Changes in Latvian river discharge regime at the turn of the century

Elga Apsīte, Ilze Rudlapa, Inese Latkovska and Didzis Elferts

ABSTRACT

The study deals with turn-of-the-century changes in the total annual river runoff distribution and high and low flows in Latvia, covering river basins within four hydrological districts which vary according to size and physiographical conditions. Mathematical statistical methods were applied in the analysis of river discharge data series for two study periods of 1951–2009 and 1881–2009. The present results confirm the basic statement concerning the Baltic countries that major significant changes in river runoff during the last two decades have occurred between spring (decrease) and winter (increase) seasons. Mostly insignificant changes in summer runoff and significant/insignificant changes in autumn runoff were found. Analysis shows that a statistically significant trend of increase in low flow for the cold period and a significant trend of decrease in the high discharge and coefficient *d* of uneven runoff distribution were detected. Changes in river hydrological regime are mainly caused by changes in large-scale atmospheric circulation processes following climate warming, which has taken place. Latvian river hydrography has therefore changed and become more similar to Western European rivers.

Key words | climate change, discharge, high and low flow, Latvia, river runoff, trends

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INTRODUCTION

Research into changes in air temperature in the northern hemisphere during the 20th century indicates that warming of the climate has taken place during the 1920s–1940s followed by a period of worsening of the climate conditions. During the last few decades at the turn of the 21st century, however, a more rapid increase in the air temperature and warming of the global climate have been observed (IPCC 2007). This has encouraged the development of many studies and discussions on causes (natural or anthropogenic) of the global climate warming and its impact upon the hydrological cycle and processes at various spatial and temporal scales, including the Baltic Sea basin, e.g. Hisdal *et al.* (2003), Pekarova *et al.* (2006), Rödel (2006), Reihan *et al.* (2007), Kriaučiūniene *et al.* (2007), Bolle *et al.* (2008) and Korhonen & Kuusisto (2010). Bolle *et al.* (2008) identified that the increase in air temperature in the Baltic Sea basin (0.10–0.07 °C/decade) over the last 100 years has been much more rapid than the warming trend of the global air temperature (0.05 °C/decade). This region is among the most sensitive regions in the world regarding global warming. It has been observed that the warming trend of the Baltic area is extending further to the Arctic (Førland *et al.* 2002). Hansen *et al.* (2007) have found that the 6 warmest years have occurred since 1998 and the 15 warmest years since 1988, with the greatest air temperature changes in winter (Box 2002). At the turn of the century climate warming is consistently associated with: changes in air temperature and precipitation; decrease of the number of days with snow cover and ice occurrences; higher frequency of extremes in hydro-climate patterns; increasing evaporation; and changes in soil moisture and runoff (Kriaučiūniene *et al.* 2007; Bolle *et al.* 2008).

Some studies have presented statistically significant links with trends in temperature, precipitation or flow. For example, in a Baltic study (Reihan *et al.* 2007) and in a Nordic study (Hisdal *et al.* 2003) the strongest relation

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between temperature, precipitation and discharge and a significant trend of increase in these indicators during the winter season were found. Some studies have detected significant trends in some data series. For example, in studies of hydrometeorological time series in the Baltic Sea area by Kļaviņš *et al.* (2007) and Stips & Lilover (2010), the so-called breakpoints during the 20th century were found. One of them refers to year 1987, which could have determined long-term changes in hydro-climate patterns during the last decades.

Several studies on climate change (e.g. Lizuma *et al.* 2007, 2010) and changes of the hydrological regime have also been carried out in Latvia (e.g. Frisk *et al.* 2002; Kļaviņš *et al.* 2002, 2004, 2006, 2009; Kļaviņš & Rodinov 2008). These studies have mainly focused on long-term changes in annual mean minimum and maximum discharges and time series of ice-break for large- and medium-sized rivers. A broader study on changes in river discharge and climate parameters in Latvia (as well as in Estonia and Lithuania) has been conducted by Reihan *et al.* (2007). However, Reihan *et al.* only studied seasonal changes as long-term trends, which does not provide an answer concerning quantitative assesment and regional peculiarities of structural changes in the runoff of Latvian rivers. The objective of the study described in this article was to analyse turn-of-the-century changes in the total annual river runoff distribution, high and low discharges and trends in Latvia in river basins within four hydrological districts, which varied according to size and physiographical conditions.

OBSERVED CLIMATE CHANGE IN LATVIA

In this study we did not analyse the meteorological parameters, but instead provide a brief overview of observed climate changes in Latvia. The studies by Lizuma *et al.* (2007) showed that the climate of Latvia has changed during the last century. The air temperature changes are influenced by two processes: global warming and changes in the urban environment. During the last 100 years the annual mean air temperature in Riga has increased by approximately 2 °C. The annual mean minimum and maximum temperatures have increased by 1.9 °C and by 1.7 °C, respectively. Lizuma *et al.* (2007) found that the annual mean air temperature in Latvia increased by 1.4 °C during the last 50 years. In the study period from 1950 to 2003, the highest increase in mean air temperature was recorded in spring (March–May) and early winter (November and December). The mean annual maximum temperature increased more rapidly in April and May, while the minimum temperature increased more rapidly in winter.

For the study periods from 1950 to 2003 (Briede & Lizuma 2007) and from 1851 to 2006 (Lizuma *et al.* 2010) it was found that overall increasing trends are evident in precipitation series for the cold period. Monthly precipitation series at most of the stations show upward trends from December to March and a statistically significant downward trend only in September and July. In a study by Apsīte *et al.* (2011) it was forecast that the annual mean air temperature and precipitation will increase by 3.8–4.1 °C and by 10–12%, respectively, in Latvia at the end of 21st century (2071–2100) in comparison to the reference period (1961–1990). Similar long-term changes and trends in air temperature and precipitation patterns during the last century were found in the Baltic countries by Jaagus (2006), Reihan *et al.* (2007) and Bukantis (2007), in Nordic countries by Hisdal *et al.* (2003) and Korhonen & Kuusisto (2010), and in the Baltic Sea basin by Bolle *et al.* (2008).

Changes in large-scale atmospheric circulation processes over Latvia have occurred during the 20th century, which have influenced the climate throughout the Baltic region. Kļaviņš *et al.* (2007) found that the zonal circulation process had been dominating since the 1950s due to the increase of southerly and easterly airflow. However, in the mid-1980s this ceased and was substituted by increased westerly circulation in winter. The year 1987 was identified as one of 'climate turning' or representative of a breakpoint in a centennial perspective, and was associated with significant changes in climate indicators such as winter temperatures and precipitation. Since 1988, Latvian winters warmed year by year until 2010. The increase in air temperature and liquid precipitation as well as early melting of ice and snow cover caused changes in hydrological regime.

DATA AND METHODS

In this study, a data series of daily discharge registered by 25 river hydrological stations were used (Figure 1). All data

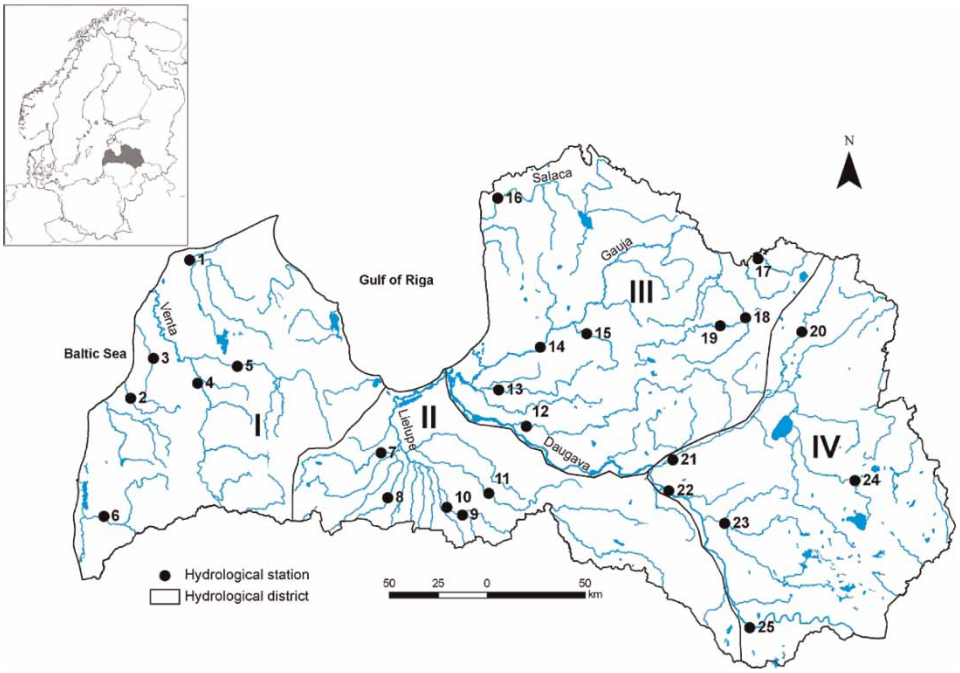

Figure 1 | Location of river hydrological stations and hydrological districts of Latvia. Hydrological districts: I. Western; II. Central; III. Northern and IV. Eastern. Hydrological stations used in this study: 1. Irbe–Vičaki; 2. Rīva–Pievīķi; 3. Užava–Tērande; 4. Venta–Kuldīga; 5. Abava–Renda; 6. Bārta–Dūkupji; 7. Bērze–Baloži; 8. Svēte–Ūziņi; 9. Lielupe–Mežotne; 10. Mūsa–Bauska; 11. Iecava–Dupši; 12. Lielā Jugla. Zaķi; 13. Ogre–Lielpēči; 14. Gauja–Sigulda; 15. Amata–Melturi; 16. Salaca–Lagaste; 17. Vaidava–Ape; 18. Tirza–Lejasciems; 19. Gauja–Velēna; 20. Pededze–Lietene; 21. Aiviekste–Aiviekste; 22. Daugava–Jēkabpils; 23. Dubna–Sīļi; 24. Rēzekne–Griškāni; 25. Daugava–Daugavpils.

were obtained from the Latvian Environment, Geology and Meteorology Centre. For the analysis of the distribution of total annual river runoff in percentage by months and seasons, three study periods were used: the entire period of 1951–2009; 1951–1987, a 37-year period with no substantial climate change impact on river runoff; and 1988–2009, a 22-year period with substantial climate change impact on river runoff observed.

The study periods were chosen for several reasons. First, in the 1990s many hydrological stations were closed due to financial problems. It was therefore difficult to find long-term data series for the entire study period in certain parts of Latvia. In the end, we selected 25 hydrological stations for this study. Second, on the basis of the previous research by Kļaviņš *et al.* (2007) on changes in large-scale atmospheric circulation processes in the Baltic region, the entire study period from 1951 to 2009 was divided into two periods as mentioned above. The structural or seasonal changes in the total annual river runoff are proven by discharge results in percentage points, which are calculated as a percentage difference between runoffs for the periods 1988–2009 and 1951–1987. The *t*-test at the significance level $p < 0.05$ (Sokal & Rohlf 1995) was used to compare mean monthly and seasonal values of the discharge between the periods of 1951–1987 and 1988–2009. Confidence intervals of 95% were calculated for the discharge data values using the Student *t*-distribution.

In the analysis of changes in river low- and high-flow, daily discharge data series from 1951 to 2009 were used. Two low-flow periods were defined as a series of the 30-day minimum discharge in a cold period ($Q_{30\text{cold}}$, November–February) and warm period ($Q_{30\text{warm}}$, May–October). The high-flow period was characterized by the maximum discharge of the year (Q_{max}) which was mainly observed during the spring flood period (March–April). The ratios of the annual low-flow discharge or maximum discharge of the year and long-term annual mean (LTM) discharge ($Q_{30\text{cold}}/Q_{\text{LTM}}$, $Q_{30\text{warm}}/Q_{\text{LTM}}$ and $Q_{\text{max}}/Q_{\text{LTM}}$) were calculated.

The coefficient d of uneven runoff distribution reflects the distribution of river runoff per year. This coefficient is calculated from 1951 to 2009 as a deficit of the annual mean discharge that corresponds to the runoff surplus over the annual mean discharge. d is defined as a deficit volume, and indicates a part of river runoff where river discharges have exceeded the annual mean discharge (Kriaučiūniene *et al.* 2007).

The multivariate Mann–Kendall test (Lettenmaier 1988; Loftis *et al.* 1991) was used to detect the trend shift in monthly and annual data analysis. The test was applied separately to each variable at each site, at a significance level of $p \leq 0.05$. The trend was considered statistically significant at the 5% level if the test statistic was above 1.96 or below −1.96. The test was used for two study periods, from 1951 to 2009 for 25 hydrological stations and from 1881 to 2009 for five hydrological stations with a long observed discharge data series at the Venta–Kuldīga, the Lielupe–Mežotne, the Gauja–Sigulda, the Salaca–Lagaste and the Daugava–Daugavpils.

In order to interpret the obtained results we used a classification of hydrological districts by Glazacheva (1980) where the territory of Latvia is divided into four districts (Figure 1):

- type I, Western: the River Venta basin and small rivers along the coast of the Baltic Sea;
- type II, Central: the River Lielupe basin and small rivers in the central part of Latvia;
- type III, Northern: basins of the rivers Salaca and Gauja, small rivers along the Riga Gulf coast; and
- type IV, Eastern: small- and medium-sized rivers in the River Daugava basin.

The division into hydrological districts was based on an extensive hydrometric database containing observations from Latvian (and partially also Lithuanian and Estonian) rivers, as well as on complex analysis of the river discharge in relation to physical geographic conditions of the basin. The hydrological districts are described in more detail in the following section.

RESULTS AND DISCUSSION

River discharge regime in Latvia

This section provides a short overview of the discharge regime in Latvia and its regional peculiarities based on the previous studies. All the numerical data on river discharge were obtained from our study over the period 1951–1987.

Latvian rivers belong to the Eastern European district, which covers a broad territory from the Baltic Sea to the Black Sea (Edelshteiju 2005). The rivers are characterized by a typical hydrograph: two high-flow periods during the spring snowmelt and in late autumn during the intensive rainfall, and two low-flow periods in winter and summer (Figure 2). However, high discharge peak could also be observed at any time during the warm period after intensive rainfall. Latvian rivers have mixed water feeding: mostly rain and snowmelt water and groundwater (on average 10–35%; Glazacheva 1980). During the period of 1951–1987 the major part of the total annual river runoff was generated in spring season (37–52%) with a peak discharge of up to 30% in April, which was followed by winter 17–30%, autumn 17–25% and summer 9–14% with the lowest discharge of 2–4% in July and August (Table 1; Figures 3 and 4).

In the Western hydrological district there is a greater impact of meteorological processes occurring over the North Atlantic and the Baltic Sea on the river hydrological regime than for other districts in Latvia, particularly in comparison to the Eastern district (Kļaviņš *et al.* 2002). This tendency changes from west to east. In this hydrological district, a comparatively shorter ice-cover period can be observed and spring floods begin earlier (Glazacheva 1980). As can be seen from Figure 2, spring flood hydrograph is characterized by a steep increase and decrease and shorter duration period due to lower thickness of snow cover. In warm winters, low discharges in rivers cannot be observed. A higher percentage of the total annual river runoff was therefore generated in winter (up to 30%) and in autumn (up to 25%) after rainfall in comparison to other districts (Table 1). The annual amount of precipitation varies from 600 to 850 mm (Briede & Lizuma 2007).

Geological and climatic conditions have determined the hydrological regime and dense river network in the Central district. The rivers flowing along the limnoglacial sediment of the Zemgale lowland are characterized by unfavourable rainfall and snowmelting water infiltration conditions. Spring floods therefore dominate, and the role of groundwater discharge during the year is comparatively low amounting to about 10–15% (Glazacheva 1980). The Central

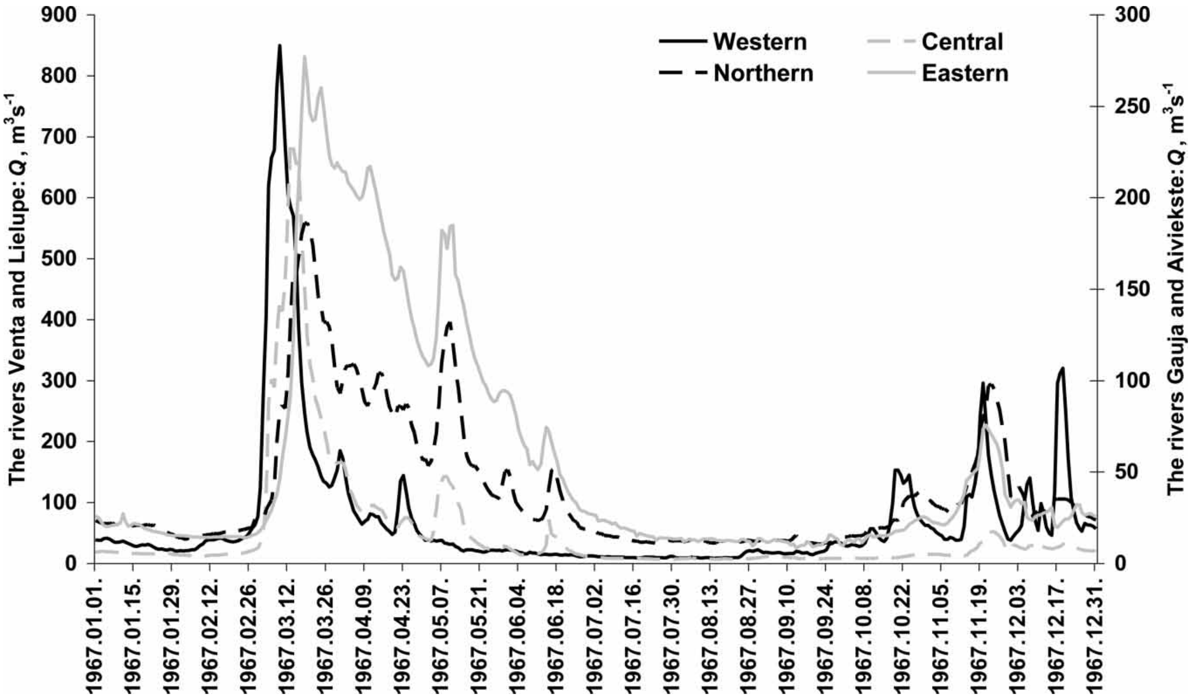

Figure 2 | Typical river hydrographs for the year 1967: the River Venta represents the Western district; the River Lielupe the Central district; the River Gauja the Northern district; and the River Aivieste the Eastern district.

Table 1 | Distribution of total annual river runoff by month and season (percentage)

	Month											
Hydrological district/country	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**
1951–2009												
Western	11.7	9.8	12.8	15.6	5.8	3.0	2.6	2.9	4.1	6.9	11.8	12.9
Central	9.1	8.9	15.5	24.5	7.8	3.5	2.9	2.7	3.2	4.8	7.7	9.3
Northern	8.0	6.9	9.9	23.8	10.3	4.3	3.5	3.8	4.7	6.7	9.2	9.0
Eastern	6.5	6.3	10.5	25.7	12.7	6.1	4.4	3.9	4.2	5.4	7.1	7.1
Total in Latvia	8.8	8.0	12.2	22.4	9.1	4.2	3.4	3.3	4.0	6.0	8.9	9.5
1951–1987												
Western	9.4	7.6	12.5	18.2	6.2	3.1	2.5	3.1	4.8	7.6	12.0	13.0
Central	6.2	6.0	14.9	28.9	8.5	3.5	2.8	2.9	3.6	5.6	7.9	9.0
Northern	6.2	4.7	7.8	27.1	11.5	4.0	3.6	4.1	5.5	7.3	9.3	9.0
Eastern	5.3	4.5	8.4	29.6	14.2	6.0	4.2	3.9	4.2	5.7	7.0	6.8
Total in Latvia	6.8	5.7	10.9	25.9	10.1	4.2	3.3	3.5	4.5	6.6	9.1	9.4
1988–2009												
Western	14.7	12.9	13.3	12.0	5.3	3.0	2.7	2.7	3.2	6.0	11.5	12.8
Central	13.5	13.1	16.4	17.3	6.4	3.6	3.4	2.5	2.7	3.7	7.7	9.7
Northern	10.8	10.3	13.1	18.3	8.3	4.6	3.5	3.5	3.7	5.8	9.1	9.1
Eastern	8.3	9.0	13.5	20.0	10.6	6.2	4.7	3.8	4.1	5.1	7.1	7.4
Total in Latvia	11.8	11.3	14.1	16.9	7.6	4.4	3.6	3.1	3.4	5.2	8.8	9.7

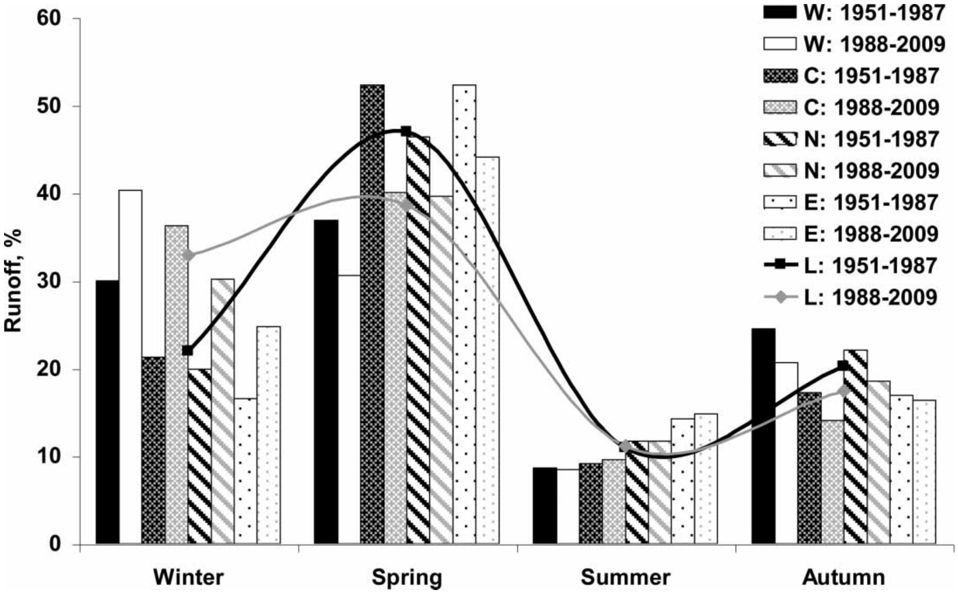

Figure 3 | The distribution of total annual river runoff in average percent by study periods, seasons, totally in Latvia (L) and hydrological districts (W: Western; C: Central; N: Northern; E: Eastern).

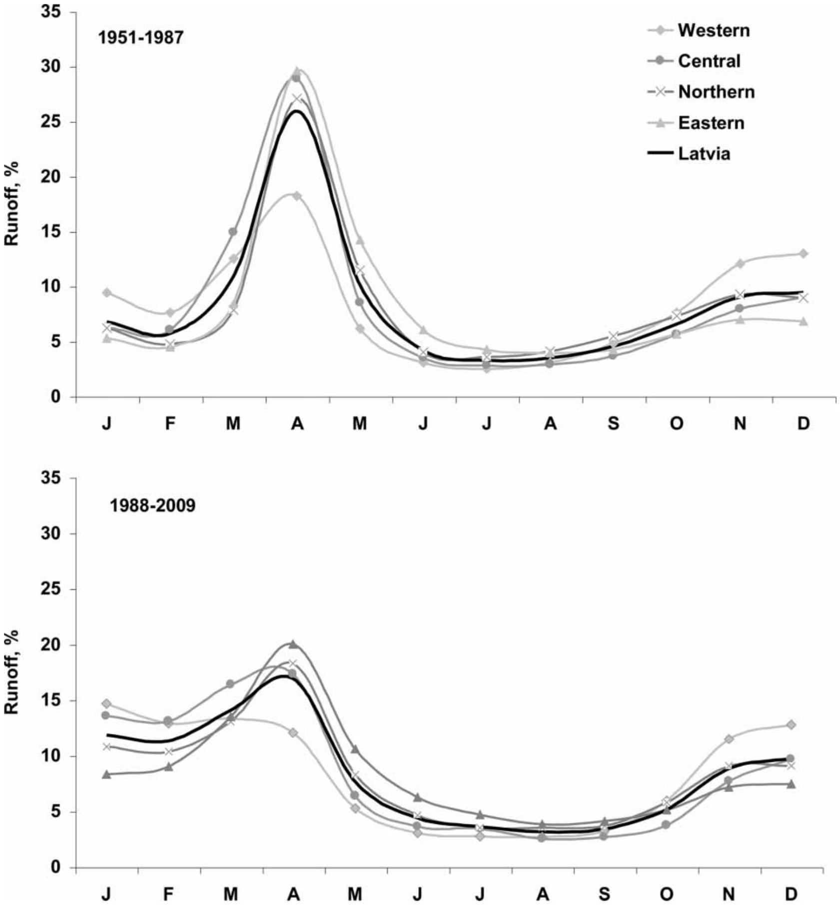

Figure 4 | River hydrograph in percent by study periods in Latvia in general and in hydrological districts.

district forms a transition territory where climatic conditions of both west and east Latvia are present; these determine peculiarities of the hydrological regime of rivers of this region. For example, spring flood in rivers starts later than for the Western district (Figures 2 and 4) and the runoff in winter is higher (on average by 21%) in comparison to Eastern and Northern districts (Table 1). It is typical for this district that the lowest annual amount of precipitation (500–600 mm) is observed (Lizuma *et al.* 2010).

The Northern district is characterized by the highest amount of precipitation per year (800 mm and more; Lizuma *et al.* 2010) and the shortest duration of vegetation period. As regards highland rivers, a higher inflow of groundwater (which can amount to up to 30% and even

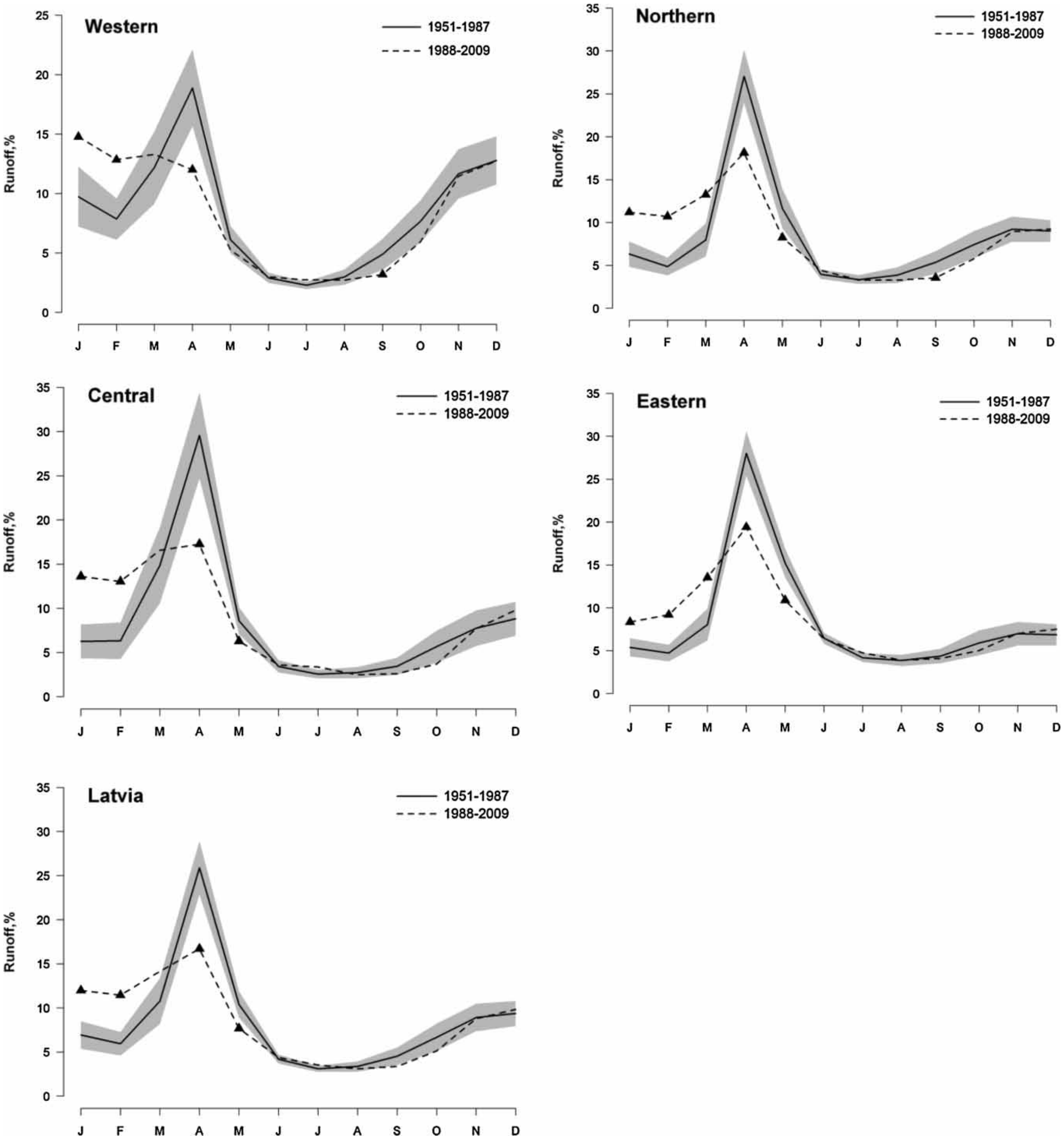

Figure 5 | Changes in the river hydrograph between two study periods in hydrological districts and Latvia. The grey area represents 95% confidence interval for the mean discharge values for the period 1951–1987. The black triangle represents statistically significant change in monthly mean discharge value for the period 1988–2009.

up to 60% in case of certain small rivers) plays an important role in the feeding (Glazacheva 1980). The rivers are characterized by high snowmelt floods, which account for 40–52% of total annual runoff, and comparatively less pronounced runoff due to rainfall in autumn (amounting to an average of 22% of total annual runoff) than compared to the Western district.

The Eastern district is characterized by more continental climate conditions than others, i.e. warmer summers and colder winters with thick snow cover. Spring floods of rivers begin later and their duration is longer (Figures 2 and 4) and they account for more than a half (on average 52%) of the total annual runoff. The river hydrograph is characterized by a typical low-flow period in winter. In this district, the smallest part of the total annual runoff in winter season was generated (on average 17%) in comparison to the other districts. About 40% of Latvian lakes are located here, which have affected the hydrograph of outflowing rivers.

Changes in distribution of total annual river runoff and trends

It is a well-known fact that changes in river hydrological regime are mainly caused by climatic factors (Reihan *et al.* 2007; Korhonen & Kuusisto 2010). As mentioned above, global warming during the last decades has also determined long-term and structural or seasonal changes of the Latvian river runoff. In the middle latitudes, where snow accumulation and melt presently dominate in the hydrological regime, major significant changes in river hydrograph are observed between the winter and spring seasons. In comparison to the study period of 1951–1987, we have found that during the last two decades (1988–2009) there was a statistically significant general increase by 11% on average in the Latvian river runoff in winter and a decrease in spring by 8% on average; it decreased slightly in autumn by 3% on average, and insignificant changes occurred in summer. Although the streamflow had significantly increased in January and February and significantly decreased in April and May, the major part of the total annual river runoff was still generated in spring season (39% on average) and the discharge peak was still maintained in April (17% on average) (Table 1; Figure 5).

Changes in seasonal and monthly river discharges were identified in all hydrological regions at the turn of the century (Figure 5). The major changes in discharges occurred in the Central hydrological district, where river runoff has increased significantly by 15% in winter (in particular in January and February) and decreased significantly by 13% in

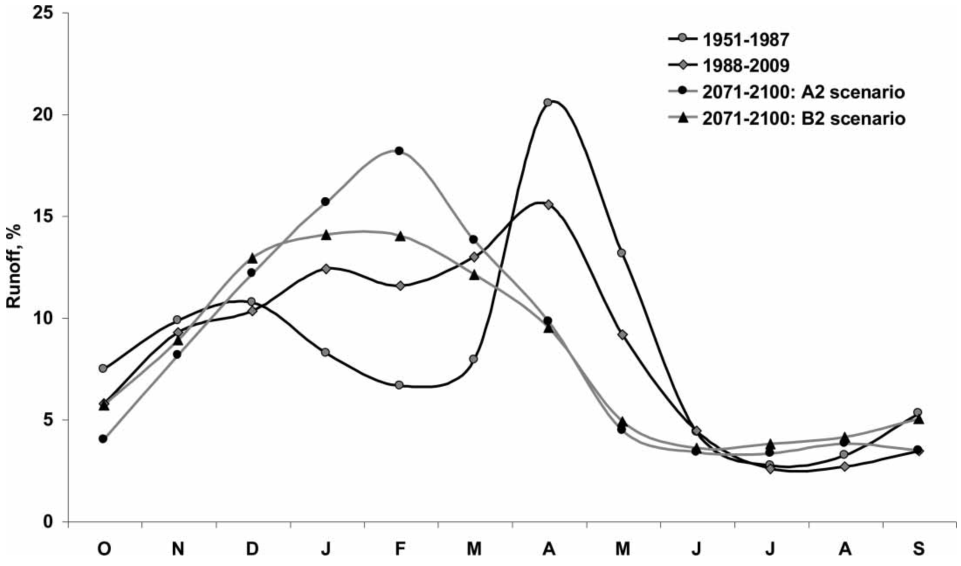

Figure 6 | Changes in river hydrograph of a hydrological year from October to September for the River Salaca under different climate change impacts. Climate changes are predicted by the regional climate model (RCM) Rossby Centre Atmosphere Ocean (RCAO) applied for the two IPCC scenarios A2 and B2 and run for the 30-year periods 1961–1990 (control period) and 2071–2100 (scenario period). Scenario A2 is a high emissions scenario in comparison with B2 and was chosen for this study to illustrate the worst-case situation.

spring (in particular in April and May). This could be explained by the fact that a greater influence of climate changes on the river runoff in winter–spring seasons was observed in the Central district than in others. During the last two decades, warm winters have dominated. Low discharges during the cold period could therefore not be observed and spring floods began earlier (Figures 4 and 5). Similar hydro-climatic conditions were observed in the Western district during the period of 1951–1987, when climate warming did not affect the river hydrograph very much.

Warmer winters were also observed in the Northern and Eastern districts, but changes in the total river runoff distribution over the year were more gradual. A statistically significant increase in runoff during January–March by 3–5.5% and statistically significant decrease in runoff

Table 2 | The results of Mann–Kendall test for monthly mean discharge, annual low, high and mean discharges from 1951 to 2009. Trend is statistically significant at the 5% level ($p \leq 0.05$) in bold

	Month											
Hydrological station	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**
Western district												
Venta–Kuldīga	**2.86**	**2.92**	1.79	**–2.99**	–1.16	**2.54**	**3.06**	0.39	–0.14	0.34	0.61	0.88
Abava–Renda	**3.02**	**2.71**	0.83	–0.53	–0.01	**3.49**	**1.94**	1.75	0.93	0.80	0.68	1.13
Irbe–Vičaki	1.81	1.44	**2.29**	–0.91	–1.26	1.03	**2.00**	0.69	0.36	0.79	1.65	0.85
Rīva–Pievīķi	**2.62**	1.87	1.09	–1.05	–1.00	0.66	0.89	0.74	–0.28	–0.09	0.22	0.78
Užava–Tērande	**2.89**	**2.50**	1.84	–1.33	–0.34	**2.04**	1.71	0.41	–0.40	0.25	0.50	0.55
Bārta–Dūkupji	**2.33**	**2.29**	**1.96**	**–2.35**	–1.07	0.94	1.91	0.72	–0.68	0.37	0.91	0.95
Central district												
Lielupe–Mežotne	**3.79**	**3.54**	**2.25**	**–2.79**	–1.20	**2.66**	**4.00**	**2.47**	1.81	0.90	1.09	**2.37**
Mūsa–Bauska	**2.91**	**3.02**	**2.15**	**–2.45**	–0.86	1.69	**2.05**	0.47	0.10	0.63	1.24	**2.09**
Svēte–Ūziņi	**2.62**	**2.45**	1.64	**–2.78**	–1.52	1.20	1.61	–0.42	–0.51	0.14	1.81	1.89
Bērze–Baloži	**2.77**	**3.15**	1.85	–1.66	–0.84	**2.35**	1.73	–0.03	–0.39	–0.28	0.29	0.84
Iecava–Dupši	**1.97**	**2.17**	**2.45**	**–3.35**	**–2.62**	0.71	1.87	0.69	0.04	–0.83	–0.65	–0.13
Northern district												
Gauja–Sigulda	**2.65**	**2.99**	**3.24**	**–2.06**	–1.53	0.99	1.06	–0.41	–1.05	–1.18	0.61	0.97
Gauja–Velēna	**3.01**	**3.21**	**2.58**	**–2.23**	–0.49	**2.31**	**2.08**	0.63	0.05	0.31	1.47	**2.02**
Amata–Melturi	**2.30**	**3.44**	**2.65**	**–2.68**	–1.14	0.55	0.16	–1.16	–1.64	–0.56	0.39	0.26
Vaidava–Ape	**2.92**	**3.18**	**3.17**	**–2.15**	–1.79	1.68	1.36	–0.35	–0.50	–0.34	1.06	1.67
Ogre–Lielpēči	**2.79**	**2.58**	**2.82**	**–2.85**	–1.59	1.54	1.43	–0.76	–1.23	–0.59	0.81	0.67
Tirza–Lejasciems	**2.26**	**2.76**	**2.75**	–1.46	–1.74	0.93	0.04	–1.50	–1.48	–0.79	0.97	1.28
Salaca–Lagaste	**3.05**	**2.92**	**3.08**	–0.60	–1.05	1.38	1.86	1.44	–0.02	–0.13	0.92	1.40
Lielā Jugla–Zaķi	**2.46**	**2.80**	**2.91**	**–3.28**	–1.37	**3.14**	1.76	0.20	–0.56	–0.03	0.95	0.22
Eastern district												
Daugava–Daugavpils	1.80	**2.89**	**3.44**	**–2.03**	**–2.13**	0.01	1.15	0.96	0.73	0.63	1.11	1.70
Daugava–Jēkabpils	**2.60**	**3.67**	**3.37**	–1.61	–1.41	–0.08	1.18	1.43	1.46	1.36	1.80	**2.65**
Aiviekste–Aiviekste	**2.65**	**2.62**	**2.72**	**–1.96**	**–3.50**	–0.91	1.04	0.32	0.25	0.94	1.26	1.68
Dubna–Sīļi	**2.35**	**2.86**	**2.96**	**–2.64**	–0.22	**2.33**	**2.00**	0.69	–0.19	–0.20	0.82	1.05
Rēzekne–Griškāni	**2.38**	**2.71**	**2.51**	–1.50	1.10	**2.23**	**2.05**	0.99	0.96	0.90	1.05	1.50
Pededze–Litene	**3.18**	**2.97**	**2.42**	**–2.00**	**–2.12**	1.22	0.13	–1.11	–0.79	0.13	0.62	1.26

during April–May by 3–9% were found for both hydrological districts.

The results of monthly analysis show no significant changes from June to August and from October to December in all hydrological districts. River runoff decreased in the autumn season, but significantly decreased by 2% on average in September in the Western and Northern districts. This could be explained by warmer autumns, increased evapotranspiration and decreased precipitation (significantly in September) in Latvia (Briede & Lizuma 2007).

According to results of the hydrological simulation forecasts by Apsīte *et al.* (2010), if global warming continues, patterns of structural changes in Latvian river runoff at the end of the 21st century (period 2071–2100) would be similar to those observed at the turn of the century. It was concluded that considerable changes in streamflow are predicted for the winter–spring and autumn seasons. The major part of the total annual river runoff will therefore be generated in winter due to a warmer and wetter climate, followed by spring, autumn and summer. Autumns will become warmer and dryer followed by streamflow decrease. No considerable change in runoff was predicted for summer. It can be seen from the river hydrograph depicted in Figure 6 that two main periods instead of four and a high flow (mostly in the cold period of the year) and low flow (mostly in the warm period) will be distinguished.

Similar results in seasonal changes in Latvian river runoff were also obtained for the entire study period from 1951 to 2009 (Table 1): the main share of discharge amounting to 44% was still generated in spring, followed by winter with 26%, autumn with 20% and summer with 11%. However, the monthly results of the Mann–Kendall test allow us to determine how significant long-term changes are at $p \leq 0.05$. The results are summarized in Table 2. A statistically significant downward or negative trend was found in April in 64% of studied sites, and it was mostly statistically significant for the Central and Northern hydrological districts. A statistically significant upward or positive trend was found for January–February for 93% and for March for 76% of studied sites. In the Central and Western districts, river runoff increased more significantly in January and February. Moreover, in the Eastern and Northern districts, significantly increased river runoff was registered for January, February and March. Generally, statistically insignificant trends were observed for the summer and autumn months. On the whole, the results of the Mann–Kendall test for the trend analysis agree well with the *t*-test results; they show considerable or inconsiderable changes in river runoff patterns in Latvia in general and among hydrological districts.

Changes in annual mean, low-flow and high-flow discharges and trends

Changes in streamflow at the turn of the century were identified in order to analyse the ratio of annual low-flow and high-flow discharges to LTM discharge for the three study periods and hydrological districts. The results of the calculated ratios allow us to evaluate the magnitude in streamflow changes and are presented in Table 3. The ratio $Q_{30\text{cold}}/Q_{\text{LTM}}$ increased for all studied rivers in the period 1988–2009 compared to the study period of 1951–1987. This ratio was higher for the Western (0.81)

Table 3 | Annual low-flow to high-flow discharge ratios and annual mean discharge

Study period	$Q_{30\text{cold}}$	$Q_{30\text{warm}}$	Q_{max}	Q_{mean}
Western district				
1951–2009	0.64	0.21	7.07	1.00
1951–1987	0.52	0.22	7.51	0.97
1988–2009	0.81	0.21	6.40	1.05
Central district				
1951–2009	0.48	0.19	8.92	1.00
1951–1987	0.34	0.19	10.4	0.99
1988–2009	0.68	0.18	6.38	1.01
Northern district				
1951–2009	0.53	0.26	7.14	1.00
1951–1987	0.40	0.26	7.79	0.97
1988–2009	0.72	0.25	6.01	1.04
Eastern district				
1951–2009	0.54	0.38	5.98	1.00
1951–1987	0.42	0.37	6.58	0.95
1988–2009	0.75	0.41	4.99	1.08
Total in Latvia				
1951–2009	0.55	0.26	7.28	1.00
1951–1987	0.42	0.26	8.07	0.97
1988–2009	0.74	0.26	5.95	1.05

and lower for the Central (0.68) districts. The ratio $Q_{\max}/Q_{\text{LTM}}$ also decreased for all studied rivers for the period 1988–2009. A higher difference in this ratio between the studied period of 1988–2009 (ratio 6.38) and 1951–1987 (ratio 10.40) was found for the rivers of the Central district, followed by rivers of the Northern, Eastern and Western districts. The calculated ratio $Q_{30\text{warm}}/Q_{\text{LTM}}$ did not demonstrate any considerable changes between studied periods.

The trend analysis (Figure 7) for the period of 1951–2009 shows a statistically significant upward trend for the 30-day minimum discharge of the cold period in all studied hydrological stations, and a statistically significant downward trend for the maximum discharge in 72% of sites. Significant negative/positive trends for the 30-day minimum discharge in the warm period were found only for four sites and significant negative/positive trends of the annual mean discharge were found in five

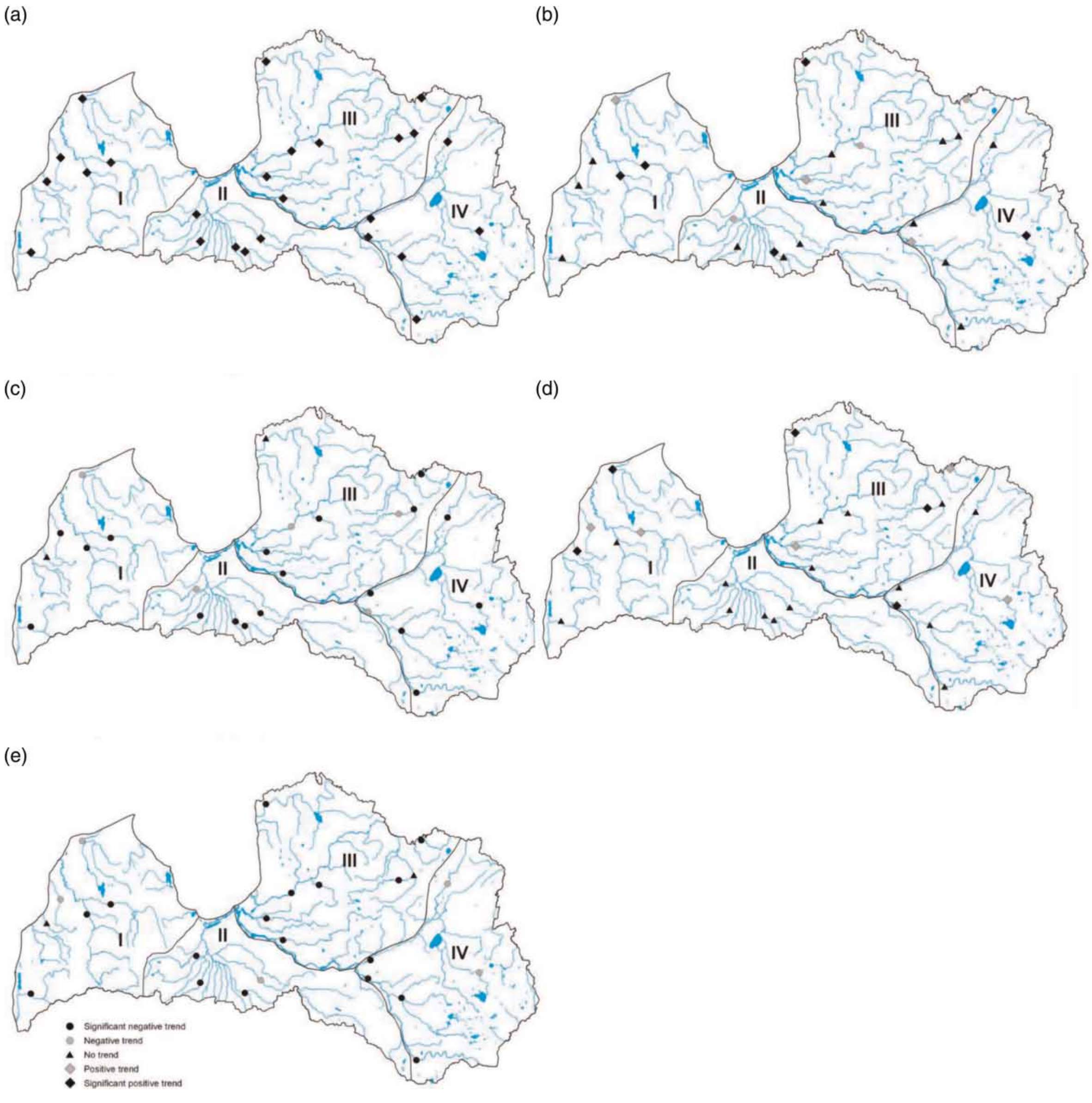

Figure 7 | Trends in low flow in the cold period (a) and in the warm period (b), annual maximum discharge (c), annual mean discharge (d) and the coefficient *d* of uneven runoff distribution (e) for the period 1951–2009.

sites. An example of the Latvian rivers where the results of the calculated ratio and Mann–Kendall test agree in terms of changes in low-flow and high-flow trends is presented in Figure 8. In general, considerable differences in low-flow and high-flow trends among hydrological districts were not identified, except for the Western district.

In most cases these results are in agreement with the Baltic studies results for the study period of 1961–2003 by Reihan *et al.* (2007). The findings of the Reihan *et al.* study

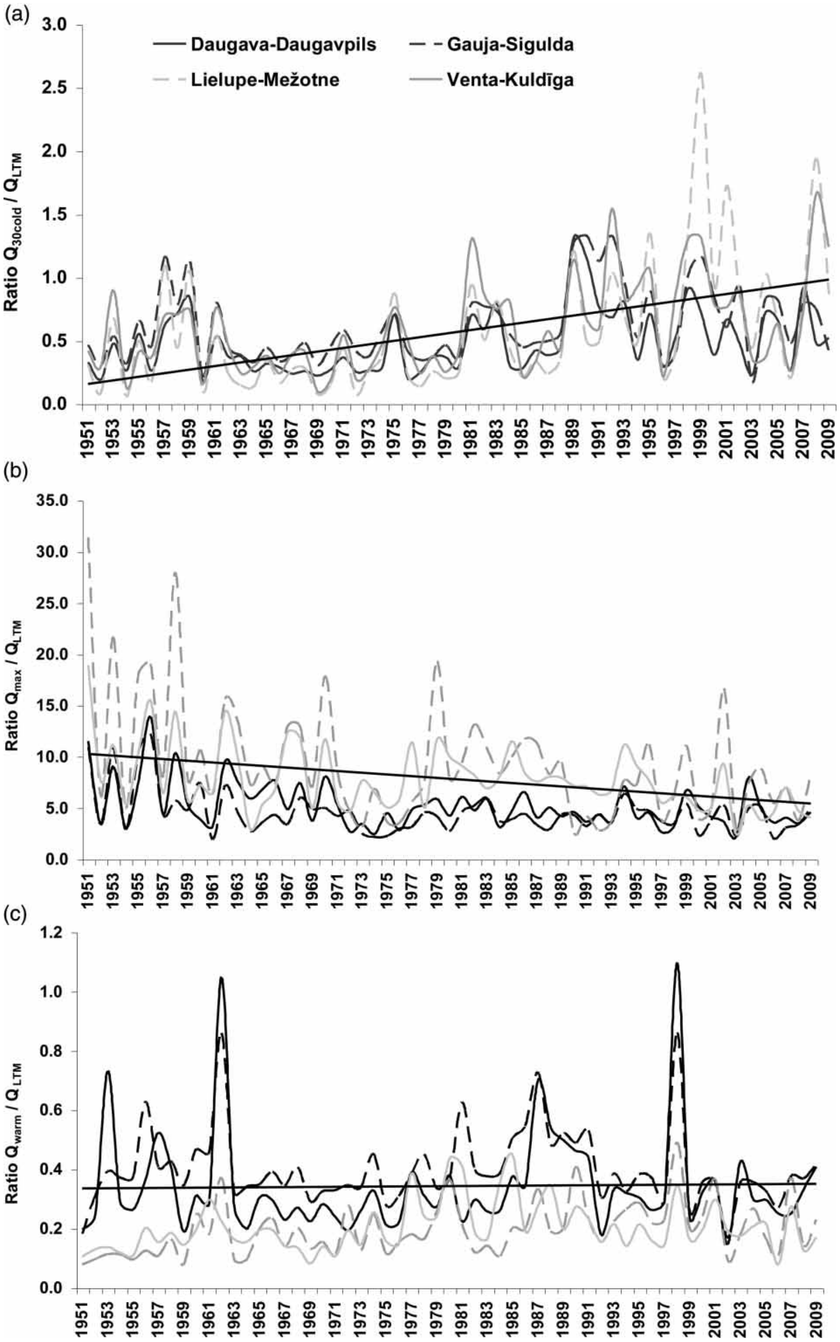

Figure 8 | Trends in low flow in the cold period (a), the annual maximum discharge (b) and low flow in the warm period (c) for the period of 1951–2009.

can be summarized as: the largest part of Lithuanian and Latvian teritory had no trend at all in summer low flow, and the systematic negative trend in spring flood was detected mostly in the continental regions of the Baltic countries. This contrasts our study results, which mostly demonstrate significant positive trends in the annual mean discharges detected for Latvia and also Estonia. Reihan *et al.* (2007) pointed out that the decrease in spring flood magnitude and an earlier start of river flooding is evidently due to increasing air temperature during the winter period. The increase in air temperature influences the decrease in the water equivalent to snow and also the number of days with snow. At the same time, differences in streamflow during summer and autumn seasons reflect tendencies observed in the precipitation and temperatures series in most cases in the Baltic countries.

In order to evaluate long-term changes in Latvian streamflow regime, the coefficient *d* of uneven runoff distribution was calculated. The trend analysis shows statistically significant negative trends in 72% of studied sites (Figures 7(e) and 9). Long-term changes in coefficient *d* could be observed in all hydrological districts except for the Western. In the study by Kriaučiūniene *et al.* (2007), the mostly significant negative trend of coefficient *d* for the study periods of 1961–2003 and 1941–2003 was detected for the Lithuanian rivers. This demonstrates that in Lithuania and also Latvia the annual distribution of runoff has become more even and the differences between the low-flow and high-flow discharges in spring have decreased during the last decades.

Long-term trends in river runoff

For the purposes of assessing the importance of the impact of the global climate warming at the turn of the century, the long-term data series of the observed river discharge during the period of 1881–2009 was studied. The results of trend analysis of monthly and annual river discharges are summarized in Table 4. Although the discharge data series differ in length from 70 to 111 years, in all five studied rivers a statistically significant trend of increase was identified regarding monthly mean discharge for January and February and the 30-day minimum discharge of the cold period. A significant downward trend was detected for the maximum discharge. No significant trend for the annual mean discharge was identified. However, certain regional differences can be distinguished in this instance. A statistically significant upward trend in the 30-day minimum discharge of the warm period and in June and July was identified for Venta and Lielupe, representing Western and Central districts, respectively. A significant increase trend in monthly mean discharge in March was found for the rivers Gauja and Salaca of the Northern district and the River Daugava of the Eastern district. One example of long-term trends in the River Daugava annual discharges

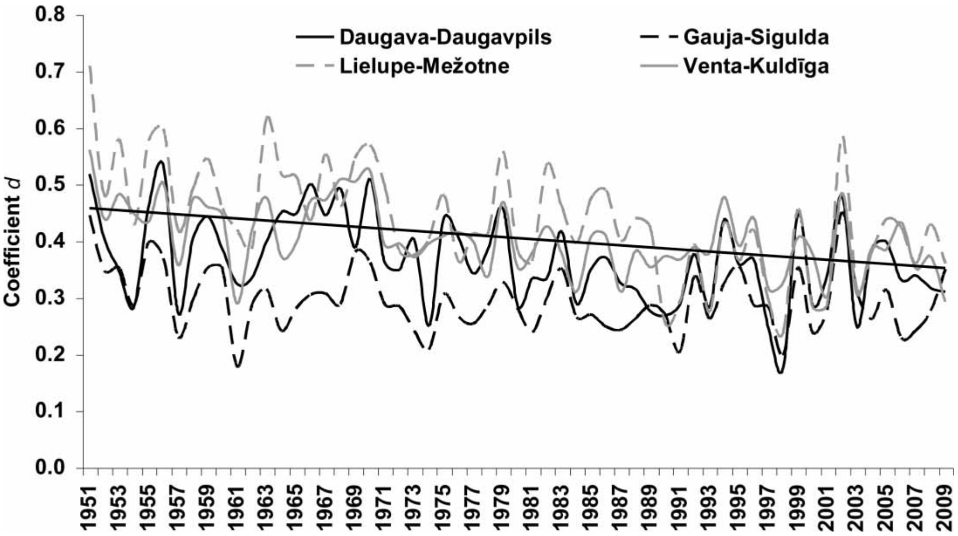

Figure 9 | Trends in uneven river runoff distribution for the period 1951–2009.

Table 4 | The results of Mann–Kendall test for monthly mean discharge, annual low, high and mean discharges from 1881 to 2009. Trend is statistically significant at the 5% level ($p \leq 0.05$) in bold

Hydrological station	**Month**															
	J	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	Q_{30cold}	Q_{30warm}	Q_{max}	Q_{mean}
Western district																
Venta–Kuldīga (1898–2009)	**2.68**	**1.99**	**2.05**	**−2.28**	−0.81	**2.04**	**2.20**	0.59	0.65	0.47	0.44	1.53	**6.87**	**5.16**	**−2.82**	0.18
Central district																
Lielupe–Mežotne (1920–2009)	**3.18**	**2.48**	0.12	−1.42	−0.44	**1.98**	**2.21**	0.07	0.90	0.38	0.26	**2.54**	**4.42**	**4.76**	**−5.29**	−1.18
Northern district																
Gauja–Sigulda (1939–2009)	**3.60**	**3.63**	**3.51**	**−2.23**	−0.66	0.81	0.04	−0.02	−0.74	−1.12	1.36	1.39	**4.26**	0.11	**−2.63**	1.77
Salaca–Lagaste (1926–2009)	**3.87**	**3.91**	**2.04**	−0.61	−0.52	0.26	0.44	−0.42	−0.94	−1.00	−0.07	1.56	**4.99**	0.55	**−2.04**	0.99
Eastern district																
Daugava–Daugavpils (1881–2009)	**5.06**	**4.91**	**2.63**	−1.44	**−3.09**	−0.08	−0.65	−1.40	−0.92	−0.23	−0.03	1.82	**5.49**	−0.33	**−3.30**	0.38

at Daugavpils site is depicted in Figure 10, which is one of the longest-observed data series in the Baltic countries. Such patterns in the long-term trends can be seen for the other studied major rivers in Latvia. Although thrends are naturally dependent upon the selected time period (Korhonen & Kuusisto 2010), the long-term trend analysis of two study periods of 1951–2009 and 1881–2009 for the same river and hydrological station shows mostly the same significat changes in monthly and annual discharge regime. From the above, it can be concluded that climate warming at the turn of the century has had a considerable impact upon changes of hydro-climatic processes both in Latvia and over a broader region, i.e. the Baltic Sea basin.

Having analysed the latest results of other studies carried out in Latvia and in the Baltic Sea basin we have identified similar changes in long-term patterns of river discharge regime. In the study of major rivers of Latvia by Kļaviņš *et al.* (2004) and Kļaviņš & Rodinov (2008), a statistically significant trend of decrease of maximal discharges (except for the River Salaca) and increase of the minimum annual discharges (except for the River Gauja) for the study period of 1881–2006 have been found. It was concluded that during the last decades virtually no years with extremely high river discharges have been observed. In the study period 1922–2003 in the Baltic countries by Reihan *et al.* (2007) a significant positive tend in annual discharge and significant negative trend in spring flood maximum discharge were identified at most sites. At the same time, no trends of summer low flow (except for the marine region of Estonia and Latvia) have been found.

The results of seasonal changes of river runoff or discharge regime in Baltic countries and Finland have shown quite similar patterns to those observed in this study. Trend analyses of 25 unregulated and regulated rivers in Finland during the study period of 1912–2004 demonstrated a statistically significant increase in winter runoff and decrease in spring runoff in 31–42% and 50–54% of studied sites, respectively. At the same time the early occurrence of the peak in spring flood was identified only at one-third of all studied sites (Korhonen & Kuusisto 2010). Similar results were published by Hisdal *et al.* (2003) in Nordic studies. These studies indicated that in the Nordic countries it would take many years to identify a more significant

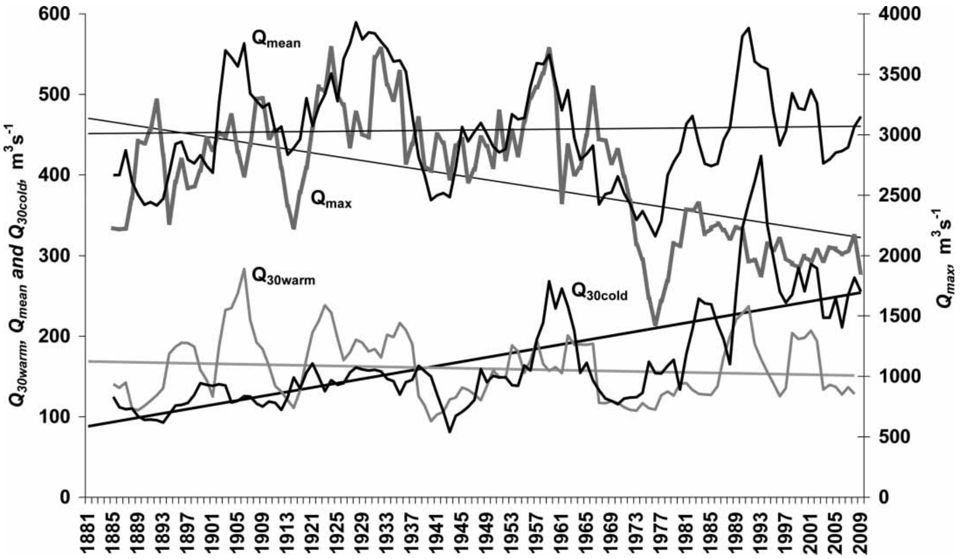

Figure 10 | Trends in low flow in cold and warm periods, annual mean and maximum discharges at the hydrological station Daugava–Daugavpils for the period of 1881–2009. Discharge curves are smoothed with 5-year moving mean.

magnitude of change in river runoff in winter–spring seasons under the impact of climate change.

CONCLUSIONS

In this study long-term and structural or seasonal changes in the river discharge regime in Latvia in general and in four hydrological districts were investigated. Climate warming which occurred at the turn of the century, i.e. during the last two decades, has modified the river hygrograph considerably which has become more similar to Western European rivers. The major significant changes in total annual river runoff were found between winter (increase) and spring (decrease) seasons in all hydrological districts, especially in the Central district. Insignificant changes in runoff were observed in summer and a decrease was seen in autumn runoff, which was statistically significant for the Western and the Northern districts rivers. However, the major amount of total annual runoff (39%) was generated in spring due to a warmer and wetter climate, followed by spring (33%), autumn (17%) and summer (11%).

This study shows that, in most cases, statistically significant overall long-term changes have not been observed in annual mean and low-flow discharges of the warm period. However, a statistically significant trend of increase in low flow of the cold period and a mostly significant trend of decrease for the high discharge and coefficient *d* of uneven runoff distribution were found. It could be concluded that the annual distribution of runoff has become more even and the differences between the low-flow and high-flow discharges in spring have decreased during the last decades.

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