Projection of Lithuanian river runoff, temperature and their extremes under climate change

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ABSTRACT

The aim of this research is to analyse and project the effects of changing climate on Lithuanian river runoff and water temperature. Climate change is expected to affect the extremes of the major river indices that impact fundamental ecological processes in river ecosystems. The available runoff and temperature data of rivers from three different hydrological regions of Lithuania were used. HBV software was applied for modelling of hydrological processes in the selected river catchments. The expected future changes of runoff and water temperature were projected according to a new set of scenarios (called representative concentration pathways) presented in the Intergovernmental Panel on Climate Change Fifth Assessment Report. The projected extreme values of runoff (flood and low flow discharges) and water temperatures in the beginning and the end of the 21st century were compared to the ones from the past period. The results showed a decrease of spring flood discharges and summer low flows and an increase of river water temperature at the end of the 21st century. The results are going to be used for an integrated assessment of the impact of climate change on aquatic animal diversity and productivity.

Key words | climate change scenarios, extreme values, HBV software, projections, runoff, water temperature

INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) states that in many regions changing precipitation or melting snow and ice are altering hydrological systems and affecting quantity and quality of water resources (IPCC 2014). From now on, representative concentration pathways (RCPs) scenarios (van Vuuren et al. 2011) are used in scientific literature for both climate projections and modelling of potential future changes in the river hydrological regime. The first published scientific works of this sort are mainly of global or regional scale. Koirala et al. (2014) used outputs from 11 atmosphere–ocean general circulation models in their global scale investigations of streamflow changes under the medium stabilisation RCP4.5 and the high warming RCP8.5 scenarios. The results revealed that, in general, at the end of the 21st century, long-term mean, high and low streamflow are all projected to increase in northern North America, northern Eurasia, Asia, eastern and central Africa and Australia, while they are all projected to decrease in regions of Europe, Middle East, Central Asia, northern and southern Africa, south-western United States and Central America. The spatial distribution of projected changes is similar under both scenarios. The change magnitudes of mean and high flows are much lower according to the projections of the medium stabilisation RCP4.5 scenario, while the extent of low flow changes is similar under both scenarios.
One of the newest investigations (Roudier et al. 2016) assessing the impacts of a +2 °C global warming on extreme floods and hydrological droughts in Europe is also following the RCP scenarios. The results of the analysis of floods and droughts together show that the impact will be the most extreme for France, Spain, Portugal, Ireland, Greece and Albania. According to the projections based on the high concentration RCP 8.5 scenario by Alfieri et al. (2015), both mean annual precipitation and average discharge are projected to decrease in southern Europe and to increase in north-eastern Europe by the end of the century. However, the trend of future discharge extremes has a rather diverse pattern, as a consequence of the interplay among various hydrological processes, which includes the effects of a warming climate on the reduced snow accumulation cycle and the growth of evapotranspiration rates. As a result, a reduction of peak discharges in southern Spain, Scandinavia and Baltic countries is declared.

Another study which uses the new set of RCP scenarios presented by Kundzewicz et al. (2016) interprets differences in flood hazard projections over Europe and identifies likely sources of discrepancy. The authors highlight that under the high-end climate change scenario (RCP 8.5) for the end of the century and for extreme events, modelling outputs are associated with high uncertainty.

The scientific work by Øygarden et al. (2014) provides an overview of the expected climatic changes in the Nordic–Baltic region. The possible effects of these changes on runoff and nitrogen losses in Sweden are presented in accordance with the new generation scenarios that project the higher probability of extreme hydrological events. Osuch et al. (2016) also project increases in flood indices for most catchments under future climate (RCP4.5 and RCP8.5 emission scenarios).

So far, there has been only little research carried out in Lithuania related to runoff projections according to RCP scenarios. The two most diverse RCPs, RCP2.6 and RCP8.5, were analysed in the study by Stoniūnas et al. (2017) to evaluate the spectrum of probable changes in the hydrology of Nemunas River basin at the end of the 21st century (2081–2100).

Change of river water temperature that directly and strongly depends on projected upward trend of air temperature is the subject of numerous scientific studies (Webb et al. 2008; Kaushal et al. 2010; van Vliet et al. 2011; Caissie et al. 2014; Orr et al. 2015) as well. However, a limited amount of work has been carried out on projecting water thermal regime according to new RCP scenarios (Ficklin et al. 2014; Santiago et al. 2016). Rising water temperature is going to be a powerful stressor on terrestrial freshwater ecosystems in the second half of the 21st century and is expected to lead to shifts in freshwater species distributions and worsen water quality problems (Ducharne 2008; Gosling et al. 2011; Sheldon et al. 2011; Ostfeld et al. 2012; Settele et al. 2014; Sternberg et al. 2015).

In Lithuania, studies of water temperature and river runoff behaviour under future climate changes are relatively fragmented and sparse. Future changes of hydrological regime get more attention than projections of river water temperature. Both past findings and future projections show that Lithuanian river runoff was and will remain mostly influenced by two main climate indices: precipitation and air temperature (Meilutytė-Barauskiienė et al. 2010; Kriauciu–nieiene et al. 2012). These indices are responsible for runoff redistribution throughout the year: increased runoff in winter and lower flood discharges in spring (Reihan et al. 2012; Hall et al. 2014; Kayhko et al. 2015; Stoniūnas et al. 2017). Warming winters are a reason for warmer waters, later freeze-up dates and shorter ice cover duration (Šarauskienė & Jurgelenaitė 2008; Jurgelenaitė et al. 2012). The main scientific works concerning analysis of the Lithuanian river thermal regime and its projections have been performed by Jurgelenaitė & Jakimavičius (2014) and Jurgelenaitė (2015). There is still a lack of scientific studies of climate change impact on the thermal and hydrological regime of Lithuanian rivers. The results of such investigations are of great importance for the mitigation of potential ecological consequences and possible impacts on the national economy. Therefore, the overall aim of this study is to project the future changes of runoff and water temperature in the 21st century according to four RCPs. The current study, unlike the previous ones in Lithuania and neighbouring countries, uses a different modelling method (HBV) and projects the changes under a new set of RCP scenarios on a daily time step.

**STUDY AREA AND DATA**

Six river catchments (Figure 1) were selected for this study. Their main runoff and water temperature characteristics are
presented in Table 1. All rivers are tributaries of the major Lithuanian River Nemunas, which rises in Belarus and flows to the south-eastern part of the Baltic Sea (through the Curonian Lagoon). The Nemunas basin is the fourth largest in the Baltic Sea drainage basin (covers 5.6%) (BACC Author Team 2008). The selected river catchments comprise 32% of the total Nemunas River basin and 31.1% of the entire Lithuanian territory.

The rivers were chosen according to the availability of hydrological as well as water quality and ichthyologic data. The rivers characterise the regime of hydrological regions to which they belong (the Minija from the western, the rivers Nevežis and Šušvė from the central and the rivers Neris, Šventoji and Žeimena from the south-eastern region). These regions differ in their precipitation, catchment morphology and contribution of the underground feeding. The main source of river feeding in western Lithuania is precipitation. The maximum discharges, resulting in rain floods, often exceed discharges of spring floods. The type of river feeding in central Lithuania is mixed. The feeding from the groundwater is not significant, therefore smaller rivers dry out in the summer. The rivers of south-eastern Lithuania have a prevailing subsurface feeding. The permeable sandy soils widespread in this region effectively absorb snowmelt and later gradually release it, supplying rivers in the low water period.

Daily data of meteorological parameters (precipitation amount and air temperature), discharge and water temperature for the present study were obtained from the Lithuanian Hydrometeorological Service. The daily meteorological data

Table 1 | The main characteristics of the studied rivers (average values of the reference period (1986–2005))

<table>
<thead>
<tr>
<th>River-WGS</th>
<th>Catchment area, km$^2$</th>
<th>$Q$, m$^3$/s</th>
<th>$Q_{\text{max}}$, m$^3$/s</th>
<th>$Q_{\text{min}}$, m$^3$/s</th>
<th>$T_{\text{avg}}$ of warm season, $^\circ$C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neris-Jonava</td>
<td>24,545</td>
<td>168.1</td>
<td>543.6</td>
<td>88.1</td>
<td>15.65</td>
</tr>
<tr>
<td>Žeimena-Pabradė</td>
<td>2,595</td>
<td>21.6</td>
<td>43.4</td>
<td>12.3</td>
<td>14.66</td>
</tr>
<tr>
<td>Šventoji-Ukmergė</td>
<td>5,381</td>
<td>44.2</td>
<td>174.1</td>
<td>15.7</td>
<td>14.81</td>
</tr>
<tr>
<td>Nevežis-Dasiūnai</td>
<td>5,514</td>
<td>34.0</td>
<td>253.4</td>
<td>6.23</td>
<td>15.77</td>
</tr>
<tr>
<td>Šušvė-Josvainiai</td>
<td>1,079</td>
<td>6.1</td>
<td>59.8</td>
<td>0.63</td>
<td>15.89</td>
</tr>
<tr>
<td>Minija-Kartena</td>
<td>1,220</td>
<td>17.3</td>
<td>146.2</td>
<td>2.92</td>
<td>15.08</td>
</tr>
</tbody>
</table>
observed in 12 meteorological stations (MS) and daily discharge data were observed in six water gauging stations (WGS). All data were used from the period of 1986–2005, which is recommended by IPCC AR5 as a reference period to estimate future projections (IPCC 2013).

METHODS

Projections of river runoff were performed according to the sequence presented in Figure 2. At the first step, a data base was prepared from available geographical and hydrometeorological information about the catchments of the selected rivers. Then, a hydrological model was applied for each river, calibrated and validated using HBV software. The generated hydrological models were used for runoff projections according to climate scenario data – the output data of RCPs (temperature (T) and amount of precipitation (P)). River water temperature projections were made using projected air temperatures: the relations (equations) were created based on the observed average monthly river water and air temperatures.

Global climate model and RCP scenarios

The data outputs of projected precipitation and air temperature acquired from three global climate models (GCM): GFDL-CM3 (the NOAA Geophysical Fluid Dynamics Laboratory, USA), HadGEM2-ES (Hadley Centre Global Environmental Model, UK) and NorESM1-M (The Norwegian Earth System Model) were adjusted using 12 MS (Figure 1) which provided the best representation of the chosen river catchments. Assumptions about future greenhouse gas emissions in the studied territories were based on four RCP scenarios. RCP2.6, the scenario developed by Netherlands Environmental Assessment Agency, is representative of scenarios that lead to very low greenhouse gas concentration levels: the projected peak in radiative forcing is at about 3 W/m² by mid-century and declines to 2.6 W/m² by 2100 (van Vuuren et al. 2011). RCP4.5, developed by the Joint Global Change Research Institute in the USA, is a stabilisation scenario in which the total radiative forcing (4.5 W/m²) is stabilised shortly after 2100, without overshooting the long-run radiative forcing target level (Thomson et al. 2011). RCP6.0, created by the National Institute for Environmental Studies in Japan, is a stabilisation scenario in which the total radiative forcing (6.0 W/m²) is stabilised shortly after 2100, without overshoot, by the application of a range of technologies and strategies for reducing greenhouse gas emissions (Masui et al. 2011). RCP8.5, a product of the International Institute for Applied Systems Analysis in Austria, is characterised by increasing greenhouse gas emissions over time, representative of scenarios that lead to high greenhouse gas concentration levels (Riahi et al. 2011).

Projected changes of air temperature and precipitation amount were made for near-future (2016–2035) and far-future (2081–2100) periods comparing with reference period (1986–2005) values.

HBV model (Swedish Meteorological and Hydrological Institute)

The HBV model created at SMHI (Swedish Meteorological Hydrological Institute) (Bergstrom 1995) was used for hydrological modelling of the selected river catchments. This software is based on a rainfall–runoff modelling method, which encompasses conceptual numerical descriptions of hydrological processes at the catchment scale (Figure 3).

The main HBV equation is described as follows (Integrated Hydrological Modelling System 2005):

$$P - E - Q = \frac{d}{dt}[SP + SM + UZ + LZ + lakes]$$

where $P$ is precipitation, $E$ is evapotranspiration, $Q$ is runoff, $SP$ is snow pack, $SM$ is soil moisture, $UZ$ is upper
groundwater zone, \( LZ \) is lower groundwater zone and \( lakes \) is lake volume.

The following input information for river runoff modelling is necessary: (1) geographical information about the territory of the modelled catchment: catchment area, presence of areas covered by forests and lakes, mean elevation (above sea level); (2) daily discharges of the rivers during the calibration and validation period; (3) daily values of precipitation and air temperature in the modelled catchment area (meteorological information).

Calibration of each river Hydrological Response Unit is carried out using 16 main parameters that depend on local conditions and are different for separate geographical regions. The parameters are chosen in five steps, starting with runoff volume (1) parameters, continuing with snow (2), soil (3) and response (4) parameters, and finishing with damping (5) parameters (Integrated Hydrological Modelling System 2005). Proper selection of calibration parameters provides more reliable results.

The created river hydrological models were calibrated according to the data from 1986 to 1995, and validated using the data from 1996 to 2005 (Table 2). The differences between observed and simulated discharge values are small. They vary from 4% for the Minija to 16% for the Nevėžis, while other studies show that this difference can even reach 35% (Winter 1988; Sattary et al. 2002; Neff & Nicholas 2005). During the calibration period the relative volume error (RE %) is small, which indicates that the average observed and simulated discharges are close to each other. Correlation (R) between observed and simulated discharges and Nash–Sutcliffe efficiency (NSE) shows satisfactory values as well.

The model calibration and validation results (Table 2), comparison of the observed and simulated hydrographs (Figure 4) and the fact that long data series have been used allow us to state that the models are adjusted to project river runoff in the periods of 2016–2035 and 2081–2100 according to different climate change scenarios.

### River water temperature

River water temperatures for future 20-year periods (2016–2035 and 2081–2100) were calculated using projected air temperatures for these periods (using averaged values of all three GCMs for each RCP scenario). The relations (equations) were created based on the observed average monthly river water and air temperatures of 1986–2005 (used as a reference period).

The equations were generated for three different time periods considering the seasonal characteristics of water warming up and cooling down. In spring (March–April), when water temperature exceeds the threshold of 0 °C, air temperature starts to grow rapidly, but since water temperature is not as inert, it rises much slower. During the warm period (May–October), the relationship between air and water temperatures stabilises. In November, the processes assume an opposite character compared to the spring period, because due to Lithuanian climatic conditions, air cools down significantly faster than water.

The water temperature data series of each river were coupled with air temperature data series of neighbouring

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**Table 2** | The calibration and validation results of the created hydrological models

<table>
<thead>
<tr>
<th>River – WGS</th>
<th>Calibration</th>
<th>Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R</td>
<td>NSE</td>
</tr>
<tr>
<td>Neris-Jonava</td>
<td>0.87</td>
<td>0.76</td>
</tr>
<tr>
<td>Žeimenas-Pabrade</td>
<td>0.73</td>
<td>0.58</td>
</tr>
<tr>
<td>Šventoji-Ukmerge</td>
<td>0.75</td>
<td>0.64</td>
</tr>
<tr>
<td>Nevežis-Dasiūnas</td>
<td>0.86</td>
<td>0.73</td>
</tr>
<tr>
<td>Šušvė-Josvainai</td>
<td>0.83</td>
<td>0.69</td>
</tr>
<tr>
<td>Minija-Kartena</td>
<td>0.88</td>
<td>0.77</td>
</tr>
</tbody>
</table>

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**Figure 3** | A conceptual scheme of HBV code (prepared according to the Integrated Hydrological Modelling System 2005).
MS. As a result, three linear relations for each distinguished time period were established. Then, the MS with the best corresponding data (i.e., the one with the highest correlation coefficient) was selected for water temperature projections. The best correlation between both temperatures was estimated for May–October (R = 0.976). It was equal to 0.942 for early spring (March–April) and reached 0.754, on average, for November. Table 3 presents the temperature equations for three rivers, each representing a different hydrological region.

**RESULTS**

**Outputs of climate change scenarios**

Air temperature and the amount of precipitation are the indices of climate change, the predicted behaviour of which is crucial for the river indices analysed in this study.

The results based on three GCMs’ projections demonstrated sizeable differences of air temperature changes in respect to the RCP scenario and selected future period. Despite that, in all the cases, air temperature is expected to rise and this rise is going to be highly significant at the end of the century. These projected changes, in turn, will affect major river indices: runoff and temperature.

The projections of air temperature in the Kaunas MS, which is located almost in the middle of the Lithuanian territory, are presented in **Figure 5**. In this MS, the changes of average annual air temperature depending on the climate scenarios (i.e., combination of GCM and RCP) are expected to vary from 0.7 to 2.6 °C in 2016–2035 and from 1.2 to 6.8 °C in 2081–2100. The changes of average monthly air temperatures (averaged by all GCMs and RCPs combinations) are expected to rise by 1.7 °C in the near future (2016–2035) and by 3.8 °C at the end of the century. The rise of temperature value of particular months is much more significant: for example, in February of 2016–2035 the monthly air temperature is projected to be higher by 5.2 °C than in the reference period according to the GFDL-CM3 model and the RCP4.5 scenario, whereas in 2081–2100 a peak equal to 9.1 °C should emerge in August under the same future changes.

At the beginning of the 21st century (2016–2035), air temperature should get higher in the cold period of the

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**Table 3** Equations between air and water temperatures, and correlation coefficients of the relations for each analysed time period

<table>
<thead>
<tr>
<th>River</th>
<th>March–April</th>
<th>May–October</th>
<th>November</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neris</td>
<td>y = 0.918x + 0.605 R = 0.964</td>
<td>y = 1.062x + 1.026 R = 0.986</td>
<td>y = 0.615x + 2.137 R = 0.826</td>
</tr>
<tr>
<td>Nevėžis</td>
<td>y = 0.919x + 1.053 R = 0.925</td>
<td>y = 1.039x + 2.127 R = 0.972</td>
<td>y = 0.507x + 2.666 R = 0.715</td>
</tr>
<tr>
<td>Minija</td>
<td>y = 0.902x + 1.430 R = 0.943</td>
<td>y = 1.033x + 1.888 R = 0.982</td>
<td>y = 0.569x + 3.071 R = 0.817</td>
</tr>
</tbody>
</table>

**Figure 4** The comparison of the observed and simulated discharges of the Neris at Jonava for the validation period (1996–2005).
year, while at the end of the century (in 2081–2100), very significant temperature changes can be expected during summer months. The GFDL-CM3 model projected the highest increase in air temperatures, whereas the least changes were expected according to the NorESM1-M model in both projected time periods.

No significant differences in the outputs were detected among the selected MS data, i.e., very similar air temperature patterns were expected for all studied river catchment areas, except that in 2016–2035 the projected changes should be less evident in western Lithuania than in the rest of the area.

The outputs of precipitation amount projections vary depending on GCM, RCP scenario and selected future period even more. In 2016–2035, GFDL-CM3 projects the greatest increase of precipitation amounts according to all RCPs and in all MSs; according to NorESM1-M, this meteorological variable is not expected to change a great deal; whereas HadGEM2-ES states that in most cases the precipitation amount should decrease or remain almost unchanged compared to the reference period. In Kaunas MS, the change of average monthly amount of precipitation that is projected according to all possible combinations of future changes might vary from $-6.3\%$ in August to $+12.6\%$ in February and December for the period of near future and from $-11.9\%$ in July to $+23.3\%$ in December at the end of the century relative to the reference period of 1986–2005 (Figure 6).

Figure 5 | Projected changes of monthly air temperature (°C) for the periods of 2016–2035 (a) and 2081–2100 (b) comparing with the reference period (1986–2005) for Kaunas MS.
In general, the amount of precipitation will increase during winter and spring and its values are going to decrease during summer and autumn, especially in the period of 2081–2100. All models project insignificant spatial differences of annual precipitation change in the territory of Lithuania. Therefore, climate change of the projected extent over the 21st century will cause significant changes to air temperature regimes and precipitation patterns in the studied river catchments. The GFDL-CM3 model and the RCP8.5 scenario project the highest future air temperatures, while according to the combination of NorESM1-M and RCP2.6, air temperature changes are likely to be the smallest. More significant changes of this climate index are expected at the end of the century (the higher RCP scenario projects, the higher value). Projection results for future precipitation are much more scattered, but overall, the projections under GFDL-CM3 and NorESM1-M GCM indicate the increase of this variable, whereas under HadGEM2-ES, the amount of precipitation is supposed to decrease.

**Projections of river runoff**

The projected data of air temperature and precipitation were used to project runoff of the selected river catchments. Since all selected GCMs produced moderately scattered output
results, the mean output value of all three GCMs for each RCP scenario was used and analysed comparing to reproduced observation data (driven by the ensemble of climate models in the reference period).

Changes of future river runoff were estimated according to projections under all four RCP scenarios in two periods (2016–2035 and 2081–2100). In most cases, mean annual discharge values are expected to decrease in relation to the reference period (Table 4). The greatest changes are going to happen at the end of the century in the Neris and Nevėžis (both having the largest catchment areas).

Figure 7 illustrates the hydrological response of the largest studied river (the Neris) to expected climate changes. Comparison of mean daily discharges in the reference period (reproduced observation data) and in two 20-year future periods according to four RCPs (simulation results) shows significant changes. These hydrographs clearly indicate the absence of spring flood peak, which would be replaced by earlier occurring smaller flood peaks, and decreased discharges during the remaining months. The most drastic changes are expected at the end of the 21st century – by this time, water level in the river should be considerably lower, since streamflow in its bed is going to decline dramatically.

The patterns of projected runoff changes were estimated by analysing the monthly discharge values. Since no significant spatial differences of meteorological indices in the studied territory were detected, the runoff projections and their causalities were analysed mainly with respect to hydrological conditions in the river catchment area.

Figure 8 provides the projected discharge results obtained for the river group from the south-eastern Lithuania hydrological region. These rivers are distinguished for their reliance on underground feeding (it constitutes from 40 to 60% of the annual runoff) and for sandy soils that quickly absorb liquid precipitation. This makes them the most sensitive to the expected climate changes. The main reason for such a response is projected higher temperatures in winter: snow cover is likely to melt or would not form at all and, as a consequence, no spring flood will occur. Instead, small, less expressed flash floods are going to emerge because of increased precipitation.

The described changes are fairly similar for projected 20-year periods; however, at the end of the century the extent of these changes will increase. During the rest of the year, the discharge behaviour is almost the same under all four RCP scenarios in the period of 2016–2035. Due to the absence of large spring flood, the catchment underground waters do not refill, while higher air temperatures increase evaporation rates and less rainwater reaches the rivers. Consequently, discharges might get smaller during the summer and autumn seasons. In 2081–2100, an especially significant projected growth of summer air temperatures and visibly decreased amount of rainfall result in marked decline of monthly discharges, which tends to increase in magnitude with higher RCPs.

The rivers from central Lithuania have mixed feeding and are less vulnerable in the context of the predicted climate change. Since impervious soils prevail in this region, these rivers are shallower and thus do not rely on the level of underground water as much. The rain water quickly reaches riverbeds.

Figure 9 proves that mostly these rivers are expected to have a similar behaviour at the beginning of a year to south-eastern rivers, i.e., the peak of spring floods are going to occur. The exception would be runoff simulated according to RCP2.6. In February of 2016–2035, this scenario projects the slightest changes of air temperature and quite significant increases in amount of precipitation. Such changes of climate indices might be favourable to generate even larger spring floods in March than at this time during the reference period. Although in the remaining months, the discharges will

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Projected changes of mean annual river discharge (%) comparing to the reference period of 1986–2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period</td>
<td>Neris</td>
</tr>
<tr>
<td>2016–2035</td>
<td>−13.1%</td>
</tr>
<tr>
<td>2081–2100</td>
<td>−23.9%</td>
</tr>
</tbody>
</table>

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probably not change a great deal in the near future based on the used RCPs, in some cases discharges of the warm period of a year are even expected to grow because of increased rainfall. At the end of the century, the runoff is projected to decrease in almost all months.

The least evident changes should occur in the river from the western Lithuania hydrological region – the Minija (Figure 10). Generally, the rivers in this region are characterised as mainly dependent on precipitation that may constitute up to 70% of the total runoff. In these rivers, discharges of rain floods often exceed discharges of spring floods. Projections of the Minija monthly discharges of the first future period showed very similar changes to the rivers of Nevėžis and Šušvė – probably due to smaller
dependence on the groundwater feeding. At the end of the century, the Minija discharges are expected to decline more (mostly in spring). Such hydrological behaviour might be caused by projected larger precipitation amounts (during both future periods) and increased air temperatures (especially in 2081–2100, when increased precipitation would not be able to outweigh higher evaporation rates due to significantly higher air temperatures).

The summarised results of performed modelling revealed that the spring flood discharges (maximum spring discharges) are expected to get smaller in both periods of the projections. In some cases, such as in the rivers of Nevėžis and Neris, the expected decrease is quite significant. Figure 11 shows the changes of maximum spring discharges indicated as a percentage of the value of the reference period, which is considered as 100%.

Low flows (minimal 30 days' discharge) (Figure 12) are projected to decrease as well; however, the rate of projected negative changes is expected to be greater than for the maximum spring flood discharges.
The results in this part indicate that the future river discharges in the period of 2016–2035 will likely decline slightly and this behaviour does not show noticeable variability with the selected RCP scenario. However, at the end of the century, changing climate drivers will lead to substantial decline of this variable and a higher RCP scenario should determine a change of a larger magnitude.

**Projections of river temperature**

Higher river water temperature is considered to be a direct impact of global air temperature increase. Since the relation between air and water temperature was used and all selected climate models projected a positive air temperature trend, the same tendencies were expected to happen in river
water temperature behaviour. Investigated rivers responded to warming in the same way, i.e., in both future periods water temperature tended to increase.

The future average monthly temperatures of the entire open-water period (March–November), the so-called warm period (May–October) and the warmest month July were calculated according to the created technique (equations) and compared to the corresponding values of the reference period (1986–2005) (Figure 13). The lowest changes are expected during the entire analysed period: from 1.29 (in the Žeimena) to 1.61 °C (in the Neris) in 2016–2035. The greatest growth of water temperatures in the period of 2081–2100 is projected in the rivers of Neris and Minija. The Šušvė is the river which is expected to warm up in July at the end of the 21st century the most – up to 4.56 °C.

The previously performed study (Jurgelnaitė et al. 2012) of the temporal and spatial variation of water temperatures in Lithuanian rivers concentrated on the available data of the warm season that are important as the time of the most intensive hydrological and hydrobiological processes in water bodies. The authors of this study classified Lithuanian rivers into three groups: warm water (t°C ≥ 14.9), cool water (13.4 °C < t < 14.9 °C) and cold water (t ≤ 13.4 °C) rivers. According to this, the rivers of Žeimena and Šventoji were classified as cool rivers, whereas the other four rivers were classified as warm ones. Figures 14 and 15 present projected monthly water temperatures for the Žeimena, distinguished as a cool river, and the Nevežis, classified as a warm river, respectively. The expected water temperature values are given under the low-range and the high warming scenarios in
Figure 13 | Projected increase of river water temperature in two future periods comparing to the reference period of 1986–2005.

Figure 14 | Projected monthly water temperatures for the Žeimena.

Figure 15 | Projected monthly water temperatures for the Nevežis.
order to show the whole range of projected changes. It is obvious that the RCP2.6 scenario for both 20-year periods and the RCP8.5 scenario for the near future project similar and not very significant changes. Much more evident upward tendencies of water temperature are expected under the RCP8.5 scenario at the end of the century: up to 25 °C in the Žeimena and 27.5 °C in the Nevėžis in July. However, even under scenarios of the slightest changes, all studied rivers will turn into warm water rivers. During the warm period, the Žeimena is expected to warm from 16.1 °C under RCP2.6 in 2016–2035 to 20.2 °C under RCP8.5 in 2081–2100, and the Nevėžis from 17.7 °C to 22.1 °C, respectively.

Taken together, these results indicate that projected air temperature changes will certainly raise river water temperatures. Water temperatures are expected to grow the most significantly under the RCP8.5 scenario in the period of 2081–2100.

**DISCUSSION**

The results of the performed investigation correspond to numerous scientific works analysing global warming impact on hydrological regime. Air temperature and the amount of precipitation are very important external climate factors that influence river runoff and temperature behaviour. Their variation may alter biochemical regime and be crucial for biodiversity and productivity of the aquatic system.

New scenarios are constantly developed and improved in respect of the most challenging and important questions in climate research. Therefore, it is necessary to provide new projections which are in accordance with the new generation of RCP scenarios (van Vuuren et al. 2011).

This analysis was based on three GCM (GFDL-CM3, HadGEM2-ES and NorESM1-M). It was estimated that in the near future (2016–2035) air temperature should significantly increase during winter months. The greatest warming is projected for August of 2081–2100 according to the RCP8.5 scenario. At the end of the 21st century, during all seasons, the RCP8.5 scenario showcases larger air temperature changes than the RCP2.6 scenario, whereas the projected changes are not so pronounced in the period of 2016–2035. These results correspond to findings of regional climate model ensemble projections for Europe made under the EURO-CORDEX initiative (Jacob et al. 2014; Kotlarski et al. 2014). The analysis of European regions revealed that warming in Northern and Eastern Europe in winter would be more intense than global warming trends (Vautard et al. 2014). In Latvia, in summer, warming is projected to be somewhat weaker than in winter (Ruosteenoja et al. 2016).

On the basis of data from the earlier IPCC AR report using two models (ECHAM5 and HadCM3), the highest absolute changes of air temperature in Lithuania are projected to occur in winter, while the lowest changes are projected to occur in summer (Rimkus et al. 2007) as well. The IPCC AR5 report declares the same tendencies: according to Keršytė et al. (2015), by the end of the 21st century, air temperature in Lithuania will mostly increase during the cold period of the year.

It was estimated (Rimkus et al. 2007) that various scenarios project that Lithuania will experience a rise of precipitation in the future. The expected amount of precipitation is going to rise in winter and spring, while in summer and autumn it should have a negative trend, particularly in 2081–2100. That is a similar tendency as shown in the results of the current study. A robust increase of precipitation in winter and summer is projected over Northern Europe (Vautard et al. 2014). In Latvia, winter precipitation amount will increase, while in summer precipitation would stay nearly unchanged or even decrease (Ruosteenoja et al. 2016).

The hydrological response of the studied Lithuanian rivers to generated potential future climate scenarios differed depending on the factors that affect their runoff formation, i.e., whether the projected change is favourable to the river feeding process or not, as well as how significant this change is going to be. The results indicated a decrease of spring flood discharges in both periods of the projections; in some rivers, flooding events are expected to diminish substantially, especially under the high warming scenario RCP8.5. The combination of the RCP8.5 scenario and the HadGEM2-ES model also projected the most drastic changes in another study of future runoff projections (Davie et al. 2013).

The importance of the flood formation drivers in particular rivers is highlighted by Polish colleagues (Osuch 2013)
et al. 2016), who also produced their hydrological simulations based on the HBV hydrological model under a future climate (RCP4.5 and RCP8.5 scenarios).

The already observed signs of significant decrease of spring floods in the Baltic rivers were detected and described in earlier studies by Reihan et al. (2007, 2012), Kriauciuniene et al. (2012) and Latkovska et al. (2012). In the mentioned studies, it was found that in the last decades, spring flood peaks tended to take place at earlier dates due to an increased air temperature in winter and subsequent replacement of snow precipitation by rainfall. The projections by Stonevičius et al. (2017) made using RCP scenarios also indicate that the hydrological response to climate change in the studied Nemunas basin would be most likely related to the change in snow climate.

In the second half of the summer and early autumn, the projected discharges are expected to remain almost unchanged in the rivers that are dependent on precipitation: this should be the result of an expected increase of precipitation and projected higher air temperatures.

Using only one hydrological model, HBV, the modelling outputs are associated with higher uncertainty, since the simulated future runoff values are the outcome of a certain selected modelling tool. In order to get more reliable results, other hydrological models should be applied and their outputs analysed and compared with each other (Jiang et al. 2007; Karlsson et al. 2016).

Many researchers agree and anticipate that studies of thermal behaviour of stream and river systems will remain a growing research area in the future (Webb et al. 2008). The temperature of the water body has a direct and indirect impact on various physical, chemical and biological processes in aquatic ecosystems. Poff et al. (2002) state that increases in water temperature will cause a shift in the thermal suitability of aquatic habitats for resident species. Other scientists emphasise the threat of such consequences on future biodiversity (Bellard et al. 2012; Sternberg et al. 2015) or valuable cold-water fish (usually salmon) species (Isaak et al. 2011).

River water temperature is expected to increase as a consequence of projected higher air temperatures in the entire Lithuanian territory. However, it is important to stress that river water temperature is not influenced exclusively by climate warming. Predicting stream temperature is challenging because it is controlled by many local and cumulative natural and anthropogenic factors (Segura et al. 2015). The level of groundwater feeding can be mentioned as one of the most significant factors. Mohseni & Stefan (1999) stated that water temperature is less sensitive to air temperature when the river is groundwater dominated. However, in this investigation, the rivers from the south-eastern hydrological region (where groundwater is considered to comprise about 45% of runoff) had close air–water temperature relations.

The results of the current study indicate that according to the RCP8.5 scenario, the majority of the studied rivers are expected to warm up by more than 5 °C at the end of the 21st century. As a comparison, in the Columbia River basin average summer stream temperatures are projected to increase 5.2 °C by the 2080s under the RCP 8.5 emissions’ scenario (Ficklin et al. 2014). Changes of such thermal behaviour can have a significant impact on aquatic habitats, making the projected water warming of 2, 3 and more degrees at the end of the century a highly important issue.

The available scientific knowledge of the impact of climate change on abiotic components of freshwater ecosystems should be used for projected impact mitigation and adaptation on the new and often unfavourable living conditions. US scientists even warn that the significance of assessment of climate change effects on ecosystem services may equate with the importance of national and global security issues (Friedel 2011). The results of the current investigation are going to be used for protection of fish species and their populations under the projected climate warming. Recommendations for environmental protection institutions will be created as a measure that should be taken in order to preserve natural resources.

**CONCLUSIONS**

The current study investigated and projected the effects of changing climate on Lithuanian river runoff and water temperature. At the end of the 21st century the following changes of abiotic environmental factors under future climate change are projected: (1) an increase of air temperature; (2) positive or negative alterations of the precipitation amount depending on the projection method; (3)
a significant decrease of spring flood discharges; (4) a significant decrease of low flows of summer period; and (5) a significant increase of river water temperatures.

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