Spatial distribution and temporal changes in river water temperature in the Baltic States

A. Jurgelėnaitė, J. Kriaučiūnienė, A. Reihan, I. Latkovska and E. Apsīte

ABSTRACT

The thermal regime of rivers in the Baltic States (Estonia, Latvia and Lithuania) is not sufficiently studied. The presented research describes the spatial distribution and temporal variation of river water temperature (WT) in the Baltic States using a unified methodology. The object of the research is the WT of rivers during the warm season (May–October) and the warmest month of the year (July). The contour maps of WT were compiled for the rivers of the Baltic States using data series for the period 1961–1990 from 17 water measuring stations in Estonia (EST), 36 stations in Latvia (LV) and 40 stations in Lithuania (LT). These maps allow the evaluation of WT for the unmonitored rivers. Analysis of long-term (1951–2010) changes of river WT showed that during the first half of this period (1951–1980), river WT decreased significantly (0.003 °C/warm season). Meanwhile, only positive trends prevailed over the last three decades (1981–2010) in the river WT of the Baltic States. During the latest period, rivers which show significant positive trends in WT warm up significantly – by 0.04 °C/warm season.

Key words | rivers of the Baltic States, spatial distribution, temporal changes, warm season, water temperature

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INTRODUCTION

Temperature is a physical parameter of water which affects a wide variety of processes in the aquatic environment. It influences other physical features (water surface tension, density, conduction, odour and other) and chemical–biological characteristics of water (Webb & Nobilis 2007). Water temperature (WT) is the most important water quality indicator used for the assessment of the ecological status of surface waters according to the Water Framework Directive (WFD) 2000/60/EC (Directive 2000/60/EC). It directly affects dissolved oxygen concentration which is an essential factor for aquatic life (Sand-Jensen & Pedersen 2005). Most aquatic organisms have a specific range of WT that they can tolerate (Durance & Ormerod 2007).

WT in rivers is mainly determined by different physical–geographic and anthropogenic factors. Climate conditions, the surrounding landscape (forest or open field), the inflow of groundwater, the spread of different types of soils and lakes in the catchment, the size of the river and the geomorphology of the basin are the main natural factors which affect WT (Uehlinger *et al.* 2003; Carrivick *et al.* 2012; Jurgelėnaitė *et al.* 2012; Hannah & Garner 2015; Swinton *et al.* 2016). Among anthropogenic factors, hydropower plants located on the river have the greatest impact on the change of the river's WT (Prats *et al.* 2010; Dickson *et al.* 2012; Gebre *et al.* 2014), but in densely populated areas an essential impact may also be caused by wastewater discharged into the river (Xin & Kinouchi 2013). Recent studies performed worldwide indicate that the change in river WT is a direct result of climate change (Kaushal *et al.* 2010; Prats *et al.* 2010; Floury *et al.* 2012; Van Vliet *et al.* 2013; Gebre *et al.* 2014; Hannah & Garner 2015).

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Climate change has been registered around the world, particularly in the last decades. The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), produced by over 800 scientists, confirms that warming of the climate system is unequivocal, as the atmosphere and the oceans have warmed. The Climate Change Report (IPCC 2014) states that the period from 1983 to 2012 was likely the warmest 30-year period of the last 1,400 years in the northern Hemisphere and the globally averaged combined land and ocean surface temperature data show a warming of 0.85 °C (from 0.65 to 1.06 °C) over the period from 1880 to 2012.

There is a growing concern that the rising air temperature under climate change may influence WT which could adversely affect freshwater ecosystems (Webb *et al.* 2008). Observed trends of increasing air temperature and decreasing water flow are believed to result in a corresponding rise in river WT. Increasing trends in river WT have been observed on global and regional scales (Webb & Nobilis 2007; Kaushal *et al.* 2010; Isaak *et al.* 2012; Van Vliet *et al.* 2013; Orr *et al.* 2015).

Kaushal *et al.* (2010) analysed historical WT records for streams across the United States and found that half of major streams and rivers have shown statistically significant linear increases in annual mean WTs. Isaak *et al.* (2010) assessed possible trends in summer WTs of mountain streams in the northern Rockies of the United States and found that average mean and maximal stream temperatures increased in the period of 1993–2006, due to positive trends in air temperature.

Arismendi *et al.* (2012) analysed WT data from sites located across the Pacific Continental United States and detected that warming trends were most prevalent in a small subset of locations with long time data series beginning in the 1950s, while more recent river WT data series (1987–2009) exhibited more cooling trends and fewer warming trends.

The spatial distribution and temporal changes of river WT are not sufficiently studied in the Baltic States. In Latvia, earlier studies of the thermal regime of rivers and lakes and their regional differences were conducted by Glazacheva in the 1960s (Glazacheva 1965, 1967). During recent years, studies of the long-term and seasonal change trends of the WT of rivers in Latvia have been performed by Latkovska & Apsīte (2016). In Lithuania, the greatest attention has been focused on the study of WT of the River Nemunas (Rainys & Lisauskienė 1977; Grižienė *et al.* 1983). Vanagaitė & Valiuškevičius (2011) performed the assessment of river WT compliance with ecological requirements. The changes of Lithuanian river WT were described by Jurgelėnaitė *et al.* (2012). The WT regime of Estonian rivers was studied in the 1960s. Since then, there has been no systematic study of changes in WT. As the mentioned research works were performed using different methodologies and data sets, they cannot be used to detect common tendencies in variation of WT in the rivers of the Baltic States.

The aim of this research is to characterize the thermal regime of rivers in the Baltic States (Estonia, Latvia and Lithuania), with an emphasis on WT spatial and temporal variability using a unified methodology. This study investigates mean WTs of the rivers in the warm season (May–October) and the warmest month of the year (July). Warm seasonal WTs play an important role in hydro-biological processes and thus can determine the distribution and survival of many aquatic organisms.

STUDY AREA AND DATA

In this research, the Baltic States were chosen as the research area. River WT data were obtained from 93 water measuring stations distributed in this region (Figure 1). The stations are managed by three organizations: Estonian Environment Agency, Latvian Environment, Geology and Meteorology Centre (LEGMC) and Lithuanian Hydrometeorological Service (LHMS). River WT data were collected from the hydrological yearbooks or data funds of these organizations.

Systematic observations of WT in most water monitoring stations of the Baltic States started in 1945. In the 20th century, the WT in the monitored rivers was measured twice a day (8 a.m. and 8 p.m.) during the ice-free season by the observer using a mercury-in-glass thermometer which was placed about 0.1–0.5 m below the water surface.

In the 21st century, automatic equipment was installed in the majority of water measuring stations in the Baltic States. All newly installed stations and most of the historical sites have been equipped with submersible WT loggers which are positioned in the river cross

Figure 1 | Map of river WT monitoring sites in the Baltic States.

section, near the bottom of the stream. In the automated stations, WT is recorded on a continual basis with 60-minute intervals.

The analysis of homogeneity of WT data was done by comparing the data of manual observations and automatic equipment. For this purpose, WT was measured hourly over a 24-hour period in the River Šventoji at the site of Anykščiai WGS and compared to the hourly WT measurements performed by the automatic equipment of LHMS during the same period (Figure 2).

The analysis revealed the differences between the WT data of manual and automatic observations. In the first case (Figure 2(a)), the river WT measured by automatic equipment is lower than that of manual measurement, while in the second case (Figure 2(b)), automatic equipment showed a higher WT. Such differences of river WT could be influenced by measurement position in the river cross section: thermometers are positioned 0.5 m below the water surface near the shoreline, while loggers are usually in the middle of the watercourse, near the stream bottom. These data are not comparable. For this reason, only the WT data of manual observations were used in this research.

For the analysis of river WT, the water measurement sites (EST – 17, LV – 36 and LT – 40 WGS, Figure 1) were chosen on the basis of manual WT measurements and completeness of data for 1945–2014. The research included only the sites that had at least 30-year standard normal period (1961–1990) observations, which is recommended by the World Meteorological Organization. The longest period of WT records is 70 years.

METHODS

Methods of statistical analysis (correlation analysis, statistical hypothesis, Mann–Kendall test) and multivariate interpolation were used for the analysis of WT variation.

WT for the warm season of each year was calculated as an average temperature of six months (May–October). For the analysis of spatial distribution of river WT across the Baltic States, the multi-year averages of WT during the warm season and the warmest month (July) for the standard normal period (1961–1990) were calculated. These data were used to create isotherm maps. Isotherm maps were constructed using the inverse distance weighting method for multivariate interpolation with a known scattered set of points. The highest summer WT of long-term records and its date were extracted for each river as well.

The critical values of the Mann–Kendall *S* statistic (S_{max}) are used to identify strong and weak trends. S_{max} values are defined using *p*-values (two-sided) of 0.05 and 0.30, which indicate the magnitude of the trend that is likely to be in the upper or lower 2.5% and 15% of the statistical distribution, respectively. When the significance of the trend was poor (70%), the trend was regarded as a weak trend (positive or negative). Only the trends at the 95% level were regarded as strong negative or strong positive.

The significance of temporal trends for the warm season WT was determined for each site for two periods using a non-parametric Mann–Kendall test. The Mann–Kendall test was also used to detect WT trends for a particular month – July. For analysis of WT trends, the long-term temperature data sets from 1945 to 2010 were divided into periods of 1951–1980 and 1981–2010.

RESULTS

Thermal diversity of rivers and streams

The analysis of WT data revealed a significant thermal diversity in the rivers of the Baltic States (Table 1). WT of studied

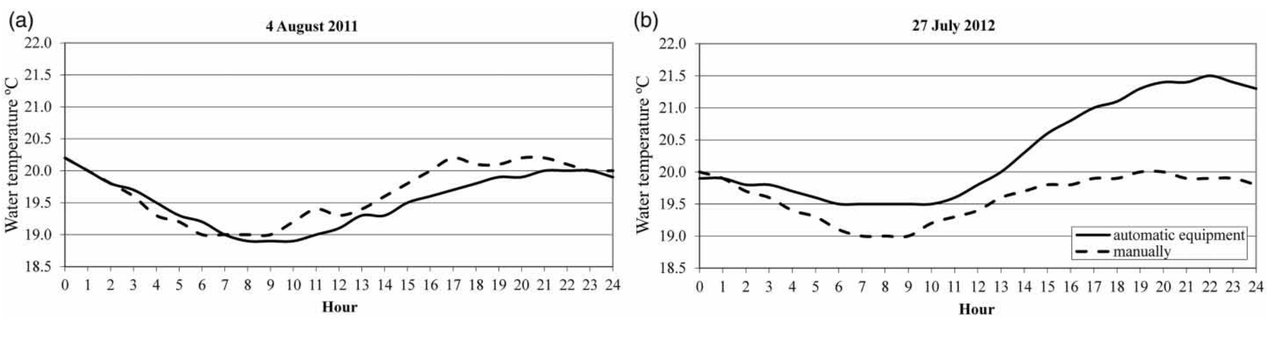

Figure 2 | Hourly manual and automatic measurements of WT in the River Šventoji – Anykščiai WGS on 4 August 2011 (a) and 27 July 2012 (b).

Table 1 | The mean WT of the warm season and July in the rivers of the Baltic States during the standard normal period (1961–1990)

		WT °C			
		Warm season		July	
No.	State	Average WT	WT limits	Average WT	WT limits
1	Estonia	13.2	10.7–14.7	17.5	13.0–19.7
2	Latvia	14.6	11.7–16.0	19.0	15.2–20.5
3	Lithuania	14.9	12.3–16.0	18.7	14.7–20.1
	Mean	14.5	10.7–16.0	18.6	13.0–20.5

rivers for the warm season of the standard normal period (1961–1990) varied from 11 °C to 16 °C with an average value of 14.5 °C (Table 1).

The coolest rivers ($\tilde{T}_{V-X} = 13.2\,^{\circ}$C) are located in the northernmost country of the Baltic States – Estonia, since the air temperature is the lowest in this country (Kriaučiūnienė *et al.* 2012). The highest average WT of the warm season ($\tilde{T}_{V-X} = 14.9\,^{\circ}$C) is in the rivers located in Lithuania, which is the southernmost of the three Baltic States, although the WT of Latvian rivers is only slightly different from the WT of Lithuanian rivers ($\tilde{T}_{V-X} = 14.6\,^{\circ}$C). The reason for this is that the observed rivers of Latvia are larger than the Lithuanian ones, therefore they have a larger amount of heat. The effect of how stream temperature is dependent on both heat load and stream discharge is well described by Poole & Berman (2001).

WT contrasts in the rivers of the Baltic States are quite notable. The lowest warm season WT was identified in Estonia, in the River Lõve at Uue-Lõve ($\bar{T}_{V-X} = 10.7\,^{\circ}$C, A = 134 km²), which thermal regime is influenced by a karst phenomenon, while the highest one ($\bar{T}_{V-X} = 16.0\,^{\circ}$C) was found in the River Lielupe at Jelgava (A = 11,900 km²) in Latvia and the River Nemunas at Smalininkai (A = 81,130 km²) in Lithuania (Table 1). The difference of long-term average WT for the warm season between warmest and coldest rivers of the Baltic States is 5.3 °C.

The analysis of July WT data showed that river WT of the warmest month was similar to that of the warm season, but some differences were found. The estimated average WT of July of all the researched rivers for the Baltic States (93 WGS) was $\tilde{T}_{VII} = 18.6\,^{\circ}$C ($\tilde{T}_{VII} = 17.5\,^{\circ}$C for Estonian, $\tilde{T}_{VII} = 19.0\,^{\circ}$C for Latvian and $\tilde{T}_{VII} = 18.8\,^{\circ}$C for Lithuanian rivers). The average river WT in July varied from 13.0 °C in the Estonian River Lõve at Uue-Lõve (A = 134 km²) to 20.5 °C in the Latvian River Lielupe at Jelgava (A = 11,900 km²). Thus, the differences for July WT between the warmest and the coldest rivers based on standard normal period reached 7.5 °C.

It is notable that the highest mean July WT was found in Latvia, which is to the north of Lithuania. In general, July higher WTs were found in the Latvian rivers: the Dubna at Višķi and the Mūsa at Bauska ($\bar{T}_{VII} = 20.3\,^{\circ}$C, A = 978 km² and A = 5,320 km²), the Daugava at Piedruja and at Daugavpils ($\bar{T}_{VII} = 20.2^{\circ}$C, A = 62,200 km² and A = 64,500 km², respectively). The WT of Latvian rivers is influenced not only by climatic factors. The influence of topography and hydrogeology of the river basin is also important. The reason for warm water in the River Mūsa could be the shallowness of this lowland river and low groundwater input. The WT of the River Dubna at Višķi is influenced by the inflow from warm Lake Višķu. The River Daugava at Piedruja and Daugavpils is a large river with a large amount of heat in its water discharge during the warm season of the year.

The highest recorded WT during the long-term period of observations was extracted for each studied river. During the entire period of observations, the highest water temperatures were recorded at 25 sites on 29–30 June, 1947. In Lithuania, the highest WT, 30.0 °C, was measured in the River Nemunas at Smalininkai, in Latvia, 29.8 °C, in the River Lielupe at Staļģene, and in Estonia, 28.0 °C, in the River Pedja at Tõrve. Additionally, extreme water temperatures were recorded in 1994, 1999, 2006 and 2010 in all three countries.

Spatial distribution in river WT

The analysis of average long-term WT of the warm season and July revealed significant spatial variation in river thermal regimes across the Baltic States. The diversity of the Baltic States' river WT could be evaluated by the map of river WT isotherms (isopleths) presented in Figures 3(a) and 4. The maps were compiled according to the average WT data of the climatological standard normal period (1961–1990) of 93 water measuring sites. In the isotherm maps, the WT isolines were drawn at 0.5 °C intervals,

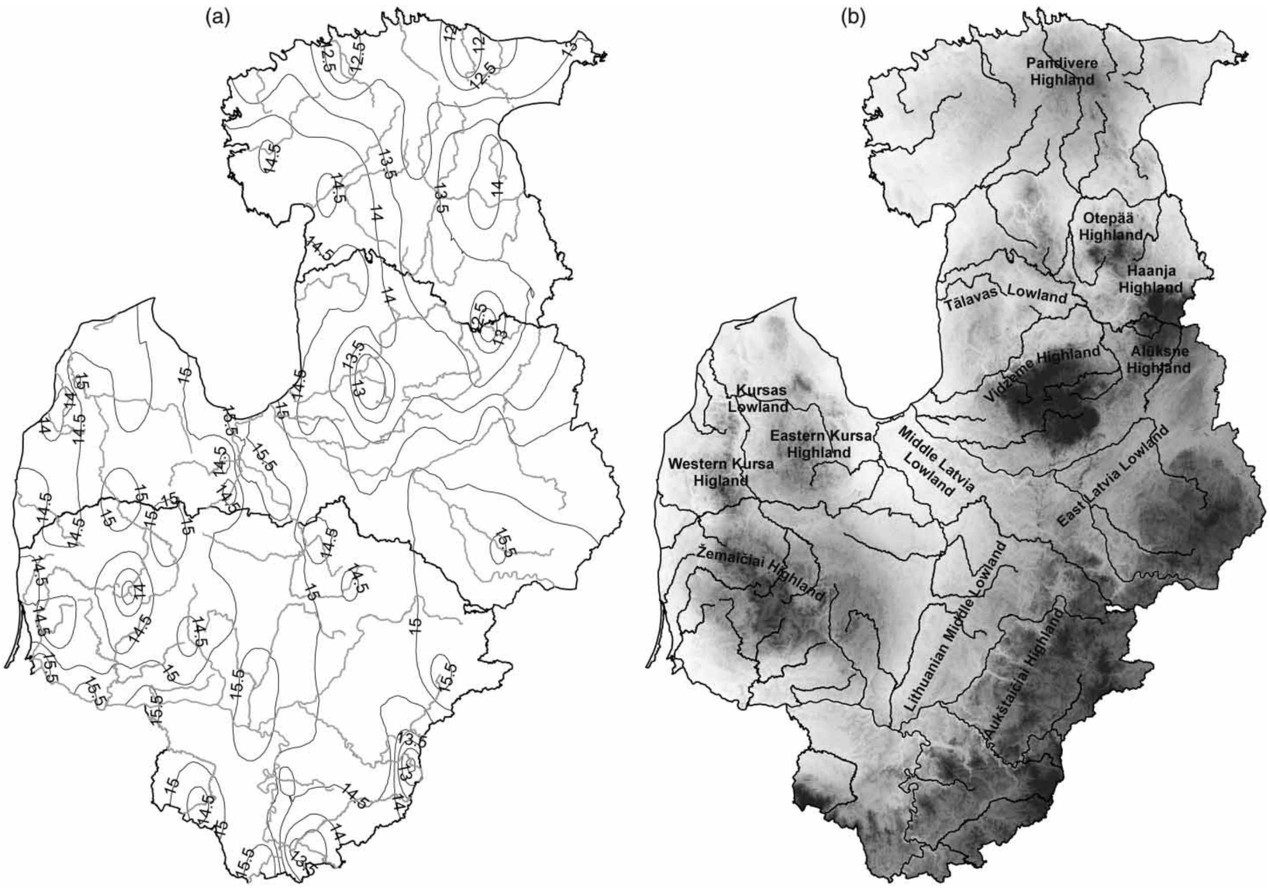

Figure 3 | Spatial distribution of multi-annual mean river WT of the warm season (May–October) (a) and relief (b) in the Baltic States.

because it was ascertained that WT differences between water measuring sites in the same river and between separate rivers were statistically different (at $\alpha = 0.05$), when $\Delta\bar{T} \geq 0.5\,^{\circ}$C.

Estonian rivers can be distinguished for prevailing isotherms of 13 °C and 13.5 °C (Figure 3(a)). Depending on the character of water exchange, WT can differ even in neighbouring rivers. In general, the rivers of northern Estonia have a lower WT and the rivers of western and southwestern Estonia have a higher WT (over 14 °C). Temperature isolines of less than 13 °C are observed in the rivers of the northern and central parts of Estonia due to the spread of karst and related hydrogeological features. Rivers with the lowest WT usually have a greater share of groundwater feeding or small watershed areas, namely the Purtse, Leivajõgi and Kunda rivers, where WT was less than 12 °C, and the River Lõve, where temperature was even lower than 11 °C.

Figure 3(a) shows that in Latvia, the warm season WT generally ranges from 14.5 to 15 °C. These isotherms surround the Vidzeme Highland and go along the eastern coast of the Gulf of Riga. Another region with isotherms of 14.5 to 15 °C is in the western part of Latvia – in the Kursas Lowland and the Eastern Kursa Highland (Figure 3(b)). A higher than 15 °C WT can be observed in the central part of Latvia (the River Lielupe and its tributaries) and the eastern part of Latvia (the River Daugava). Rivers with a cold WT are located in the Vidzeme Highland and the Alūksne Highland, where the basins of the River Gauja and its tributaries are located. Slightly cooler water was also observed in the western part of Latvia in the rivers flowing from the west slopes of the Western Kursa Highland. In these rivers, WT is lower due to significant groundwater input in river feeding.

According to the warm season isotherm map presented in Figure 3(a), the 15 °C isotherm dominates in the territory

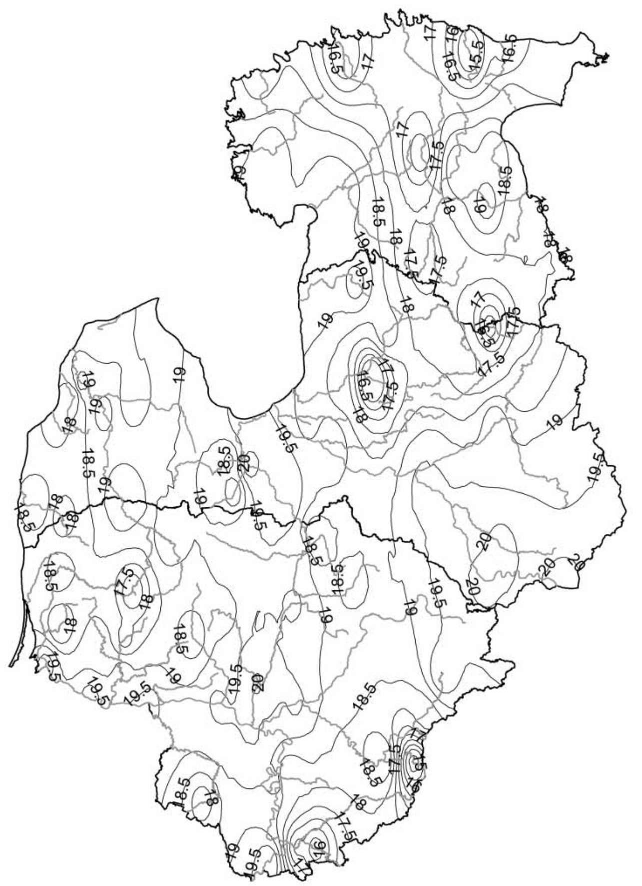

Figure 4 | Spatial distribution of multi-annual mean river WT in July in the Baltic States.

of Lithuania. The 15 °C isotherm clearly surrounds the Žemaičiai Highlands, goes through all the Lithuanian Middle Lowland and encircles the Aukštaičiai Highlands that are mostly dominated by lakes. The warmest water (15.5 °C–16 °C isotherms) is in southwest and middle Lithuania (in the basins of the River Nemunas and the River Mūša). The isotherms from 12.5 °C to 14 °C are prevalent in southeast Lithuania and the Žemaičiai Highlands. The rivers flowing in these uplands have low WT due to significant groundwater inputs and sandy basins covered with conifer forests. The largest region with low WT is southeast Lithuania where the River Merkys and its tributaries flow. Sandy soils cover about two-thirds of this river basin area and through this sandy layer the River Merkys and its tributaries get over 60% of annual runoff. In the isotherm map, the influence of other local factors is also noticeable, including elevation, lakes, reservoirs, rate of stream flow, etc.

Figure 4 shows an isotherm map which characterizes the river water thermal conditions in July, which features the highest average monthly WT in the rivers of the Baltic States. The isotherm maps of July and the warm season have a similar character of WT distribution; however, the ranges of WT isotherms are different (15–20 °C in July and 12–16 °C in the warm season).

Constructed maps of spatial distribution of WT show that in Latvia and Lithuania the coolest rivers are in the highlands. Meanwhile in Estonia, where the topography is low in elevation and flat, contrasts in relief do not have significant influence on river WT. In this country, WT of rivers depends on other factors such as the influence of lakes and karst topography. The large rivers of the Baltic States flowing in the lowlands have the warmest water due to the massive size of water which accumulates a high amount of heat during the warm season. Groundwater input in these rivers is not significant. According to the isotherm maps, it is possible to determine the WT of a river which has not been monitored.

Temporal changes in river WT

The long-term WT changes in large and small rivers of the Baltic States were analysed. The chronological variation of mean warm season WT during a long period of observation (1945–2010) in three large and three small rivers of Estonia, Latvia and Lithuania is presented in Figures 5 and 6. There are similar tendencies of synchronic inter-annual variation of mean WT in three large rivers. Large rivers show warming tendency during the entire period of observation (Figure 5). The warming rates of large rivers are similar, but it is notable that the larger the river, the greater is the warming rate (Table 2). The lowest temperature is determined for all of them in 1976 (for the River Emajõgi at Tartu – 13.0 °C, the River Daugava at Piedruja – 13.8 °C and the River Nemunas at Druskininkai – 14.7 °C), while the highest temperature was observed during the last decade.

A different nature was identified in the multi-annual variation of WT of small rivers (Figure 6). The small rivers of Latvia and Lithuania show an increase during the long-term period, while the River Kunda at Sämi in Estonia has a cooling trend in WT with a high cooling rate of −0.0344 °C/year. This river has a greater share of groundwater feeding,

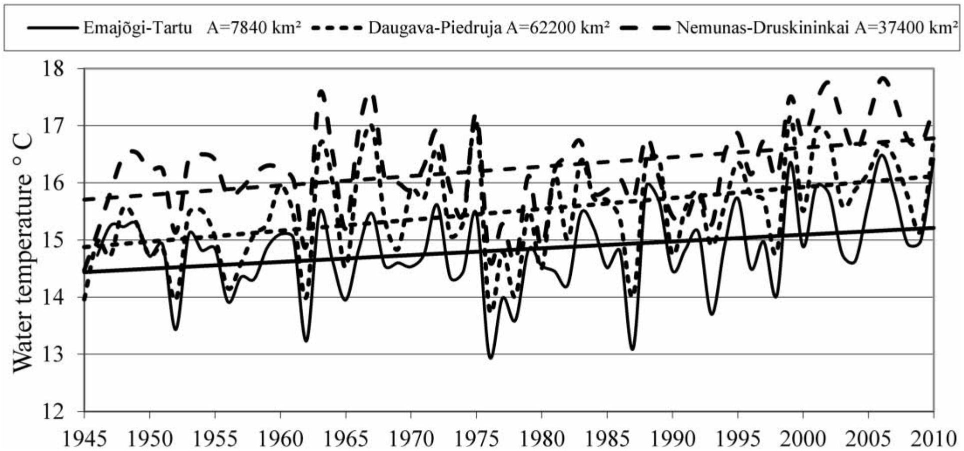

Figure 5 | Long-term changes in warm season mean WT in the large rivers of the Baltic States in the period of 1945–2010.

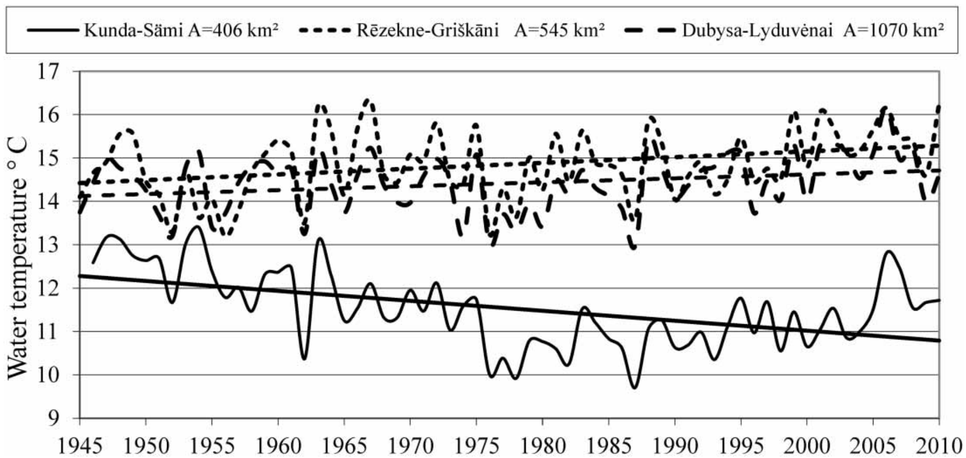

Figure 6 | Long-term changes in warm season mean WT in the small rivers of the Baltic States in the period of 1945–2010.

Table 2 | Temporal changes of water temperature in the rivers of different size of the Baltic States in the period of 1945–2010

				WT °C		Warming/cooling rate °C/year	
	River	Station	A km²	May–October	July	May–October	July
Large rivers							
EST	Emajõgi	Tartu	7,840	14.8	19.8	0.0119	0.023
LV	Daugava	Piedruja	62,200	15.5	20.4	0.0191	0.0312
LT	Nemunas	Druskininkai	37,400	16.3	20.6	0.0165	0.0217
Small rivers							
EST	Kunda	Sämi	406	11.5	15.4	−0.023	−0.0344
LV	Rēzekne	Griškāni	545	14.9	19.7	0.0133	0.0194
LT	Dubysa	Lyduvėnai	1,070	14.4	18.6	0.0091	0.0138

therefore rising air temperatures have only an insignificant impact on the river's WT.

The analysis of the warming rate of average WT in some large and small rivers reveals that WT of the warm season and July is higher in large rivers than in small ones. It is especially evident in WT of July (Table 2). The WT of the warmest month increases by 1.3–1.9 times faster than WT of the entire warm season in large rivers. In small rivers, the July WT increases 1.5 times faster than in the warm season.

The analysis of long-term changes in river WT of the Baltic States showed that the entire multi-annual period of WT change in most rivers consists of two dissimilar periods: before the second half of the 1980s, WT had a cooling tendency, while after the 1980s, it had a warming tendency. In the period of 1981–2010, the river water warming could be related to the air temperature increase in the Baltic region as a strong correlation was found between the air and river water temperatures (Jurgelėnaitė & Jablonskis 2011).

Trend analysis of WT in the rivers of the Baltic States was performed for two 30-year periods: 1951–1980 and 1981–2010. The Mann–Kendall test was applied and trends with a different significance level (significant positive, positive, negative, significant negative and insignificant) were used for the analysis. The results were assessed in different ways using the significance of trends in the WT of the Baltic States' rivers (Table 3), maps of temporal variability of the WT trends for two periods and box plot analysis.

Table 3 | Trends of warm season water temperatures in rivers of the Baltic States

		1951–1980		1981–2010[a]	
State	**Trend**	**Positive**	**Negative**	**Positive**	**Negative**
Total	Significant	0	15	32	0
	70%	0	10	6	0
	Insignificant	56		12	
EST	Significant	0	4	9	0
	70%	0	4	3	0
	Insignificant	7		3	
LV	Significant	0	0	4	0
	70%	0	0	0	0
	Insignificant	31		3	
LT	Significant	0	11	19	0
	70%	0	6	3	0
	Insignificant	18		6	

[a]WT data sets of some rivers are 1–3 years shorter than 30 years.

Table 3 and Figure 7(a) illustrate that insignificant and negative trends in WT of the warm season prevail in the period of 1951–1980 in the rivers of the Baltic States. Insignificant trends represent 69% of all trends, while significant negative and negative trends of WT represent 31% of stations (19% and 12%, respectively) during this period.

The most significant changes in river WT of the Baltic States were identified in the last 30-year period (1981–2010). Most of the warm season WT trends became positive for the studied rivers (Table 3 and Figure 7(b)). There are no negative trends in WT data of this period. From 1981 to 2010, WT increased at 76% of the river sites (significant positive and positive trends represent 64% and 12%, respectively). Figure 7(b) shows that during the last three-decade period (1981–2010), significant positive trends prevailed in WT of the warm season in the rivers of Estonia and Lithuania, whereas in Latvian rivers the number of significant positive and insignificant trends was almost equal.

Maps presenting the trends of river WT for July (Figure 8) show that WT of this month experienced cooling during the period of 1951–1980 and warming during the period of 1981–2010. These tendencies are similar to the WT trends of the warm season (Figure 7). However, the insignificant trends prevail in the July WT of rivers in the period of 1951–1980 (Figure 8(a)). During the last 30-year period (1981–2010), WT tended to warm up rapidly only in the Lithuanian rivers, while just four significant positive trends were found in the July WT data in Estonian rivers and two in Latvian rivers (Figure 8(b)).

Temperature trend magnitudes are calculated in °C per warm season in the selected data sets. Trend magnitudes are presented by box plots which show the maximum, minimum, 25th and 75th percentiles as well as the mean temperature data values for three periods: the entire period of 1951–2010, the period of 1951–1980 and the latest 30-year period of 1981–2010. Figure 9 demonstrates that during the entire period of observation (1951–2010), the river WT increased slightly (rates of increase are 0.01 °C/warm season). During the first half of this period (1951–1980), river WT decreased significantly (0.003 °C/warm season). During the latest 30-year period of 1981–2010, WT rose significantly – by 0.04 °C/warm season. Only the maximum and minimum values (25% and 75% percentiles) of the slopes differ significantly. The possible reason for

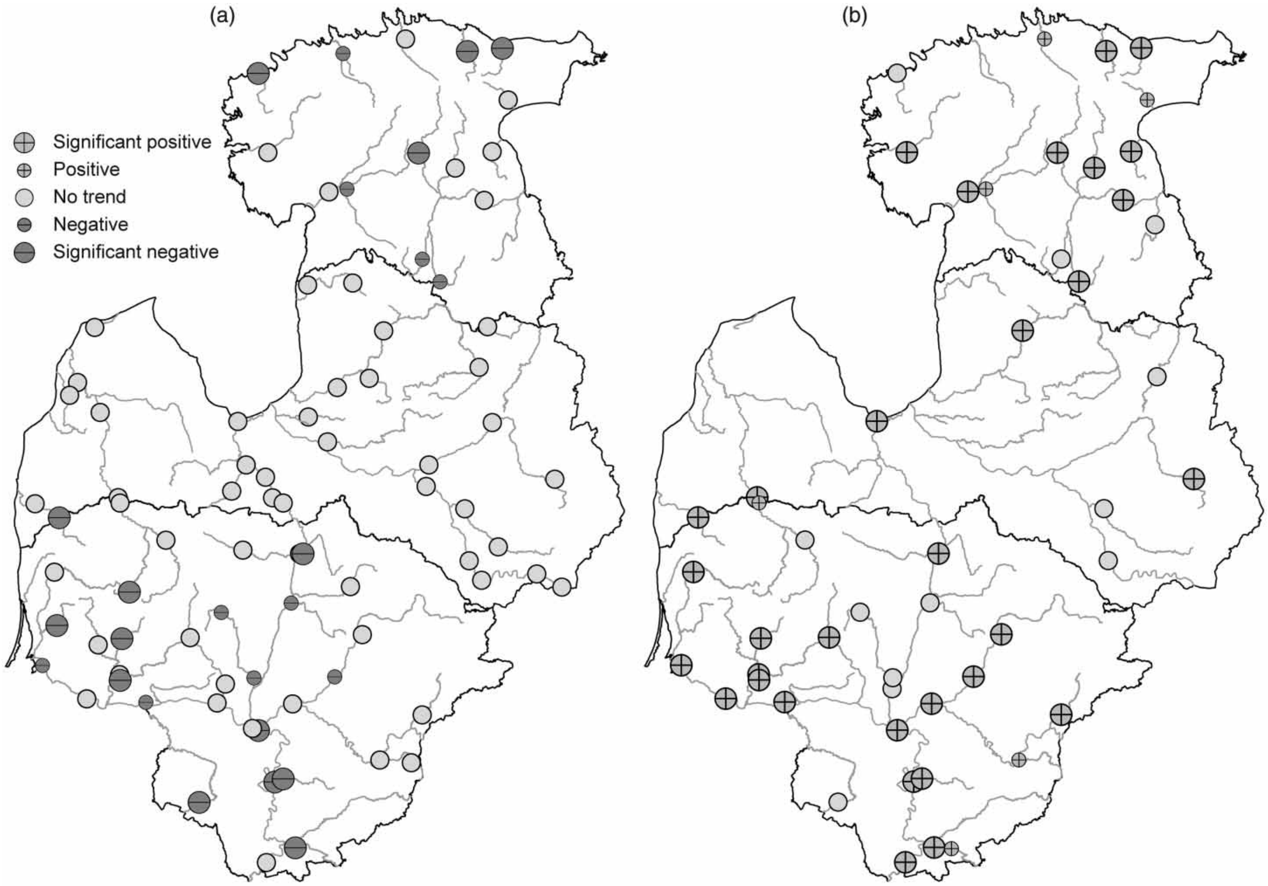

Figure 7 | Distribution of trends of river WT for the warm season across the Baltic States for the periods of 1951–1980 (a) and 1981–2010 (b). Significance of trends is described in the figure.

these changes could be the increasing air temperature brought about by climate change.

Since the early 1980s, the territory of the Baltic States has experienced an overall increase in river WT. On average, mean WT increased by 0.04 °C/warm season (from 0.0134 °C to 0.0746 °C per warm season) in all water measuring sites where the calculated trends were statistically significant. The most rapid rate of WT increase was estimated in the rivers of Latvia (0.0463 °C/warm season), while the slowest increase was observed in the rivers of Lithuania (0.0367 °C/warm season).

DISCUSSION

The understanding of spatial and temporal changes of WT in streams and rivers is an ongoing challenge (Webb *et al.* 2008; Steel *et al.* 2016). The main task of this study was to identify spatial and temporal changes in WT of the rivers of the Baltic States using a unified methodology. The research covers the entire Baltic States region, which includes river basins of different size.

This study aimed to identify all available long-term WT data sets in the rivers of the Baltic States. The longest and the most complete records were used for the statistical analysis carried out to detect long-term trends in river WT. An advantage of the river WT data sets used for the analysis is that WT was measured at stationary water measuring sites, manually, using a unified methodology. The majority of river water measuring sites in Estonia and Lithuania and some sites in Latvia had WT records spanning a 60-year period (1951–2010). All water measuring sites had WT records covering the 30-year standard normal period (1961–1990).

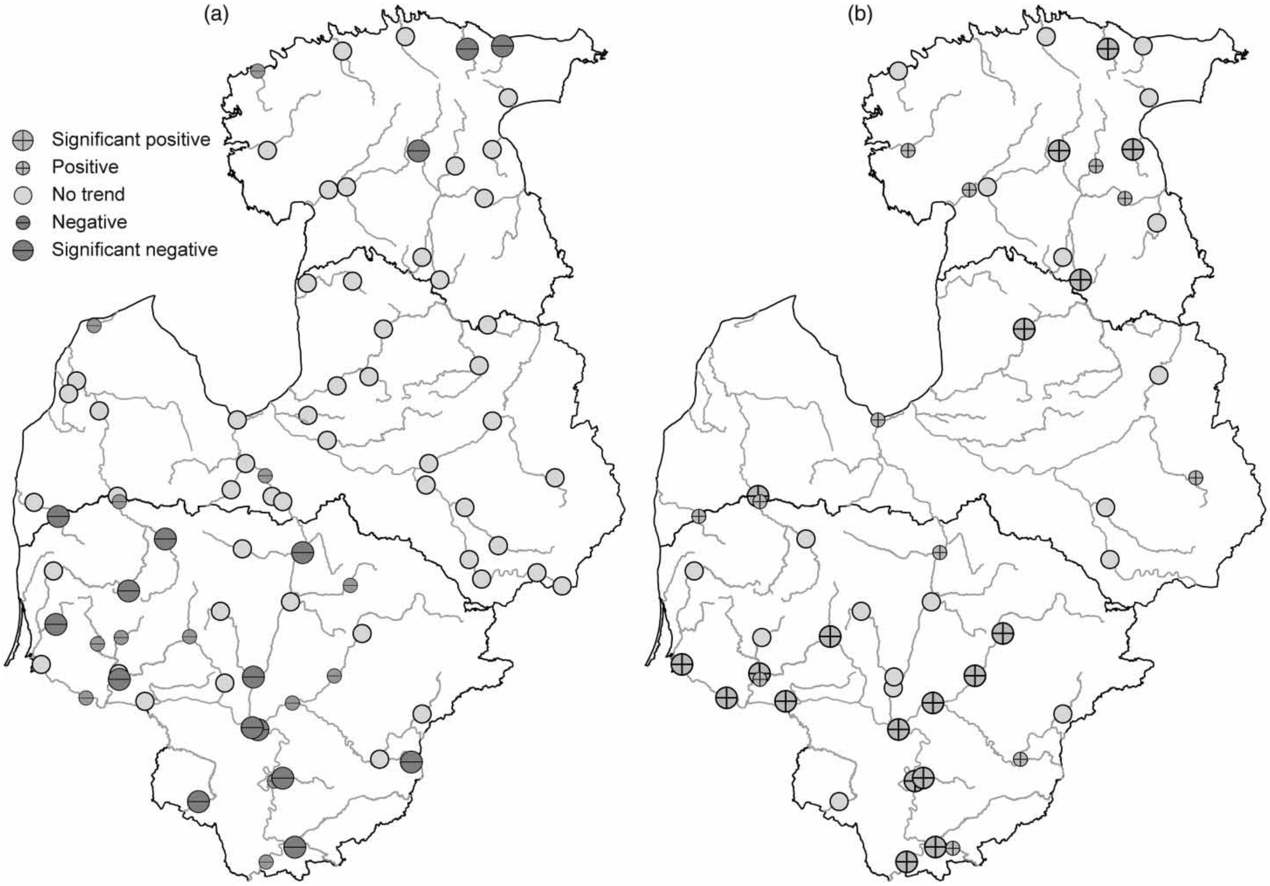

Figure 8 | Distribution of trends of river WT for July across the Baltic States for the periods of 1951–1980 (a) and 1981–2010 (b). Significance of trends is described in the figure.

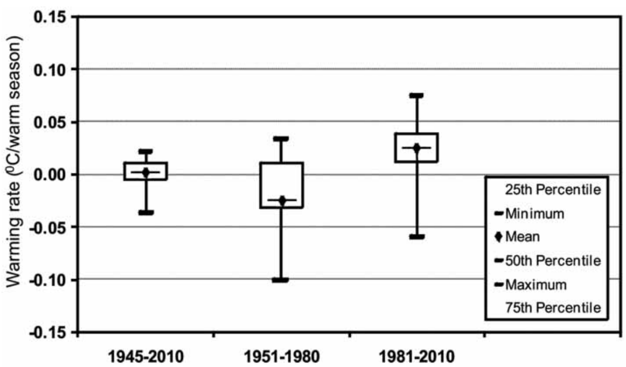

Figure 9 | Box plots of river WT warming rate for three periods: entire period, 1951–1980 and latest 30-year period (1981–2010).

The river WT of the warm season (May–October) was used for analysis. The ice phenomenon usually occurs in the rivers of the Baltic States during the cold season, therefore WT was not measured during this period. In other scientific studies, the authors frequently used annual or seasonal WT data (Isaak *et al.* 2010; Kaushal *et al.* 2010; Arora *et al.* 2016).

River WT depends on local physical–geographic factors (Caissie 2006; Webb *et al.* 2008; Toone *et al.* 2011; Garner *et al.* 2014). Isotherm maps constructed in this research show that basin orography, is one of the factors that have an impact on river WT. WT of the warm season and July in the rivers flowing in the uplands (for example, the Vidzeme Upland (height 257 m) is 3–4 °C lower than in the rivers of surrounding plains. The scientific novelty of this work is that the maps of isotherms for WT of the warm season and July were constructed for the entire region of the Baltic States. Such maps allow the identification of the river WT's dependence on relief elevation or other physical–geographic characteristics of the region. The WT of unmonitored rivers can be determined according to these isotherm maps as well.

The trend analysis of warm season WT demonstrated an obvious warming in the rivers of the Baltic States during the last 30-year period (1981–2010). The significant trends of the warm season WT became positive for the majority of the studied rivers of this region. From 1981 to 2010, the WT increased at 76% of the river sites. Significant positive trends represent 64% of sites, while positive trends represent 12%. WT in the rivers of the Baltic States increased by an average of 0.04 °C/warm season (from 0.0134 °C to 0.0746 °C/warm season) in all water measuring sites, where the calculated trends were statistically significant. One of the main reasons of such trend distribution in the last 30-year period can be a significant increase of air temperature (Kļaviņš *et al.* 2007; Lizuma *et al.* 2007; Russak 2009; Jaagus *et al.* 2014).

The tendencies of warming trends of river WT during the last decades are also fixed in other scientific research (Webb & Nobilis 2007; Isaak *et al.* 2010; Kaushal *et al.* 2010; Orr *et al.* 2015; Arora *et al.* 2016). Arora *et al.* (2016) performed an analysis of WT in seven river basins of Germany and highlighted that the majority of the sites experienced significant river warming (by 0.03 °C per year) during 1985–2010. Orr *et al.* (2015) analysed river WT for England and Wales and found increases in WT from 1990 to 2006 at a large number of sites (86% from 2,773). In these sites, mean annual WTs increased at an average rate of 0.03 °C per year. Isaak *et al.* (2010) found that during the period of 1993–2006, summer WTs of mountain streams in the northern Rockies of the United States increased by 0.027 °C/year and maximal WT increased by 0.034 °C/year. Kaushal *et al.* (2010) stated that WT is increasing in many rivers throughout the United States. The rates of increase of annual mean WT in 20 major rivers located in the United States were from 0.009 to 0.077 °C/year. The territory of the Baltic States has experienced an increase in river WT (0.04 °C/warm season) during the last decades, which is similar to the tendencies of WT variability in other countries.

CONCLUSIONS

This research is innovative in presenting an assessment of spatial and temporal variability of river WT of the warm season in the Baltic States using a unified methodology.

For the entire Baltic States region, the isotherm maps of the warm season and July mean WT were compiled for the first time. Isotherm maps allow identification of the river WT dependence on relief elevation or other physical–geographic characteristics of the region. Regional analysis of 93 water measuring sites revealed that the majority (76%) of the sites underwent significant river warming during the study period of 1981–2010. Over the last three decades, mean WT increased by an average of 0.04 °C per year.

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