Changes in water discharges of the Baltic states rivers in the 20th century and its relation to climate change

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Abstract The river discharge changes in three Baltic States and its relation to changes in the main climatic variables such as precipitation and air temperature were analyzed using observed data and methods of empirical statistical analysis. The study is important for the development of efficient water resource management systems and validation of climate change impact models. The application of the Mann-Kendall test reveals that a significant increasing trend in winter air temperature and precipitation was determined for all 3 investigated periods (1923–2003, 1941–2003 and 1961–2003). The same trend was found for the winter and annual discharge time series. No trend was observed for the spring, summer and autumn seasonal streamflow and summer low flow series for most of the Baltic region. In general the relation between the main meteorological and hydrological parameters and the tendency in river discharge trends is common for all of the Baltic States, and might be associated with the regional impacts of global climate change.

Keywords Baltic States; climate change; long-term variability; river discharge trends

Introduction

Large-scale weather patterns associated with pressure systems are an important factor influencing the total amount of precipitation and its spatial and seasonal distribution over central and eastern Europe (Dayan and Lamb 2005). These weather patterns may change with the changing climate and will in turn affect the water resource availability. During recent decades, considerable attention has been paid to the study of global climate change (IPCC 2001) and how changes in the hydrological time series can be related to climate change (Kite 1993; Hiltunen 1994; Arnell and Reynard 1996) and its regional impacts (Gleick 1986). Trends in river discharge have been extensively analysed. For example, an increasing trend in river discharge was found in the USA (Lins and Slack 1999) and, at the same time, a decreasing trend in river discharge was found in northern Canada (Dery and Wood 2005). The impact of climate change on river discharge has been identified in the Nordic countries as well (Bergstrom *et al.* 2001; Hisdal *et al.* 2003; Lindström and Alexandersson 2004; Roald *et al.* 2006). Vehviläinen and Lohvansuu (1997) state that in Finland climate change may increase the mean discharge of rivers by 20–50%. The possible increase of Danish river discharge (by 12%) is described by Thodsen (2007). Changes in river discharge of the Baltic States have also been investigated in individual national studies. The Latvian studies conclude that changes of discharge are minimal and significantly increased only for the main rivers (Klavins *et al.* 2002). Changes in the water balance structure of Lithuanian rivers under different climate change scenarios are investigated by

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Kilkus *et al.* (2006). The relation between the global processes of atmospheric circulation (NAO, ENSO) and the hydrological cycle are studied by Glazacheva (1988) and Jaagus *et al.* (1998). Aspects of climate change along the Estonian coast were investigated by Jaagus (1998). Results indicate a significant increase in spring air temperature and a significant decrease in the ice cover along the Estonian coast which results in an early spring and a remarkable decrease in the number of days with ice (by 1–2 months on average). Sea ice conditions along the Estonian coast were studied through the reconstruction of a long-term climatic time series (Tarand and Nordli 2001) and by spring heat accumulation (Tooming and Kadaja 1998). In Latvia, Lizuma (2000) and Lizuma and Briede (2001) made a thorough investigation of air temperature and precipitation trends.

The previous studies of meteorological and hydrological trends confirm the importance of investigations regarding the effects of climate change on the hydrologic cycle, especially considering the predicted climatic changes in the Baltic region.

The aim of the present study is to analyse the long-term changes in river discharge, precipitation and air temperature time series in the territory of the Baltic States with respect to climate change. The study includes a comparison of the streamflow trend results for the Baltic countries with trends for the Nordic countries.

Data and methods

The climate in the Baltic States (Figure 1) is influenced by the inflow of Polar Maritime air masses from the North Atlantic and Polar Continental air masses from Siberia. The Baltic region is crossed by 60–140 storm events annually with a duration of about 200 d on average. In spite of the small territory, 175 000 km^2, climatic differences within the Baltic States are quite distinct; the climate is wet and comparatively cold. Air temperature in January varies from −2.2°C to −6.6°C, while in July it varies from +18.8°C to +17.0°C. The amount of precipitation varies from 850 mm per year in the Uplands of Vidzeme in Latvia to 560 mm per year in the middle of Lithuania. The amount of precipitation in Estonia

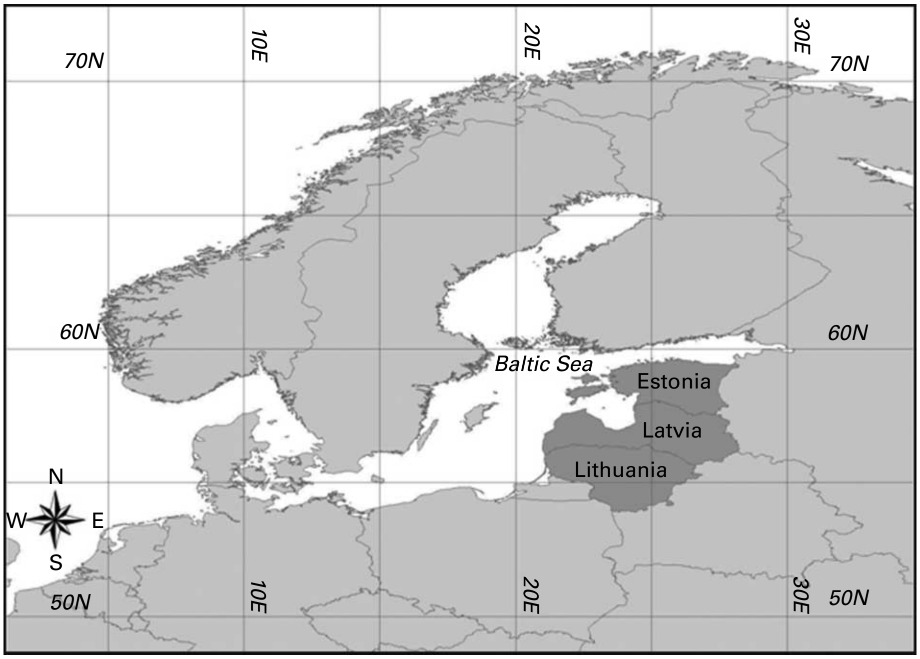

Figure 1 Location of the study area

varies within the interval, with an average maximum precipitation of 750 mm. Precipitation supports a dense network of rivers and the main density of the river network is 0.23–0.39 km/km^2. Different precipitation distributions and geology form the mixed water feeding types of Baltic Region rivers: snow melt, rain and groundwater.

The hydrological regime of the Baltic rivers depends not only on climatic factors (air temperature and precipitation), but also on geomorphology, geology, land use type and soil structure. Depending on the hydrological regime, rivers in the region could be grouped into 3 major types – marine, transitional and continental as mentioned by Gailiušis *et al.* (2001) and Frisk (2002). The main source of feeding of marine type rivers is precipitation, which exceeds 50%; snow melt and groundwater sources being 30% and 20%, respectively. Due to the frequent thaws in the wintertime "marine" climate rivers often have "winter floods", some of which are higher than spring floods. Approximately 35% of annual runoff falls during the winter period and 30% during the spring. For the continental type of rivers the water rate of snow melt is almost equal to the groundwater. The "continental" rivers have a typical hydrological regime like most East European rivers, with the maximum flood in spring from snow melt. More then 40% of the annual flow occurs during that period. The feeding type of transitional rivers is mixed. Snow melt and rain contributions vary from 35% to 50%. The hydrological regime is characterised by an irregular runoff distribution over the year and a small portion of groundwater.

A total number of 154 meteorological stations with records of monthly temperature and precipitation data from Estonia, Latvia and Lithuania were analysed. Three time periods of data were selected: 1923–2003 (47 stations), 1941–2003 (107 stations) and 1961–2003 (154 stations).

Changes in river discharge were analysed using a total number of 70 stations with a record length of 84 years of daily discharge data. The same time periods utilized in meteorological data analysis were selected for hydrological data analysis, except the long-term period that started in 1922 (22 stations). The second analysed period was 1941–2003 (31 stations) and the last one 1961–2003 (70 stations). The station density during the periods of 1922–2003 and 1941–2003 are similar in all Baltic States: however, there are more stations analysed in Lithuania during the 1961–2003 period.

Annual and monthly stream flow data were used for the seasonal data series trend analysis. Seasons were defined as three-month averages: *winter* (December, January, and February), *spring* (March, April, May), *summer* (June, July, and August) and a*utumn* (September, October, November). For the spring flood peak the period from 1 December to 30 June was defined. The maximum measured flow data were used for the analysis. It was evident that the daily minimum flow data series contained many casual errors. Therefore 30-d minimum discharge averages were used for the summer low flow analysis in order to obtain more reliable calculation results.

Homogeneity testing was done for the annual, extremes and seasonal data series of all hydrological and meteorological stations. In the hydrological data analysis the double-mass plot technique was used to assess the hydrological data series homogeneity in Latvia and Lithuania; also, the pair correlation analysis was used for each pair of time series. In Estonia the Standard Normal Homogeneity Test (SNHT) (Alexandersson and Moberg 1997) was used. The SNHT for single shift was applied for the meteorological data analysis using the ratio (for the precipitation data) and difference (for the temperature data) methods. Each station was compared with four to nine reference stations. The homogeneity test results shows that data for long-term water discharges are nearly homogeneous. The Mann–Kendall test (the details of the theory are described in Gilbert (1987)) with a 5% significance level, which is a relatively robust method concerning missing data, recommended by the WMO (1988), was applied for each data series analysis. In addition, positive and negative trends that are only significant at the 30% level were applied. Analysis of significant trends indicates change only in the tendencies of parameters. The magnitude of trends expressed by the slope of the Kendall–Thiel Robust Line (Helsel and Hirch 2002) allows for the quantitative evaluation of changes in parameters during the time period.

Results and discussion

The results have been assessed in two different ways: summary statistics of the significant trends in the air temperature, precipitation and river discharge time series for all of the Baltic States; and maps of the spatial and temporal variability of trends in river discharge (all periods).

Trends in temperature, precipitation and river discharge

The significant positive and negative trends for temperature and precipitation are presented in Table 1 for the three analysed periods. A significance level of 5% implies that significant trends at 5% of the stations can be expected. Positive trends of annual, winter, spring and summer temperatures were determined for all periods. An increase in the summer air temperature was determined especially for the last 40 years mainly caused by an increase in July temperature.

Positive trends of winter precipitation were determined for all periods. The same tendency was determined for annual precipitation trends, however only for the period from 1941. There are only some significant trends in precipitation for spring, summer and autumn (all periods).

The percentage of stations with significant positive and negative river discharge trends are summarised in Table 1 (annual, seasonal and extreme flow). The summary trends for the Baltic States region characterise only common tendencies (a larger total percentage of significant trends) of changes in river discharge parameters but not distribution throughout the territory.

Except for the autumn season, more than 5% significant trends were found for all periods. Negative trends prevail for the 1922–2003 period and positive trends for the 1961–2003 period. Both negative and positive trends were observed for the 1941–2003 period. The same tendency was found for precipitation.

Regarding annual discharge, a significant negative trend was found in about 18% of stations for the 1922–2003 period and positive trends dominated for the 1941–2003 (36% of stations) and 1961–2003 (47% of stations) periods. Most significant positive tendencies were found in the winter season river discharge series. The number of significant trends increases from 55% (1922–2003 period) to 81% (1961–2003 period). In the spring season negative trends dominate. For the longest period, about 31% of these trends were found, for the shortest period – only 6%. In the summer period the number of positive and negative trends strongly depends on the period analysed. For the 1922–2003 period negative trends (7% of all stations) were found, whereas in the 1961–2003 period positive trends (9% of all stations) were found. In the autumn the trends have the same tendencies as in the summer. Only for the period 1941–2003 no significant trends were found. For flood peaks only negative significant trends (62–70%) were found for the 1922–2003 and 1941–2003 periods. In the 1961–2003 period positive and negative trends were found in less than 11% of stations. For summer low flow, the positive trends (about 24%) were dominant for the long period. Both negative and positive trends were found for the two other periods.

Precipitation has significant influence on the river discharge quantity in the Baltic States. However, the present study shows that correlation between precipitation and river discharge can be weak. For example, coefficients of correlation of annual variables differ from 0.65 to 0.85 in Western Lithuania and from 0.45 to 0.70 in Southeastern Lithuania. In Estonia these

Table 1 Percentage of the significant trends of temperature, precipitation and rivers discharge in three time intervals

	Air temperatures		**Precipitations**		**Discharges**	
	Positive trend	**Negative trend**	**Positive trend**	**Negative trend**	**Positive trend**	**Negative trend**
1922–2003						
Annual	82	0	9	9	0	18
Winter	93	0	94	0	55	0
Spring	100	0	2	11	0	32
Summer	6	0	0	21	0	14
Autumn	0	0	0	6	0	18
July	0	0	0	23	–	–
Spring peak	–	–	–	–	0	64
Drought discharge	–	–	–	–	23	0
1941–2003						
Annual	100	0	36	1	36	3
Winter	89	0	72	0	64	0
Spring	100	0	10	0	0	17
Summer	6	0	0	4	3	0
Autumn	0	0	6	2	0	0
July	7	0	0	0	–	–
Spring peak	–	–	–	–	0	58
Drought discharge	–	–	–	–	18	15
1961–2003						
Annual	100	0	61	0	48	0
Winter	87	0	83	0	81	0
Spring	100	0	4	1	2	5
Summer	47	0	3	0	18	0
Autumn	0	0	1	1	8	0
July	80	0	0	0	–	–
Spring peak	–	–	–	–	12	9
Drought discharge	–	–	–	–	11	12

values were less and vary from 0.30 to 0.70. The strongest relation between temperature, precipitation and discharge was in the winter season. The winter season temperature had increased for all three time periods. There was also a significant increasing trend for winter season precipitation and river discharge.

Spatial distribution of trends in annual discharge

The annual flow trends are shown in Figure 2. The long-term trends of annual flow were not significant except for the southern part of Lithuania, and the marine regions of Latvia and Estonia, where a significant negative and a weak positive trend were found, respectively. For the period 1941–2003, a positive trend also appears in some parts of the continental regions but the whole Estonian territory has a significant positive trend. An increase in annual flow has occurred during the last 40 years (1961–2003) over the Baltic States, except in southern Lithuania where in most cases no trend was found. Evidently the prevailing groundwater feeding and sandy soils cause these differences in trend. In most cases these results are in agreement with Nordic studies' results (Hisdal *et al.* 2003).

Spatial distribution of trends in spring floods

The spring flood in the Baltic region usually is a combination of snow melt and rainfall, with a dominant snow melt contribution. The spring flood magnitude trend analysis (Figure 3) shows the systematic negative trend in the continental regions of the Baltic for all periods. In the marine regions there was no trend for the long period, 1922–2003, but for the shortest period, 1961–2003, the systematic pattern is present. Regarding the common sources of the spring flood volume it is not possible to evaluate the snow melt and rainfall component changes. The decrease in spring flood magnitude and earlier start of river flooding is evidently due to the increasing air temperature for the winter period. The increase in air temperature influences the decrease of the water equivalent of snow and the number of days with snow as well. The Nordic results showed no systematic trends (Hisdal *et al.* 2003): however, the general tendency was positive, which differs from the current results.

Spatial distribution of trends in summer low flow

The number of water discharge series for summer low flow analysis was comparatively less due to the large anthropogenic impact on the base flow. The time series of dam regulated rivers were eliminated from the analysis of summer low flow. For a long-time period the trend of summer low flow (Figure 4) is positive in the marine region of Estonia and Latvia. In the

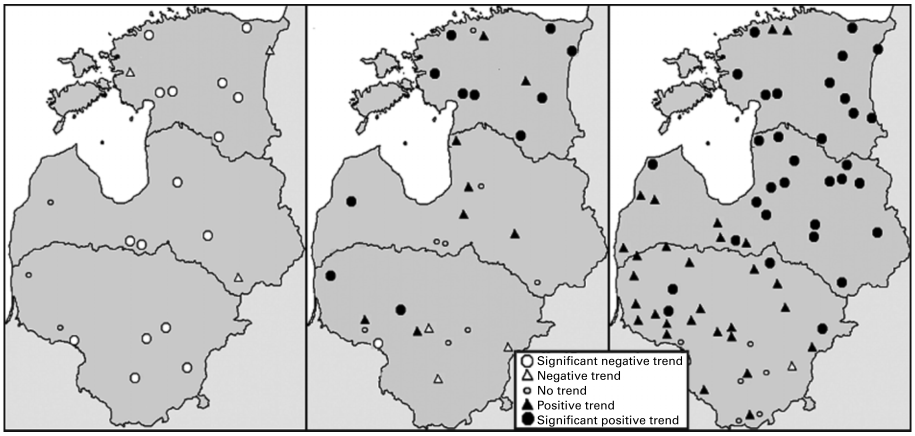

Figure 2 Trends in annual stream flow for the periods 1922–2003 (left), 1941–2003 (middle)

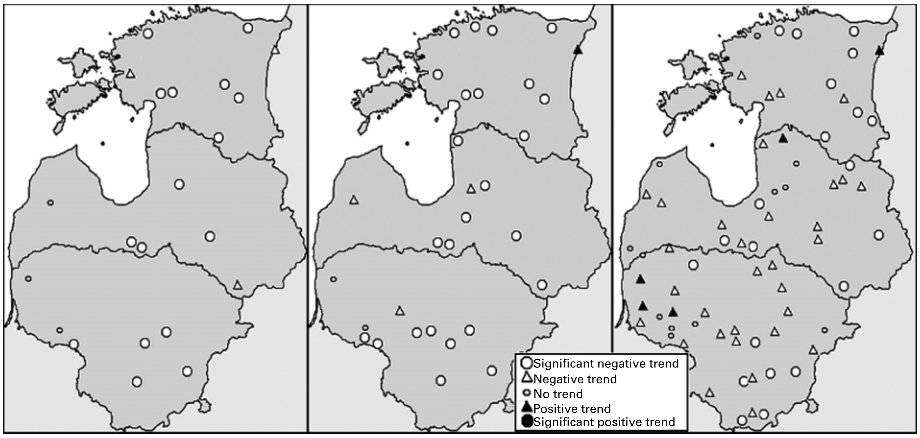

Figure 3 Trends in spring flood maximum discharge for the periods 1922–2003 (left), 1941–2003 (middle) and 1961–2003 (right)

rest of the Baltic territory the summer water discharges had no changes. For the 1941–2003 period a negative trend appeared in the transitional regions of Lithuania, where some rivers could become dry. In this study the negative trend can be explained by an increase in air temperature that affects the summer low flow. For the latter period of 1961–2003 the largest part of the Latvian and Lithuanian territory had no trend at all. The trend was positive and even significantly positive in the marine regions of Latvia and in eastern Estonia where Lakes Peipsi and Võrtsjärv regulate river discharge. In general, Estonian trend results were similar to Nordic results (Hisdal *et al.* 2003). In other Baltic regions, where the overall tendency is different (e.g. in some parts of Lithuania), there it is a tendency for more frequent low flow periods, that are in agreement with Nordic results (Hisdal *et al.* 2003).

Spatial distribution of trends in the seasonal streamflow

The most remarkable changes are related to the winter season (Figure 5). The increasing of air temperature results in an increase in the amount of precipitation and river discharge. In addition, as stated elsewhere (Reihan 2002; Klavinš *et al.* 2006) the beginning of the spring flood has shifted to an earlier time, contributing snowmelt to the winter season. For all

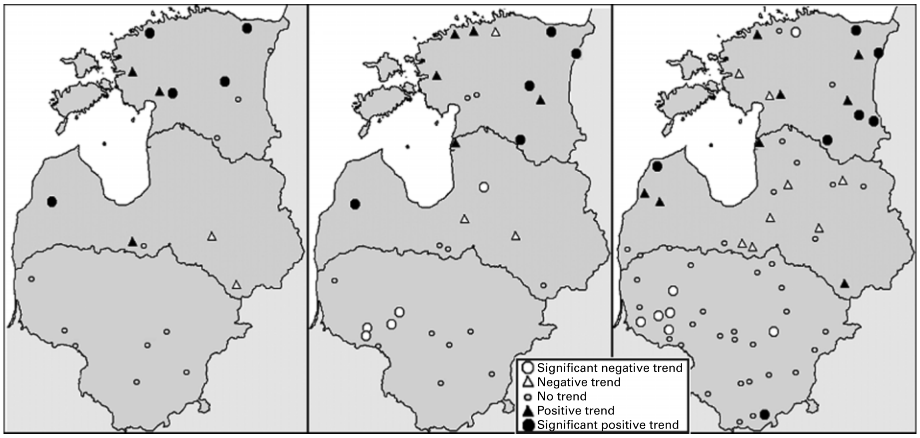

Figure 4 Trends in summer low flow for the periods 1922–2003 (left), 1941–2003 (middle) and 1961–2003 (right)

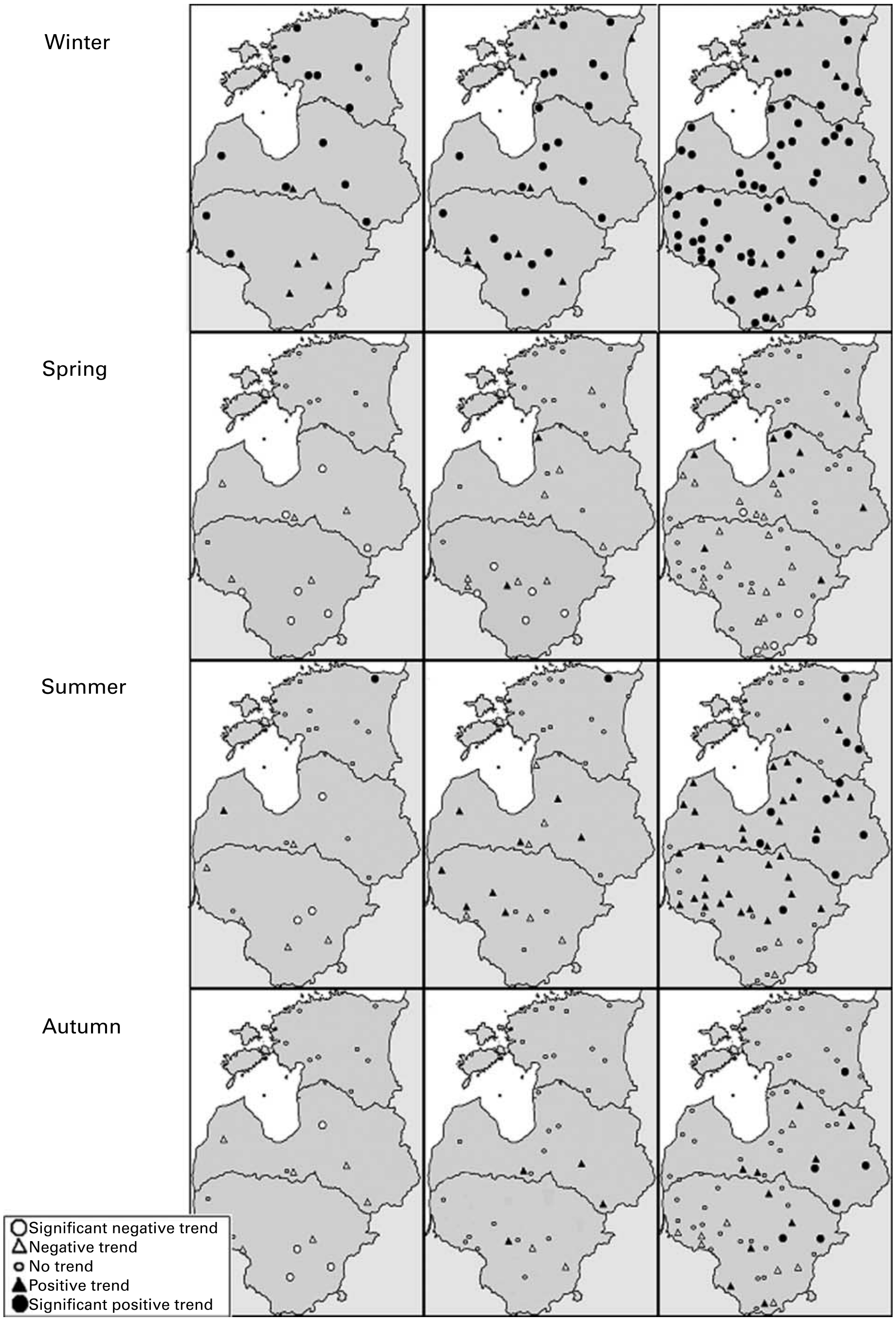

Figure 5 Trends in seasonal flow: from top to bottom – winter, spring, summer and autumn; 1922–2003 (left), 1941–2003 (middle) and 1961–2003 (right)

periods there was a significant positive trend in winter stream flow in almost all regions of the Baltic. For the long-time period of 1922–2003 south Lithuania had a weak (30% significance) positive trend, which is related to the groundwater dominated feeding. The weak negative trend in the East of Estonia is a result of river discharge regulations by Lake Peipsi.

In general, for the 1922–2003 and 1941–2003 periods there was no trend in the spring season flow in the marine regions of the Baltic and in Estonia. The costal and transitional regions of Latvia and Lithuania had both significant and weak (5% and 30% significance) negative trends. For the last period (1961–2003) the positive trend appeared in the regions with lake regulations.

No systematic pattern was found in summer streamflow for the 1922–2003 and 1941–2003 periods – both negative, positive and even no trend at all were found. For the short period of 1961–2003, positive trends (5% and 30% significance) were found in most parts of the Baltic territory. In the marine regions of Estonia and in southern Lithuania there was no trend.

In the autumn during the period of 1922–2003 there was a tendency for reduced flow in the continental regions of Latvia and Lithuania. In the rest of the Baltic territory this trend was not found. For the period of 1941–2003, there also appeared a weak positive trend in the continental part of Latvia. The short period of 1961–2003 was characterised by a positive trend in some continental parts of the Baltic. In general, autumn stream flow had no trend at all.

The seasonal changes in river discharge are in agreement with the Nordic results for the winter and autumn seasons. Spring did not have a clear pattern and summer flow had an increasing tendency only for the last 40 years in the Baltic States. Therefore there are both similarities and differences in spatial and temporal distributions comparing with the Nordic results.

Impact of changes of temperature and precipitation on the rivers discharge in winter season

Positive significant trends of temperature, precipitation and river discharge were determined for all periods for the winter season (Table 1). Trend magnitude estimates were made using slope estimator (Helsel and Hirch 2002). For temperature and its range, trend magnitudes are in degree Celsius: for precipitation – in mm and for discharge – m^3/s per winter season (December, January and February). Trend magnitudes are presented as box plots which show the maximum, minimum, 25th and 75th percentiles as well as the mean. All characteristics of temperature and precipitation slopes were increasing for all periods (Figure 6). Precipitation had increased mostly in 1961–2003 (rate of increase is 1 mm per one winter season or 43 mm per period for 1961–2003). The increase in temperature totalled 3°C during this period (rate is 0.7°C per winter season). The mean slopes of river discharge were similar in 1941–2003 and 1961–2003 (rates of increase were 0.61 and 0.64 m^3/s per winter season). Only the maximum values of discharge slopes differ significantly. This implies that the discharge of large rivers (such as the Nemunas and Dauguva) has increased more then 4–5 m^3/s per winter season during the 1961–2003 period. Analysis of trend magnitude shows that the greatest amount of change for all parameters occurred during the period 1961–2003. During this period the average winter temperature (data from 154 meteorological stations) had increased by 3°C and precipitation increase was 43 mm. These climate changes influenced the river discharge for the winter season. Runoff to Baltic Region rivers had increased by 19 mm for the winter season for the period 1961–2003 (data of 70 hydrological stations).

Outputs of ECHAM4 circulation and GDFL-R30 general circulation models as well as A2 and B2 emission scenarios were chosen for estimating change in the hydrological regime in Lithuania (Kilkus *et al.* 2006). Tendencies of these scenarios could be used for all of the Baltic territory. According to climate scenarios precipitation will increase mostly in February and January. Forecasted evaporation is close to zero. The increase of air temperature in the Baltic region will result in a decreased possibility of permanent snow cover, accumulation of water reserves and a reduced number of days with snow cover. Soils with heavy mineral content and a dense hydrographical network of rivers dominate in some

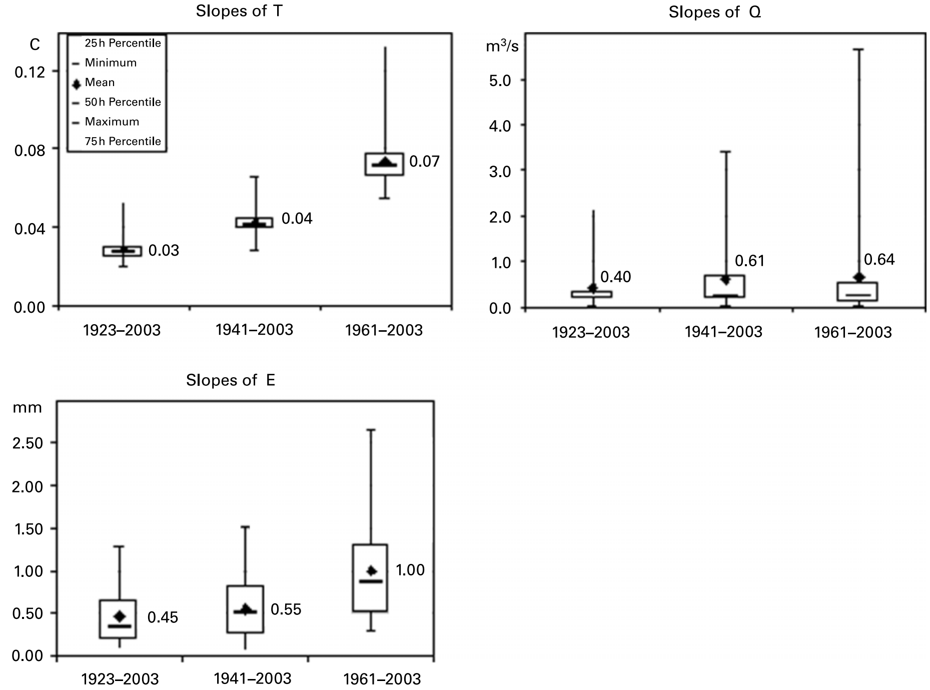

Figure 6 Box plots of trend slopes for temperature, precipitation and river discharge for the winter season during the periods 1923–2003, 1941–2003 and 1961–2003

parts of the region. These conditions will contribute to the fast inflow of snow melt water and precipitation into the riverbed. For these reasons a significant increase in river discharge is forecasted for the winter season. The winter season trend analysis of temperature, precipitation and river discharge has validated this prediction.

Conclusions

The analysis of trends in air temperature in the Baltic States shows increasing trends for all analysed periods except autumn. The greatest changes were in the winter and summer seasons for the last 40 years. The winter precipitation significantly increased for all periods: however, for annual precipitation increasing trends are observed only for the 1941–2003 period. The statistically significant increasing trend of winter streamflow has been detected in almost all regions of the Baltic. Analysis of the correlation between streamflow, air temperature and precipitation shows that the strongest relations are in the winter season. Thus, these changes in winter discharge seem to be associated with climatic variability, for example the significant increase in winter temperature. Average winter temperature had increased by 3°C as precipitation had increased 43 mm during the 1961–2003 period. These climate changes influenced the river discharge for winter season when river runoff had increased by 19 mm for the Baltic States. At the same time, there is not a systematic pattern for other seasons; however, differences in streamflow (no changes, positive and negative changes) during the summer and autumn seasons reflect tendencies observed in the precipitation and temperatures series in most cases. A significant decrease in spring floods was found. Even though there was no clear tendency for summer low flow, a tendency for more low-water flow years was observed. In most cases river discharge changes were similar to the Nordic results; however the decrease of spring floods in the Baltic rivers are in disagreement with the Nordic result.

In general streamflow changes show the redistribution of runoff throughout the year: a significant increase of winter river discharge and a tendency for decreasing spring floods. This might require more careful water management plans and the development of quantification tools for the winter season.

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