Features and causes of catastrophic floods in the Nemunas River basin
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ABSTRACT
The Nemunas River basin falls within the territories of five different countries – Belarus, Lithuania, Russia, Poland and Latvia. In general, the beginning of spring floods highly depends on rapid rise of air temperature, heavy precipitation and sudden snow melting in the analysed basin. In this paper, the conditions of formation and consequences of two catastrophic floods in 1958 and 1979 in the Nemunas River basin were studied regarding the hydrometeorological parameters (maximum snow water equivalent before the beginning of flood and precipitation amount during the flood) as well as runoff coefficients for each selected catastrophic flood. Differences between the main drivers and evolution of these floods were analysed. Spatial distribution of maximum snow water equivalent and precipitation, as well as runoff coefficient in different parts of the river basin, were identified as having the most significant impact on the formation of the studied catastrophic floods.

Key words catastrophic flood, flood volume, Nemunas River, runoff coefficient, snow water equivalent

INTRODUCTION
According to numerous scientific studies, including Intergovernmental Panel on Climate Change (IPCC 2013), more frequent and destructive floods all over the world may happen as a consequence of climate change. Beyond the fact that a number of catastrophic weather phenomena continue to grow and often result in awesome catastrophic floodings, they generate huge economic losses and kill people. For obvious reasons, huge floods are attracting significant attention of the mass media, as well as scientific society. Tweed (2011) describes the term catastrophic flooding as exceptional or rare floods with high magnitude. In general, catastrophic floods can be characterised by abruptness of water level rise and increase of intensity of flood phenomenon that are followed by enormous monetary losses and fatalities. Economic flood exposure is simulated to increase by about 200% between 2010 and 2050 (Jongman et al. 2012), whereas the number of flood-affected people may increase five-fold by the end of the 21st century (Hirabayashi et al. 2013).

The historical records of catastrophic floods reveal that their increased occurrence is mostly caused by extreme precipitation events. However, natural causes of fluvial floods are not limited to increased precipitation due to higher temperatures; snowmelt processes and soil conditions prior to flooding are also of high significance. Berghuijs et al. (2016) exposed the primary drivers of flooding across the contiguous United States and found that for most catchments soil moisture-dependent precipitation excess, snowmelt and rain-on-snow events are much better predictors of the flooding responses. Many other studies also confirm that floods are the result of a complex interaction between pre-event meteorological characteristics and hydrological catchment conditions (Nied et al. 2014; Beniston & Stoffel 2016;
Hence, flood magnitude is determined by a certain flood-prone combination of hydrometeorological patterns before the event. An attempt to quantify multi-continental changes in the frequency and magnitude of extreme floods revealed that the key drivers of extreme floods strongly vary between catchments (Berghuijs et al. 2017).

Existing studies in Lithuania have mostly concentrated on spring flood phenomena in the Nemunas River basin (Stankunavicius et al. 2007; Rimkus et al. 2013; Meilutytė-Lukauskiene et al. 2017). However, only a few very old written sources about the catastrophic floods in the Nemunas River basin are available (Kolupaila 1932). Some information on water resources dynamics in the Nemunas River basin, which influenced extreme events, can be found in Korneev et al. (2015). Therefore, the aim of this research is to analyse the main drivers and conditions of the formation of two (1958 and 1979) catastrophic floods in the Nemunas River basin and to find the most unfavourable combination of hydrological and meteorological factors which may cause catastrophic floods in river catchments of Eastern Europe.

**STUDY AREA AND DATA**

The Nemunas River is the 14th longest river in Europe and the 4th longest in the Baltic Sea drainage basin. The river basin covers an area of around 98,200 km² and it mainly includes the territories of Belarus and Lithuania, whereas small parts of this basin fall within Russia (Kaliningrad district), Poland and Latvia (Figure 1). The length of the Nemunas River is 937 km, i.e., 436 km flows in Belarus (from the springs), 116 km of this river coincides with state borders between Lithuania and Belarus as well as Lithuania and Russia (Kaliningrad district) and the other 359 km – in Lithuania. Three types of climate (marine, transitional and continental) on the regional scale are detected in the territory of the Nemunas River basin. These types of climate...
climate highly depend on the distance of the Baltic Sea and local topography. The area with the highest precipitation ratio (700–900 mm) is located in the downstream part of the selected river basin. The amount of precipitation (450–650 mm) slightly decreases moving from downstream to the upstream as well as increase in amplitude of the air temperature due to the Baltic Uplands, which together with the distance from the Baltic Sea have significant impact on the distribution patterns of different meteorological parameters. Consequently, these local conditions cause more intensive accumulation of snow cover in the upper part of the selected river basin. The main reasons for the floods in the Nemunas River basin are a sudden snow melting combined with intense rainfall; also there is a probability of floods caused by dam failure and landslides. However, the local floods in the Nemunas River basin can happen suddenly because of ice jams. Such a distribution of factors was confirmed by investigation of the Environmental Protection Agency of Republic of Lithuania (EPA 2012), where the main causes of catastrophic floods are identified: the snow melting and ice jam events (75%), heavy rainfall (15%) and others factors (10%).

In this basin, the hydrological observation network consists of 73 water gauging stations (WGS). Eighteen of them are situated in the territory of Belarus, 52 stations in the territory of Lithuania, and 3 of them in the Kaliningrad district (Russia). Smalininkai WGS (water gauging station) has one of the longest series of water level (since 1812) and discharge continuous observations in Europe. The network of monitoring stations (MS) of meteorological observations comprises 26 meteorological stations: 13 stations in Belarus and 13 in Lithuania. The MSs include those stations which observed casual meteorological parameters ($T$, $P$, $SWE$, etc.) as well as stations where only $SWE$ was measured.

The evaluation of impact of meteorological and hydrological parameters on formation of the catastrophic floods was carried out using long-term series of daily discharge data from 12 WGS (Table 1), as well as data of daily precipitation ($P$, mm), monthly air temperature ($T$, °C) and decadal (i.e., measured every tenth day) snow water equivalent ($SWE$, mm) from 58 MS.

### METHODS

The beginning of spring flood in the Nemunas River basin mainly depends on climatic conditions (air temperature, precipitation, snow melting), whereas the end of flood may be influenced by many different elements (such as size, form and slopes of the basin, snow reserve in the basin, density of river network, etc.). In Figure 2, a scheme of flood formation in the Nemunas River is displayed, where the beginning of spring flood with abrupt increase of discharges, its course and culmination is presented. Sudden increase of

| No. | Country | River | WGS           | Distance from the mouth, km | Basin area, km² | Watercourse slope, % | Forests, % |
|-----|---------|-------|---------------|----------------------------|-----------------|---------------------|------------|
| 1   | Belarus | Nemunas| Stolbtsy      | 854                        | 3,070           | 0.93                | 35         |
| 2   | Belarus | Nemunas| Belica        | 673                        | 16,700          | 0.54                | 27         |
| 3   | Belarus | Nemunas| Mosty         | 598                        | 25,600          | 0.47                | 28         |
| 4   | Lithuania| Nemunas| Druskininkai  | 450                        | 37,100          | 0.40                | 27         |
| 5   | Lithuania| Nemunas| Nemajūnai     | 339                        | 42,800          | 0.37                | 27         |
| 6   | Belarus | Neris  | Stesici       | 455                        | 1,230           | 1.30                | 48         |
| 7   | Belarus | Neris  | Zalesje       | 353                        | 6,840           | 0.68                | 41         |
| 8   | Lithuania| Neris | Vilnius       | 165                        | 15,200          | 0.47                | 36         |
| 9   | Lithuania| Neris | Jonava        | 39                         | 24,600          | 0.45                | 27         |
| 10  | Lithuania| Nemunas| Lampėdžiai   | 206                        | 71,400          | 0.35                | 27         |
| 11  | Lithuania| Nemunas| Smalininkai  | 112                        | 81,200          | 0.54                | 18         |
| 12  | Russia  | Nemunas| Neman         | 72                         | 91,600          | 0.54                | 20         |
air temperature (above zero) together with a high rate of precipitation influences decline in thickness of the snow cover. Then, intensive snow melting causes abrupt increase of the water level in the river and these conditions give rise to the spring flood in the river basin.

A general scheme of the research methodology is presented in Figure 3. The first step in this research was probability distribution analysis in order to find out the floods of rare probability in the selected river basin. After selection of catastrophic floods, assessment of the main hydrological (water level during the flood ($h_{\text{flood}}$, cm), daily discharge during the flood ($Q_{\text{flood}}$, m$^3$ s$^{-1}$)) and meteorological (maximum snow water equivalent before the flood ($\text{SWE}_{\text{max}}$, mm) precipitation amount during the flood ($P_{\text{flood}}$, mm) and air temperature ($T$, °C)) characteristics was carried out. In the following step, the number of investigated variables was reduced by keeping the most important ones: $Q_{\text{flood}}$, $\text{SWE}_{\text{max}}$, and $P_{\text{flood}}$. SWAT BF (Soil and Water Assessment Tool) tool was used for determination of the part of the surface runoff ($Q_{\text{surface}}$, m$^3$ s$^{-1}$) by eliminating the runoff part of groundwater feeding. Volume of catastrophic flood ($V_{\text{flood}}$, km$^3$) in the Nemunas River was calculated from the data of $Q_{\text{surface}}$. The flood volume in the WGS catchment (an area between two WGS, i.e., from upstream WGS to outlet WGS – $V_{\text{WGSflood}}$, km$^3$) was assessed as well. In parallel, IDW (inverse distance weighted) method was used for analysis of the spatial distribution of height of maximum snow water equivalent before the beginning of the flood.
(\(H_{SWEmax}\), mm) and height of precipitation amount during the flood (\(H_{Pflood}\), mm). After that, the total amount of water resources (\(V_{res}\), km\(^3\)) from \(SWEmax\) and \(P_{flood}\) in the Nemunas River basin was estimated. Additionally, water resources in the WGS catchment (\(V_{WGSres}\) km\(^3\)) were calculated within the scale of separate WGS catchments. Finally, analysis of runoff coefficients in WGS catchments \(\eta_{WGS}\) was carried out for the evaluation of surface runoff conditions during both catastrophic floods.

**IDW (inverse distance weighted)** interpolation (using ArcGIS Spatial Analyst extension) was applied in this study for the creation of isoline maps of certain indices on the catchment scale. The IDW method defines MS values, when, according to linearly weighting, the neighbouring MS values are established. The weight of monitoring stations is based on the function of inverse distance. The surface point values of \(SWEmax\) and \(P\) were interpolated according to the dependent variable of the closest MS. IDW method also was used to estimate values of the ungauged areas, which were calculated according to the surrounding MS data. The values of the closest monitoring stations had more influence on the unmeasured areas than stations further away. Accordingly, the total amount of water resources from \(SWEmax\) and \(P_{flood}\) in the Nemunas River basin was estimated.

**SWAT (Soil and Water Assessment Tool) Baseflow Filter (BF) program** (https://swat.tamu.edu/software/) was used to separate a part of the groundwater feeding and surface runoff from the data of historical observations (i.e., hydrograph). This software provides an opportunity to investigate the influence of the surface processes on volume of the spring flood. The methodology of hydrograph separation is described by Arnold & Allen (1999) in more detail. In this research, SWAT BF tool was used for determination of the part of the volume of catastrophic flood (\(V_{flood}\)) in the Nemunas River, which was caused by the surface runoff in the basin. Eliminated groundwater feeding from the daily discharge during the flood (\(Q_{flood}\)) allows assessment of the discharge part from surface runoff during the flood (\(Q_{surface}\)). Surface runoff during the flood gives an opportunity to estimate the interaction between surface processes (precipitation and snow melting) and catastrophic flood runoff. \(V_{flood}\) in the Nemunas River basin was compared with water resources in the WGS catchment (\(V_{WGSres}\)).

**Calculations of hydrometeorological variables.** In the Nemunas River basin, \(V_{res}\) consists of water from \(SWEmax\) together with \(P_{flood}\), which determine \(V_{flood}\). Volume of the selected flood was calculated by using the equation:

\[
V_{flood} = \sum_{i=1}^{n} Q_{surfacei} \cdot t
\]

where \(Q_{surfacei}\) is daily discharge during the flood without groundwater feeding (estimated from output of SWAT BF) (m\(^3\) s\(^{-1}\)), \(t\) is daytime (s), \(i\) is from 1 to \(n\), \(n\) is flood duration expressed by days (the time period from the beginning until the end of spring flood, i.e., from the first day of sudden increase of hydrograph until the last day of sharp decrease in hydrograph after maximum discharge of the spring flood).

The volume of water resources \(V_{res}\) in the Nemunas River basin was calculated as:

\[
V_{res} = (\bar{H}_{SWEmax} \cdot S_{basin}) + (\bar{H}_{Pflood} \cdot S_{basin})
\]

where \(\bar{H}_{SWEmax}\) is average height of maximum snow water equivalent (calculated from area of the whole basin) before the beginning of the spring flood (mm), which was selected from decadal (i.e., measured every tenth day) data of snow water equivalent, \(\bar{H}_{Pflood}\) is average height of precipitation amount (calculated from area of the whole basin) during the spring flood (mm), which was calculated by assessing the time period from abrupt rise of the river discharge until the maximum peak of catastrophic flood, \(S_{basin}\) is area of selected basin (km\(^2\)). Average heights of \(SWEmax\) and \(P_{flood}\) were estimated from the isoline maps.

In analysis of surface runoff processes, the runoff coefficient, an important input parameter in hydrologic modelling, characterised as the ratio of runoff volume and rainfall volume, is widely used. In the present study, the runoff coefficient \(\eta\) is defined as a portion of accumulated water resources that directly becomes a part of the volume of catastrophic flood. A runoff coefficient was calculated for each WGS catchment (\(\eta_{WGS}\)) and showed the ratio between \(V_{WGSflood}\) and accumulated water resources from \(SWEmax\) and \(P_{flood}\) (\(V_{WGSres}\)):

\[
\eta_{WGS} = \frac{V_{WGSflood}}{V_{WGSres}}
\]
Thus estimation of $\eta_{WGS}$ shows which part of the river basin has the greatest weight on the volume of catastrophic flood and spatial differences in the surface runoff conditions between WGS catchments.

ArcGIS (ArcMap, version 10.5, http://desktop.arcgis.com/en/) software was used for mapping of the research results.

RESULTS AND DISCUSSION

Hydrological characteristics of investigated floods

This research concentrates on two catastrophic floods. One of them (1958) occurred before the construction of Kaunas Hydro Power Plant (Kaunas HPP), and the second one after that (1979). These two floods were among the largest in this basin and both of them have available series of daily data and other related variables (meteorological data) which are necessary for the investigation. The flood of 1958 (one of the biggest floods in this basin of the last 200 years) affected large territories, covered three countries and reached a historical peak discharge (6,580 m$^3$/s at Smalininkai WGS in Lithuania). The flood peak in 1979 (the last biggest in this basin after the flood in 1958) reached 5,300 m$^3$/s (at Neman WGS in Russia) and caused a great deal of damage as well. In 1959, Kaunas HPP (227 km from the mouth of the Nemunas River) was set into operation and, since then, floods of the magnitude of that in 1958 have not been recorded. HPP significantly changed the hydrological regime of the river and conditions of flood formation below the HPP dam. Analysis of the probability distribution of the 200-year data set of the Nemunas River (at Smalininkai WGS) (Figure 4) showed flood peaks of rare probability (1% and 10%) in 1958 and 1979, respectively. These probabilities were calculated from the data series of annual maximum discharge of the period of 1812–2017.

Both floods took place in the period March to April. The peak discharge of flood in 1958 was 2.5 times greater than the average of maximum discharges at Smalininkai WGS, while in 1979 it was 1.5 times greater (Figure 5).

In 1958, spring started almost a month later than usual, i.e., 10–16 April (mean annual date of floods in the Nemunas River is 18–22 March). A few days later, the catastrophic flood hit the Nemunas River basin (Figure 6). The peak discharge of this flood exceeded 7,000–8,000 m$^3$/s. The 74,000 hectares of Kaliningrad District and 57,000 hectares of Lithuanian territory were flooded (Ginko 1982). Many structures were demolished, many dams were washed out, protected areas suffered from the overflowing waters as well (Figure 7). During this flood, the Lithuanian cities of Kaunas, Alytus, Balbieriškis, Prienai, Druskininkai and Birštonas were inundated; many houses and streets were damaged. Over the observation period, the highest water level $h_{\text{flood}}$ was recorded at Druskininkai WGS (10.93 m on 24 April). In Kaunas city, the factories and
churches were flooded, and construction work of Vilijampolė Bridge (at that time it was under construction) was disturbed. In Belarus, \( h_{\text{flood}} \) of 7.10 m was observed at Michaliski WGS on 21 April. Grodno city experienced the biggest losses during this disaster (Briliovski 2012). In this city, \( h_{\text{flood}} \) rose to 8.63 m and many houses, cellars, a beer factory, port and city water pumping station were destroyed.

In March 1979, another large flood hit the large areas in the Nemunas River basin. This flood happened on 20–25 March, i.e., at the usual time. Although the spring season weather was not uncommon, in February it was extremely cold and a great deal of snow fell. During this flood, the maximum discharge at Neman WGS was 5,300 m\(^3\)/s (4 April). This time, the municipalities were ready for the flood and a significant amount of water (from the Neris River – the major tributary of the Nemunas) was detained in the water reservoir of Vileika; and large parts of the population along the rivers were successfully evacuated. However, an area of 50,000 hectares was flooded and many communication lines were damaged (Ginko 1982). The oldest WGS station of the Nemunas (Smalininkai WGS) was almost destroyed and temporarily no measurements were taken there (Jablonskis & Lasinskas 2011). During this flood, the Lithuanian cities of Kaunas, Smalininkai and Druskininkai were inundated. The highest \( h_{\text{flood}} \) was observed in the WGS of Druskininkai and Smalininkai (7.28 m on 7 April and 7.40 m on 5 April, respectively). In Druskininkai, the sanatoriums were flooded (and had to be closed); the Nemunas levee was breached (Ginko 1982). During this flood, the Belorussian city of Grodno suffered
the most (Sajapin 2012). Many streets, houses, a beer factory, main bus station and church were inundated and damaged.

**Characteristics of the meteorological conditions before catastrophic floods in 1958 and 1979**

In general, the weather in the winter season of 1957/1958 was not unusual, i.e., the amount of precipitation as well as temperatures were very similar to average values. However, the spring season was extremely cold, especially March (air temperature was very low). For example, in March at Raseiniai MS, the mean temperature was equal to $-5.2^\circ C$ (whereas, the annual mean of 1950–2015 is $-0.7^\circ C$). Thus, the beginning of spring could be regarded as exceptionally cold and having favourable conditions for formation of snow cover before the flood. Meanwhile, the winter season of 1978/1979 was completely different compared with 1957/1958. The winter season of 1978/1979 was very cold and air temperature in the Nemunas River basin territory was abnormally low. The mean values of air temperatures in December of 1978 varied from $-7.6^\circ C$ (Ivacevici MS) to $-11.6^\circ C$ (Lyntupy MS), whereas in January of 1979 it was from $-7.7^\circ C$ (several MS) to $-9.3^\circ C$ (Lyntupy MS) and in February from $-6.9^\circ C$ (Taurage MS) to $-9.3^\circ C$ (Naroc MS). Therefore, the winter of 1978/1979 was cold and the major part of water resources was accumulated in snow cover, which resulted in such extensive flooding.

Interaction between precipitation and air temperature determines the form of precipitation – liquid (rainfall), freezing (drizzle) or frozen (snowfall). A large amount of snow was accumulated in the basin area after intense snowfall over the period from December 1957 to March 1958. For example, in February and March, the precipitation amount was significantly bigger than the annual mean (1950–2015) in three MS (Figure 8). In the winter season of 1978/1979, the amount of precipitation was distributed unequally: in January/February, it was close to the annual mean, whereas in March it was particularly high – 73.6 mm (at Lyntupy MS).

Estimated values of maximum snow water equivalent before the floods of 1958 and 1979 differed from each other. In 1958, $SW_{Emax}$ was very high and in some parts of the Nemunas River basin it exceeded 200 mm. The highest value of $SW_{Emax}$ was estimated in March and April (207 mm at Novogrudok MS in April, 189 mm at Varėna MS in March). Meanwhile, in the winter season of 1978/1979, accumulated $SW_{Emax}$ was high as well – in some MS greater than 140 mm. The largest $SW_{Emax}$ was identified in February at the monitoring stations of Tauragė and Novogrudok (144 mm and 159 mm, respectively). Abundant precipitation (snowfall and rainfall) and accumulation of thick snow cover could lead to such significant floodings in the Nemunas River basin. Therefore, analysis of spatial distribution of $SW_{Emax}$ and $P_{flood}$ was performed.

![Figure 8](http://iwaponline.com/hr/article-pdf/51/2/308/682255/nh0510308.pdf)

**Figure 8** | Monthly distribution of the annual mean (1950–2015) and the monthly amount of precipitation from December (1957 and 1978) to April (1958 and 1979) in three MS of the Nemunas River basin.
Spatial distribution of meteorological conditions in the Nemunas River basin

The analysis of spatial distribution of $SWE_{\text{max}}$ and $P_{\text{flood}}$ was accomplished for the selected floods of 1958 and 1979 in the Nemunas River basin. The largest amount of water resources was accumulated in the snow cover before the flood of 1958 (Figure 9) when the isoline of $SWE_{\text{max}}$ of 100 mm divided the basin in two different parts. These parts are characterised by distinct water resources and distribution of $SWE_{\text{max}}$ (Figure 9(a)). The largest resources of $SWE_{\text{max}}$ were concentrated in the southeastern part of the basin and they slightly decreased in the northwest (closer to the Baltic Sea). Consequently, formation of the flood of 1958 highly depended on the snow melting processes in the southeastern part of the Nemunas River basin; whereas the resources of $SWE_{\text{max}}$ were smaller before the flood of 1979. They were concentrated in the northeastern and central parts of the basin (Figure 9(b)). This area was separated by the isoline of 100 mm and this division coincided with uplands in the analysed basin. These differences in distribution of the $SWE_{\text{max}}$ are among the many factors which have led to major differences between the catastrophic floods of 1958 and 1979.

The spatial distributions of $P_{\text{flood}}$ of 1958 and 1979 are displayed in Figure 10. During the flood of 1958, the amount of rainfall was also greater (same as maximum $SWE_{\text{max}}$) than in the flood of 1979. In the major part of the Nemunas River basin, the amount of precipitation exceeded 50 mm, whereas in the central part it was even greater than 60 mm. Such large amount and even distribution of precipitation indicated a significant impact of $P_{\text{flood}}$ on formation of the catastrophic flood in the analysed basin compared with the flood of 1979. Meanwhile in 1979, $P_{\text{flood}}$ reached up to 40 mm in the largest part of the basin. Only in the northern part was the increase of precipitation observed. During formation of the catastrophic floods in the Nemunas River basin, after snow melting, rainfall immediately becomes the major part of surface runoff. These conditions are formed due to the soils, which are already waterlogged before the cold period; and all moisture surplus is draining together with surface runoff due to the frozen soils. Therefore, the significant impact of precipitation amount on the magnitude of catastrophic flood is obvious.

Distribution of $V_{WGSres}$ and $V_{WGSflood}$ in different WGS catchments (the whole analysed basin was divided into separate catchments and each catchment was described by the outlet WGS) in 1958 and 1979 is shown in Figure 11. The largest differences of $V_{WGSflood}$ between the two analysed floods were identified in the southeastern part of the basin (in the catchment of Belitsa WGS). These differences originated due to the high volume of water resources from

Figure 9 | The isolines of $SWE_{\text{max}}$ (mm) before the floods in the Nemunas River basin in 1958 (a) and 1979 (b).
$SWE_{max}$ (Figure 9(a)) in 1958 and smaller input of water from $P_{\text{flood}}$ (Figure 10(b)) in the southeastern part of the basin during the flood of 1979. Also, significant distinctions between $V_{WGS\text{flood}}$ of 1958 and 1979 were established in the

catchments of Zalesje WGS and Vilnius WGS, where differences of $V_{WGS\text{res}}$ were not as large as differences in flood volume. The influence of Vileika Reservoir and the water system of Vileika-Minsk (built in 1976) are reflected in the

\[\text{Figure 10} \quad \text{The isolines of } P_{\text{flood}} \text{ (mm) in the Nemunas River basin in 1958 (a) and 1979 (b).}\]

\[\text{Figure 11} \quad \text{Volumes of floods } V_{WGS\text{flood}} \text{ and water resources } V_{WGS\text{res}} \text{ in the Nemunas River basin at different WGS catchments (in 1958 and 1979).}\]
differences obtained in Belarus, because these constructions collected part of the flood water in the reservoir; water losses during the pumping and infiltration in Vileika-Minsk water system also have to be considered. In the catchment of Jonava WGS, the smallest differences in \( V_{WGS\,res}^{1958} \) and \( V_{WGS\,flood}^{1958} \) were estimated. Such consistent patterns may be a result of the large amount of precipitation in the mentioned WGS catchment (Figure 10(b)). Summarising, the largest amounts of \( V_{WGS\,res} \) and \( V_{WGS\,flood} \) were detected in the WGS of Belitsa, Mosty and Druskininkai, which are located in the southeastern part of the Nemunas River basin. Thus, water resources from these WGS catchments had the most significant impact on flood formation during the analysis of the two catastrophic floods.

The development of flood volume and increase of water resources from Stolbtsy WGS to Neman WGS in the investigated basin are shown in Figure 12. The changes of \( V_{flood} \) and \( V_{res} \) according to different WGS indicated the most significant increase of volumes in different sections of the basin. At Smalininkai WGS, \( V_{res} \) of 1958 and 1979 floods were estimated as 12.27 km\(^3\) and 9.40 km\(^3\), respectively. The significant inflow part of \( V_{res} \) was from the Neris River, which is the right tributary of the Nemunas River between Nemajūnai and Lampėzdžiai WGS. Also, large increases of \( V_{flood} \) were estimated in the upper reach of the analysed basin (catchments of Belitsa, Mosty and Druskininkai WGS). The impact of \( V_{res} \) on floods in 1958 and 1979 is clearly expressed at Lampėzdžiai WGS by sudden increase of this variable. At outlet WGS (Smailininkai), the total volume of catastrophic floods \( V_{flood} \) consisted of 7.54 km\(^3\) in 1958 and 4.33 km\(^3\) in 1979.

**Variability and spatial distribution of runoff coefficients in WGS catchments of the Nemunas River basin**

The variability of runoff coefficients \( \eta \) highly depends on meteorological and hydrological factors at the catchment scale. These factors influence processes of the surface runoff and differences between runoff conditions, which are expressed by the runoff coefficient. Maximum discharge \( Q_{max} \), height of maximum snow water equivalent \( SWE_{max} \), precipitation amount during the flood \( P_{flood} \) and runoff coefficient \( \eta_{WGS} \) were calculated in catchments of different WGS for both analysed catastrophic floods (Table 2). Estimated \( \eta_{WGS} \) indicated the part of \( SWE_{max} \) and \( P_{flood} \) that turned into the flood volume of different WGS catchments. The highest \( \eta_{WGS} \) (0.78) of the catastrophic flood of 1958 was estimated at the catchment of Stolbtsy WGS, meanwhile the average values of \( \eta_{WGS} \) fluctuated in the range of 0.51–0.62. During the flood of 1979, the \( \eta_{WGS} \) were lower and varied from 0.28 to 0.57. The highest \( \eta_{WGS} \) was obtained in Stolbtsy WGS catchment for both floods, but the lowest \( \eta_{WGS} \) were determined at WGS catchments of the Neris River – in the WGS of Vilnius and Zalesje (0.28 and 0.29, respectively). These differences revealed the parts of the Nemunas River basin that had the largest weight on flood volume.

The isoline map of annual \( \eta \) in the Nemunas River basin was created according to the studies of Jablonskis & Janučienė (1978) and Makarevič (2017) (Figure 13). This map was used for comparison of obtained runoff coefficients \( \eta_{WGS} \) and the annual values of \( \eta \). The obtained \( \eta_{WGS} \) were higher than the annual values of \( \eta \) in almost all analysed WGS catchments. This tendency confirmed the significance of surface runoff on magnitude of flood volume \( V_{flood} \), because a larger part of water resources \( V_{res} \) directly transformed into \( V_{flood} \). Several WGS catchments of the southeastern part of the basin had much higher \( \eta_{WGS} \) than the annual runoff coefficients, especially in the catchment of Belitsa WGS. Here,
Table 2 | $Q_{\text{max}}$, height of SWEmax, $P_{\text{flood}}$ and $\eta$ at catchments of different WGS during the floods of 1958 and 1979

| River          | WGS     | WGS catchment area (km²) | Maximum discharge $Q_{\text{max}}$ (mm) | Average height of SWEmax (mm) | Average height of $P_{\text{flood}}$ (mm) | Runoff coefficient $\eta$ |
|----------------|---------|--------------------------|-----------------------------------------|-------------------------------|------------------------------------------|---------------------------|
| Neris Stesici  | 1,228   | 12.2 6.4 113.4 84.1 49.3 22.8 0.59 0.44 |
| Neris Zalesje | 6,162   | 12.4 5.3 103.8 88.5 48.3 28.3 0.61 0.29 |
| Neris Vilnius | 7,893   | 8.4 3.6 106.9 97.8 53.2 40.9 0.51 0.28 |
| Neris Jonava   | 9,244   | 7.3 4.7 68.2 67.1 53.1 45.4 0.54 0.39 |
| Nemunas Stolbtsy | 3,182 | 18.3 9.6 119.2 78.1 51.4 34.0 0.78 0.57 |
| Nemunas Belitsa | 13,935 | 12.2 6.8 130.0 94.0 53.8 35.7 0.62 0.50 |
| Nemunas Mosty  | 10,866  | 9.7 5.3 109.8 70.8 48.8 36.3 0.59 0.49 |
| Nemunas Druskininkai | 10,126 | 7.4 4.5 86.4 77.5 47.3 30.4 0.58 0.49 |
| Nemunas Nemajūnai | 5,113 | 7.0 4.2 98.4 87.6 55.1 40.3 0.57 0.44 |
| Nemunas Lampėdžiai | 3,940 | 6.4 3.8 79.7 62.5 55.4 39.8 0.55 0.39 |
| Nemunas Smalininkai | 9,841 | 7.0 4.2 72.5 48.8 52.3 45.7 0.61 0.46 |
| Nemunas Neman  | 10,332  | – 5.0 – 53.2 – 38.7 – 0.54 |

Figure 13 | Spatial distribution of annual coefficient of surface runoff in the Nemunas River basin according to Jablonskis & Janukëniene (1978) and Makarevic (2017).
the annual mean of $\eta$ fluctuated in the range of 0.15–0.25, while the obtained $\eta_{WGS}$ was 0.62 and 0.50 during the catastrophic floods of 1958 and 1979, respectively. These variations of $\eta$ could be explained by a high difference in elevation as well as steeper slopes of the catchments in the southeastern part of the analysed basin.

The calculated runoff coefficients $\eta_{WGS}$ during the catastrophic floods in the Nemunas River basin related to accumulated water resources from $SWE_{max}$ and $P_{flood}$ correspond with the studies from other research. Usually, the runoff coefficients are small in the catchments of Austrian rivers, but these coefficients increase significantly with event rainfall including snowmelt (Merz et al. 2006). Meanwhile, in the research of Alpine areas of Austria, runoff coefficients ranged from 0.2 to 0.6 during the flood of 2013 (Blöschl et al. 2013). Runoff coefficient computed for the catchments of the eastern Italian Alps confirmed an increase of $\eta$ with event snowmelt floods and it is relatively low for rain floods (Norbiato et al. 2009).

CONCLUSIONS

In this study, the main drivers of the formation of catastrophic flood were analysed in the Nemunas River basin (situated in Eastern Europe). During the catastrophic floods of 1958 and 1979, the strong dependence of the flood severity on the distinctive combination of meteorological factors and hydrological characteristics was revealed.

The large amount of accumulated maximum snow water equivalent (up to 207 mm in the southeastern part of the Nemunas River basin and up to 120 mm in the central part, respectively, in 1958 and 1979) before the floods was the main factor which caused both catastrophic floods in the Nemunas River basin. Such conditions could occur due to a long period of negative temperatures during the cold season. The impact of excessive precipitation (average height of $P_{flood}$ was 51.6 mm in 1958, while in 1979 it was 36.3 mm) during both analysed floods was significant as well, because this precipitation interacted with snow melting and consequently it was transformed into flood volume. Hence, the magnitude and interaction between these meteorological parameters resulted in the following volumes of catastrophic floods in the lower reaches of the basin at Smalininkai WGS: 7.54 km$^3$ (in 1958) and 4.33 km$^3$ (in 1979).

In order to find which part of the basin has a greater input on the flood volume formation, this basin was divided into separate WGS catchments. The runoff coefficient ($\eta_{WGS}$) was expressed as a ratio between the volume of catastrophic flood in WGS catchment and the volume of water resources in WGS catchment. $\eta_{WGS}$ provides an opportunity to evaluate surface runoff processes in each WGS catchment, i.e., it enables the detection of the areas having the greatest weight on the volume of catastrophic flood and spatial differences of flood runoff formation. The highest values of $\eta_{WGS}$ were estimated in the catchments of Stolbtcy (0.78 and 0.57) and Belitsa (0.62 and 0.50) WGS during the floods of 1958 and 1979, respectively, and these WGS were located in the upper reaches of the Nemunas River basin. The reason for the mentioned consistent patterns could be related to the different physical-geographical factors (steeper slopes, different soils, forest area, etc.).

The findings of the study extended our knowledge and have direct practical relevance for regional flood management, because the obtained results showed the significance of hydrometeorological processes on formation of catastrophic floods in the separate parts (WGS catchments) of the Nemunas River basin. Such subdivision of the analysed river basin highlighted the relevant WGS catchments with the highest weight on volume of selected catastrophic floods. These particular parts of WGS catchments should be investigated further in the future, to see if the similar meteorological conditions would be repeated with the obtained distribution patterns in the analysed river basin. Moreover, the warning systems and preventative actions as a consequence of catastrophic floods should be adapted and improved in each WGS catchment. The lack of available data of other floods with catastrophic status in the Nemunas River basin produces some limitations on the final results. Accordingly, more detailed investigation is required in smaller scale of the selected basin for better understanding of the flood formation process and identification of other possible drivers of catastrophic flooding.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this paper is available online at https://dx.doi.org/10.2166/nh.2019.147.
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