delta since the 1970s and the role of the high runoff values during snowmelt might have decreased.

The increased intensity of water level rise in the Nemunas River at the Rusnė gauging station during the last five days prior to the flood peak (the most intensive water rise stage) suggests a shift in the flood drivers. In 1926–1970, the mean water level rise was 16.9 cm per day before the flood peak, while it was 13.8 cm per day in the period 1971–2016.

Tendencies in flooding length and the rate of water level rise show that severe flood parameters are affected not only by one factor, but by a shift in the complex of drivers (air temperature, water flow, ice regime, storm surge, changes in river bottom morphology, et). The changes in the hydrological regime of the Nemunas River from the beginning of the 20th century have been strongly affected by the long-term fluctuations of the water balance and Kaunas hydropower station, which is in operation since 1961 (Gailiušis *et al*. 2001; Reihan *et al*. 2012). These causes have most affected the long-term means of the maximum water level at the Smalininkai gauging station over a long historical period of more than 200 years (solid line in Fig. 6). The most important driver of recent changes of flood parameters in rivers within the Baltic region, however, is likely to be climatic change (Čerkasova *et al*. 2016; Stonevičius *et al*. 2017).

Climate change has particularly shifted the start and end dates of floods and the frequency of severe floods. This can easily be noticed by analysing the

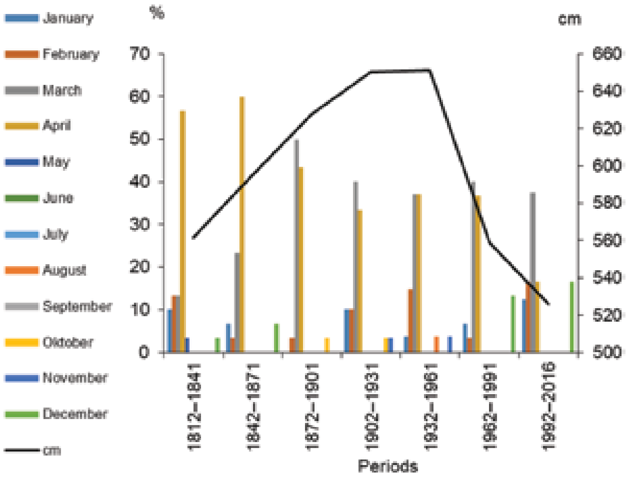

Fig. 6. Long-term changes in the mean annual maximum water level (black solid line) in the Nemunas River at the Smalininkai gauging station and the frequency of the annual maximal water levels in different months of the year (different colour columns) during different 30-year periods from 1812 to 2016

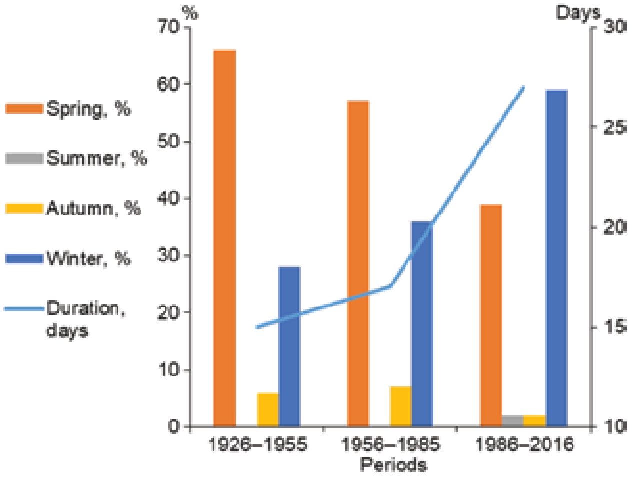

Fig. 7 The number of days when water levels exceeded the severe level threshold (solid line) and the seasonality of start dates of severe floods (columns) in the Atmata Branch in different 30-year periods from 1926 to 2016

seasonal distribution of cases of maximum annual water levels in different months at the Smalininkai gauging station over the 1812–2016 period (Fig. 6). In the first half of the 19th century, more than 50% of the maximum annual water level events recorded at this station occurred in April, while from the beginning of the 20th century, maximum water levels in the lower reaches of the Nemunas River have been observed earlier and earlier. In recent years, a significant increase in the frequency of highest annual water levels occurring in December has been recorded (while such cases were extremely rare until 1961, they accounted for 13% of the total number of cases in 1962–1991 and 17% in the period 1992–2016). These facts possibly evidence a sudden change in winter and spring hydrometeorological conditions in the region.

Similar trends are observed not only in the lower reaches of the Nemunas River, but also in its delta. Although the time series of Rusnė gauging station data are considerably shorter than the data from the Smalininkai station, the seasonal distribution of the severe water levels display a similar pattern in 1926–2016 (Fig. 7). There is a clear downward trend of severe flood events starting in spring: from about 66% of all severe floods in 1926–1955, to only 39% in 1986–2016. At the same time, the proportion of severe floods starting in winter significantly increased (28% in 1926–1955, 59% in 1986–2016).

The duration of ice cover in Baltic Sea coastal waters, as well as in the Curonian Lagoon, has also shortened (Dailidienė 2007). Therefore, water flows in the Nemunas River Delta are more frequently countered by strong westerly and north-westerly winds that lead to wind surge and bring water from the Baltic Sea to the Curonian Lagoon and from the Curonian Lagoon to the Nemunas River Delta, thereby effectively damming the river.

DISCUSSION

The primary factor for the formation of a severe flood is the high water equivalent of snow cover accumulated within the basin before the start of the snowmelt. Nevertheless, even in extremely snowy winters, the spring flood does not always exceed the severe flood threshold. Frequently, the snow melts gradually and over a longer period the water infiltrates into the ground or drains into the rivers. Therefore, the rise of the water level in rivers is relatively low.

A severe spring flood occurs as the seasonal snow pack melts rapidly, this triggered by meteorological factors such as high air temperature and liquid precipitation during snowmelt. Often, rapid rises in the river's water level occur due to deep-frozen ground and ice jams that may temporarily block large sections of the river.

The effects caused by ice jams can be observed only if such ice jams occur in river sections located within the visible range of one of the gauging stations. Therefore, in many cases it is hard to accurately assess the impact of ice jams on flood formation. S. Vaikasas (2005) confirmed this by using empirical observations – while ice jams were observed almost every second year near Rusnė during the period 1970–1989, such phenomenon occured only one time per 10 years on average according to the Rusnė gauging station data. It remains the case, however, that spring runoff is the main factor responsible for flooding over large areas of land within the Nemunas River Delta.

The flood regime in the lower reaches of the Nemunas River and delta region has experienced significant changes during the last few decades. Severe water levels in the delta region were usually recorded once per year during the first half of the 20th century, but they are now more frequent and may occur 3–4 times per year.

Reoccurring floods greatly impair the transport and communication possibilities of the local communities – extremely high water levels isolate many settlements in this region from the rest of the country. Moreover, conventional techniques of flood forecasting and flood management have become more redundant as there can now be a series of consecutive years without severe flood events, followed by years with very severe water levels occurring several times per year and also in different seasons.

Changes in river ice regime are likely to be the main driver of changes in severe flood parameters. Ice jams in particular play an important role. The change in rates of water level rises during the last few days before a flood peak would suggest that the role of ice jams in the evolution of extreme flooding has decreased. Whether the frequency of occurrence of ice jams has increased or decreased in the lower reaches of the Nemunas River is still unclear due to the lack of ice phenomena observation data. It is also possible that the location of ice jams during floods has shifted from their typical formation sites (river stretches, cross-sections) over the historical period.

Unfortunately, most authors who have studied this phenomenon in the south-eastern part of the Baltic region (Stonevicius *et al*. 2008; Klavins *et al*. 2009; Glavickas, Stonevičius 2012) acknowledge that accurate characterization of changes in the ice and ice jam regime within the Nemunas River and other Lithuanian rivers is not possible with current data. The main issue of such inaccuracies is the observational time step (except automatic observations available for the last few years) of water level data available from the Lithuanian Hydrometeorological Service. Currently, it is only possible to estimate the average effect of ice jams on the daily river water level and the most intense water level changes that take place within a few hours during ice jam formation.

The shift of the peaks of water level from April to earlier months is likely to be connected to increased surface air temperatures during winter and early spring. Considering the complex of severe flood formation conditions showed in Fig. 3, it might be argued that such a pronounced shift in the initial dates of extreme high water levels testifies to a decrease in the stability of meteorological conditions (in recent decades the seasonal features of the winter season have become more characteristic of the spring season). As air temperatures become higher in the cold season, the frequency of winter thaws has also increased and this leads to a thinner snow cover depth in February and March (Stonevičius *et al*. 2017).

Wind surges also contribute to more prolonged and higher flood waves in the Nemunas Delta region. Changes in all these drivers are more or less related to climate change and lead to a higher frequency and longer total length of severe floods in the lower reaches and delta region of the Nemunas River. The decrease of water resources accumulated in snow cover leads to decreases in the water level maximums during the flood events, but usually water levels still significantly do exceed the severe water level threshold. An increase in the number of thaws and an increased probability of wind surges makes the occurrence of severe floods more frequent and less predictable.

CONCLUSIONS

Severe floods in the lower reaches and delta region of the Nemunas River are caused by a complex of different drivers. Intensive snowmelt is able to induce a flood wave that can inundate large areas of the delta region, this on occasion being amplified by multiple ice jams and/or wind surges from the Curonian Lagoon side. Such extreme conditions lead to rapid rises of the water levels which can remain high for a longer period. A total of 111 severe flood events (lasting longer than one day) were recorded in the 1926–2016 period, i.e. water levels at the Rusnė station exceeded the severe flood threshold of 1.37 m above sea level. Therefore, the average frequency of severe floods equals 1.3 times per year. The mean length of severe floods (total number of days when the water level exceeds the threshold) was 12.4 days in the 1926–2016 period.

The flood regime in the Nemunas River Delta region has changed over the last three decades. In the first half and the middle of the 20th century, most severe floods at the Rusnė station were recorded during the spring runoff season, but since the 1980s, the number of severe floods has also increased in other seasons, for example winter. The number of severe floods per year has also increased – since the 1980s, the delta region may typically be flooded 3–4 times per year. Although the lifetime of individual floods has become shorter, the total number of days with extremely high water levels has often exceeded 20 days per year over the last 30 years (for instance, 61 days in 2013). Since 1986, the frequency of severe floods in winter has increased significantly. Most of the severe floods that lasted more than 10 days were recorded in the 1926–1970 period, when the peak of water discharge exceeded 2500 m^3/s. Since the 1970s, the length of severe high water levels in the delta region has seemed to be not strictly dependent on the maximal discharge and is often related to a complex of influencing factors.

Regional climate change also contributes to flood wave formation in the Nemunas River Delta region: in recent years, floods have tended to occur either due to ice jams or wind surge rather than to intensive snowmelt. The frequency of such extreme events is likely to increase in the future, resulting also in an increased number of days with severe high water levels.

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