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Impact of climate change on the development of the islands of the Neris River (eastern part of the Baltic Sea basin)

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ABSTRACT

The frequency of high floods is one of the most important factors shaping the riverbed and influencing other aspects, such as sediment transport and deposition, vegetation establishment and growth. The aim of this study is to assess the impact of climate change on the flood regime of the Neris River (eastern part of the Baltic Sea basin) and the related changes in river islands, morphometric indicators of the riverbed, and vegetation colonization. To identify changes in the hydrological regime of the river, water level measurement data from the Buivydžiai and Jonava hydrological stations were used. To assess vegetation coverage and the presence of islands in the Neris River, orthophotos at a scale of 1:10 000 from the years 2005–2006, 2012–2013, and 2018–2020 were analyzed. Using the ArcGIS ArcMap software package, river island area and island forest coverage were calculated. The results of the study show that during the observation period (2005–2020), in the lower course of the river, the area of the islands increased, and island forest coverage grew from 7% to 18%. Between 2005 and 2020, the water level in the lower course rose above 300 cm (above the station's zero line) only twice. The absence of high floods creates favorable conditions for plants to colonize alluvial environments. Consequently, this may lead to extreme flood events in the future, caused by a restructured river channel following a prolonged period of low flood activity.

Introduction

Rivers are natural water systems whose planform reflects a balance between flow energy, sediment size, sediment transport, and vegetation (Gurnell et al. 2009). With climate change, there are alterations in river flow and sediment regimes (Bravard 1990; Comiti 2012; Schneider et al. 2013; Robins et al. 2016), the ratio of coarse to fine sediments (Termini 2021), the formation, growth, stabilization, or disappearance of islands (Knighton 1998; Osterkamp 1998; Kollmann et al. 1999; Gurnell et al. 2001, 2018; Wyrick and Klingeman 2011; Baubinienė et al. 2015; Gurnell and Bertoldi 2022), riverbed morphometric indices, and riverbed water permeability. Biotic and abiotic factors lead to the development of heterogeneous channel forms (Schumm 1972; Rijn 1993; Wyzga 1993, 2007; Gurnell and Petts 2002; Tockner et al. 2003; Keesstra et al. 2005; Kondolf et al. 2007; Hooke and Yorke 2011; Surian et al. 2014; Gurnell et al. 2015, 2018; Hooke and Chen 2015; Termini 2021; Picco et al. 2023) and alter the spatial distribution of vegetation both along the riverbanks and throughout the river basin (Hickin 1995; Liébault and Piégay 2002; Rinaldi 2003; Surian and Rinaldi 2003, 2009; Rovira et al. 2005, Gurnell et al. 2009). Global warming induces prolonged drought phases (Brummer et al. 2016), alters the seasonality of floods, and both increases and decreases flood events across European rivers (Mangini et al. 2018; Blöschl et al. 2019; Blöschl 2023).

The results of our research align with the findings of other scholars, who report that rising temperatures contribute to a reduction in flood frequency in eastern and northern Europe. Approximately 78% of monitoring stations indicate a decreasing trend in flood occurrence, with an average decline of 6% per decade (Blöschl et al. 2019). In the boreal region, the annual average number of flood events is the lowest, a phenomenon largely driven by runoff regimes dominated by snow accumulation and melt processes (Mangini et al. 2018). This hydrological shift clearly affects the morphometric characteristics of river channels and islands, as well as vegetative expansion processes.

Climate change, by extending the intervals between high-magnitude flood events – creating a so-called window of opportunity – favors the colonization of alluvial environments by vegetation. The resulting expansion of vegetation on islands and within the riverbed, coupled with the increase in island area, reduces the river's hydraulic capacity and promotes conditions conducive to elevated water levels and flood events caused by restricted flow.

The aim of this article is to assess the impact of climate change on the flood regime of the Neris River (eastern Baltic Sea basin) and its associated effects on the morphometric indices and vegetative growth of river islands and riverbeds, as well as the hydraulic riverbed permeability. This study supplements research conducted on river islands and vegetated river corridors in western Europe.

Materials and methods

Lithuania is situated in the cool temperate climate zone, characterized by moderately warm summers and moderately cold winters. The long-term average air temperature in Lithuania for the period 1991–2020 is 7.4 °C. However, in recent decades, an increase in the average annual temperature has been observed. Compared to the 1981–2010 period, it rose by 0.5 °C during 1991–2020. The number of days with maximum air temperatures exceeding 30 °C has increased. All seasons in Lithuania have warmed, with winter showing the most pronounced warming. Between 1961 and 2018, the average duration of winter precipitation events decreased by 34 days, the snow cover duration shortened by 30 days, and the maximum snow depth decreased by 3 cm. Models predict a significant rise in air temperature in Lithuania during the 21st century. Particularly great changes are modeled for winter. Over the next 100 years, the average temperature is predicted to increase by 4–8 °C in winter, 2–4 °C in spring, 1.5–3.5 °C in summer, and 2.5–4.0 °C in autumn. The amount of precipitation is projected to drop markedly in summer and autumn. However, all climate change models without exception indicate that the greatest increase in precipitation (5–60 mm per 100 years) will occur during winter. Furthermore, all scenarios predict a decrease in summer precipitation (up to –0.3088 mm/year). With increasing air temperature, the proportion of liquid precipitation in winter will gradually increase (Rimkus et al. 2007).

The Neris River is one of the few rivers of its size in Europe whose channel has remained largely natural, and its hydrological regime is mostly unaltered. River discharge is monitored by three hydrological monitoring stations (HMS): Buivydžiai (river basin area F = 11 100 km^2, operational since 1966), Vilnius (F = 15 200 km^2, since 1922), and Jonava (F = 24 600 km^2, since 1877). The average annual discharge of the Neris River is 68 m^3/s at Buivydžiai, 109 m^3/s at Vilnius, and approximately 180 m^3/s at the river mouth. The average water level at Buivydžiai HMS (1966–2023) is 256 cm; at Vilnius HMS (1922–2023), 277 cm; and at Jonava HMS (1882–1915, 1919–2023), 82 cm. The specific runoff in the Belarusian part of the Neris River basin is approximately 6.5 $L \cdot s^{-1} \cdot km^{-2}$, while in the Lithuanian part, it is notably higher – around 7.8 $L \cdot s^{-1} \cdot km^{-2}$.

Since the beginning of the 21st century, the Neris River has experienced an increase in periods characterized by low flow conditions, which are becoming progressively longer. These changes have been driven by both natural factors and human activities. Since 1960, a negative anomaly in annual maximum floods has been observed. Although similar anomalies occurred in the past, they were typically short-lived – lasting only a few years. The long-term anomaly in maximum flood levels coincides with a similar period during which an anomaly in average annual air temperature began to emerge (Jones and Hulme 1996; Hansen et al. 2010). It is well established that the increase in average annual temperature has been significantly influenced by rising temperatures during the cold season (November to April) (Barry 1985; Fallot et al. 1997).

Warmer cold-season conditions have led to reduced snow-derived water reserves, resulting in lower annual peak floods. Between the late 20th and early 21st centuries (1979–2012), compared to the late 19th and early 20th centuries (1877–1910), the average annual maximum flood levels decreased by 43% (Baubinienė et al. 2015). The Vileika Hydroelectric Power Plant also operates on the Neris, retaining part of the river's flow during the warm season and contributing to increased evaporation. Since 2020, the Astravyets Nuclear Power Plant in Belarus has been operating and uses water from the Neris for cooling purposes. Additionally, uneven runoff distribution and increased sedimentation are influenced by the anthropogenically modified landscape of the river basin and widespread deforestation in both Lithuania and Belarus.

The Neris River is part of the Baltic Sea basin, with a significant portion (56% of the basin area) located within Lithuania, and the remaining 44% extending into Belarus. In Lithuania, the river flows through the plateau of the middle Nemunas River and the lower Neris River, an undulating glacial lake plain, and traverses several orographic zones formed by heterogeneous geomorphological processes (Česnulevičius and Baubinienė 1997) (Fig. 1).

From the border with Belarus to the confluence with the Žeimena River (212.6 km from the Žeimena River mouth to the Neris River mouth), the Neris River flows northwest along the edge of a limnoglacial basin, through a deep, steep-sided valley (35–60 m), flanked by wavy and flat terrains. The riverbed width varies between 50 and 140 m. Below the mouth of the Žeimena River, the Neris River turns southwest and crosses terminal morainic deposits, with a riverbed width of 80–120 m, narrowing to 50–60 m at the rapids. The valley width ranges from 1.5 to 2.0 km. In the mid-valley region, large low and medium-height morainic hills, as well as medium-sized low and medium-height glaciofluvial and morainic hills, are prevalent (Česnulevičius and Baubinienė 1997). From Vilnius city (where small, medium-height, and high glaciofluvial hills dominate) to the confluence with the Šventoji River (44.5 km from the Šventoji River mouth to the Neris River mouth), the Neris River flows northwest, traversing the Baltic Heights through a narrow (0.5–1.0 km wide), deep (60–70 m) valley. This valley widens to 2–3 km before

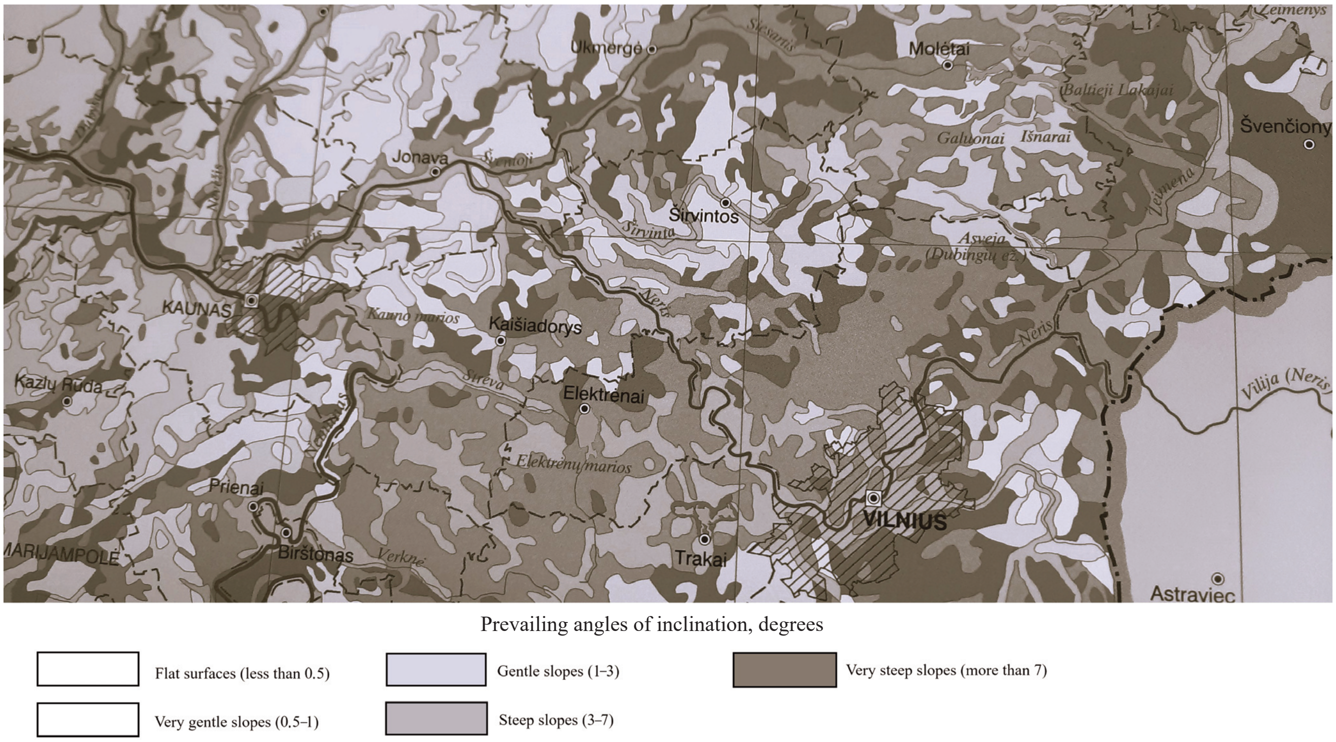


Fig. 1. Relief morphometric map, scale 1:1 000 000 (The National Atlas of Lithuania 2014).

reaching the mouth of the Šventoji River. The area is characterized by a predominance of wavy limnoglacial topography. Downstream of the confluence with the Šventoji River, the Neris River turns southwest (Fig. 1). On the right bank, a series of terminal moraines extend, while the left bank is characterized by undulating and flat plains (Fig. 1). The Neris River's elevation fall is 163 m, with an average inclination of 0.32 m km^{-1}. A few kilometers before reaching the mouth, the inclination decreases to 0.20 m km^{-1}. The river's depth ranges from 1 to 3 m, and the flow velocity varies between 0.6 and 1.9 m s^{-1}.

From the confluence with the Šventoji River to the confluence with the Nemunas River, the Neris River features a pronounced valley with a width of 1–1.5 km. The river is tranquil and sediment-rich, with a floodplain covering 30–60% of the total valley area. Riverbed width ranges from 100 to 140 m, increasing to 180–290 m near Kaunas city. The slopes of the river valley rise to 30–50 m. The lower course of the Neris is among the river segments with the most islands (Baubinienė et al. 2015). During ice drift, ice jams frequently form around these islands, which are covered with shrubs and trees. Near Jonava, Turžėnai, Kleboniškis, and closer to the river mouth, ice jams can cause flooding by rapidly raising river water levels and inundating nearby inhabited areas (Fig. 1).

Given the recurrent flooding, detailed studies have been conducted on the river's lower course with islands, where ice jams form in Salupiai, Saliai, Kleboniškis, and Vilijampolė segments (Fig. 2). At various spatial and temporal scales, the interactions among water flow, sediment, and vegetation shape the riverbed. Changes in these dynamics have been monitored at two profiles of the Neris River (eastern Baltic Sea basin), located 187.0 km apart. The Buivydžiai profile is situated in the river's middle section, 8.6 km from the Belarusian border and 225.9 km from the river mouth. The Jonava profile is in the lower course, 30.0 km from the river mouth (Fig. 2).

During the vegetation period, measurements were taken of the river channel width (m), average and maximum river depths (m), and the areas of the transverse profiles of the riverbed were calculated (m^2) at both profiles. The Buivydžiai profile was analyzed using data from 2000 to 2021 (Buivydžiai HMS data), while the Jonava profile was examined using data from 1977 to 2009 (Jonava HMS data) (Fig. 2). Additionally, the width of river islands and channels was measured and assessed by comparing available orthophotos at a scale of 1:10 000 from 1995 to 2020. Changes in island area were monitored over a 30 km stretch of the river's lower course, from Jonava to Kaunas. The area of islands per unit area of water was calculated based on orthophotos from 2005 to 2006, 2012 to 2013, and 2018 to 2020 (geoportal.lt) using the ArcGis ArcMap software. The following formula was used to calculate the ratio of island area to the river's water surface area:

$$S_{\text{area of islands per unit area of water}} = S_{\text{islands}}/S_{\text{river}}\ (\%), \qquad (1)$$

where $S_{islands}$ is the area occupied by islands (m^2) and S_{river} is the water surface area (m^2).

Area calculations of shrub and tree coverage (%) were conducted in four segments of the lower Neris River: Salupiai, Saliai, Kleboniškis, and Vilijampolė (Fig. 2). The following formula was used:

$$S_{\text{island coverage with trees and shrubs}} = S_{\text{forests}}/S_{\text{island}}\ (\%), \qquad (2)$$

where $S_{forests}$ is the area occupied by trees and shrubs in the island (m^2) and S_{island} is the area of the island (m^2).

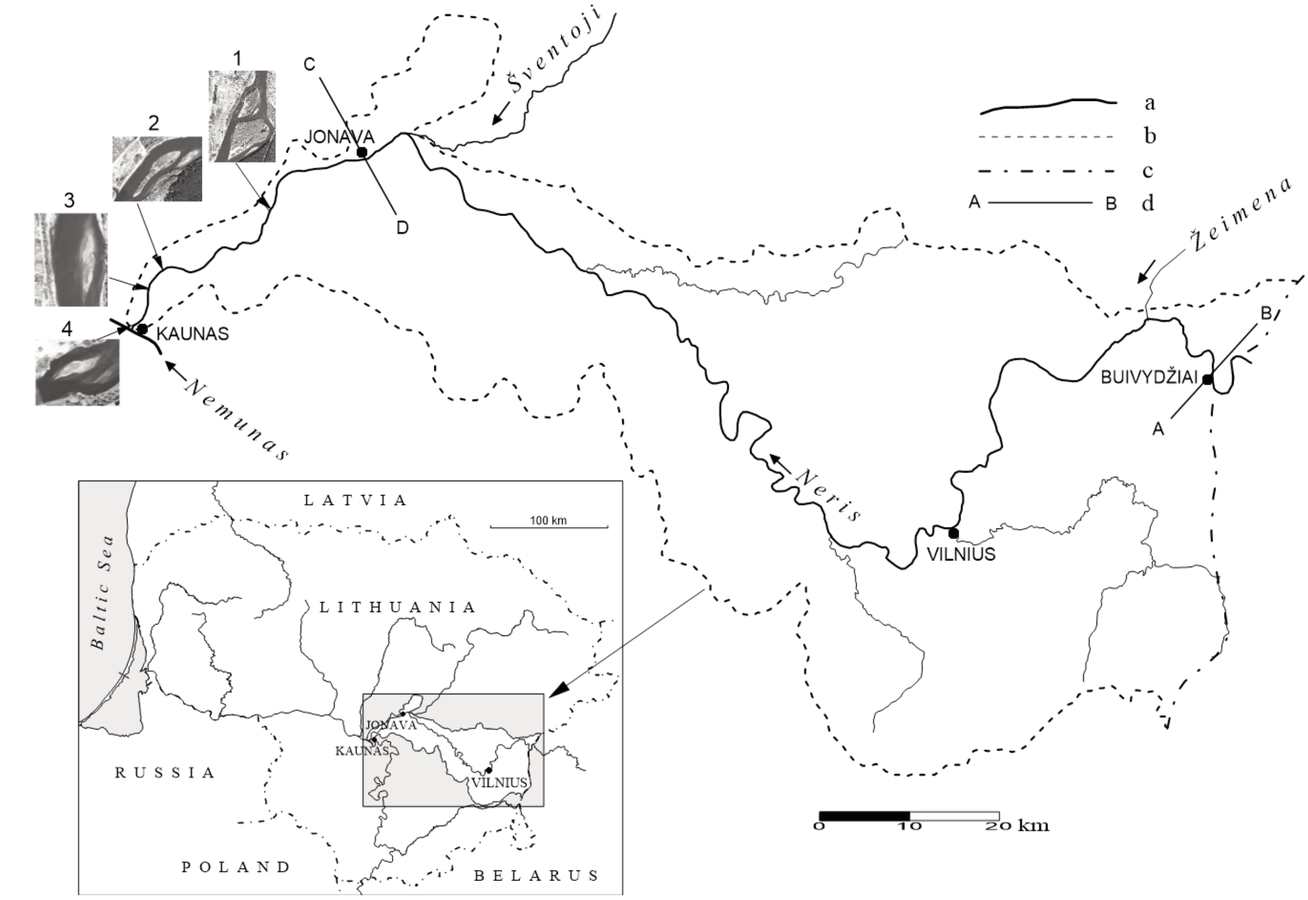


Fig. 2. Neris River basin and study locations: **a** – river, **b** – watershed of Neris basin, **c** – state border, **d** – profile (**A–B**: Neris riverbed profile near Buivydžiai, **C–D**: Neris riverbed profile near Jonava). Numbered sites indicate complex island research segments: 1 – Salupiai, 2 – Saliai, 3 – Kleboniškis, 4 – Vilijampolė. Drawing by Rimas Petrošius.

The ratio of island area to the river's water surface area yields a derived metric known as river "island cover" (%), which indicates the proportion of the riverbed occupied by islands. This metric reflects changes in sediment deposition within the riverbed, water permeability, and the river's hydrological regime. In the absence of sediment data, this indicator can provide insights into sediment dynamics.

When delineating island outlines within the same river segment at different time points, variations in river water levels may introduce measurement errors in island area calculations. To minimize this, orthophotos of the Neris River were taken during similar periods with comparable water levels: in May for the years 2005, 2009, 2015, and 2018; in July for 2012; and in June for 2021. During these periods, the water level was elevated by 31–48 cm above the station's zero line, which did not significantly impact island area measurements. An exception occurred in 2005, when the water level was 166 cm above the zero line, resulting in complete inundation of the island nearby Kleboniškis.

The hydrological regime of the Neris River was assessed using water level data from the Buivydžiai and Jonava HMSs. By selecting days with high river water levels (>300 cm and >200 cm above the station's zero line), the frequency of floods during the observation period was calculated. Additionally, fluctuations in water levels in Buivydžiai and Jonava hydrogeological wells were analyzed for the period from 2005 to 2023 and correlated with river water level variations over the same period. The data used in this study are presented in Table 1.

Table 1. Measurement data used in the study

Data type	Observation period	Location
River water levels	1967–2022 1922–2022	Buivydžiai hydrological monitoring station Jonava hydrological monitoring station
Groundwater levels from hydrogeological wells	2005–2022 1996–2023	Buivydžiai hydrogeological wells Jonava hydrogeological wells
River channel cross-sectional profile indicators	2000–2021 1977–2009	Buivydžiai hydrological monitoring station Jonava hydrological monitoring station
River island area and forest coverage indicators	2005–2006 2012–2013 2018–2020	Lower reach of the Neris River, from Jonava to the river mouth
Morphometric indicators of the river channel and islands	1995–2020	Neris River section from the Belarusian border to the river mouth

Results

Changes in the morphometric indicators of the Neris River channel

Previous field studies conducted between 1978 and 1980 documented an increase in riparian vegetation along the Neris River, affecting both low- and steep-inclination sections of the riverbank (Baltakis et al. 1982). In areas with lower inclination, sediment accumulation formed significant vegetated banks that extended into the riverbed, creating a complex riverbank profile. During 1978–1980, sedimentation in straighter river sections reduced the channel width by 10–15% in some places (Baltakis et al. 1982). Local observations suggest that the proliferation of riparian vegetation in the Neris River has been noticeable since the sixth decade of the 20th century (Baltakis et al. 1982).

During our research, we observed a general trend of narrowing in the secondary channels between the riverbank and islands, as well as within the riverbed itself, from the Belarusian border to the river mouth. By 2020, the area of nearly all observed islands in this section had increased compared to 1995.

From 2000 to 2021, in the Buivydžiai HMS profile, measurements taken from June to August showed a 3% decrease in riverbed width, a 43% reduction in average riverbed depth, and a 15% reduction in maximum depth. The cross-sectional area of the riverbed in this profile decreased by 44%.

In contrast, in the Jonava HMS profile, the average and maximum depths of the river channel remained almost unchanged during the period from 1977 to 2009. The average riverbed depth was 0.94 m, and the maximum depth was 1.55 m. In the lower course (Jonava HMS), a slight reduction in the riverbed cross-sectional area was observed (Fig. 3). Over the observation period of nine years (2000–2009), a reduction in the cross-sectional areas of the river profiles was identified in both the Buivydžiai and Jonava profiles (Fig. 3).

The analysis indicates that significant vegetation erosion is driven by relatively frequent floods, with a recurrence interval of 1–2.5 years. However, the reduced intensity and frequency of such floods have allowed vegetation to flourish within the riverbed, leading to its narrowing.

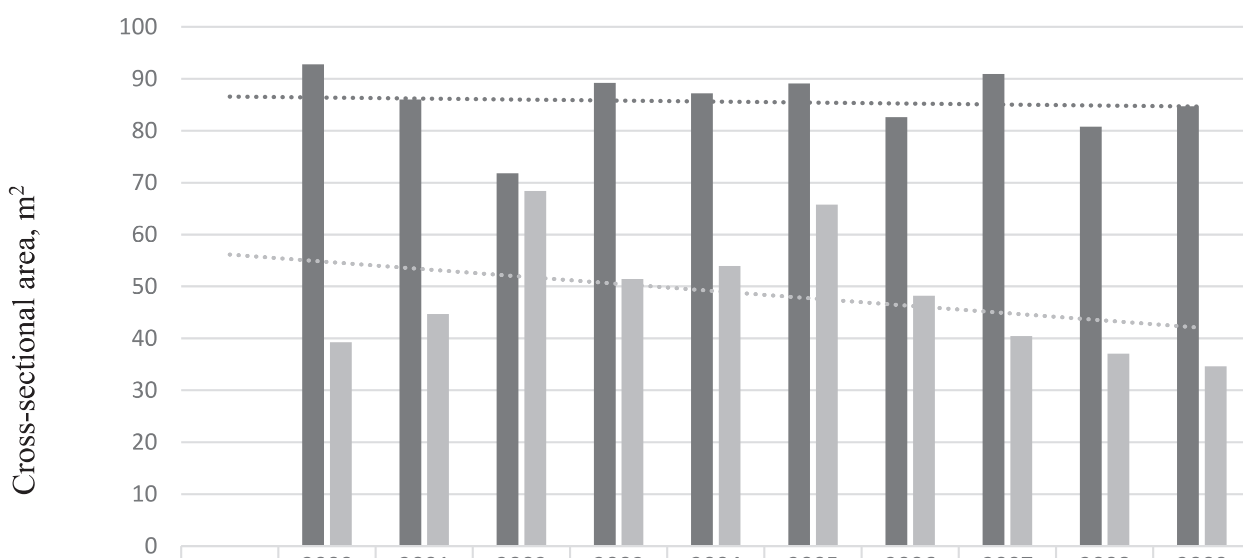
Morphodynamical changes of islands in the lower Neris River

Based on calculations of island area in the lower Neris River for the period from 1995 to 2020, accumulative processes were more significant than erosive ones for most islands. During the observation period from 1995 to 2010, the island area in the lower course of the river increased both in absolute and relative terms. Specifically, the total island area grew by 0.24 ha between 1995 and 2010, and by 0.04 ha between 2010 and 2020. The relative growth of the islands was 0.61 ha/1 ha from 1999 to 2010, and 0.26 ha/1 ha from 2010 to 2020 (Table 2).

Newly formed islands during this period accounted for 21%. Many of these new islands formed after the spring floods of 2010 and 2013. The last maximum water levels recorded at Jonava HMS were 373 cm above the station's zero line in 2010 and 312 cm in 2013. In subsequent years (2013–2022), water levels exceeding 300 cm were not recorded at Jonava HMS.

Based on the observed increase in island area, it can be inferred that the most significant changes occurred in the lower course of the river, specifically affecting islands up to one hectare in size. The areas of larger islands changed only slightly or remained stable.

In the lower course of the Neris River, the percentage of the river's surface area covered by islands was calculated for the Salupiai, Saliai, Kleboniškis, and Vilijampolė segments over the period from 2005 to 2020. In the Salupiai and Saliai segments, island coverage increased by 2% between 2005



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Jonava HMS	92.8	86	71.8	89.2	87.2	89.1	82.6	90.9	80.8	84.7
Buivydžiai HMS	39.3	44.7	68.4	51.4	54	65.8	48.2	40.4	37.1	34.6

Fig. 3. Changes in the cross-sectional areas of the Neris River profiles at Buivydžiai and Jonava hydrological monitoring stations during the period from 2000 to 2009.

Table 2. Changes in island area in the Neris River over a 25-year period (1995–2010 and 2010–2020)

Island number	Area, ha			Increase in area			
				Total, ha		Relative, ha/1 ha	
	1995–1999	2009–2010	2018–2020	1995–2010	2010–2020	1995–2010	2010–2020
1	0.02	0.04	0.05	0.02	0.01	1	0.25
2	1.88	2.12	2.26	0.24	0.14	0.13	0.07
3	0.51	0.65	0.66	0.14	0.01	0.27	0.02
4	3.73	3.76	3.77	0.3	0.01	0.08	0
5	0.09	0.16	0.34	0.07	0.18	0.78	1.13
6	10.54	10.6	10.61	0.06	0.01	0.01	0
7	0.18	0.32	0.49	0.14	0.17	0.78	0.53
8	0.23	0.66	0.73	0.43	0.07	1.87	0.11
9	0.09	0.12	0.37	0.03	0.25	0.33	2.08
10	0.58	0.73	0.8	0.15	0.07	0.26	0.1
11	0.18	0.24	0.29	0.06	0.05	0.33	0.21
12	0.22	0.2	0.24	–0.02	0.04	–0.09	0.2
13	0.34	0.35	0.19	0.01	–0.16	0.03	–0.46
14	0.83	2.24	1.99	1.41	–0.25	1.7	–0.11
15	0.93	N/A*	N/A*	N/A*	N/A*	N/A*	N/A*
16	0.31	0.99	0.9	0.68	–0.09	2.19	–0.09
17	0.67	0.66	0.69	–0.01	0.03	0.01	0.05
18	0.37	0.66	0.86	0.29	0.2	0.78	0.3
Total	21.7	24.5	25.24	4	0.74	10.46	4.39
Average	1.21	1.44	1.48	0.24	0.04	0.61	0.26

* During the period from 2010 to 2020, two islands in the lower course of the river "merged" as the channel between them became filled with sediments and vegetation. Along the entire length of the river within Lithuanian territory, 15% of all islands observed from 1995 to 2020 "merged" with the floodplain due to sediment accumulation in the separating channels.

and 2020. In the Kleboniškis segment, the island was submerged in 2005, but from 2010 to 2020, island coverage also increased by 2%. In the Vilijampolė segment, located closer to the river mouth, island coverage increased significantly – by 8%.

Calculations of island forest coverage (growth of shrubs and trees) from 2005 to 2020 indicate that it increased in all examined segments of the lower Neris River. In the Salupiai segment (22 km from the river mouth), forest coverage was 75% in 2005. By 2012–2013, it had increased to 78%, and by 2018–2020, it had further grown to 82%. From 2005 to 2012, the growth of shrubs and trees on the islands increased by 3%; from 2013 to 2020, it increased by 4%. In the Saliai segment (8 km from the river mouth), the changes in island forest coverage were even more significant, increasing from 57% in 2005 to 63% in 2012. By 2020, it had reached 87%. Overall, from 2005 to 2020, island forest coverage in this segment increased by 18%.

The accelerating growth of shrubs and trees on the islands suggests that, since the 1970s, the increase in island forest coverage has been driven by a changed hydroclimatic situation.

Hydrological data

The analysis of water level changes in the Neris River shows a decrease in the number of days per year with maximum floods since the mid-20th century. At Buivydžiai HMS, the percentage of days per year with water levels exceeding 300 cm above the station's zero line decreased from 15% to 10% during the observation period (1966–2022). Notably, in 2019 and 2020, water levels at Buivydžiai HMS did not rise above 300 cm (Fig. 4). At Jonava HMS, water levels did not exceed 300 cm above the station's zero line during either of the periods from 1994 to 2010 (16 years) or from 2013 to 2022 (9 years) (Fig. 4).

The accelerating overgrowth of islands with shrubs and trees suggests that, since the 1970s, changes in hydroclimatic conditions have contributed to increased forest coverage on these islands.

Until 1970, water levels at Jonava HMS rose above 300 cm almost every year during the observation period (1920–2022) (Fig. 4). Over more than fifty years (1971–2022), water levels in the lower Neris River (Jonava HMS) exceeded 300 cm above the station's zero line only six times: in 1979, 1987, 1988, 1994, 2010, and 2013 (Fig. 4). The longest duration of water levels remaining above this height was in 1994, lasting 22 days, followed by 11 days in 1979, 7 days in 2010, 5 days in 1987, 4 days in 2013, and 3 days in 1988. For sixteen consecutive years, from 1994 to 2010 (the longest interval during the observation period), water levels at Jonava HMS did not rise above 300 cm even once (Fig. 4).

The number of days when water levels rose above 200 cm at Buivydžiai HMS has remained consistent throughout the observation period (1967–2022), averaging 80 days per year (Fig. 5). Meanwhile, groundwater levels in the Buivydžiai well have slightly decreased (Fig. 6). Although groundwater

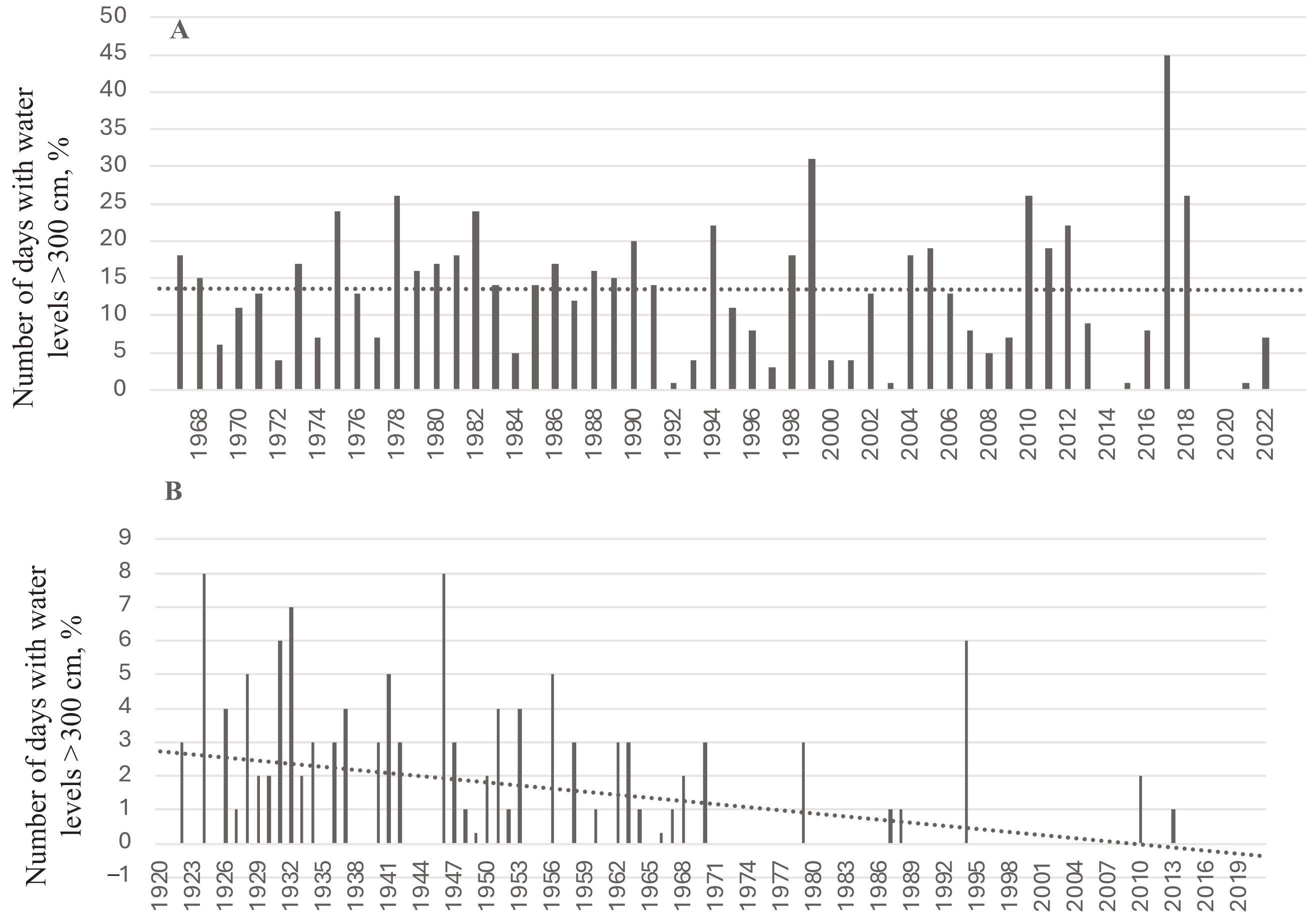


Fig. 4. Number of days per year, with water levels exceeding 300 cm above the station's zero line at Buivydžiai (A) and Jonava (B) hydrological monitoring stations.

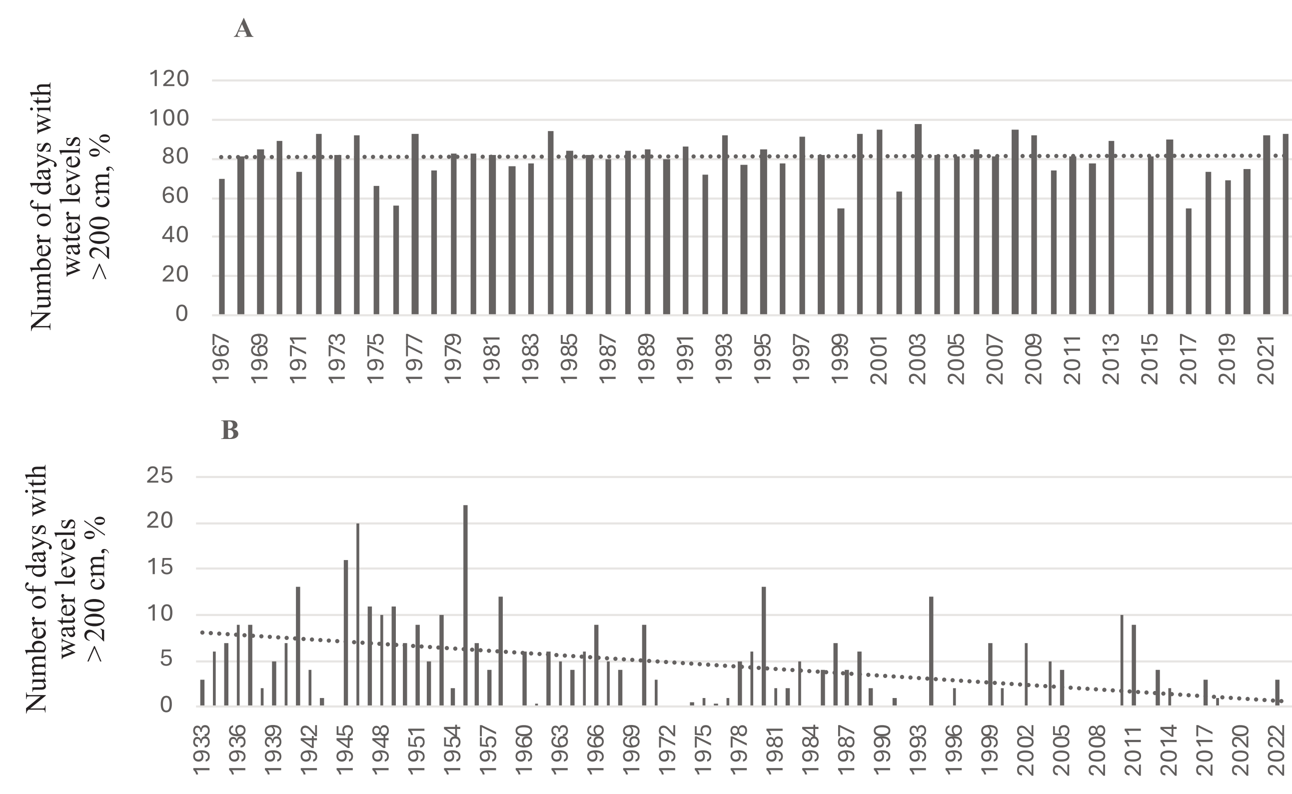


Fig. 5. Number of days per year, with water levels exceeding 200 cm above the station's zero line at Buivydžiai (A) and Jonava (B) hydrological monitoring stations.

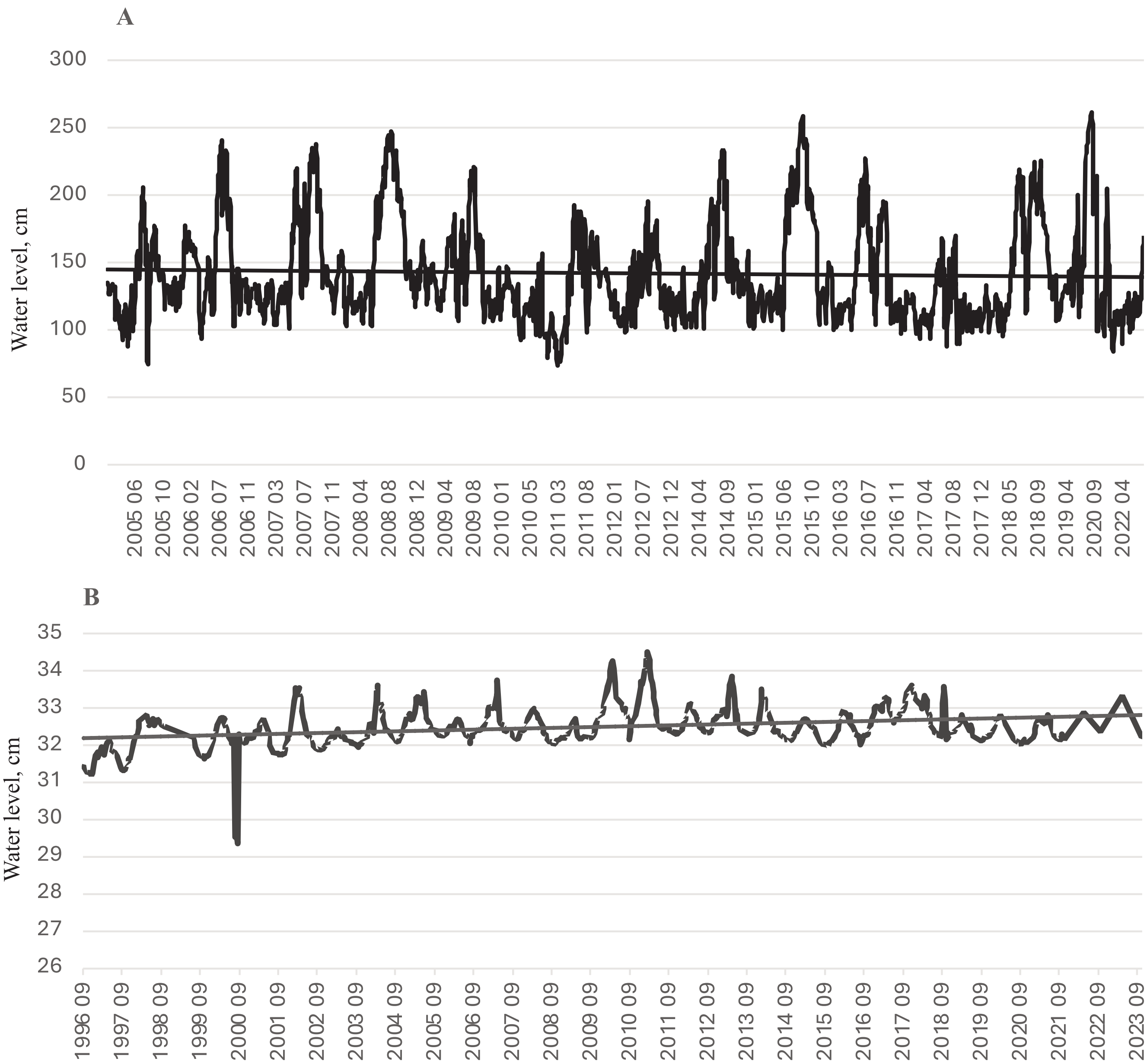


Fig. 6. Groundwater level fluctuations in Buivydžiai (A) and Jonava (B) hydrogeological wells.

levels are declining, water levels in the Neris River above 200 cm at Buivydžiai have persisted for an average of 80 days annually. These sustained high water levels are possibly maintained by the narrowing of the riverbed and increased vegetation within it.

From 1920 to 2022, a noticeable decreasing trend is observed in the number of days per year at Jonava HMS when water levels in the Neris River exceed 200 cm (Fig. 6). During the period from 1921 to 1958, water levels rose above 200 cm annually, remaining at or above this level for an average of 38 days per year. However, from 1959 to 2022, water levels in the Neris did not exceed 200 cm for 23 years (34% of time) (Fig. 5). The longest continuous interval without exceeding 200 cm was four years, from 2006 to 2009. Water levels remained above 200 cm for the longest durations in 1980 (49 days), 1994 (43 days), and 2010 (38 days).

However, from 1920 to 2022, there has been an increase in the number of days per year when water levels in the Neris River rise 100–200 cm above the station's zero line (Jonava HMS). Particularly notable changes have occurred since 1960 (Fig. 7). Before 1960, the average number of days with water levels in this range was 38 days per year. After 1960, water levels in this range have been sustained for an average of 72 days per year. During the observation period, the longest duration at this level occurred in 2017, lasting 216 days (Fig. 7). This increase may be related to groundwater inflow and the overgrowth of vegetation in the riverbed.

Until 1959, larger amplitudes of water level fluctuations were observed in the Neris River, causing more intense erosion processes in the river channel and valley. Since 1960, these fluctuations have diminished. From 1920 to 2020, the amplitude of water level fluctuations decreased from 600 to 100 cm (Fig. 8).

Lower islands remain submerged for longer periods, promoting sediment deposition as the water recedes. The reduced frequency of high floods increases the likelihood that these lower islands will not be eroded away.

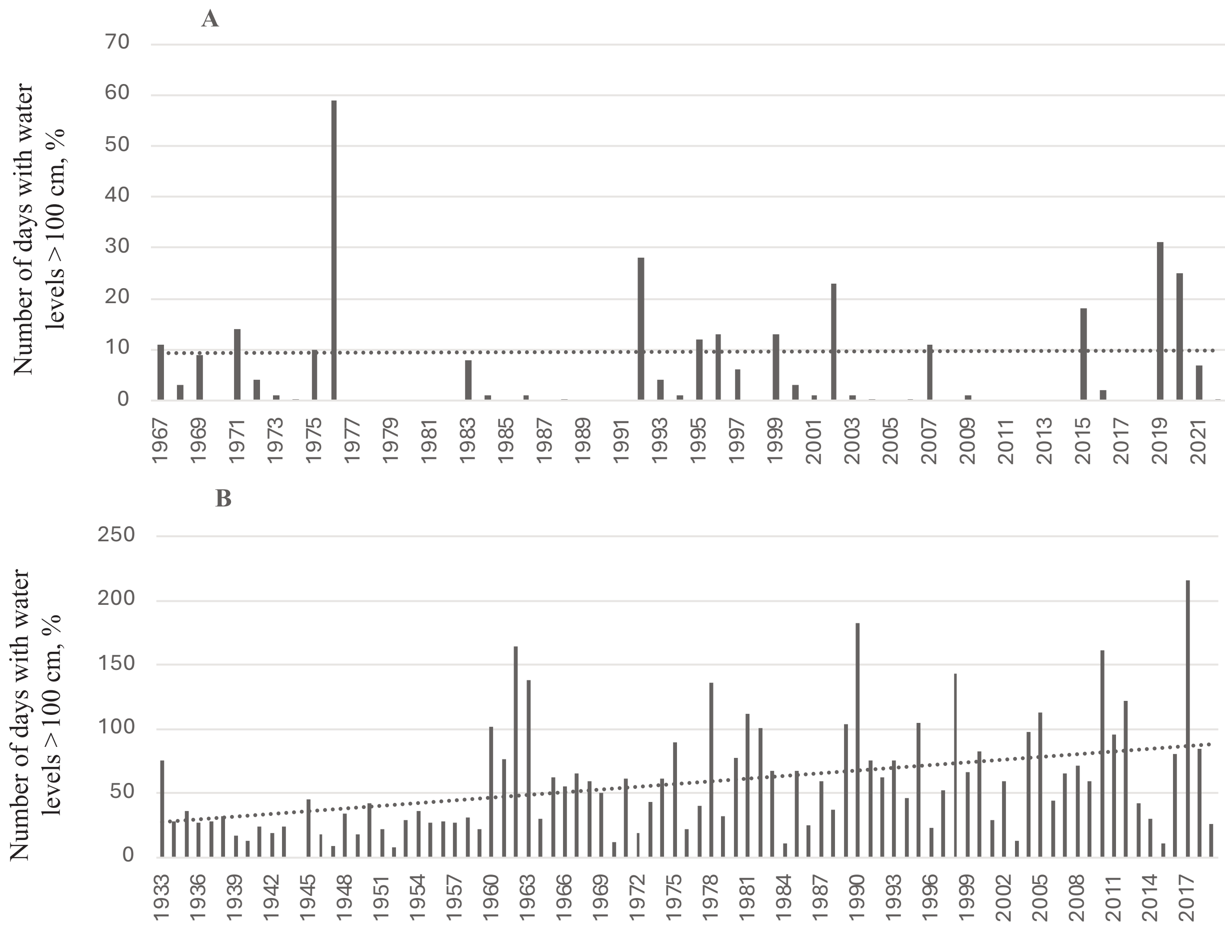


Fig. 7. Number of days per year, with water levels rising 100–200 cm above the station's zero line at Buivydžiai (A) and Jonava (B) hydrological monitoring stations.

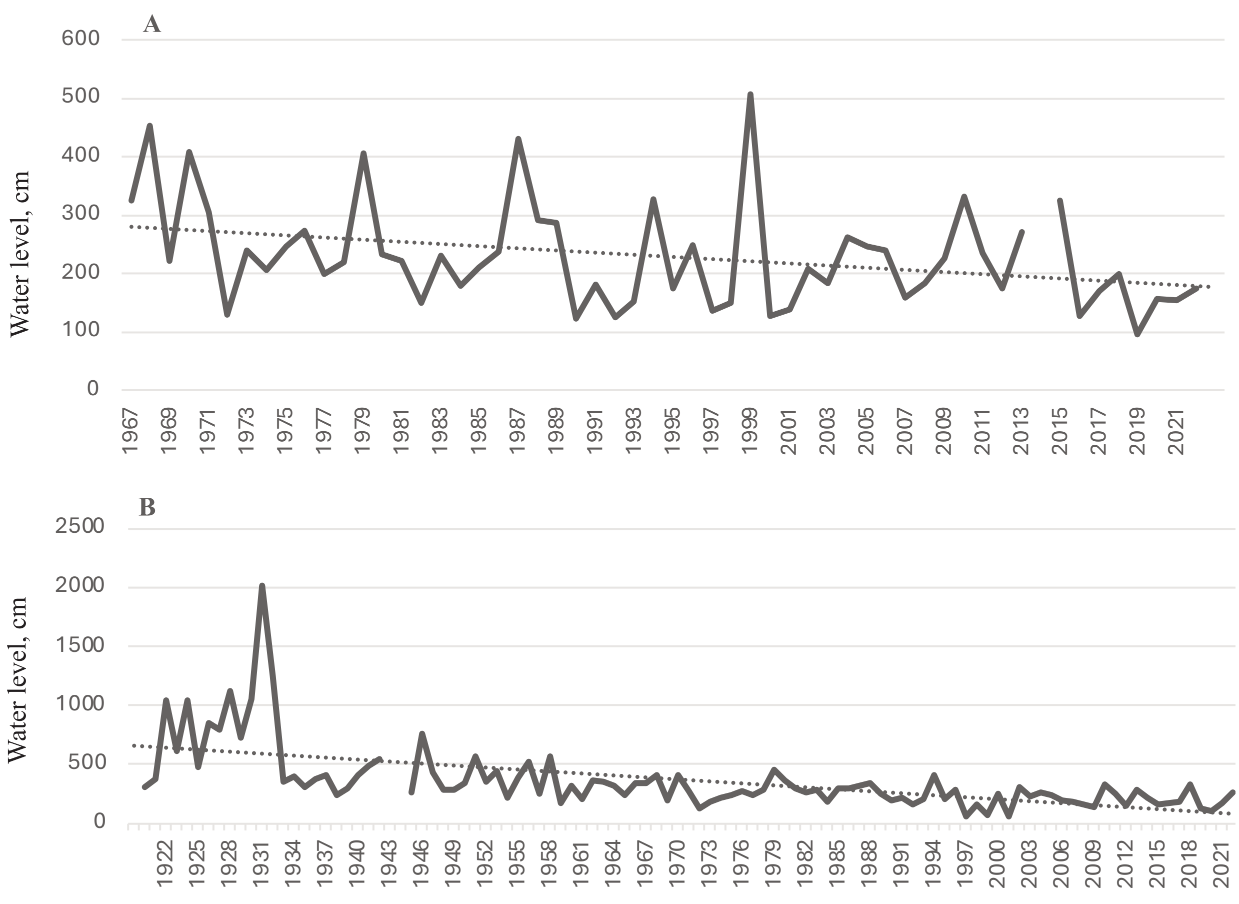


Fig. 8. Amplitudes of Neris water level fluctuations at Buivydžiai (A; 1967–2022) and Jonava (B; 1920–2022) hydrological monitoring stations.

Conclusion

The analysis of high water levels in the Neris River, located in the eastern part of the Baltic Sea basin, revealed a clear decreasing trend in the number of days with peak floods since the 1950s. This trend, primarily driven by climate change, has resulted in the absence of significant floods in recent decades, facilitating a notable expansion of vegetation in the riverbed. The increasing time interval (window of opportunity) between major floods creates favorable conditions for the growth of riparian and island vegetation. Consequently, this has led to the gradual narrowing of the riverbed, a reduction in its cross-sectional area, and a decline in the riverbed's capacity and water permeability.

The research findings are consistent with the conclusions of other researchers who state that the absence of large-scale flood events promotes the expansion of vegetated areas (Picco et al. 2014; Hooke and Chen 2015). Vegetation colonization is mainly controlled by growth conditions, disturbance energy, and the temporal window between major floods (Gurnell and Petts 2002).

The important role of vegetation in shaping channel morphology has gained increasing support through field studies (Simon and Collison 2002), numerical modeling (Murray and Paola 2003), and laboratory experiments (Bertoldi et al. 2009; Braudrick et al. 2009; Tal and Paola 2010). In gravel-bed rivers, vegetation has been shown to enhance bank stability, leading to channel narrowing (Picco et al. 2023).

Dams contribute to reduced flood peaks, elevated base flows, and sediment retention (Kondolf 1997). These altered conditions promote vegetation establishment on gravel bars, which further stabilizes them (Lobera et al. 2015) and contributes to a reduction in active channel width by increasing connectivity between fluvial islands and floodplains (Picco et al. 2014). This trend is further reinforced by recent changes in flood regimes – largely driven by climate change – characterized by extended drought periods (Brummer et al. 2016).

The declining frequency of high floods in the Neris River during the period 1922–2022 has altered the intensity of water-induced erosional processes and reduced the influx of sediment into the river.

On the other hand, the shortening of the river's overflow period into the floodplain has lowered sediment deposition in the floodplain itself. This reduction may increase sediment deposition in the riverbed, accelerating the formation of shallows and islands.

Overall, the decreasing frequency of high floods, which regulate sediment deposition, island dynamics, and changes in riverbed morphometry, has led to a significant expansion of vegetative cover. In the lower course of the Neris, island forest coverage increased from 7% to 18% between 2005 and 2020, while the area of islands per unit area of water rose from 2% to 8%.

The urbanized lower course of the river, characterized by numerous islands and historically prone to high flood inundation, may face even more extreme conditions in the future due to elevated water levels around the islands, potentially occurring even under average flow conditions. Climate change effects, which hinder the formation of stable snow and ice cover, have altered the primary causes of flooding. Floods are now increasingly caused by heavy rainfall and ice jams rather than snowmelt. The increasing area of islands per unit area of water and island forest coverage in the lower river course contribute to higher water levels and greater flood extent. Observed trends in riverbed dynamics suggest that in the future, extreme floods may occur, driven by a reorganized river channel following prolonged periods of low flood activity. Historically, even average river discharge could cause hazardous flooding in the river valley. Therefore, it is essential to begin developing adaptation strategies now for these anticipated changes. A better understanding of riparian vegetation and island dynamics, which largely depend on the river's hydrological regime, will support the development of appropriate management methods to mitigate negative impacts on the surrounding environment.

Data availability statement

All data used in this study are contained within the article.

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