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Temporal variation of spring flood in rivers of the Baltic States

Alvina Reihan, Jurate Kriauciuniene, Diana Meilutyte-Barauskiene and Tatjana Kolcova

ABSTRACT

Extreme floods can be caused by various combinations of hydrological and meteorological factors and river basin conditions that have not been observed for a long time. Long-term observational series permit estimation of both the frequency and variation of spring floods – the key issues of protection systems. Fortunately, Baltic States have a long-term record of hydrological data for the last 80 years. In this research, spring flood parameters (maximum discharge, height of maximum discharge and its timing) for the Baltic countries were assessed for four periods (1922–2008, 1941–2008, 1961–2008 and 1991–2008). In total, 70 hydrological data series of spring flood parameters were used. To detect trends in time series for these periods, the Mann–Kendall test and the nonparametric Sen's method for the magnitude of the trend were used. The index flood method was used to estimate the maximum discharge in ungauged catchments. The results showed that maximum discharges and heights of spring floods decreased over a longer period. Spring flood peaks took place on earlier dates. Only some significant trends of maximum discharges and their timing were found in the last time period (1991–2008). All these changes could be caused by the increasing ambient temperature and precipitation in the later decades.

Key words | Baltic countries, flood variation, index flood, spring flood, trends

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INTRODUCTION

Floods have been the most widely occurring natural disaster in human history. Some develop slowly, giving people time to prepare or evacuate. Others, called flash floods, form quickly and can appear with little or no warning. There have been many reports about worldwide inundations in which people perish. In China, the Yellow River flood in 1887 had a death toll of 900,000 lives. The flood on the Mississippi River in 1927 left 650,000 people homeless and killed 313 (Clark 1982). The beginning of the current century is also marked by big floods. According to the data of the Pakistani government, floods in 2010 directly affected about 20 million people, mostly by destruction of property, livelihood and infrastructure, with a death toll close to 2,000 (Singapore Red Cross 2010). In Europe, floods at the end of the 20th century and at the beginning of 21st century also resulted in death of people and damage to property. Extensive changes have been observed in the distribution of floods, making it more difficult to estimate future changes in floods behaviour, especially under the current climate changing conditions. For example, investigation of the Rhine River runoff shows that the frequency of floods will probably increase (Kwadijk & Middelkoop 1994). Kundzewicz *et al.* (2005), while examining 70 river discharge time series in Europe, found that the overall maxima (for the whole 1961–2000 period) occurred more frequently (46 times) in the second 20-year sub-period (1981–2000) than in the first 20-year sub-period (1961–1980) (24 times). Similar results were obtained in the Nordic countries (Bergström *et al.* 2001; Lindström *et al.* 2006). As concluded by Wilson *et al.* (2010) and

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Hisdal *et al.* (2006), the strongest trends found are coherent with changes expected mainly due to the temperature increase, which in its turn has increased winter discharge and discharge in spring flood, and earlier snowmelt floods. On the contrary, Polish results show a negative trend in spring maximum discharges for most of Poland's rivers (Kaczmarek 2003). A regional change in the timing and nature of floods has been observed in many areas of Europe, and less snowmelt and ice-jam-related floods have been recorded. However, there exist some expected changes that are not reflected in the trends, such as the expected increase in autumn discharge and autumn floods. Finnish researchers Veijalainen & Vehviläinen (2007) investigated the impact of climate change on floods and proposed that warm spells during winter would increase winter floods. However, the most extreme floods in Finland are now caused by snowmelt during spring. The occurrence of these floods will probably decrease because increased temperatures will reduce the amount of snow. Spring flood is a very significant hydrological phase of rivers in the Baltic States. Snow melting and ice jams result in higher levels of upstream water. Flood investigations in Lithuania (Meilutytė-Barauskienė & Kovalenkovienė 2007) showed that in some regions spring floods were expected to increase and in some to decrease. However, Latvian and Estonian studies have shown a decrease in spring floods almost everywhere (Kļaviņš *et al.* 2002; Reihan 2008).

In the Baltic countries, recent years were marked by very early floods with multiple peaks, causing additional difficulties in their management. In addition, under the current climate change conditions, extreme flood events become an increasing hazard in terms of risk and damage potential. Therefore, the forecasting and managing of floods is the key issue of protection systems. However, forecasts still include some level of uncertainty. The uncertainty may be controlled and managed if good hydrological data and statistical analysis are used for long-term predicting flood hazards. Fortunately, the Baltic countries have long-term series of hydrological data for the last 80 years which make it possible to estimate flood variations and tendencies. Until now, all national studies have been focusing on one country only, as mentioned in Reihan (2008) and Meilutytė-Barauskienė & Kovalenkovienė (2007) or, in addition, on only one or two selected rivers in the neighbouring country (Kļaviņš *et al.* 2008). This situation is why the present work has a wider regional focus, covering all three Baltic countries. The study addresses the following topics: (a) variability and trends of spring flood peaks and their dates in the following four periods: 1922–2008, 1941–2008, 1961–2008 and 1991–2008, (b) changes in the maximum height of spring flood, (c) index flood determination using direct data and its transfer into ungauged areas. The sections below describe the hydrological regions in the Baltic countries, the data, methods and obtained results.

Description of the study area

The Baltic States is the common name for three East-European countries: Estonia, Latvia and Lithuania. The territory of the Baltic States is relatively small, the total area being 175,117 km^2 (Figure 1). However, hydrometeorological differences can be extensive. Baltic rivers can be grouped into three major groups depending on their hydrological regime: marine, transitional and continental, as mentioned by Eipre (1972), Gailiušis *et al.* (2001) and Provorova (1969).

The main source of feeding for marine type rivers (Figure 1: LT-W, LV-W, ES-W) is precipitation (exceeding 50%), while snow melt and groundwater sources give 30 and 20%, respectively. Due to frequent thaws in winter, marine climate rivers have about 20% of 'winter floods' which can be higher than spring floods. For continental type rivers (Figure 1: LT-SE, LV-SE, ES-E) the snow melt water rate is almost equal to groundwater. The 'continental' rivers have the typical hydrological regime of most East-European rivers with the maximum flood in spring from snow melt. More than 40% of the annual flow occurs during that period. The feeding type for transitional rivers (Figure 1: LT-C, LV-C, ES-N) is mixed. Snow melt and rain contributions vary from 35 to 50% of the whole runoff. The hydrological regime is characterised by an irregular runoff distribution over the year and a small portion of groundwater. Recently, hydrological regionalization was performed according to river feeding sources (snowmelt, precipitation, groundwater) and variability of long-term series of temperature, precipitation and river runoff for all

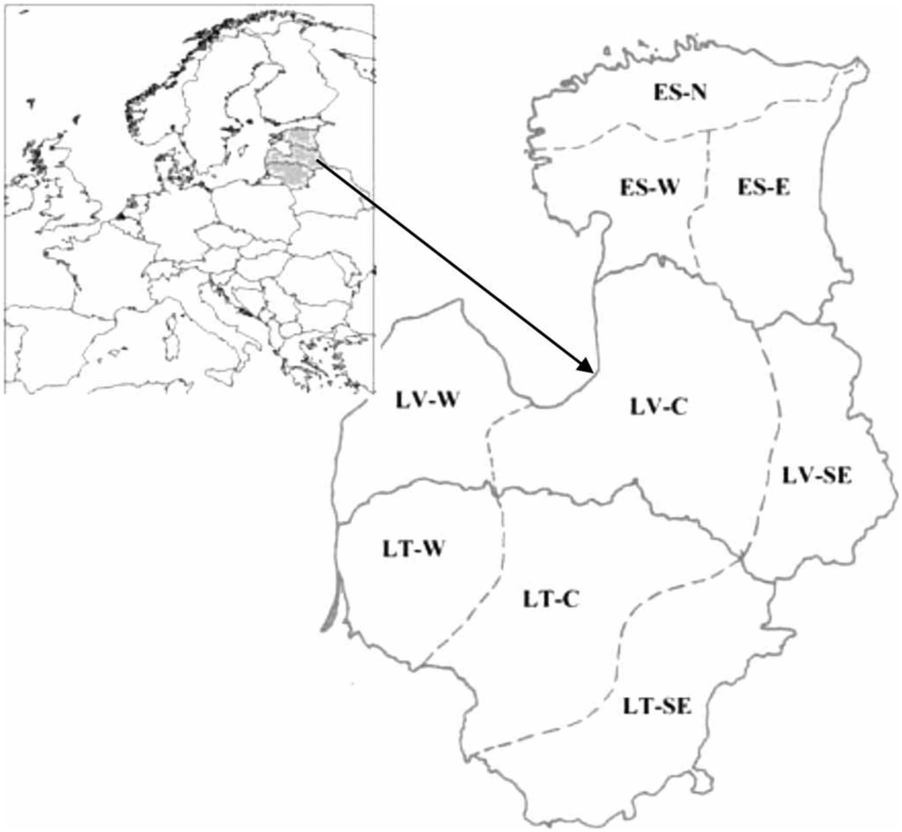

Figure 1 | Location of the study area in Europe and the regions in the Baltic countries: Lithuania (LT) – west (W) marine, central (C) transitional, southeast (SE) continental; Latvia (LV) – west (W) marine, central (C) transitional, southeast (SE) continental; Estonia (ES) – west (W) marine, north (N) transitional, east (E) continental.

the territories of the Baltic States (Kriaučiūnienė *et al.* 2010). The territory was divided into nine hydrological regions (three regions in each country) (Figure 1). The regions of western Lithuania and Latvia, the territory which is close to the Baltic Sea, belong to the marine climate zone and the main source of river feeding is precipitation. South-eastern Latvia and Lithuania and eastern Estonia are the continental part of the Baltic States. The rivers of this territory have prevailing snowmelt and subsurface feeding and the annual discharge of these rivers is distributed rather equally. The patterns of river discharge of the other hydrological regions of the Baltic States are of a more individual character. Although Latvia had originally four hydrological districts, as mentioned in Glazacheva (1990), in the present study the spring flood of rivers of the north-eastern and central regions of Latvia were analysed jointly.

There are big differences among small and large water basins in terms of the response of floods to precipitation/snow and geography and morphology. Floods of larger rivers depend on precipitation and basin parameters; however, floods of small rivers mainly depend on basin characteristics rather than on precipitation. For smaller catchments the duration of floods is shorter but the hydrograph curve is sharper and floods may be more devastating. The study area is covered by lakes, forests and swamps in many parts, and all these elements regulate the runoff, decreasing the maximum discharge and flood height and prolonging runoff duration. Therefore, there were no extremely high floods in the history of instrumental runoff observations. However, because of the flat landscape, there were years when the area of flooding exceeded several hundred square kilometres. For example, at the beginning of the last century, in 1928, over 900 km^2 (2% of the Estonian territory) was inundated (*Resursy Poverhnostnyh Vod SSSR* 1972). The highest floods in Latvian rivers were observed in 1931, 1951 and 1956. Figure 2(a) demonstrates one of the highest floods in Latvia on the Venta River in 1956. The

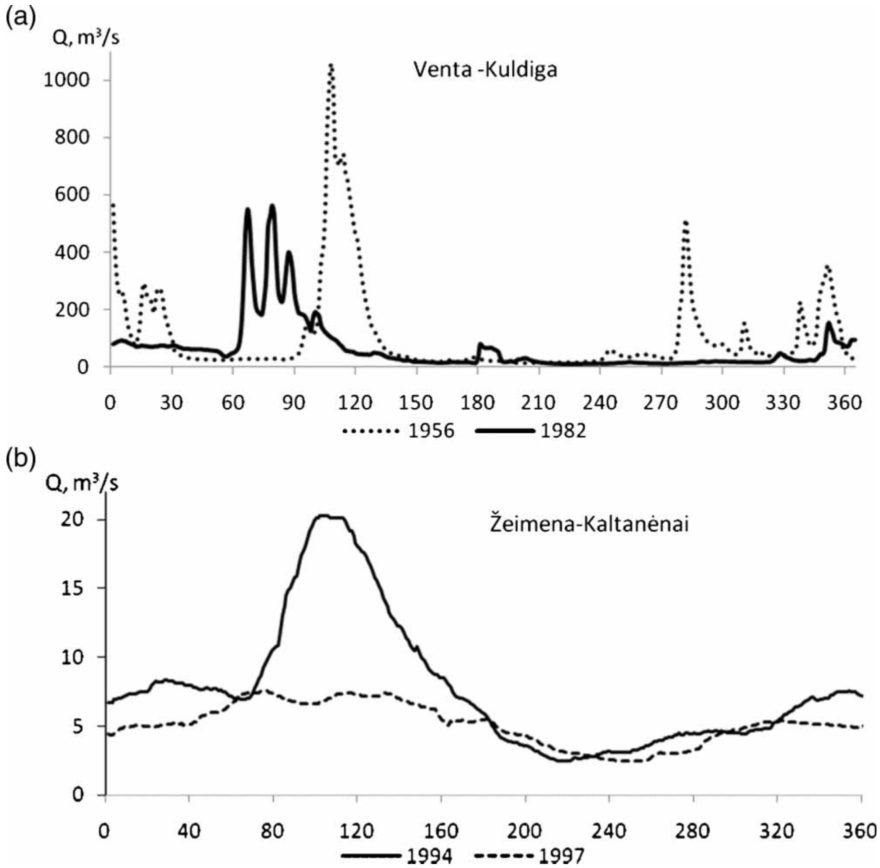

Figure 2 | Fluctuation of streamflow (Q, m^3/s) for the (a) Venta River – Kuldiga station – river in West-Latvia; (b) Žeimena River – Kaltanėnai station in 1994 and 1997 – river in Southeast of Lithuania.

biggest discharges in Lithuanian rivers were observed in 1931, 1941, 1951, 1953, 1956, 1958, 1968, 1970, 1979 and 1985. Most of them have a return period of less than 5 years in 100 years.

Data

The main parameters such as spring flood maximum discharge, the date of flood peak, and calculated flood runoff height were evaluated for all the Baltic countries for the period between January 1 and May 30. To determine the maximum discharge and its timing, daily observation data of river discharges were used. The height of maximum flood peak (h_{max}) was estimated as $h_{max} = Q_{max}/1{,}000A$, where A – basin area, km^2.

Variability of spring flood runoff was characterized by:

1. Maximum discharge of spring flood (Q_{max}, m^3/s);
2. height of maximal flood peak (h_{max}, mm);
3. timing of maximum discharge (Q_{date}, days).

Spring flood parameters were assessed for four periods: 1922–2008, 1941–2008, 1961–2008 and 1991–2008. The first three periods were chosen as recommended in the project 'Climate and Energy' (Hisdal *et al*. 2004). Period 1991–2008 was selected as a period when spring runoff was influenced by significant changes in hydrometeorological conditions (Kriaučiūnienė *et al*. 2008) that can have an impact on the analysis as a whole. We used 70 hydrological data series of spring flood parameters (23 – Latvia, 32 – Lithuania, 15 – Estonia) for the period 1961–2008, then 31 hydrological data series (9 – Latvia, 11 – Lithuania, 11 – Estonia) for the period 1941–2008 and 23 hydrological data series (6 – Latvia, 7 – Lithuania, 10 – Estonia) for the long-term period 1922–2008. Regional series of temperature and precipitation were compiled on the basis of data from 59 meteorological stations: 17 stations from Lithuania, 32 from Latvia and 10 from Estonia.

METHODOLOGY

In this research, the parameters of spring flood in rivers and regional series of temperature and precipitation of the Baltic States are statistically analysed. To detect trends in time series for different periods, the Mann–Kendall test (Gilbert 1987) and the nonparametric Sen's method (Helsel & Hirsch 2002) were used. The Mann–Kendall test was used as missing values are allowed and the data need not conform to any particular distribution. Sen's method is not greatly affected by gross data errors or outliers, and it can also be computed when data are missing. Two significance levels, very significant 95% ($\alpha = 0.05$) and weakly significant 30% ($\alpha = 0.30$), were used to identify all the series that imply possible trends. When the significance of a trend was poor, only 30%, the trend was regarded as a general trend, while only trends at the 95% level were regarded as significant.

The index flood (IF) method is widely used in hydrology for flood estimation (Hosking & Wallis 1997). The methodology was originally developed by Dalrymple in 1960 (Dalrymple 1960). First, regionalization of gauged basins should be performed by using the so-called normalised flood data of each station. Normalisation is performed by dividing single flood values by a quantity that represents the location of the record sample, e.g. the average of the annual maximum flood series. This quantity is termed as Index Flood. It is based on the so-called Region of Influence approach adopted in the UK Flood Estimation Handbook, FEH (1999) and has been used in this analysis. There exist two methods to estimate IF: direct methods, using the data on maximum annual flood peak in gauged station, and indirect methods, when the observed data from streamflow gauged stations are transferred into a neighbouring ungauged basin with similar land use and geophysical conditions. We used the direct method and took into account only the highest flood peak observed each year from 1 January to 30 May. In our analysis IF was estimated as the mean of sampled maximum flood peak discharges

$$q_i = \frac{1}{n}\sum_{i=1}^{n} q_n \tag{1}$$

where n = number of years when maximum flood peak discharges are available, $q_{i\,\dots\,n}$ = number of samples. The standard error was estimated as follows:

$$\delta_{qi} = \sqrt{\frac{1}{n(1-n)}\sum_{i=1}^{n}(q_n - q_i)^2} \tag{2}$$

The limits $q_i \pm \delta_{q_i}$ are also called sigma bounds that correspond to an 84% level of confidence. Increasing the number of samples in a time series reduces the standard error of estimated values.

Index flood was estimated at streamflow gauged stations that had no human impact (i.e. were not used as reservoirs or for water extraction). The selection of stations for regionalization and data quality estimation plays a significant role in any analysis. In this work we used the results of a data homogeneity test and regionalization of the study area in previous studies (Reihan 2008; Kriaučiūnienė et al. 2010). Stations were selected by using the following criteria: the longer the time series, the lower the occurrence of standard errors and uncertainties of estimated values. The location of stations was selected so as to provide a more even coverage of the study area in terms of the measured data and a more or less equal number of stations in each region. Such distribution of stations permits definition of similar hydrological regions more accurately. We selected gauging stations with basin areas from 100 to 10,000 km^2.

In order to detect whether one flood is larger than another, the K value, which is named the Francou-Rodier coefficient (Francou & Rodier 1967), was used. Francou and Rodier proposed that the total catchment (A, km^2) upstream from a given station is related to the peak flood discharge (Q, m^3/s), by using the following equation:

$$K = 10[1 - (\log Q - 6)/(\log A - 8)] \tag{3}$$

Anomalies of precipitation (%) were calculated by dividing the long-term series by the mean values of reference period (1961–1990), whereas temperature series were normalized by subtracting the mean and dividing by the standard deviation. The regional series were estimated as the average of the standardized individual series (Kriaučiūnienė et al. 2008).

RESULTS AND DISCUSSION

Condition of spring floods formation

The nine hydrological regions of the Baltic States (Figure 1) could be joined into more well known hydrological regions (marine, transitional and continental) according to the conditions of spring flood formation.

The beginning of spring floods can be observed by intensively increasing discharges, as depicted in hydrographs (Figure 2). Flood beginning and duration depend on climatic conditions, whereas flood ending depends on many elements (snow reserve in the basin, size, form and slope of the basin, river system). Spring floods begin in the south-east at the beginning of March and move to the north of the study region in the first half of April.

The course of a spring flood depends on snow reserves in the river basin, intensity and duration of snow melting, freezing degree of the soil, air temperature during snow melting time and precipitation during flood duration time. Floods in the Baltic countries are sometimes intensive and have one wave. But very often water level increases more slowly and the flood has two or three waves mainly caused by rains on the flood, especially in the marine area and in some western rivers of the Baltic States (Figure 2(a)).

Snow reserves depend on snow which has accumulated during winter. Snowmelt periods in winter decrease snow reserves, especially in western regions. The average duration of snow cover varies from 70 days in Western Lithuania to 120 days in Northern Estonia. The average thickness of snow cover is from 15 to 30 cm (Gailiušis *et al.* 2001) in Lithuania, to the average of 30 cm in the uplands Haanja and Pandivere in Estonia (Kadaja & Tooming 2006). Extensive water storage in snow, steady cold winters and intensive snow melting can cause very high spring floods. According to the observed data for the last 100 years, the biggest floods in the Baltic countries were observed at the beginning of the 20th century, in 1931 and in the middle of the 20th century, in 1956.

The volume and duration of floods are primarily affected by lakes and sandy coverage of basins. These elements regulate runoff: they decrease the maximum discharges and flood height and prolong runoff duration (Figure 2(b)). Swamps and forests play different roles in spring flood formation and duration. A growing wetlands area can reduce the spring flood in one region but increase the flood in another (Eipre 1972). As such, it has no big impact on spring floods. Forests decrease maximum discharges and prolong the duration of spring flood. However, when taking into consideration both factors – swamps and forests – their impact on spring flood is minor. The average flood duration varies from 45 to 60 days and in large regulated rivers from 80 to 100 days.

Changes in maximum discharges of spring flood

Spring flood in the Baltic region is usually a combination of snow melt and rainfall with dominant snow melt contribution. One of the most important parameters of spring flood runoff is the maximum discharge which is many times higher than the average annual discharge of rivers. In order to evaluate changes in spring flood under the conditions of the climate change, a trend analysis was performed for all the 70 analysed hydrological stations by the Mann–Kendall test for four periods (1922–2008, 1941–2008, 1961–2008 and 1991–2008). Trends with different significance levels (significant positive, positive, negative, significant negative) were used for the analysis.

A summary of the trends of maximum discharges (Q_{max}) is presented in Table 1. Significantly decreasing Q_{max} was determined for the periods 1922–2008 and 1941–2008 (83–84% of all the hydrological stations in the Baltic States).

There are only some insignificant trends of Q_{max} in these periods (17 and 13% of the stations, respectively). The percentage of insignificant trends increased in 1961–2008 to 43%. All other trends are negative or significant negative. In the last year period (1991–2008) almost all trends (84% of stations) of Q_{max} became insignificant. The reason for such a trend distribution is that in all regions of the Baltic States the greatest river discharges were observed more often in the first half of the last century (1926, 1928, 1931, 1941, 1951, 1956, 1958). As the frequency of the observed big floods in the later periods was lower (1970, 1979, 1985, 1994), the magnitude of maximum discharges changed insignificantly.

Table 1 | Percentage of significant and insignificant trends of maximum discharge, timing of maximum discharge and flood runoff height in four periods (% of all hydrological stations in the Baltic States)

	Significant positive trend	Positive trend	Insignificant trend	Negative trend	Significant negative trend
1922–2008					
Maximum discharge	0	0	17	0	83
Timing of max discharge	0	0	61	13	26
Maximal height of flood runoff	4	0	18	4	74
1941–2008					
Maximum discharge	0	0	13	3	84
Timing of max discharge	0	0	16	16	68
Maximal height of flood runoff	3	6	16	3	72
1961–2008					
Maximum discharge	0	0	43	26	31
Timing of max discharge	0	0	24	26	50
Maximal height of flood runoff	6	4	52	14	24
1991–2008					
Maximum discharge	0	0	84	7	9
Timing of max discharge	0	4	96	0	0
Maximal height of flood runoff	1	3	72	9	16

We conducted a spatial analysis of maximum discharges of river runoff in all the Baltic States (Figure 3). The trend analysis shows a systematic negative trend in the continental regions of the Baltic States for 1922–2008 and 1941–2008. There were no trends for some hydrological stations in the western regions of Latvia and Lithuania. In these regions spring flood formation depends on snow melt and rainfall component changes.

In 1961–2008, $Q_{\max}$ decreased mostly in Estonia and Latvia (73 and 61% of negative and significant negative trends, respectively) and less in Lithuania (47% of stations). No significant trends (83% of stations) were observed in the western part of Lithuania. The reason for this tendency is the maximum discharge of spring flood in 1994 when the biggest flood of the last 80 years was observed. In Western Lithuania, river discharges were also big in 1968, 1970, 1979 and 1985.

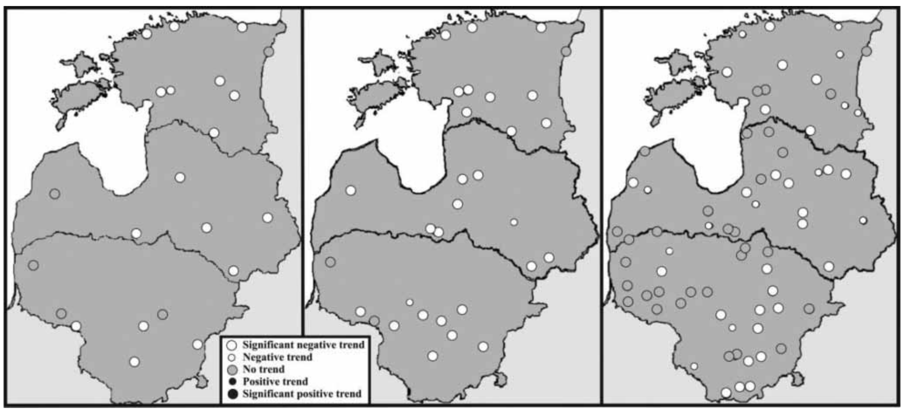

Figure 3 | Trends in spring flood maximum discharge for 1922–2008 (left), 1941–2008 (middle) and 1961–2008 (right).

Changes in maximal flood height of spring flood

The maximum discharge of rivers depends on the size of the river basin. In order to compare flood parameters for both small and large rivers, the maximal flood height (h_{max}) was calculated. We performed a summary trend analysis of the maximal flood height for four periods (1922–2008, 1941–2008, 1961–2008 and 1991–2008) (Table 1). The highest value of negative and significant negative trends (78–75% of stations) was found for 1922–2008 and 1941–2008. The largest number of insignificant trends (72% of stations) dominated in the last period of 1991–2008. These changes in h_{max} have similar tendencies as changes in Q_{max}.

The spatial distribution of the maximal height of river runoff is described in Figure 4. The maximal flood height decreased in all the regions of the Baltic States in 1922–2008 and 1941–2008, except in five stations with insignificant trends. In 1961–2008, changes in h_{max} showed no clear patterns in the Baltic States. Most of the negative and significant negative trends of h_{max} were found in Latvia and Estonia (61 and 53% of the stations, respectively). Only in Lithuania the trend distribution had another pattern. In seven stations (30% of Lithuanian stations) positive and significant positive trends of h_{max} were observed and in only four stations (17%) negative and significant negative trends were detected. The reason for the increase in the maximal flood height in some regions of Lithuania is the occurrence of more extensive regional floods in 1968, 1970, 1979, 1985 and 1994.

By analysing trends with the Mann–Kendall test, we can determine only the increasing or decreasing tendencies of spring flood parameters. Trend magnitude estimates were made using a slope estimator (Helsel & Hirsch 2002). For the maximal height of spring flood, trends magnitudes are calculated in mm as changes in h_{max} per year in the selected period. Trends magnitudes are presented by box plots which show the maximum, minimum, 25th and 75th percentiles as well as the mean (Figure 5). The maximal height of spring flood decreased the most in 1922–2008 and 1941–2008, by 0.8 and 1.0 mm per year, respectively. In 1961–2008 h_{max} decreased less – by 0.6 mm per year. There were insignificant changes in h_{max} in the last period of 1991–2008, where the rate of decrease was 0.05 mm per year. Only the maximum and minimum values of the slopes differ significantly Particularly significant changes occurred in 1922–2008 and 1941–2008.

The analysis of chronological time series of the maximum height of spring floods for nine rivers in the Baltic States was conducted by using the moving average of 10 years (Figure 6(a)). Rivers were selected

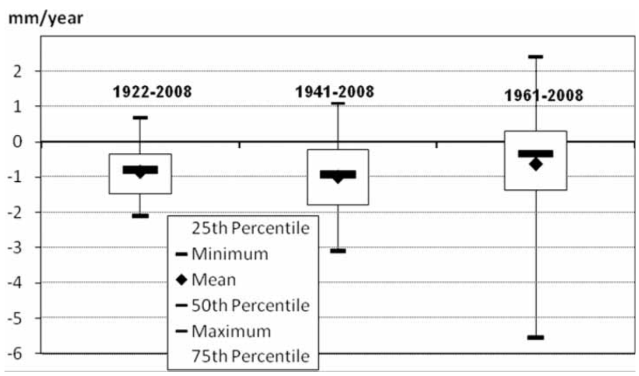

Figure 5 | Slope analysis of maximum height of flood runoff for three periods.

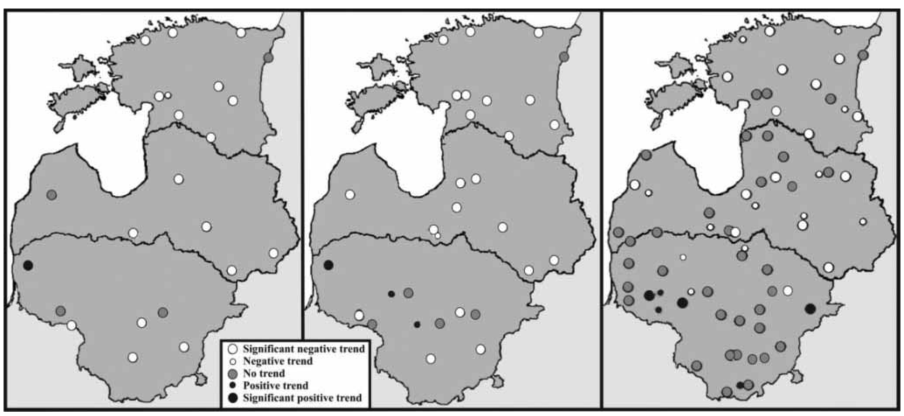

Figure 4 | Trends of maximal flood height for 1922–2008 (left), 1941–2008 (middle) and 1961–2008 (right).

from all the Baltic countries and from all hydrological regions (West, Central/North and Southeast). The lowest maximal height and its variations were observed for the Minija, Dubysa and Šventoji rivers (Lithuania) and the highest maximal height was observed for the Kasari River (West Estonia) and Venta River (West Latvia). We determined the decreasing h_{max} in all time series from the seventh decade onwards.

It is well known that flood formation and its parameters depend on temperature and precipitation. The anomalies of regional series of temperature and precipitation in nine regions of the Baltic States (Figure 1), analysed by Kriaučiūnienė *et al.* (2008), were compared with the time series of maximum height of spring floods for nine rivers (one river in one region). Correlation coefficients were calculated between the maximum height of floods and the

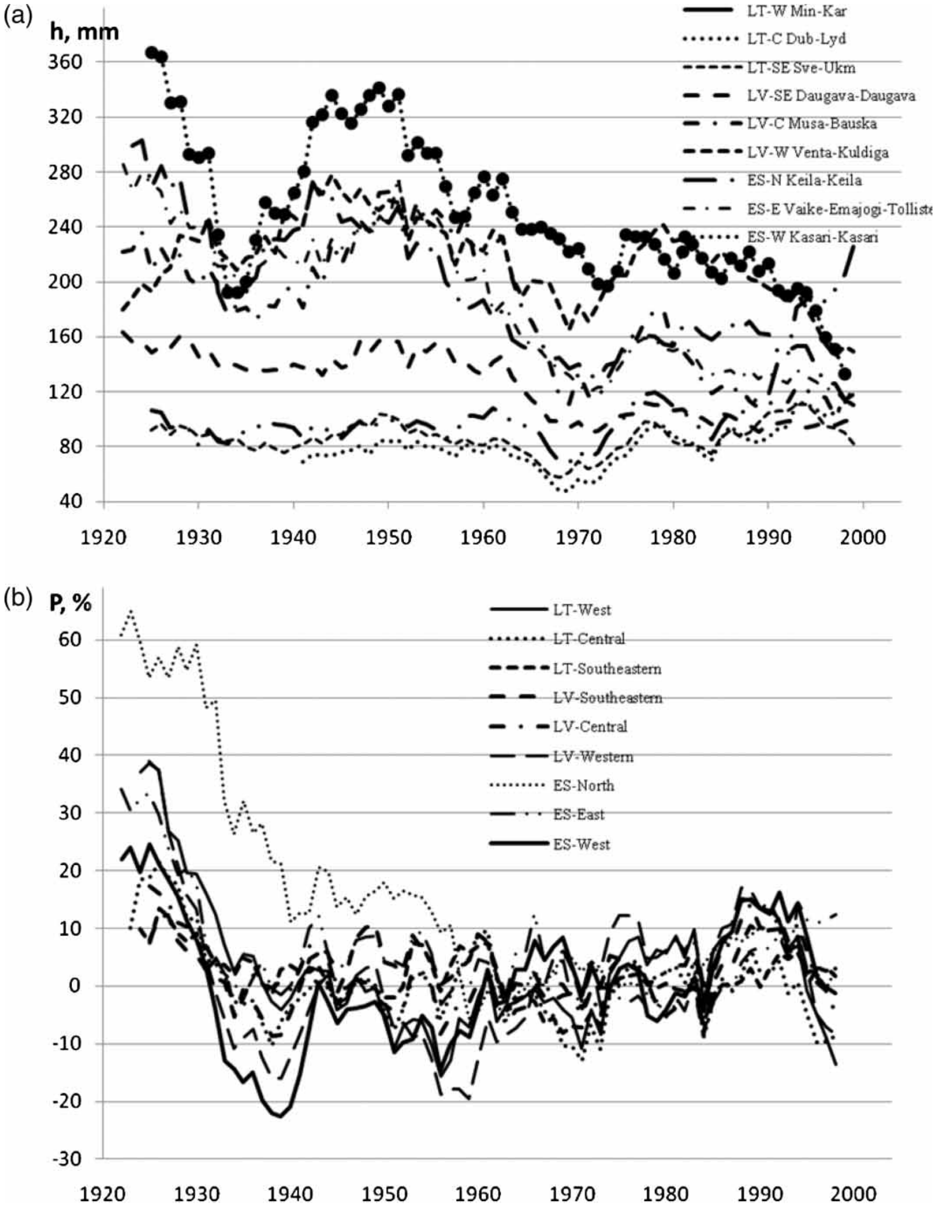

Figure 6 | Chronological time series with the moving average of ten years: (a) maximum height (mm) of spring runoff of nine rivers in the Baltic States, (b) precipitation anomalies (%) of spring season in nine regions of the Baltic States.

anomalies of temperature and precipitation in winter and spring seasons (h_{max} of the selected river was analysed by anomalies of the corresponding region). The best correlation coefficients (0.52–0.64) were found between h_{max} and anomalies of spring season precipitation (Figure 6(b)). The anomalies of precipitation decreased from the seventh decade and anomalies of spring season increased from the eight decade. These changes had an influence on the variation of the maximum height of spring floods.

Changes in the timing of maximum discharges of spring flood

The timing of maximum discharges (Q_{data}) is the day from the beginning of the year when flood reaches the maximal level. We conducted a summary trend analysis of Q_{data} in order to evaluate the changes in flood date – did spring floods occur earlier or later in different periods?

Many insignificant trends of maximum discharge timing (61% of stations) were found in the longest period of 1922–2008 (Table 1). Negative and significant negative trends of Q_{data} dominated in 1941–2008 and 1961–2008 (84 and 76% of stations, respectively). It means that floods occurred early in the Baltic States. This result is in agreement with the previous studies in the region, as mentioned by Kļaviņš et al. (2008) in Latvia and by Reihan (2008) in Estonia. However, there are no trends (96% of stations) in the last period and only 4% of stations have positive trends. An earlier start of river flooding is evidently due to the increasing air temperature in winter in the Baltic States, as stated in the results of local research (Meilutytė-Barauskienė & Kovalenkovienė 2007; Reihan 2008).

The spatial distribution of Q_{data} trends is described in Figure 7. In 1922–2008, negative and significant negative trends were detected in North-Estonia and West- and Southeast-Lithuania. There were no significant trends in other regions of the Baltic States. In 1941–2008 negative and significant negative trends of Q_{data} dominated on the territory of the Baltic States, except in East-Estonia and Southeast-Latvia. As regards the timing of spring peak, different tendencies were detected for 1961–2008. A prevailing number of negative and significant negative trends of Q_{data} dominated in Lithuania (94% of stations) and Estonia (73% of stations). A significant increase in winter temperatures in this period can be the reason for earlier floods in these regions.

A slope analysis of the timing of maximum discharges (Figure 8) showed decreasing rates of Q_{data} in 1922–2008, 1941–2008 and 1961–2008 (0.1, 0.3 and 0.4 days per year, respectively). It means that in all these periods floods occurred increasingly earlier. A completely different tendency was found for the last period of 1991–2008 when the slopes of Q_{data} were positive (rate of increase was 0.5 days per year). The later occurrence of the maximum flood is related to the temperature anomalies in the winter season which had decreasing tendencies in the last year period (Figure 9(b)).

The patterns of slopes can be better explained by the analysis of chronological time series of the timing of maximum discharges for nine rivers in the Baltic States (Figure 9(a)). The earliest floods are observed in Lithuanian

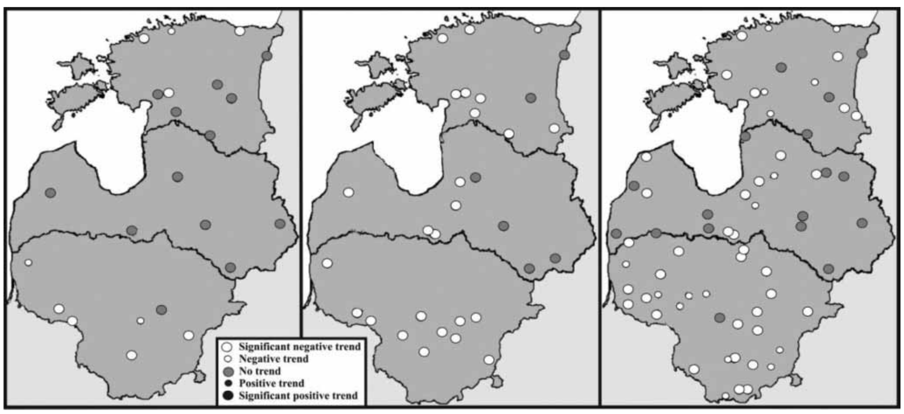

Figure 7 | Trends in timing of spring flood maximum discharge for the periods 1922–2008 (left), 1941–2008 (middle) and 1961–2008 (right).

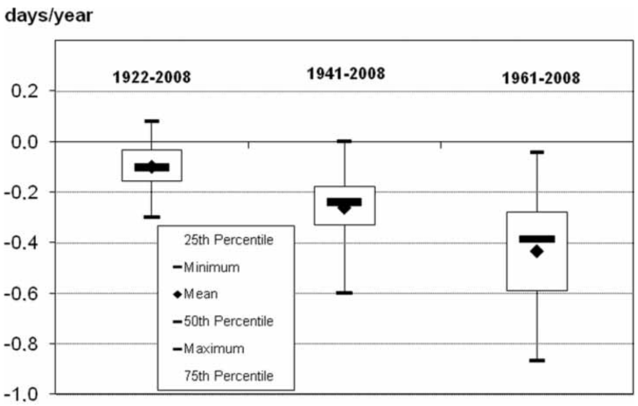

Figure 8 | Slope analysis of the timing of maximum discharges in three periods.

rivers, 13 days earlier than in Estonian rivers (Figure 9(a)). This is due to the lowest average winter and spring temperatures in Estonia.

The latest floods from the analysed nine rivers were observed in the Daugava River which is one of the largest rivers in the Baltic States. As a rule, flood formation in large basins, because of different geographical conditions, is different in the river course and in the river mouth. The Daugava River flows from east to west, therefore its flood formation takes longer than in other rivers in the region. The most decreasing Q_{data} in the time series of nine rivers was found in the ninth decade. Hence, in 1991–2008 the floods in two Latvian and two Estonian rivers occurred later and Q_{data} in the Lithuanian rivers did not change considerably.

Correlation coefficients were calculated between the timing of maximum discharge and anomalies of temperature and precipitation in winter and spring seasons. Negative correlation coefficients were found between Q_{data} and anomalies of temperature in winter and spring seasons (from −0.42 to −0.68 and from −0.39 to −0.59, respectively). Anomalies in winter season temperature increased very significantly from 1980 (Figure 9(b)) onwards and floods occurred earlier in all rivers from this year.

Index flood series

Index flood values were first estimated on the spot as the mean of the maximum spring flood discharge $\bar{Q}_{max}$ and then as the average for each homogeneous region. This value has no dimension, therefore it should be rescaled by multiplying it by the IF of the subject catchment area. Mean value of Q_{max} annual is considered as discharge with a return period of 2.33 years. The regional relationship between mean annual flood Q (m^3/s) and drainage area A (km^2) (Figure 10) can be expressed as $Q = CA^b$, where C is a coefficient and b is exponent.

A robust estimation of the basin area and index flood relationship was given for the three common regions over the study area (Figure 10) without taking into account specific geomorphological characteristics of the basin. The estimated errors varied within the range of 30%, however, the equations found for each region permit estimation of spring flood discharge in ungauged basins for catchment areas from 100 to 10,000 km^2 with similar hydrological regime. The estimated coefficients C and exponent b vary within 0.16–0.22 and 0.75–0.89, respectively. The correlation coefficient between Q and A was higher ($r = 0.97$) in the central regions of Latvia and Lithuania and in the north of Estonia, and lower ($r = 0.91$) in the south-east and eastern regions, where geomorphological conditions are more complex and can impact the $Q = f(A)$ relation more than in other regions. This estimation was done for the first time for all the Baltic countries and the relationship between Q and A needs to be evaluated in the future, taking into account the size of the basin and its specific geomorphoclimatic characteristics.

To compare floods in different regions, the Francou-Rodier coefficient K was estimated for nine regions by using Equation (3). Floods with their K value higher than 5 are considered as extreme floods on a global scale. In our case K varies from 0.14 to 2.9 with average value from 1.16 in the eastern and south-eastern to 1.76 in the western regions. Compared to the global scale, extreme spring floods in the Baltic countries are minor and with only local impact on the livelihood, property and infrastructure. The maximum K value (2.34) was obtained for the rivers in the western region where floods can be caused by both precipitation and snow melt. However, the highest floods in this region are caused by snow melt. The southeastern regions in Lithuania and Latvia and eastern regions in Estonia have the lowest variations in K (1.67) because these areas are characterised by mixed type of river feeding and irregular runoff distribution over the year, resulting in smaller floods. The descriptive statistics of the largest annual floods are presented in Table 2.

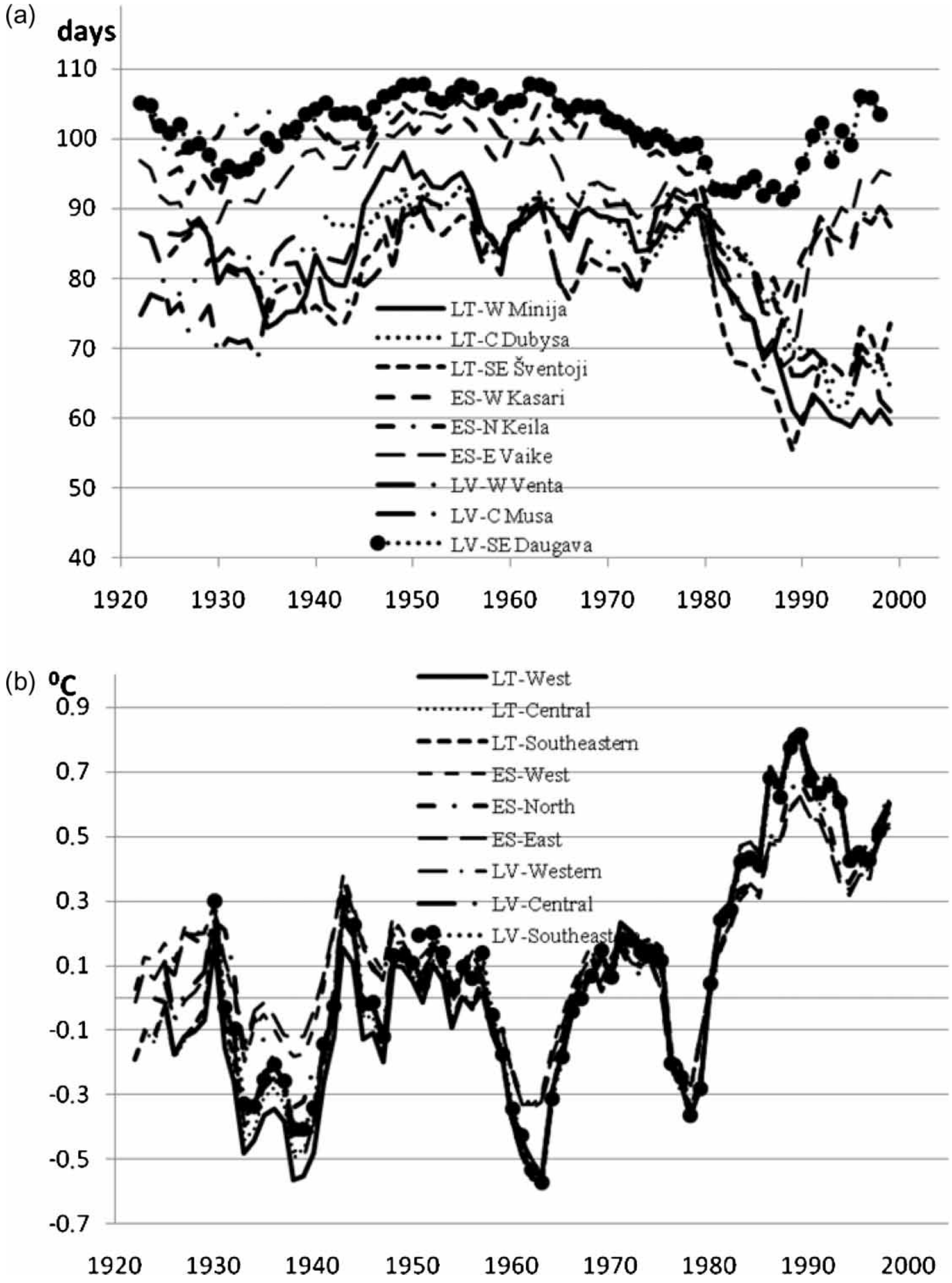

Figure 9 | Chronological time series with the moving average of ten years: (a) timing of maximum discharge for nine rivers in the Baltic States, (b) temperature anomalies (°C) of winter season in nine regions of the Baltic States.

CONCLUSIONS

The biggest floods ever recorded in the Baltic States were observed in the period 1926–1970. The greatest spring floods were observed in the western regions and the lowest floods in the eastern and south-eastern parts of the study area. The tendencies of maximum discharge timing are similar in all the hydrological districts. Everywhere trends are definitely negative, i.e. maximum discharges are observed earlier and earlier (because of

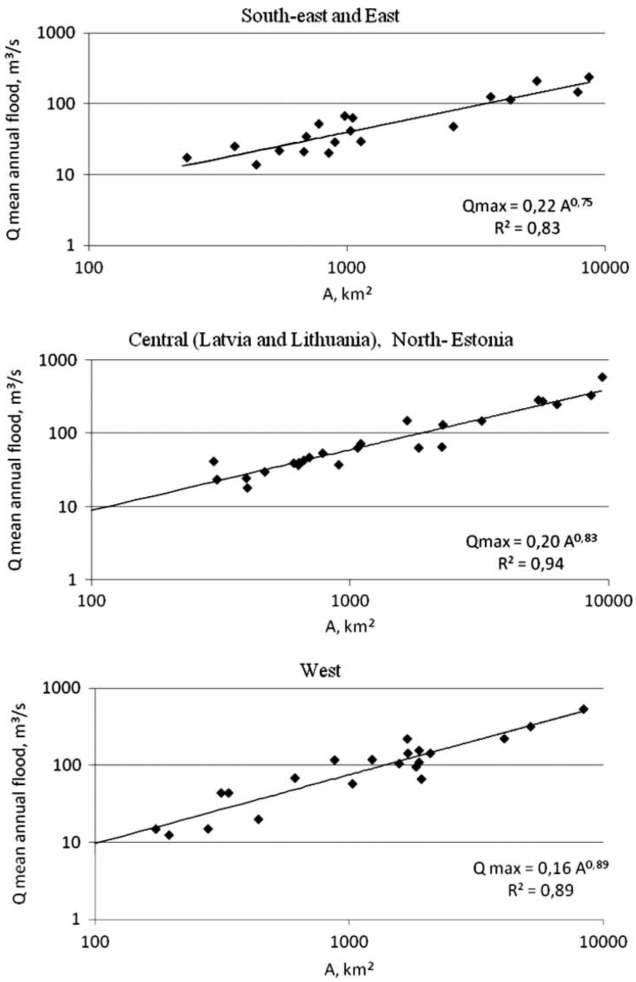

Figure 10 | Relationship between mean annual flood *Q* (m^3/s) and catchment area *A* (km^2) (both parameters are in log scale).

warmer winters). A decrease in maximum discharges of spring floods (negative trends) was detected in the long periods of 1922–2008, 1941–2008 and 1961–2008 for almost the whole territory of the Baltic States, except for some hydrological stations in the western regions of Latvia and Lithuania. In these regions the main source of river feeding is precipitation and, thus, spring flood formation depends on snow melt and rainfall component changes. In the last period (1991–2008) there were fewer changes in maximum discharges (significant trends were practically not observed for any river in the Baltic States). The reason for such trend distribution is that there were no big floods in the last period. The trends of maximal flood heights have the same tendencies as maximum discharges in all four periods. The maximal height of spring flood decreased most in the period of 1941–2008, by 1.0 mm per year, and less in the period of 1991–2008, where the rate of decrease was only 0.05 mm.

A regional relationship between the average maximum discharge and drainage area for the estimation of spring floods in ungauged basins was found. A robust estimation of the basin area and index flood relationship was made for the three common regions over the study area without taking into account specific geomorphological characteristics of the basin.

The study showed that spring floods have decreased significantly and flood risk tends to decrease as well. Nevertheless, it does not mean that extensive spring floods will not occur in the future.

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Table 2 | Descriptive statistics for the largest annual, flood/area rations and *K* coefficients in three regions of the Baltic States

		Q **(m^3 s^{-1})**			***Q/A*** **(m^3 s^{-1}/km^2)**			***K*** **(Francou-Rodier coeff.)**		
Region	**Number of stations**	**Mean Mean**	**Annual Stdv**	**Flood Max**	**Mean**	**Stdv**	**Max**	**Mean**	**Stdv**	**Max**
East and South-east	21	69.1	66.1	236	0.038	0.019	0.073	1.16	0.34	1.67
West	27	121	123	540	0.081	0.032	0.140	1.76	0.32	2.34
Central Latvia and Lithuania, North Estonia	22	107	134	589	0.065	0.027	0.139	1.53	0.25	2.07

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